

Quality

Quality is defined as the extent to which the customer expectations are fulfilled or even exceeded. The desired quality is determined by the customer. With his demands and expectations, he determines what quality is – in both products and services. Because competition leads to increased customer expectations, quality remains a dynamic quantity. Quality is defined through product- and service-related factors which are susceptible to quantitative or qualitative analysis. The preconditions for achieving high quality are:

Quality policy: The company commitment to quality as a top-priority corporate objective,

Leadership: Employee-motivation measures,

Quality assurance.

Quality management

Quality system

All elements in a quality system and all quality-assurance measures must be systematically planned. The individual assignments and the areas of competence and responsibility are to be defined in writing (Quality-Assurance Handbook). Quality systems are also described in international standards, such as DIN ISO 9001 – 9004.

Increased requirements for defect-free products (zero-defect target) and economic considerations (defect prevention in place of sorting and reworking, or scrapping) make it imperative that preventive quality-assurance measures be applied. These serve the following objectives:

- To develop products that are insensitive to production fluctuations.
- To establish production processes to ensure that quality requirements are maintained within the specified limits.
- To apply methods which identify the sources of defects at an early stage, and which can be applied to rectify the manufacturing process in good time.

Three types of “audit” are employed in the regular monitoring of all elements in a quality system:

- System audit: Evaluation of the effectiveness of the quality system regarding its comprehensiveness and the practical application of the individual elements.
- Process audit: Evaluation of the effectiveness of the quality-management (QM) elements, confirmation of quality capability, of adherence to and suitability of particular processes, and the determination of specific measures for improvement.
- Product audit: Evaluation of the effectiveness of the QM elements performed by examining the final products or their components.

Quality management in development

At the outset, every new product which must fulfill the customer's quality and reliability demands is allocated a project specifications manual.

As early as the definition phase, its contents serve as the basis for the planning of all sample and endurance tests required to verify the new product's serviceability and reliability.

Quality assessment

At the conclusion of specific development stages, all the available data regarding quality and reliability are subjected to a quality-assessment procedure, leading to initiation of the required corrective measures. Responsible for the quality assessment are staff members from development, production engineering, and quality assurance; these, in turn, receive support from the specialists in the specialist departments.

Failure Mode and Effects Analysis (FMEA)

This cost-reduction and risk-prevention procedure is suitable for investigating the types of defects which can occur in system components and their effects on the system (for details, see “Reliability”, P. 165).

Quality management during procurement

This aspect must extend beyond the receiving inspection; it must comprise an entire system. This system must ensure that the components purchased from suppliers contribute to the reliable fulfillment of the Technical Specifications defined for the finished product.

Example of application of Failure Mode and Effects Analysis (FMEA)

BOSCH		FMEA Actuator 9 319 150 342 Part 6: Parts production and assembly of bushing holder										DEPT. FMEA PAGE DATE	FVB 75 1289940001 10 10.10.88	MEASURES V/T:	
QUALITY ASSURANCE		NO.	COMPONENT PROCESS	FUNCTION PURPOSE	DEFECT TYPE	DEFECT EFFECT	DEFECT CAUSES	DEFECT PRE- VENTION	DEFECT DETECTION	S	-	E	SxE RZ		
		1110	Assemble bushing holder	Prepare parts for soldering process	Damaged sealing sur- faces	Actuator leaking to surroundings → gasoline vapors in en- gine compart- ment	Swarf in assembly device	Wash before assembly, clean tools regularly	100 % visual inspection of soldering; surface check; 100 % visual inspection prior to pack- ing	10	2	1	20		
		1180	Solder bushing holder	Hold parts together	Part not soldered		No solder	Scan solder feed	100 % visual inspection of soldering; 100 % visual inspection of surface; 100 % leak test	10 (10	2 2	2 1	40 20)	100 % leak test of bushing- holder assembly V: FVB2 T: 01.89	
				Ensure leak- tightness	Part leaking (bubbles)		Insufficient solder	Scan solder feed	100 % visual inspection of soldering	10 (10	4 3	6 2	240 60)	100 % leak test V: FVB2 T: 01.89 + Design improve- ment at solder- ing joint V: EVA3 T: 03.89	

S = Severity of fault
V = Department responsible

A = Probability of occurrence
T = Deadline for introduction

E = Probability of detection
RZ = Risk number = S x A x E
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It is imperative that suppliers' quality capabilities be supported by modern, preventive quality-assurance techniques (e.g. SPC Statistical Process Control or FMEA). All individual requirements for the product must be specified in a clear and unambiguous manner in order to allow the subcontractor to achieve and competently evaluate comprehensive compliance with the individual quality requirements for the product. These guidelines generally are in the form of drawings, order specifications, standards, formulas, etc.

For example, the actual manufacturer of the supplied product performs the first initial sample inspection. This inspection must be reproduced by the purchaser when the product is received (with particular emphasis on the interrelationships involving manufacturing processes and the finished product), and confirmed by means of an incoming inspection.

The supplier's final or shipping inspection can take the place of the purchaser's incoming inspection in those cases where the subcontractor possesses special knowledge and/or the technical equipment necessary for carrying out specific forms of quality testing. The supplier confirms the relevant quality inspections on the products in quality certificates in accordance with DIN 55 350 or material test certificates in accordance with DIN 50 049. The test results obtained must be forwarded to the purchaser.

Quality management in production engineering

The preconditions for supplying assured quality are established in the production-planning phase. Compliance with the following conditions is required:

- Planning of the production process and material flow.
- Planning of resources requirements.
- Selection and acquisition of suitable production methods and production equipment, as well as the requisite test stands (e.g. for SPC).
- Examination of manufacturing methods, production equipment and machines to determine machine and process capability.
- Documentation of the production procedure in the production-sequence plan.
- Determination of the necessary level of employee qualification.
- Preparation of technical drawings and parts lists.

The Process FMEA provides a means of methodically anticipating potential faults in the manufacturing process and of assessing their effects on the quality of the attribute or the product. The Process FMEA is employed to discover the sources of defects, and to avoid the defects or minimize their effects. This makes it possible to initiate the necessary production and test-engineering procedures required for defect prevention.

FMEA working group

Area of operation	Product FMEA	Process FMEA	FMEA contribution
FMEA moderator			Coordination Methods
Construction (ⓧ = Responsibility)	ⓧ		Construction
Testing			Functionality
Endurance testing			Durability Climate resistance
Technical marketing			Project specifications
Customer service			Customer service
Pre-production (ⓧ = Responsibility)		ⓧ	Manufacturing verifiability procedures
Quality services			Quality and reliability assurance
Production			Production
Materials			Subcontractor supply
Miscellaneous			

Inspection planning comprises the following points:

- Analysis of the functions to be tested.
- Determination of the test criteria.
- Selection of suitable inspection methods and measuring and inspection equipment.
- Determination of the extent and frequency of the inspection.
- Documentation of the test procedure in the inspection plan.
- Planning of recording and documentation of quality data (e.g. in quality-control charts for SPC).
- Planning for control of inspection, measuring, and test equipment.
- Possible planning of quality-data documentation.

The specified inspection criteria must always include all essential characteristics of the finished products.

Suitable means for compilation and evaluation of the inspection results are to be specified for assessing the quality of products and their components, and for controlling production processes. Test results are to be processed in such a manner as to be suitable for application in open-loop and closed-loop process-control systems, fault analysis and fault rectification.

Machine and process capability

The evaluation of machine capability is to confirm performance potential in the following two areas:

- The machine under examination must operate with verifiable consistency. If necessary, this consistency must be formulated with the aid of statistical quantities, e.g. as normal distribution with mean value $\bar{x}$ and standard deviation s .
- The machine must be able to maintain production within specified tolerances. This can only be confirmed using the quantification of consistency indicated above.

Testing of machine capability is restricted to a limited period, and to the investigation of the equipment-related effects on the production process. However, it should be noted that equipment-related and non-equipment-related factors (e.g. effects of material or procedures) cannot usually be separated completely. Individual tests are designed to determine whether:

- unusual process results are recognized,
- mean values and scatter range remain stable within the measurement series (the verification limits of statistical process control are employed for this examination).

If no unusual process results are present, and the mean and the scatter range are stable, then the process is considered to be fully controlled; the suitability of the equipment is then described using the familiar statistics c_m and c_{mk} . The value for c_m only reflects the scatter range for the machine; it is calculated with the following equation:

$$c_m = (OGW - UGW) / (6 \cdot \hat{\sigma})$$

On the other hand, the value for c_{mk} reflects not only the machine's scatter range, but also the position of the mean within the tolerance range. It is essential that it be calculated for the production machinery on which adjustments are either imprecise or impossible. It is calculated as follows:

$$c_{mk} = (\bar{x} - UGW) / (3 \cdot \hat{\sigma}) \text{ or } c_{mk} = (OGW - \bar{x}) / (3 \cdot \hat{\sigma})$$

with the lesser value being valid. The definitions are:

- $\bar{x}$ Total mean value
- UGW Lower tolerance-range limit
- OGW Upper tolerance-range limit
- $\hat{\sigma}$ Estimate for process control

Bosch only designates production equipment as capable of ensuring that manufacture will result in the required product attributes when c_{mk} is at least 1.67.

Unusual process results, or an unstable mean or scatter range indicate that the process is not fully controlled. In this case, non-random influences (interference factors) are affecting the process. These must be eliminated or compensated for. The examination of machine capability is then repeated.

If the result of the machine-capability test is positive, it is followed by an examination of the process capability. This is intended to ensure that the production process is capable of consistently meeting the quality requirements placed upon it.

The examination of process capability extends over a longer period of time. All changes to the process (e.g. material

changes, tool changes or method changes) are taken into account when the scope and intervals of sample testing are determined, and then included in the examination procedure.

Once compiled, the data are subjected to a statistical analysis comparable to that employed for determining equipment performance potentials. Particular attention is devoted to ascertaining whether the process mean and process control are stable, i.e., whether the process is fully controlled. If the process is fully controlled, then the process capability is confirmed using the known statistics c_p and c_{pk} . These statistics are calculated in the same way as those for c_m and c_{mk} where the values $\bar{x}$ and $\hat{\sigma}$ from the process examination are used.

If the process is not fully controlled, calculation of c_p and c_{pk} is not permitted. In this case, the causes of the instability in the process must be either eliminated or compensated for. The process-capability analysis is then repeated.

Bosch designates a process as capable of ensuring the required product attributes only in cases where c_{pk} is at least 1.33.

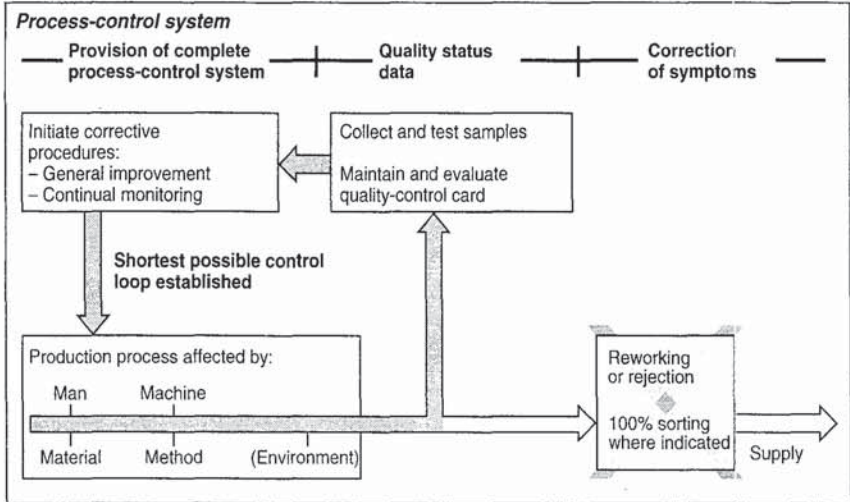
Machine- and process-capability analysis are necessary preliminary checks prior to introduction of SPC. However, both investigations are also important for processes which are not controlled by SPC, as the required potential must be confirmed for each type of process.

Statistical Process Control (SPC)
SPC is a process-control system intended to assist in the prevention of errors and their associated costs. SPC is employed in production, being applied for attributes which are vital to operation (for details, see "Technical Statistics", P. 160).

Measuring and inspection equipment

The measuring and inspection equipment must be able to demonstrate whether the inspection features of the finished product conform to the prescribed specifications. Measuring and inspection equipment must be monitored, calibrated and maintained. Uncertainty of measurement is to be considered when using measuring and inspection equipment. It must be minimal relative to the tolerance range for the attribute being tested. With measuring and inspection equipment, attention is to be paid to:

- Defining the measurements to be performed, the required precision and the suitable measuring and inspection equipment.
- Ensuring that the measuring and inspection equipment meets precision requirements, i.e. the uncertainty of measurement is generally not to exceed 10% of the tolerance range.
- All measuring and inspection equipment and measurement systems used for



- product quality-assurance are to be specified in an inspection plan; they must be labeled, and are to be calibrated and adjusted at prescribed intervals.
- Calibration procedures must be specified. These must comprise individual data on the type of unit, its identification, application area and calibration intervals, and are also to include the steps to be taken in case of unsatisfactory results.
 - Measuring and inspection equipment must be provided with appropriate identification verifying their calibration status.
 - Calibration records (histories) are to be maintained.
 - The appropriate environmental conditions for calibrating, testing and measurement must be maintained.
 - Measuring and inspection equipment is to be carefully stored and protected against contamination in order to maintain consistent levels of precision and suitability for use.
 - The measuring and inspection equipment and the software are to be protected against any influences which might invalidate their calibration.

Control of inspection, measuring, and test equipment: Type and extent

Satisfactory arrangements for monitoring test equipment embrace all measuring devices employed in development, production, assembly and in customer ser-

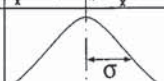
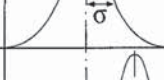
vice. This category includes calipers, unit standards, instruments, recording devices, and special test equipment along with its ancillary computer software. In addition, the equipment, mounts and clamps, and instruments employed for process control are also monitored.

Procedures which extend to include the equipment and the abilities of the operator are employed in evaluating whether a test process is controlled. Measurement errors are compared with the quality specifications. Appropriate corrective actions are to be introduced when the requirements for precision and function in measuring and inspection equipment are no longer satisfied.

Measuring instruments subject to calibration

German legal requirements on weights and measures stipulate that calibration of measuring devices which are for use in "business transactions" be officially certified in those cases where the results of their measurements are employed to determine the price of goods or energy. This category includes equipment for measuring length, surface area, volume and mass, and thermal and electrical energy. If these conditions apply, then the calibration of the measuring instruments concerned must be officially certified. Continuing compliance must then be monitored by an official or an officially approved agency.

Relationship between measurement results, statistical analysis and process capability

Process	←Tolerance T→	Status	Process capability
Individual values		Unsure	Not calculated
Statistical analysis		Result negative due to excessive variance	$C_p = \frac{T}{6\sigma} = 0.67$ Outside T by 4.6%
Minimum requirement		Result positive, low variance Mean value maintained	$C_p = 1.33$ Outside T by 63 ppm
Mean tolerance value displaced		Result negative despite low variance	$C_p = 2.0$ but $C_{pk} = \frac{D}{3\sigma} = 0.67$ i.e. outside T by 2.3%

Technical statistics

Purpose of statistics

Descriptive statistics

To describe sets of similar units with specific, different characteristic values using statistical characteristics which allow objective comparisons and evaluations.

Rating statistics

To provide information on the statistical characteristics of larger sets (populations) based on relatively few individual data (samples).

Because such statements are based on the laws of chance and the theory of probability, their validity is always subject to a certain level of confidence, usually 95% in the field of engineering.

Examples of populations:

- All products of the same type produced under constant manufacturing conditions.
- Set of all the possible results of a measurement under unchanging conditions.

There are two different types of characteristics:

- Quantitative characteristics, e.g., physical quantities (referred to as "measured values"),
- Attribute characteristics, e.g. "OK" or "Defective" etc. (referred to as "test results" in the following).

Statistical analysis methods provide valuable assistance for ensuring and improving quality standards in industrial products. Today's levels of vehicle reliability would be impossible without it.

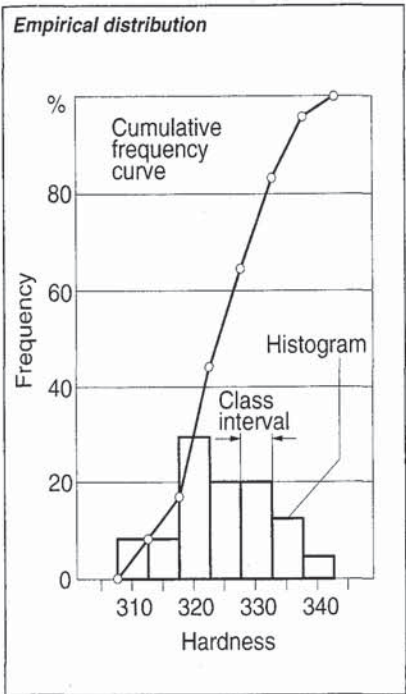
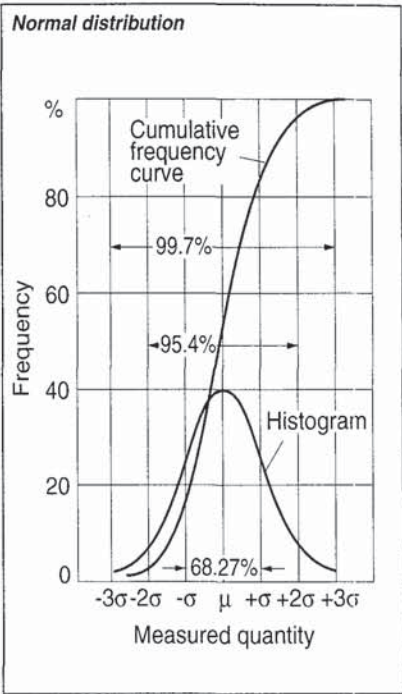
Presentation of measured values

- N Population size: the number of all items which form the basis of statistical analysis
- n Number of measured values in the sample

P_A	Confidence level
x	Individual measured value
R	Range: $R = x_{\max} - x_{\min}$
k	Number of classes into which R is divided. $k = \sqrt{n}$ (at least 5)
w	Class width
i	Ordinal number of measured values (as subscript)
j	Ordinal number of classes (as subscript)
x_j	Midpoint of class no. j
n_j	Absolute frequency of class no. j : number of measured values in class no. j
h_j	Frequency in class no. j , $h_j = n_j/n$
h_j/w	Frequency density
G_j	Cumulative absolute frequency: absolute frequency summed up to a particular class
	$G_j = \sum_{r=1}^j n_r$
H_j	Cumulative frequency = G_j/n
$F(x)$	Distribution function: probability for values $\leq x$
$f(x)$	Frequency-density function $\frac{dF(x)}{dx}$
μ	Arithmetic mean of population
$\bar{x}$	Arithmetic mean of a sample
	$\bar{x} = \sum_{i=1}^n x_i/n$
$\bar{\bar{x}}$	Arithmetic mean of several $\bar{x}$ values
σ	Standard deviation of population
s	Standard deviation of sample
	$s = \sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 / (n - 1)}$
V	Variation coefficient $V = s/\bar{x}$
u	Dispersion factor
X, Y	Random variable
Z	

Histogram and cumulative frequency curve of an empirical distribution

The simplest way of clearly presenting a larger number of characteristic values is the histogram (frequency diagram). In the case of attributes or variables with few discrete values, bars are drawn over the characteristic values whose height is proportional to the relative frequency of the values, i.e. the frequency h_j of the attribute j in proportion from the total number of all the values $\sum_j h_j$.



In the case of variable attributes with a continuous range of values, the range is divided into k classes and the bars entered over the class midpoints. If the classes are not all the same size, the bars become rectangles whose areas are proportional to the relative frequencies of the classes. Thus, in these cases, the heights of the rectangles are also proportional to the frequency density.

If conclusions are to be drawn from the sample presentation described concerning the population, it is essential to define the classes in such a way that there are at least five values in each class.

Another way of presenting the distribution of attributes is the cumulative frequency curve. The advantage of this curve for variable attributes is that for each value or each interval the percentage of measured values below or above can easily be read off (estimate of fraction defectives outside the tolerance). The cumulative curve can be determined from the histogram by summing the relative frequencies up to the relevant value or interval. For the population, it thus represents the integral over the density function.

Distributions and statistical parameters

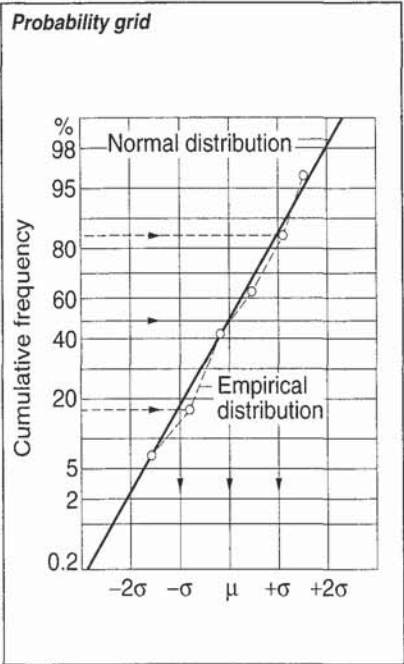
A random variable X is characterized by its distribution. The distribution function $F(x)$ describes the relationship between the variable value x and the cumulative frequency or probability for values $\leq x$. In empirical distributions, this function corresponds to the cumulative frequency curve. The histogram corresponds to the density function $f(x)$.

The most important parameters of a distribution are the arithmetic mean μ and the standard deviation σ .

Normal distribution

Normal, or Gaussian, distribution is the mathematically idealized limit case which always results when many mutually independent random effects are added together. The probability-density function of the Gaussian distribution clearly defined by μ and σ forms a symmetrical bell-shaped curve.

The total area under the bell-shaped curve corresponds to $1 = 100\%$. The standard deviation σ and its multiples allow the delimitation of specific areas with the boundaries $\mu \pm u\sigma$ in which $P\%$ of the



values fall (Table 1). The percentages $\alpha = (100 - P)/2$ lie outside these areas on either side.

Empirical and normal distribution in probability grid
In a "probability grid", the ordinate is distorted in such a way that the S-shaped cumulative frequency curve is transformed into a straight line.
Determination of μ and σ from the probability grid:
1. Read off μ at 50 % cumulative frequency.
2. Read off abscissa values at 16 % and 84 %.
The difference corresponds to 2σ .

Sums of random variables
For the mean and standard deviation of a random variable
 $Z = a \cdot X + b \cdot Y$, created by the linear combination of 2 independently distributed random variables X and Y , the following apply:
$$\mu_z = a \cdot \mu_x + b \cdot \mu_y$$
$$\sigma_z^2 = a^2 \cdot \sigma_x^2 + b^2 \cdot \sigma_y^2$$

Typical applications
1. Fits.
Hole diameter: x .
Shaft diameter: y .
Clearance: $z = x - y$.
For $\sigma_x = \sigma_y$ the following applies:
 $\sigma_z^2 = 2 \cdot \sigma_x^2$

2. Combined dimension.
If the individual dimensions are statistically independently distributed about their mean tolerances, the tolerance for the combined dimension can be calculated by quadratic addition (cf. DIN 7186).

Evaluation of series of measurements

Random interval for $\bar{x}$ and s
(direct conclusion)
If many samples each containing n values are taken from one and the same population with the mean μ and the standard deviation σ , the mean values $\bar{x}_1, \bar{x}_2, \dots$ of the samples are dispersed with the standard deviation

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \text{ about the true value } \mu.$$

In a similar way, random intervals can be defined for s and R .

Table 1. Value frequency P within and α outside $\pm u\sigma$

u	1.00	1.28	1.64	1.96	2.00	2.33	2.58	3.00	3.29
$P\%$	68.27	80	90	95	95.4	98	99	99.7	99.9
$\alpha\%$	15.86	10	5	2.5	2.3	1	0.5	0.15	0.05

Quantity	Random interval	
	Lower limit	Upper limit
$\bar{x}$	$\mu - u \frac{\sigma}{\sqrt{n}}$	$\mu + u \frac{\sigma}{\sqrt{n}}$
S	$D_u \cdot \sigma$	$D_o \cdot \sigma$
R	$D_u \cdot \sigma \cdot d_n$	$D_o \cdot \sigma \cdot d_n$

D_u and D_o as functions of n and P from Tables 1 and 2.

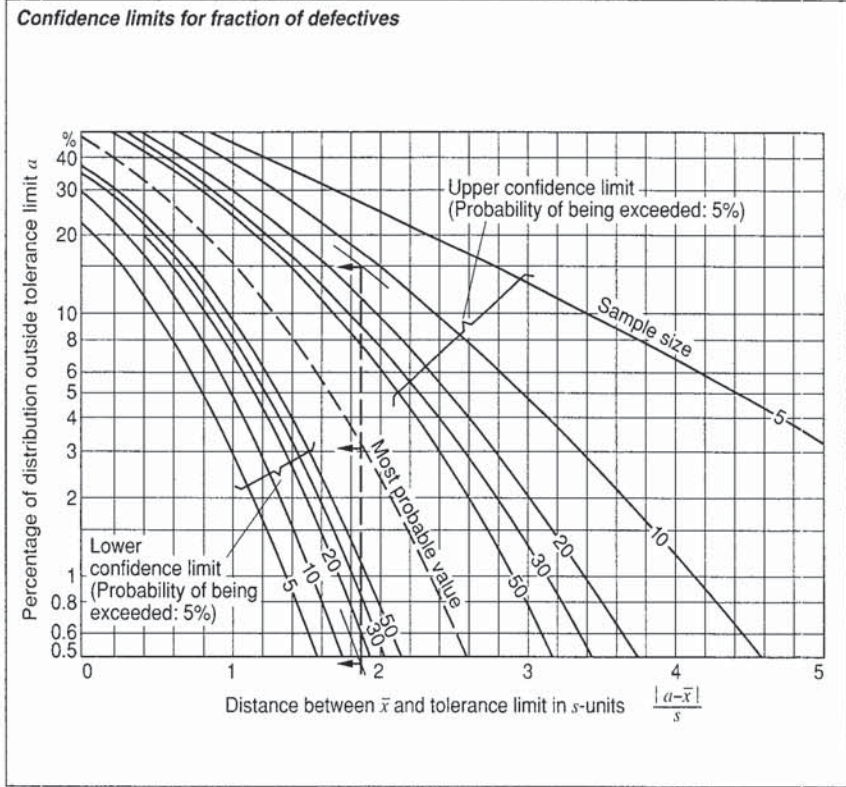
Table 2. Auxiliary constants for evaluation of measurement series

n	d_n	t values for $P =$			D_u	D_o
		90 %	95 %	99 %		
2	1.13	6.31	12.7	63.7	0.03	2.24
3	1.69	2.92	4.30	9.92	0.16	1.92
5	2.33	2.13	2.78	4.60	0.35	1.67
10	3.08	1.83	2.26	3.25	0.55	1.45
20	3.74	1.73	2.09	2.86	0.68	1.32
50	—	1.68	2.01	2.68	0.80	1.20
∞	—	1.65	1.96	2.58	1.00	1.00

Confidence intervals for μ and σ
(conclusion)
If only samples with x and s are known and a statement is to be made on the true mean value μ resulting from an infinite number of measurements, a so-called confidence interval can be specified which features μ with a probability of $P_A\%$. The same holds true for σ .

Quantity	Confidence interval	
	Lower limit	Upper limit
μ	$\bar{x} - t \frac{s}{\sqrt{n}}$	$\bar{x} + t \frac{s}{\sqrt{n}}$
σ	$\frac{s}{D_o}$	$\frac{s}{D_u}$

t , D_o and D_u from Table 2.



Comparison of mean values

Two samples with values of n_1 and n_2 have the same standard deviations $s_1 = s_2$ but different mean values $\bar{x}_1 \neq \bar{x}_2$. The confidence interval for the difference $\mu_1 - \mu_2 = 0$ is:

$$\pm t \cdot s_A \cdot \sqrt{1/n_1 + 1/n_2}$$
$$s_A^2 = ((n_1 - 1) s_1^2 + (n_2 - 1) s_2^2) / (n' - 1)$$
$$n' = n_1 + n_2 - 1$$
 determines t in Table 2.

If the difference $x_1 - x_2$ is outside this confidence interval, the two samples come with confidence level P from different populations (e.g. different manufacturing conditions).

Estimation of nonconforming fractions

The percentage of parts lying outside the tolerance limit a is to be estimated based on $\bar{x}$ and s from a sample series.

Calculation procedure:
If μ and σ are known, then the percentage outside a in Table 1 or in the Figure "Confidence limits for nonconforming fractions" ("most probable value" curve) is determined by:

$$u = |a - \mu| / \sigma.$$

A value of e.g. $u = 1.65$ corresponds to a percentage of 5%. But now only $\bar{x}$ and s of the sample are known, not the values μ and σ of the population. As these values are random, the nonconforming fraction can only be specified in terms of the confidence range in which it lies with a particular probability.

In the figure, the confidence limits can be read off as a function of $|a - \bar{x}| / s$ which are exceeded only with a probability of 5%. Separate analyses are required for each of the two tolerance limits.

Example:

Prescribed tolerance for ground rollers $14^{+0.016}_{-0.043}$ mm.

Tested are 14 parts of 13.961 to 13.983 mm. $\bar{x} = 13.972$ mm; $R = 0.022$ mm.

Estimated value for s from R with d_n from Table 2:

$$s = 0.022 / 3.5 = 0.0063$$

Upper tolerance limit exceeded:

$$\frac{|a - \bar{x}|}{s} = \frac{13.984 - 13.972}{0.0063} = \frac{0.012}{0.0063} = 1.9$$

Referring to the figure:

- Upper confidence limit $\approx 15\%$
- Most probable value $\approx 3.1\%$
- Lowest confidence limit $\approx 0.5\%$

Lower tolerance limit exceeded:

$$\frac{|a - \bar{x}|}{s} = \frac{|13.957 - 13.972|}{0.0063} = \frac{0.015}{0.0063} = 2.38$$

Referring to the figure:

- Upper confidence limit $\approx 9\%$
- Most probable value $\approx 1\%$
- Lowest confidence limit $< 0.5\%$

Statistical Process Control (SPC)

Quality-control charts are employed to ensure consistent quality in manufacturing processes. Small samples are tested at specified intervals; the values $\bar{x}$ and R are entered for test results while the defects are entered for attribute testing.

- T_{lo}, T_{up} Lower/upper tolerance limits,
- T Difference between upper and lower tolerance limit (tolerance range),
- $T = T_{lo} - T_{up}, T_m = (T_{lo} + T_{up}) / 2,$
- $\bar{x}, \bar{R}$ Values from ≥ 20 samples,
- $\sigma = \bar{R} / d_n =$ Standard deviation,
- $c_p = T / (6 \times \sigma) =$ Process capability.

- A process is considered to be "controlled" if 1) $c_p > 1$ (better: $c_p \geq 1.33$),
- 2) the curve displays no unusual variations (no trends, etc.),
- 3) $\bar{x}$ and R lie within the "action limits" of the corresponding random intervals.

Table 3 shows the approximate values for action limits as a percentage of T . The calculation is based upon the assumptions that values are: 99.7% random intervals and $c_p = 1$.

Table 3. Action limits as % of T

n	3	4	5	6	7	8	10	12	15
$R/T < \%$	72	78	82	84	86	88	91	93	95
$(\bar{x} - T_m) < \%$	29	25	22	20	19	18	16	14	13

Weibull distribution of service lives

Weibull distribution has gained acceptance as the standard in the investigation of the service lives of technical products. Its distribution function (probability for service lives $\leq t$) is:

$F(t) = 1 - e^{-(t/T)^b}$
Survival probability (reliability function)
 $R(t) = 1 - F(t)$
Failure rate (failures per unit time referred to remaining products)
 $\lambda(t) = f(t) / R(t)$
where

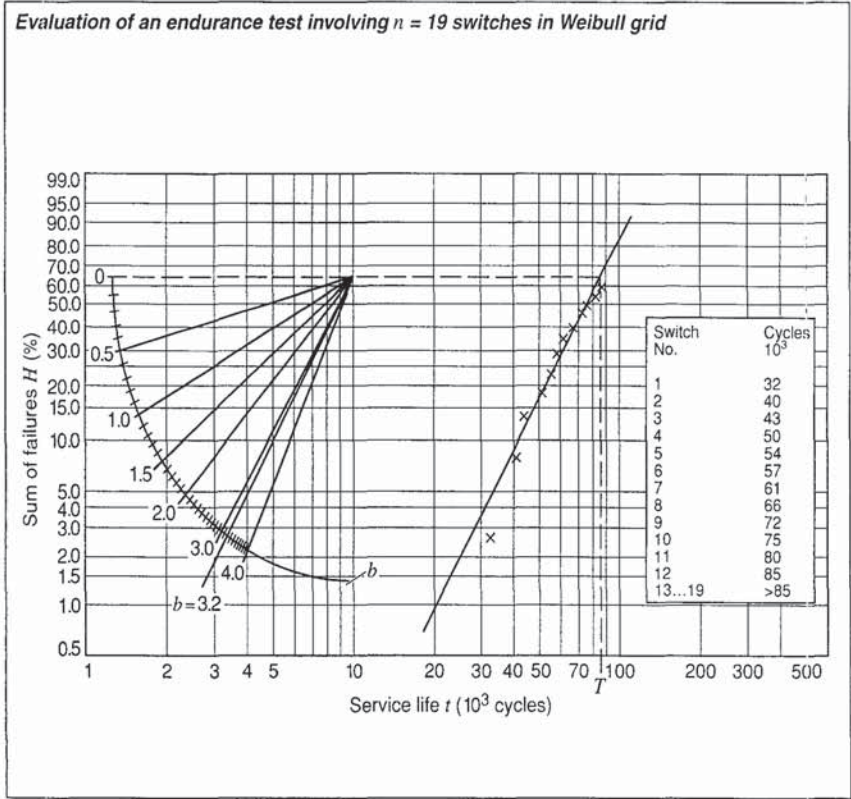
- T Characteristic service life, corresponding sum of failures 63.2%.
- b Failure steepness (Weibull slope),
 - $b < 1$: falling (early failures)
 - $b = 1$: constant (random failures)
 - $b > 1$: rising (wear)

In the Weibull grid with abscissa $\ln t$ and ordinate $\ln (-\ln R[t])$, $F(t)$ becomes a straight line.

Evaluation of an endurance test involving n test specimens:

The diagram shows the evaluation of an endurance test involving $n = 19$ switches, of which $r = 12$ have failed. Against the service lives t ordered according to length in cycles, the sum of failures is plotted as $H = (i - 0.5)/n$.

The result is:
 $T = 83 \cdot 10^3$ cycles
 $b = 3.2$ (wear).
 T and b are random values like $\bar{x}$ and s . Approximate confidence intervals ($n \geq 50$) for the "true values" are provided by the formulae:
 $T \pm (u/\sqrt{n}) \cdot (T/b)$
 $b - 0.5 \cdot (u/\sqrt{n}) \cdot b \dots b + (u/\sqrt{n}) \cdot b$
 u from Table 1.



For incomplete observations ($r < n$):

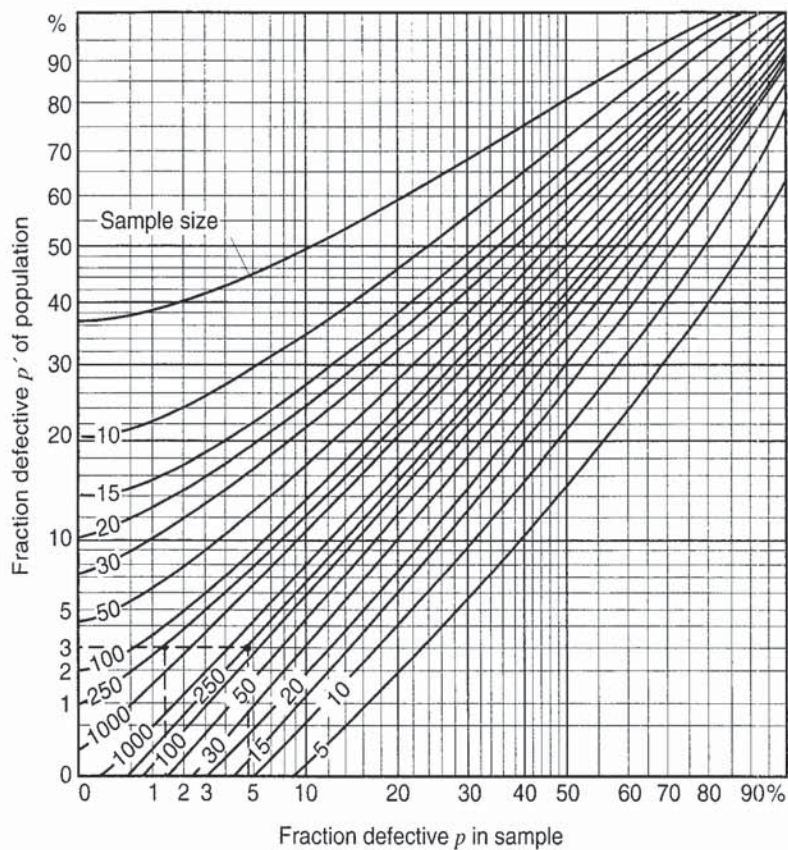
$$n' \approx r \cdot (1 + (r/n))/2$$

T , b are therefore less precisely defined by r failures at $r < n$ than at $r = n$. The proportion exceeding a specific life expectancy is estimated in the following section.

Statistical evaluation of test results

- N Size of population (batch). An attribute divides the batch into two classes, e.g. "failed" and "OK".
- n Number of sample units
- I Number of defects in batch
- i Number of defects in sample
- p Defective fraction in sample
- $p = i/n$
- p' Defective fraction in batch
- $p' = I/N$.

Random and confidence limits for fractions defective (binomial distribution)
Probability of each limit being exceeded $\alpha = 10\%$.



Distribution of defective fraction p in random samples

The number of defectives i within the sample is a random variable. Larger batches ($N > 10 \cdot n$) are characterized by binomial distribution, expected value: $E(i) = n \cdot p'$,

Standard deviation:
 $\sigma_i = \sqrt{n \cdot p' \cdot (1 - p')}$.

Random ranges for p (p' known) and confidence intervals for p' (p known) dependent on n are provided by the diagram on P. 162 with an exceeding probability of $\alpha = 10\%$ for each limit.

For the range $p' < 5\%$, frequently encountered in practice, binomial distribution is replaced by Poisson's law of infrequent events which is exclusively dependent on $n \cdot p'$ with $E(i) = n \cdot p'$, $\sigma_i = \sqrt{n \cdot p'}$.

Examples:

1. Binomial distribution (diagram P. 162)
In endurance testing with $n = 20$ units, $i = 2$ units have failed after extended usage.

What percentage p' of the series will not achieve the corresponding service life T ?

Percentage in random sample $p = 2/20 = 10\%$.

At $p = 10\%$, $n = 20$, the diagram provides the following figures:

$$p_u' = 2.8\%, p_o' = 24\%.$$

With constant quality, the percentage with a service life $< T$ will lie within this range.

2. Poisson distribution (Table 4)

During receiving inspection, a random sampling of $n = 500$ parts found $i = 1$ part which was out of tolerance.

What is the maximum percentage of defective parts in the batch as expressed with 90 % probability?

At $i = 1$, $\alpha = 10\%$, Table 4 provides:

$$np_o' = 3.89$$

$$p_o' = 3.89/500 = 7.78\%.$$

Approximation formula for Poisson distribution

The approximate value for $i > 10$ can be derived using:

$$n \cdot p' = i + u \cdot \sqrt{i} + k$$

(see Table 4 for u, k).

Example for Poisson approximation:

In a preproduction series consisting of $n = 10\,000$ units, there were $i = 17$ warranty claims. With 97.5 % probability, what is the limit for warranty claims which will not be exceeded in normal series production if identical conditions are maintained?

Inserting the values from Table 4 into the approximation formula given above provides the following:

$$np_o' = 17 + 1.96 \cdot \sqrt{17} + 2 = 27.08$$

$$p_o' = 27.08/10\,000 = 2.7\%.$$

Table 4. Confidence limits for infrequent events

Obs. no. i	Lower limit np_u' Probability of being exceeded		Upper limit np_o' Probability of being exceeded	
	2.5 %	10 %	10 %	2.5 %
0	—	—	2.30	3.69
1	0.025	0.105	3.89	5.57
2	0.242	0.532	5.32	7.22
3	0.619	1.10	6.68	8.77
4	1.09	1.74	8.00	10.24
5	1.62	2.43	9.27	11.67
6	2.20	3.15	10.53	13.06
7	2.81	3.89	11.77	14.42
8	3.45	4.66	12.99	15.76
9	4.12	5.43	14.21	17.08
10	4.80	6.22	15.41	18.39
u	- 1.96	- 1.28	+ 1.28	+ 1.96
k	+ 1.0	+ 0.2	+ 1.2	+ 2.0

Measurement: basic terms

Measurements can only be used as the basis for responsible decisions if their limits of error are known. Here, statistical terms are used.

Definition of terms (as per DIN 1319):

Measured variable

Physical variable which is measured (length, density, etc.).

Measured value

Particular value of the measured variables, e.g. 3 m.

Measurement result

Value calculated from one or more measured values, e.g. mean $\bar{x}$.

Measurement error $F = x_a - x_r$

x_a indicated measured value;

x_r "correct" measured value.

Causes: measured object, measurement equipment, measurement procedure, environment, observer.

Relative measurement error

Normally: F/x_r

For designation of measuring devices F/x_a , where x_a = full-scale deflection of measuring device.

Systematic measurement errors

Measurement errors which, under the same conditions, have the same magnitude and sign.

Those systematic errors which can be detected are to be corrected $B = -F$, otherwise the measurement result is incorrect. Systematic errors which cannot be detected are to be estimated (f).

Random measurement errors

Measurement errors whose magnitudes and signs are randomly dispersed. Estimated using the standard deviation s .

Result of a series of measurements

If n measured values x_i are measured under the same conditions, the following should be specified as the measurement result:

$y = \bar{x}_E \pm u$ Confidence limits for correct measured value, where:

$\bar{x}_E = \bar{x} + B$ Corrected mean value

$u = t \cdot s / \sqrt{n} + |f|$ Measurement uncertainty.

Calculation of s P. 156,

for t , see Table 2 P. 159,

f Non-detected systematic errors.

Separation of measurement and manufacturing accuracy

On each of n products, a characteristic x_i is measured twice with measurement error f_{ik} :

$$y_{ik} = x_i + f_{ik} \quad (i = 1, \dots, n; k = 1, 2)$$

The differences between the 2 measured values on the same product contain 2 measurement errors:

$$z_i = y_{i1} - y_{i2} = f_{i1} - f_{i2}$$

$$\sigma_z^2 = 2 \sigma_f^2$$

$$\sigma_y^2 = \sigma_x^2 + \sigma_f^2$$

The last two relationships can be used to determine the standard deviation σ_f of the measurement errors and the corrected standard deviation σ_x of the product characteristic x .

Standards

DIN 55 303 Statistical assessment of data

DIN 53 804 Statistical assessments

DIN 55 350 Quality assurance and statistics terms

DIN 40 080 Regulations and tables for attributive sampling

DIN 7186 Statistical tolerances

DIN/ISO 9000 Quality systems

DGQ-11-04 Quality-assurance terms and formulas (Beuth)

Literature

Graf, Henning, Stange: Formeln und Tabellen der Statistik (Formulas and tables for statistics) Springer-Verlag, Berlin, 1956;

Rauhut: Berechnung der Lebensdauer-Verteilung (Calculation of service life distribution) Glückauf-Verlag, Essen, 1982.

Reliability

According to DIN 40041, reliability is the sum total of those characteristics in the unit under investigation which exert an effect on the unit's ability to achieve specified requirements under given conditions during a specified period of time. Reliability is a constituent element of quality ("reliability is quality based on time").

The essential concept here is the word dependability. Dependability comprises the terms reliability, availability, safety, security and maintainability. Dependability therefore equates to the confidence placed in a service which is to be provided by a system.

Reliability quantifies availability; it is the probability that at any given time a system will prove to be fully operational. The failure rate is the conditional probability density of a component failing before time $t+dt$ provided it has survived beyond time t . The failure rate generally has the shape of a "bathtub curve", which can be described as the superimposition of three Weibull distributions with varying failure steepness components (see Chapter "Technical statistics").

Failure in electronic components is generally spontaneous, with no advance indication of impending defects. This condition is described by a constant failure rate (middle section of the curve). Neither quality control nor preventive maintenance can prevent such failures. Failures caused by incorrect component selection,

excessive loads or abuse or manufacturing defects show a "burn-in behavior", described by a failure rate that falls with time while ageing of a component is represented by a rising failure rate (left or right section of the curve).

Reliability analysis and prediction

Mutually supplementary analysis methods are applied to determine the potential failure risk associated with a product, i.e. to discover all possible effects of operational and internal failure, as well as external interference factors (e.g. operator error); these methods are used in different phases of the product's life cycle. Mainly FMEA and fault-tree analysis are used in the development of motor vehicles.

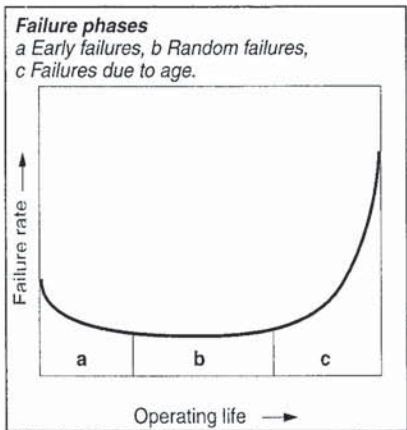
FMEA (DIN 25448, IEC 812)

FMEA (Failure Mode and Effects Analysis) is a "bottom-up" analysis. Starting from faults at the lowest level of the system hierarchy (generally components in design FMEA, function blocks in system FMEA, work steps in process FMEA), the analysis examines the way in which they spread to higher levels. In this way, all those critical system states caused by individual failures are detected and also evaluated in relation to each other. FMEA can be used in various stages of development and production.

Design FMEA: Under the precondition that the parts are manufactured in accordance with their drawings, products/components are examined for conformity between design and specifications in order to avoid errors in system design and to facilitate detection of field risks.

Process FMEA: Under the precondition that the specifications are correct, the process of product manufacture is examined for conformity with the drawings in order to avoid manufacturing errors.

System FMEA: The system components are examined as to their correct combined operation in order to avoid errors in system design and to facilitate detection of field risks.



Fault-tree analysis (DIN 25 424)

Fault-tree analysis (FTA) is a "top-down" analysis procedure, which permits quantitative assessment of probabilities. Starting from the undesirable event (top event), all the conceivable causes are enumerated, even combinations of individual failures. When the occurrence probabilities of individual failures are known, it is possible to calculate the probability of the undesirable event occurring. For this purpose, above all for electrical components, there are data collections of failure rates such as Mil Hdbk 217E or SAE 870050. However, their suitability for use with motor vehicles must be critically checked in individual cases.

Reliability enhancement

System reliability can always be improved by avoiding errors or narrowing tolerances. Preventive measures include e.g. selecting more reliable components with higher permissible loads; or (for electronic systems), since the availability of systems declines markedly as the number of components increases, reducing the number of components and thus connections through increased integration. As a rule of thumb, purely electronic components such as transistors or integrated circuits are responsible for 10% of failures and sensors and final controlling elements for 30%; however the connections between components and with the outside world are responsible for 60% of failures. If preventive measures do not prove sufficient, then fault-tolerance measures (e.g. multi-channel circuitry, self-monitoring) must be implemented in order to mask the effects of a defect.

Reliability planning

In the case of products to be newly developed, the reliability growth management procedure (RG, Mil Hdbk 189) provides a planning basis for the extent of testing work required to achieve a reliability target depending on the reliability initially available.

In the course of the development of a product, its reliability improves thanks to the causes of observed failures being an-

alyzed and eliminated as far as possible. Strictly speaking, a statistical evaluation of the reliability of a product in its final version can only be started at the end of its development. However, in the case of the service lives demanded in the automobile industry, any such evaluation requires so much time as to delay the series launch. Under certain preconditions, the RG method allows engineers to assess the reliability of a product at any stage in its development. This assessment is based on the data of earlier product versions and the effectiveness of the failure-correction measures introduced. In this way, this procedure on the one hand reduces the time needed until series launch and on the other hand increases the available data volume and thus the confidence level.

If the current average service life MTTF (Mean Time To Failure) is plotted on a log-log scale against the cumulated operating time (total test time of all the test specimens), experience shows that on average this MTTF value increases in a straight line. Depending on the product and the effort expended, the upwards gradient of this line will be between 0.35 and 0.5. This empirical relationship between testing effort and achieved reliability can be used for planning.

A comparison between planning and current status can be made at any time. As the RG program progresses, intermediate reliability targets, specified in advance, must also be met. When planning the test program, it is essential to strike an acceptable balance between testing time, testing effort and available resources, and also to make a realistic estimate of the possible reliability gains.

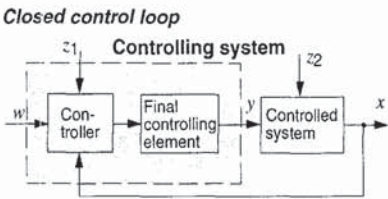
Control engineering

Terms and definitions (in accordance with DIN 19226)

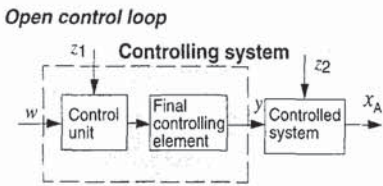
Closed-loop control	Open-loop control
<p>Closed-loop control</p> <p>Closed-loop control is a process by which a variable, the variable to be controlled (controlled variable x), is continuously recorded, compared with another variable, the reference variable w_1, and influenced according to the result of this comparison in the sense of an adaptation to the reference variable. The ensuing action takes place in a closed control loop.</p> <p>The function of closed-loop control is to adapt the value of the controlled variable to the value specified by the reference variable in spite of disturbances even if the given conditions do not allow for a perfect match.</p>	<p>Open-loop control</p> <p>Open-loop control is the process in a system in which one or more variables as input variables influence other variables as output variables on account of the rules characteristic of that system.</p> <p>This type of control is characterized by the open action via the individual transfer element or the open control loop.</p> <p>The term "control" is often used not only to denote the control process itself but also the entire system in which the control function takes place.</p>
<p>Closed control loop</p> <p>The closed control loop is formed by all the elements which take part in the closed action of the control operation.</p> <p>The control loop is a closed path of action which acts in one direction. The controlled variable x acts in a circular structure in the form of negative feedback back on itself.</p> <p>In contrast to open-loop control, closed-loop control takes into account the influence of all the disturbances (z_1, z_2) in the control loop.</p> <p>The closed control loop is subdivided into controlled system and controlling system.</p>	<p>Open control loop</p> <p>An open control loop is an arrangement of elements (systems) which act on each other in a chain structure.</p> <p>An open control loop as a whole can be part of a higher-level system and interact in any fashion with other systems.</p> <p>An open control loop can only counter the effect of the disturbance which is measured by the control unit (e.g. z_1); other disturbances (e.g. z_2) are unaffected.</p> <p>The open control loop is subdivided into controlled system and controlling system.</p>

Controlling system (open and closed loops)
The open-loop or closed-loop controlling system is that part of the control loop which acts on the controlled system via the final-controlling element as determined by the control parameters.

System boundaries
The open-loop and closed-loop controlling systems include all those devices and elements which act directly to produce the desired condition within the control circuit.



Input variables and output variable of closed-loop controlling system
The input variables to the controlling system are the controlled variable x , the reference variable w and the disturbance(s) z_1 . The output variable from the controlling system is the manipulated variable y .



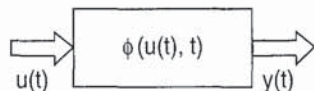
Input variables and output variable of open-loop controlling system
The input variables to the controlling system are the reference variable w and the disturbance(s) z_1 . The output variable from the controlling system is the manipulated variable y .

Closed-loop control	Open-loop control
<p>Controlled system (open and closed loops) The open-loop or closed-loop controlled system is that part of the control loop which represents the area of the system to be influenced according to the function.</p>	
<p>Input variables and output variable of closed-loop controlled system The input variables to the controlled system are the manipulated variable y and the disturbances z_2. The output variable from the controlled system is the controlled variable x.</p>	<p>Input variable and output variable of open-loop controlled system The input variable is the manipulated variable y. The output variable is the object variable x_A or an output variable which influences the object variable in a predetermined manner.</p>
<p>Transfer elements and system elements Open- and closed-loop controls can be subdivided into elements along the control loop. In terms of equipment design and function these are called system elements and transfer elements, respectively. In terms of closed- or open-loop control function, only the relationship between the variables and their values which act upon one another in the system are described.</p>	
<p>Loop, direction of control action Both the open control loop and the closed control loop comprise individual elements (or systems) which are connected together to form a loop. The loop is that path along which open- or closed-loop control takes place. The direction of control action is the direction in which the control function operates. The loop and the direction of control action need not necessarily coincide with the path and the direction of corresponding energy and mass flows.</p>	
<p>Final controlling element, control point The final controlling element is that element which is located at the upstream end of the controlled system, and which directly affects the flow of mass or energy. The location at which this action takes place is called the control point.</p>	
<p>Disturbance point The disturbance point is the location at which a variable not controlled by the system acts on the loop, thereby adversely affecting the condition which the control is designed to maintain.</p>	
<p>Manipulated variable y, manipulating range Y_h The manipulated variable y is both the output variable of the controlling system and the input variable of the controlled system. It transfers the action of the controlling system to the controlled system. The manipulating range Y_h is the range within which the manipulated variable can be adjusted.</p>	
<p>Reference variable w, reference-variable range W_h The reference variable w of an open- or closed-loop control is a variable which is not acted on directly by the control; it is input to the loop from outside the control, and is that variable whose value is to be reflected by the output variable in accordance with the control parameters. The reference-variable range W_h is that range within which the reference variable w of an open- or closed-loop control may lie.</p>	
<p>Disturbances z, disturbance range Z_h Disturbances z in open- and closed-loop controls are all variables acting from outside the control which adversely affect the action of the control. In many cases, the most important disturbance is the load or the throughput through the system. The disturbance range Z_h is that range within which the disturbance may lie without adversely affecting the operation of the control.</p>	
<p>Object variable x_A, object range X_{Ah} The object variable x_A of an open- or closed-loop control is that variable which the control is intended to influence. The object range X_{Ah} of an open- or closed-loop control is that range within which the object variable may lie, with full functional capability of the control.</p>	

Control methods

Transfer elements

Transfer elements are the basic modules and core elements for the control-engineering analysis and synthesis of dynamic systems. They each contain an illustration specification which allows an output variable to be clearly assigned to each input variable that is permitted for the corresponding transfer element. The general graphical representation of a transfer element is the block diagram (see illustration).



The illustration specification ϕ is often termed the operator. With the operator ϕ , the functional relationship between the input and output variables of a transfer element can be described by

$$y(t) = \phi(u(t), t).$$

A summary of the simplest transfer elements can be found in the accompanying table.

A particular position among the general transfer elements is taken up by linear time-invariant transfer elements. For these elements, the following superposition principle applies

$$\phi(u_1(t) + u_2(t)) = \phi(u_1(t)) + \phi(u_2(t))$$

together with the condition of time invariance

$$y(t) = \phi(u(t)) \rightarrow y(t-T) = \phi(u(t-T)), T > 0.$$

With the transfer elements connected to each other by the action lines, it is possible to depict complex dynamic systems such as e.g. a DC motor, hydraulic systems, mechatronic servo-systems etc.

Controller design

A series of analytical and synthesizing processes are available for application in control engineering. Control engineers distinguish here between time-range and frequency-range procedures. A classical

and effective example of the frequency-range approach is the design of controllers using Bode diagrams. An efficient time-range procedure is the design of a state controller by means of pole specification or the Riccati controller.

Many of the problems posed by the requirements of control engineering are solved by using certain controller types which are composed as far as possible of the following four transfer elements:

- *P* element (proportional-action transfer element),
- *I* element (integral-action transfer element),
- *D* element (derivative-action transfer element),
- *P-T_i* element (1st order time-delay element).

Parallel connection on the input side, addition of the output variables from the three transfer elements *P*, *I*, *D* and downstream connection of the *P-T_i* element can be used to create the controller types *P*, *I*, *PI*, *PP*, *PD*, *PID*, *PPD*. See DIN 19226 for characteristics and system performance.

Subdivision of control modes

In control-engineering practice, distinctions are made between the individual control modes according to the following attributes: continuous-time/continuous-value, continuous-time/discrete-value, discrete-time/continuous-value and discrete-time/discrete-value. Of these four attributes, only the instances of continuous-time/continuous-value and discrete-time/discrete-value control are of significance.

Continuous-time/ continuous-value control

In continuous-time/continuous-value control, the controlled variable is recorded in an uninterrupted process and compared with the reference variable. This comparison provides the basis for continuous-time and continuous-value generation of the manipulated variable.

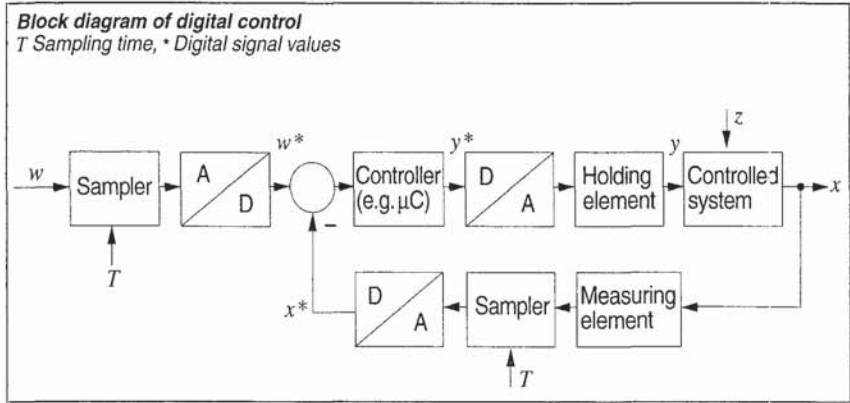
Continuous-time/continuous-value control is also referred to as analog control.

Table: Summary of some transfer elements

Designation	Functional relationship	Transfer function	Course of step response	Symbol
P element	$y = Ku$	K		
I element	$y = K \int_0^t u(\tau) d\tau$	$\frac{K}{s}$		
D element	$y = K\dot{u}$	Ks		
TZ element T_1 element	$y(t) = Ku(t - T_1)$	$Ke^{-T_1 s}$		
S element	$y = u_1 \pm \dots \pm u_p$			
P- T_1 element, VZ ₁ element	$T\dot{y} + y = Ku$	$\frac{K}{1 + Ts}$		
P- T_2 element, VZ ₂ element	$T^2\ddot{y} + 2dT\dot{y} + y = Ku$	$\frac{K}{1 + 2dT s + T^2 s^2}$	<div>Periodic case: $d < 1$ </div> <div>Aperiodic limit case: $d \geq 1$ </div>	

Discrete-time/discrete-value control
In discrete-time/discrete-value control, the controlled variable is recorded, quantified and subtracted from the quantified reference variable only at the sampling instants. The manipulated variable is calculated on the basis of the control difference thus created. For this purpose, an algo-

rithm is generally used which is implemented in the form of a software program on a microcontroller. A/D and D/A converters are used as process interfaces. Discrete-time/discrete-value control is also referred to as digital control.



Examples of closed-loop control systems in motor vehicles (simplified)

Control system	Variables		Disturbances (z)	Controlling system	Elements	
	Object variable (x_A)	Controlled variable (x)			Final controlling element	Controlled system
Lambda closed-loop control	Air/fuel ratio (λ)	O_2 content of exhaust gas	Manipulated variable (y) Injected fuel quantity	Lambda control unit and lambda sensor	Fuel injectors	Combustion chamber; part of intake system and exhaust system up to λ sensor
Rotational-speed control in diesel engines	Engine speed		Reference variable (w) $\lambda = 1.0$ (fixed-command control)	Governor	Fuel-injection pump	Mixture-formation area in engine
Antilock braking system (ABS control)	Wheel slip	Wheel slip	Injected fuel quantity	Controller in ABS control unit	Pressure-control valve	Tires, road
Temperature control (passenger compartment)	Interior temperature	Interior, discharge, outside-air temperatures	Braking pressure Hot-water flow rate or hot-/cold-air mixture ratio	Temperature regulator and temperature sensor	Electromagnetic heating valve or air flap	Passenger compartment

Examples of open-loop control systems in engines

Control system	Variables			Disturbances (z)	Manipulated variable (y)	Elements	
	Object variables (x_A)	Reference variables (v)	Input variables of controlling system			Controlling system	Final controlling element
Jetronic gasoline injection	Air/fuel ratio	Air/fuel ratio (setpoint)	Engine speed, engine temperature, vehicle system voltage, air quantity, air temperature, throttle-valve position	Fuel temperature, manifold-wall fuel condensation	Duration of injection	Jetronic control unit with various measuring elements	Fuel injectors
Electronic ignition systems	Ignition point	Ignition point (setpoint)	Engine speed, crankshaft position, intake-manifold pressure, throttle-valve position, engine temperature, vehicle system voltage	Condition of spark plugs, air/fuel ratio, fuel quality, mechanical tolerances	Ignition point	Ignition control unit	Ignition output stage
							Combustion chamber in engine

Data processing in motor vehicles

Requirements

Highly sophisticated state-of-the-art open-loop and closed-loop control concepts are essential for meeting the demands for function, safety, environmental compatibility and comfort associated with the wide range of automotive subsystems installed in modern-day vehicles. Sensors monitor reference and controlled variables, which an electronic control unit (ECU) then converts into the signals required to adjust the final controlling elements/actuators. The input signals can be analog (e.g. voltage characteristic at pressure sensor), digital (e.g. switch position) or pulse-shaped (i.e. information content as a function of time; e.g. engine-speed signal). These signals are processed after being conditioned (filtering, amplification, pulse shaping) and converted (analog/digital); digital signal-processing methods are preferred.

Thanks to modern semiconductor technology, powerful computer units, with their accompanying program and data memories, and special peripheral circuitry, designed specifically for real-time applications, can all be integrated on a limited number of chips.

Modern vehicles are equipped with numerous digital control units (ECUs), e.g. for engine management, ABS and transmission-shift control. Improved performance and additional functions are obtained by synchronizing the processes controlled by the individual control units and by mutual real-time adaptation of the respective parameters. An example of this type of function is traction control (TCS), which reduces the driving torque when the drive wheels spin.

Up to now, data between the control units (in the example cited above, ABS/TCS and engine management) have been exchanged mostly through separate individual circuits. However, this type of point-to-point connection is only suitable for a limited number of signals. The data-

transmission potential between the individual ECUs can be enhanced by using a simple network topology designed specifically for serial data transmission in automotive applications.

Microcomputer

The microcomputer comprises both the central processing unit (CPU) for processing arithmetic operations and logical relationships, and special function modules to monitor external signals and to generate the control signals for external servo elements. These peripheral modules are largely capable of assuming complete control of real-time operations. The program-controlled CPU could only discharge these at the price of both additional complication and curtailment in the number of functions (e.g. determining the moment at which an event occurred).

Computing capacity

Apart from the architecture (e.g. accumulator, register machine) and the word length (4...32 bits), the product of the internal clock frequency and the average number of clock pulses required per instruction determines the capacity of a CPU:

- Clock frequency: 1...40 MHz (typical),
- Clock pulses per instruction: 1...32 pulses (typical), depending on the CPU's architecture and the instruction (e.g. 6 pulses for addition, 32 pulses for multiplication).

Electronic control unit (ECU)

Digital input signals

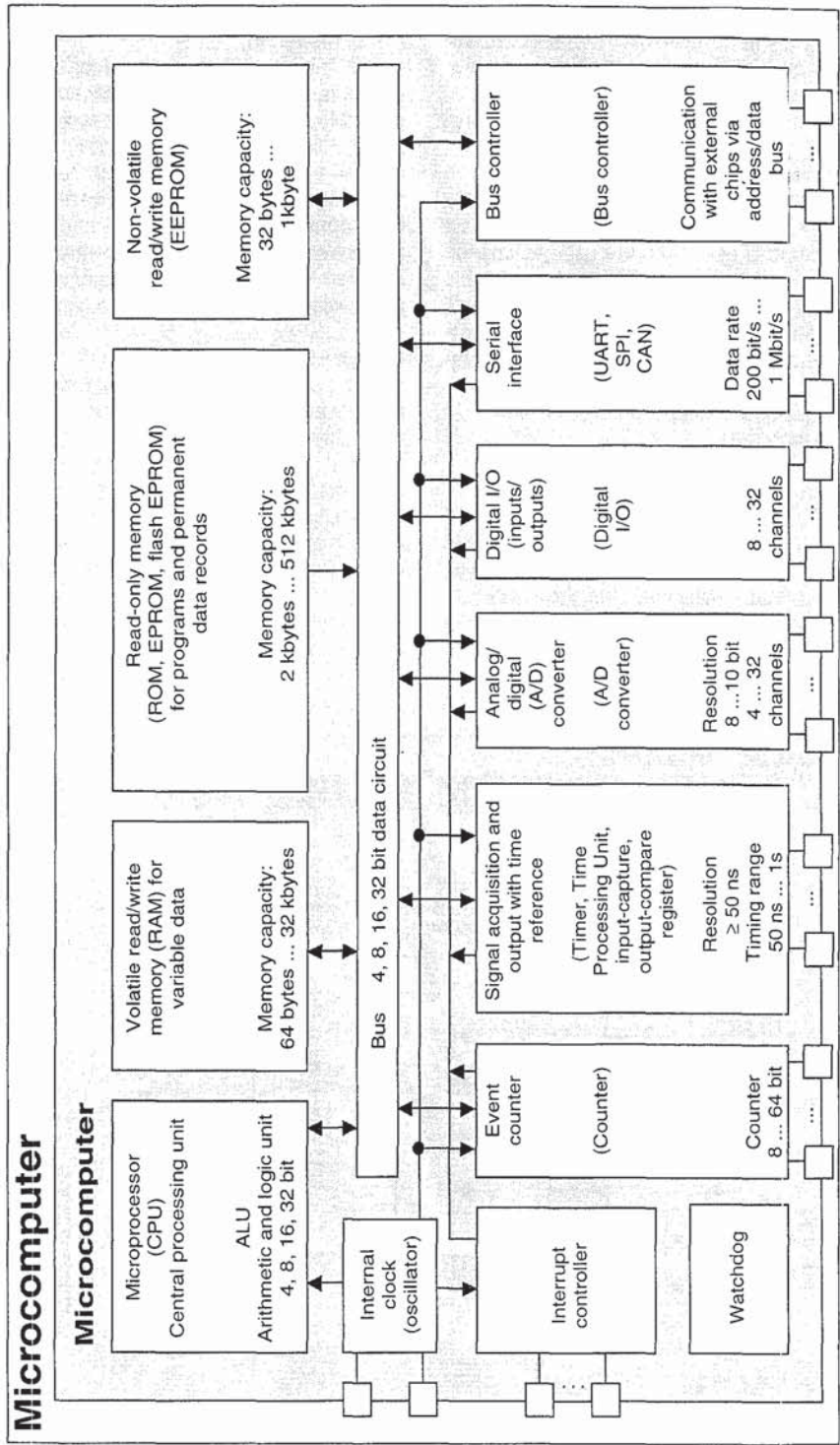
Register a switch position or digital sensor signals (e.g. rotational-speed pulses from a Hall-effect sensor).

Voltage range: 0 V to battery voltage

Analog input signals

Signals from analog sensors (lambda sensor, pressure sensor, potentiometer).

Voltage range: several mV up to 5 V.



Pulse-shaped input signals
Signals from inductive min⁻¹ sensors. After signal conditioning, they are processed further as digital signals.
Voltage range: 0.5 V to 100 V.

Initial conditioning of input signals
Protective circuits (passive: R and RC circuits; active: special surge-proof semiconductor elements) are used to limit the voltage of the input signals to acceptable levels (operating voltage of the microcomputer). Filters remove most of the superimposed noise from the transmitted signals, which are then amplified to the microprocessor's input voltage.
Voltage range: 0 V to 5 V.

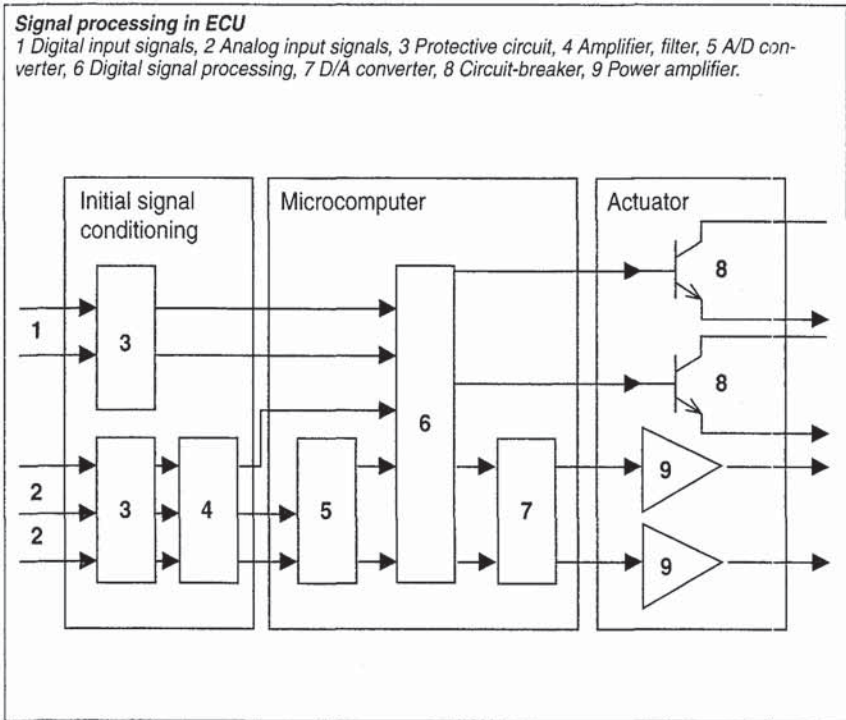
Signal processing
ECUs generally process signals in digital form. Rapid, periodic, real-time signals are processed in hardware modules specifically designed for the particular function. Results, e.g. a counter reading or the time of an event, are transmitted in registers to the CPU for further processing. This procedure substantially reduces

the CPU's interrupt-response requirements (µs range).

The amount of time available for calculations is determined by the open-loop or closed-loop control system (ms range).

The software contains the actual control algorithms. Depending on the data, an almost unlimited number of logic operations can be established and data records stored and processed in the form of parameters, characteristic curves and multidimensional program maps.

Output signals
Power switches and power-gain circuits amplify the microprocessor's output signals (0 to 5 V, several mA) to the levels required by the various final-controlling elements/actuators (battery voltage, several A).



Complete system

Logistical concept (CARTRONIC)

The concept divides the total automotive electrical system into conveniently-dimensioned subsystems. Units with closely-related functions (units with a high rate of mutual data exchange) are combined in a sub-network. This logistical concept results in sub-networks with varying requirements for transmission capacity, while data transmission remains compatible.

Topology

At the logical level, all of the known communications systems developed for automotive applications are based on a single serial connection of the ECUs. The physical layout employs one-wire or differential two-wire interfaces in bus form to connect the control units with one another.

Protocol

The protocol consists of a specific collection of execution statements which are used to control data communications between the individual control units. Procedures have been laid down for bus access, message structure, bit and data coding, error recognition and response and the identification of faulty bus users (CAN, P. 884).

Transmission speed

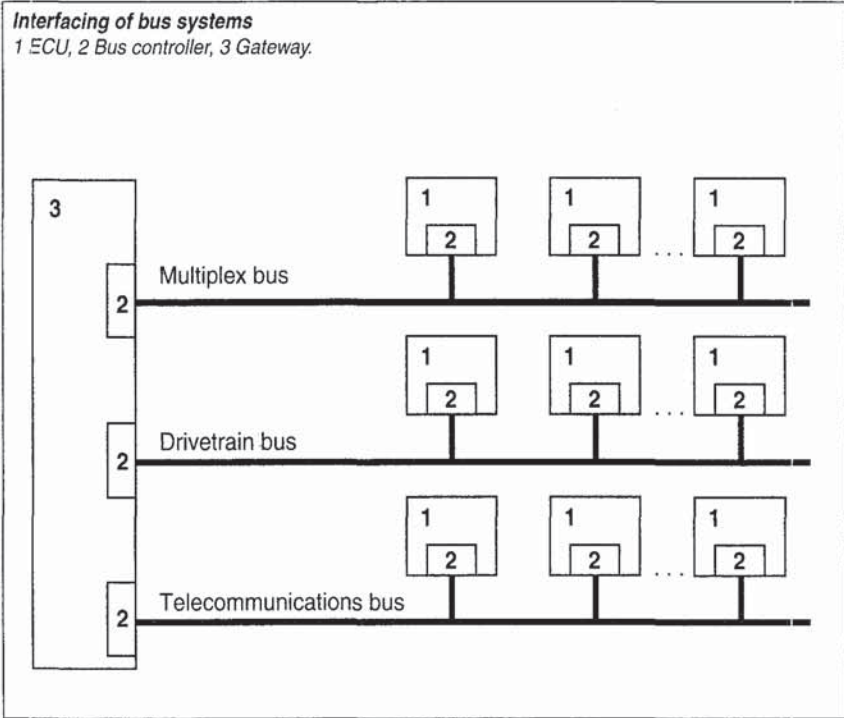
Multiplex bus: 10 kbit/s...125 kbit/s
Drivetrain bus: 125 kbit/s...1 Mbit/s
Telecommunications bus:
10 kbit/s...125 kbit/s.

Latency time

The period that elapses between the transmitter's send request and the target station's receipt of the error-free message.
Multiplex bus: 5 ms...100 ms
Drivetrain bus: 0.5 ms...10 ms
Telecommunications bus:
5 ms...100 ms.

Interfacing of bus systems

1 ECU, 2 Bus controller, 3 Gateway.



Chemical elements

Element	Sym-bol	Type ¹⁾	Atomic number	Relative atomic mass	Valence	Year dis-covered	Discoverer(s)
Actinium	Ac	m	89	227	3	1899	Debierne
Aluminum	Al	m	13	26.9815	3	1825	Oersted
Americium ²⁾	Am	m	95	243	2; 3; 4; 5; 6	1944	Seaborg et al
Antimony	Sb	m	51	121.760	3; 5	Antiquity	
Argon	Ar	g	18	39.948	0	1894	Ramsay, Rayleigh
Arsenic	As	n	33	74.9216	3; 5	C13	Magnus
Astatine	At	n	85	210	1; 3	1940	Corson, MacKenzie, Segré
Barium	Ba	m	56	137.327	2	1808	Davy
Berkelium ²⁾	Bk	m	97	247	3; 4	1949	Seaborg et al
Beryllium	Be	m	4	9.0122	2	1797	Vauquelin
Bismuth	Bi	m	83	208.9804	1; 3; 5	C15	Unknown
Bohrium ²⁾	Bh	m ³⁾	107	262	— ⁴⁾	1981	Armbruster, Münzenberg et al
Boron	B	n	5	10.811	3	1808	Gay-Lussac, Thénard, Davy
Bromine	Br	n	35	79.904	1; 3; 4; 5; 7	1826	Balard
Cadmium	Cd	m	48	112.411	1; 2	1817	Strohmeyer
Caesium	Cs	m	55	132.9054	1	1860	Bunsen, Kirchhoff
Calcium	Ca	m	20	40.078	2	1808	Davy
Californium ²⁾	Cf	m	98	251	2; 3; 4	1950	Seaborg et al
Carbon	C	n	6	12.011	2; 4	Antiquity	
Cer	Ce	m	58	140.116	3; 4	1803	Berzelius et al
Chlorine	Cl	g	17	35.4527	1; 3; 4; 5; 6; 7	1774	Scheele
Chromium	Cr	m	24	51.9961	1; 2; 3; 4; 5; 6	1780	Vauquelin
Cobalt	Co	m	27	58.9332	1; 2; 3; 4; 5	1735	Brandt
Copper	Cu	m	29	63.546	1; 2; 3	Antiquity	
Curium ²⁾	Cm	m	96	247	2; 3; 4	1944	Seaborg et al
Dubnium ²⁾	Db	m ³⁾	105	262	5 (?)	1967/70	Disputed (Flerov or Ghiorso)
Dysprosium	Dy	m	66	162.50	2; 3; 4	1886	Lecoq de Boisbaudran
Einsteinium ²⁾	Es	m	99	252	3	1952	Ghiorso et al
Erbium	Er	m	68	167.26	3	1842	Mosander
Europium	Eu	m	63	151.964	2; 3	1901	Demarcay
Fermium ²⁾	Fm	m ³⁾	100	257	3	1952	Ghiorso et al
Fluorine	F	g	9	18.998	1	1887	Moissan
Francium	Fr	m	87	223	1	1939	Perey
Gadolinium	Gd	m	64	157.25	2; 3	1880	de Marignac
Gallium	Ga	m	31	69.723	1; 2; 3	1875	Lecoq de Boisbaudran
Germanium	Ge	m	32	72.61	2; 4	1886	Winkler
Gold	Au	m	79	196.9665	1; 3; 5; 7	Antiquity	

¹⁾ m Metal, n Nonmetal, g Gas.
²⁾ Artificially produced; does not occur naturally.
³⁾ Unknown. The elements are presumably 100...112 metals.
⁴⁾ Unknown.

Element	Sym- bol	Type ¹⁾	Atomic number	Relative atomic mass	Valence	Year dis- covered	Discoverer(s)
Hafnium	Hf	m	72	178.49	4	1923	Hevesey, Coster
Hassium ²⁾	Hs	m ³⁾	108	265	− ⁴⁾	1984	Armbruster, Münzenberg et al
Helium	He	g	2	4.003	0	1895	Ramsay, Cleve, Langlet
Holmium	Ho	m	67	164.9303	3	1878	Cleve, Delafontaine, Soret
Hydrogen	H	g	1	1.0079	1	1766	Cavendish
Indium	In	m	49	114.818	1; 2; 3	1863	Reich, Richter
Iodine	I	n	53	126.9045	1; 3; 5; 7	1811	Courtois
Iridium	Ir	m	77	192.217	3; 4	1803	Tennant
Iron	Fe	m	26	55.845	2; 3; 6	Antiquity	
Krypton	Kr	g	36	83.80	0; 2	1898	Ramsay
Lanthanum	La	m	57	138.9055	3	1839	Mosander
Lawrencium ²⁾	Lr	m ³⁾	103	262	3	1961	Ghiorso et al
Lead	Pb	m	82	207.2	2; 4	Antiquity	
Lithium	Li	m	3	6.941	1	1817	Arfvedson
Lutetium	Lu	m	71	174.967	3	1907	Urbain, James
Magnesium	Mg	m	12	24.3050	2	1755	Black
Manganese	Mn	m	25	54.9380	2; 3; 4; 6; 7	1774	Grahn
Meitnerium	Mt	m ³⁾	109	266	− ⁴⁾	1982	Armbruster, Münzenberg et al
Mendelevium ²⁾	Md	m ³⁾	101	258	2; 3	1955	Seaborg, Ghiorso et al
Mercury	Hg	m	80	200.59	1; 2	Antiquity	
Molybdenum	Mo	m	42	95.94	2; 3; 4; 5; 6	1781	Hjelm
Neodymium	Nd	m	60	144.24	2; 3; 4	1885	Auer von Welsbach
Neon	Ne	g	10	20.1797	0	1898	Ramsay, Travers
Neptunium ²⁾	Np	m	93	237	3; 4; 5; 6	1940	McMillan, Abelson
Nickel	Ni	m	28	58.6934	2; 3	1751	Cronstedt
Niobium	Nb	m	41	92.9064	3; 4; 5	1801	Hatchett
Nitrogen	N	g	7	14.0067	2; 3; 4; 5	1772	Rutherford
Nobelium ²⁾	No	m ³⁾	102	259	2; 3	1958	Ghiorso, Seaborg
Osmium	Os	m	76	190.23	2; 3; 4; 5; 7; 8	1803	Tennant
Oxygen	O	g	8	15.9994	1; 2	1774	Priestley, Scheele
Palladium	Pd	m	46	106.42	2; 4	1803	Wollaston
Phosphorus	P	n	15	30.9738	3; 5	1669	Brandt
Platinum	Pt	m	78	195.078	2; 4; 5; 6	Antiquity	(Mayas)
Plutonium ²⁾	Pu	m	94	244	3; 4; 5; 6	1940	Seaborg et al
Polonium	Po	m	84	209	2; 4; 6	1898	M. Curie
Potassium	K	m	19	39.0983	1	1807	Davy
Praseodymium	Pr	m	59	140.9076	3; 4	1885	Auer von Welsbach
Promethium	Pm	m	61	145	3	1945	Marinsky et al
Protactinium	Pa	m	91	231.0359	4; 5	1917	Hahn, Meitner, Fajans

1) m Metal, n Nonmetal, g Gas.
2) Artificially produced; does not occur naturally.
3) Unknown. The elements are presumably 100...112 metals.
4) Unknown.

Chemical elements (continued)

Element	Sym- bol	Type ¹⁾	Atomic number	Relative atomic mass	Valence	Year dis- covered	Discoverer(s)
Radium	Ra	m	88	226	2	1898	P. & M. Curie
Radon	Rn	g	86	222	0; 2	1900	Dorn
Rhenium	Re	m	75	186.207	1; 2; 3; 4; 5; 6; 7	1925	Noddack
Rhodium	Rh	m	45	102.9055	1; 2; 3; 4; 5; 6	1803	Wollaston
Rubidium	Rb	m	37	85.4678	1	1861	Bunsen, Kirchhoff
Ruthenium	Ru	m	44	101.07	1; 2; 3; 4; 5; 6; 7; 8	1808	Klaus
Rutherfordium ²⁾	Rf	m ³⁾	104	261	4 (?)	1964/69	Disputed (Flerov or Ghiorso)
Samarium	Sm	m	62	150.36	2; 3	1879	Lecoq de Boisbaudran
Scandium	Sc	m	21	44.9559	3	1879	Nilson
Seaborgium ²⁾	Sg	m ³⁾	106	263	— ⁴⁾	1974	Ghiorso et al
Selenium	Se	n	34	78.96	2; 4; 6	1817	Berzelius
Silver	Ag	m	47	107.8682	1; 2	Antiquity	
Silicon	Si	n	14	28.0855	2; 4	1824	Berzelius
Strontium	Sr	m	38	87.62	2	1790	Crawford
Sodium	Na	m	11	22.9898	1	1807	Davy
Sulfur	S	n	16	32.066	1; 2; 3; 4; 5; 6	Antiquity	
Tantalum	Ta	m	73	180.9479	1; 3; 4; 5	1802	Eckeberg
Technetium	Tc	m	43	98	4; 5; 6; 7	1937	Perrier, Segré
Tellurium	Te	m	52	127.60	2; 4; 6	1783	Müller
Terbium	Tb	m	65	158.9253	3; 4	1843	Mosander
Thallium	Tl	m	81	204.3833	1; 3	1861	Crookes
Thorium	Th	m	90	232.0381	2; 3; 4	1829	Berzelius
Thulium	Tm	m	69	168.9342	2; 3	1879	Cleve
Tin	Sn	m	50	118.710	2; 4	Antiquity	
Titanium	Ti	m	22	47.87	2; 3; 4	1791	Gregor
Tungsten	W	m	74	183.84	2; 3; 4; 5; 6	1783	Elmhüjar
Ununbium ²⁾ ⁵⁾	Uub	m ³⁾	112	277	— ⁴⁾	1996	Armbruster, Hofmann
Ununnilium ²⁾ ⁵⁾	Uun	m ³⁾	110	270	— ⁴⁾	1994	Armbruster, Hofmann
Unununium ²⁾ ⁵⁾	Uuu	m ³⁾	111	272	— ⁴⁾	1994	Armbruster, Hofmann
Uranium	U	m	92	238.0289	3; 4; 5; 6	1789	Klaproth
Vanadium	V	m	23	50.9415	2; 3; 4; 5	1801	del Rio
Xenon	Xe	g	54	131.29	0; 2; 4; 6; 8	1898	Ramsay, Travers
Ytterbium	Yb	m	70	173.04	2; 3	1878	de Marignac
Yttrium	Y	m	39	88.9059	3	1794	Gadolin
Zinc	Zn	m	30	65.39	2	Antiquity	
Zirconium	Zr	m	40	91.224	3; 4	1789	Klaproth

¹⁾ m Metal, n Nonmetal, g Gas.
²⁾ Artificially produced; does not occur naturally.
³⁾ Unknown. The elements are presumably 100...112 metals.
⁴⁾ Unknown.
⁵⁾ Provisional IUPAC designation.

Material terminology¹⁾**State of aggregation**

There are three classical states of aggregation depending upon the arrangement of the elementary particles (atoms, molecules, ions): solid, liquid and gaseous. Plasma (ionized gas which has high electrical conductivity) is often considered as a fourth state of aggregation.

Solution

A solution is a homogeneous mixture of different materials which are distributed at the atomic or molecular level.

Compound

A compound is the union of two or more chemical elements whose masses are always in the same ratio with respect to one another. Compounds which have metallic characteristics are called intermetallic compounds.

Dispersion

A dispersion or disperse system consists of at least two materials; one material, called the disperse phase, is finely distributed in the other material, called the dispersion medium.

Suspension

A suspension is a disperse system in which solid particles are distributed in a liquid. Examples: graphite in oil, clay in water.

Emulsion

An emulsion is a disperse system in which droplets of one liquid are distributed in a second liquid. Examples: drilling oil, butterfat in milk.

Colloid

A colloid is a disperse system in which the particles of the disperse phase have linear dimensions ranging from roughly 10^{-9} to 10^{-6} m. Examples: smoke, latex, gold-ruby glass.

¹⁾ The following is a list of the most important material terms and parameters which appear in subsequent materials tables and are not defined elsewhere.

Material parameters¹⁾**Density**

Density is the ratio of the mass to the volume of a specific amount of substance.

See DIN 1306, 1984 edition, for special density terms.

Radial crushing strength

Radial crushing strength is a strength parameter which is specified in particular for the sintered metals used for plain bearings. It is determined from the pressure test when a hollow cylinder is crushed.

For additional information see "Technical Conditions of Delivery for PM Parts (Sint. 03)", Aug. 1981 edition.

Yield strength (0.2%)

The 0.2% yield strength is that tensile stress which causes permanent (plastic) elongation of 0.2% in a solid body; it is determined from the σ - ϵ curve of a tensile test with a defined stress-increase rate.

Cyclic loading of a test specimen by tensile/compressive stresses with increasing amplitude yields the cyclic σ - ϵ curve and from this the cyclic 0.2% yield strength. When compared with the monotonic 0.2% yield strength, this value is a measure of possible softening or hardening brought about by cyclic over-stressing.

The yield strength ratio is the ratio of the cyclic to the monotonic 0.2% yield strength. $\gamma > 1$ signifies cyclic hardening, $\gamma < 1$ cyclic softening.

Fracture toughness

Fracture toughness, or K_{Ic} factor, is a material parameter of fracture mechanics. The K_{Ic} factor is that stress intensity ahead of a crack tip which leads to unstable crack propagation, and therefore to the fracture of the structural part. If the K_{Ic} factor of a material is known, the critical fracture load can be determined from crack length, or critical crack length can be determined from the given external loading value.

Specific heat capacity

Specific heat capacity (specific heat) is the quantity of heat in J required to raise the temperature of 1 kg of a substance by 1 K. It is dependent on temperature.

In the case of gases, it is necessary to differentiate between specific heat capacity at constant pressure and at constant volume (symbols: c_p and c_v , respectively). This difference is usually negligible in the case of solid and liquid substances.

Specific heat of fusion

The specific heat of fusion of a solid is the quantity of heat in J required to transform 1 kg of a substance at fusion temperature from the solid to the liquid state.

Specific heat of evaporation

The specific heat of evaporation of a liquid is the quantity of heat in J required to evaporate 1 kg of this liquid at boiling temperature. The specific heat of evaporation is highly dependent upon pressure.

Thermal conductivity

Thermal conductivity is the quantity of heat in J which flows in 1 s through a material sample which has a surface area of 1 m² and a thickness of 1 m if the temperatures of the two end surfaces of the sample differ by 1 K.

In the case of liquids and gases, thermal conductivity is often highly dependent upon temperature, whereas temperature is generally not significant in the case of solids.

Coefficient of thermal expansion

The coefficient of linear (or longitudinal) expansion indicates the relative change in length of a material caused by a change in temperature of 1 K. For a temperature variation ΔT , the change in length is defined as $\Delta l = l \cdot \alpha \cdot \Delta T$. The cubic or volume coefficient of expansion is defined in the same way. The volume coefficient of expansion for gases is roughly 1/273. For solids, it is roughly three times as large as the coefficient of linear expansion.

Permeability

Permeability μ or relative permeability μ_r describes* the dependence of magnetic induction on the applied field:

$$B = \mu_r \cdot \mu_0 \cdot H$$

Depending on the application in which the magnetic material is used, there are roughly 15 types of permeability. These are defined according to modulation range and type of loading (direct-current or alternating-current field loading). Examples:

Initial permeability μ_a

Slope of the virgin curve for $H \rightarrow 0$. In most cases, however, the slope for a specific field strength (in mA/cm) is specified rather than this limit value. Example: μ_a is the slope of the virgin curve for $H = 4 \text{ mA/cm}$.

Maximum permeability $\mu_{\max}$

Maximum slope of the virgin curve.

Permanent permeability μ_p or μ_{rec}

Average slope of a retrograde magnetic hysteresis loop whose lowest point usually lies on the demagnetization curve.

$$\mu_p = \Delta B / (\Delta H \cdot \mu_0)$$

Temperature coefficient of magnetic polarization $TK(J_s)$

This temperature coefficient indicates the relative change in saturation polarization as the temperature changes, it is given in % per kelvin.

Temperature coefficient of coercive field strength $TK(H_c)$

This temperature coefficient indicates the relative change, in % per kelvin, of coercive field strength as the temperature changes.

Curie point (Curie temperature) T_c

The Curie point is the temperature at which the magnetization of ferromagnetic and ferrimagnetic materials becomes zero and at which they behave like paramagnetic materials (sometimes defined differently, see characteristic values of soft ferrites on P. 208).

Material groups

The materials in current industrial use can be classified according to one of four categories. Each of these, in turn, includes various subclassifications:

- Metals: wrought, rolled, cast etc. metals, sintered metals,
- Nonmetallic inorganic materials: ceramic materials, glass,
- Nonmetallic organic materials: natural materials, plastics and elastomers
- Composite materials.

Magnetic materials form an important material group with special characteristics, and will be described separately.

Metals

Metals generally exhibit a crystalline structure. Their atoms are arranged in a regular crystal lattice. The valence electrons of the atoms are not bound to a special atom, but rather are able to move freely within the metal lattice (metallic bond).

This special metal-lattice structure explains the characteristic properties of metals: high electrical conductivity which decreases as temperature increases; good thermal conductivity; low transparency to light; high optical reflectivity (metallic luster); ductility and the resulting high degree of formability. Alloys are metals which consist of two or more components, of which at least one is a metal.

Wrought, rolled, cast etc. metals

Apart from small flaws such as shrink-holes and nonmetallic inclusions, such metals contain no voids. Components are produced by casting, either directly (e.g. gray cast iron, diecast aluminum) or from wrought products (machined with or without cutting).

Sintered metals

Sintered metals are usually produced by pressing powder or by the injection-molding of mixtures composed of metallic powder and plastic. Following the removal of parting agents and plasticizers, the parts

are then sintered to give them their characteristic properties. Sintering is a type of heat treatment in a range from 800 to 1300 °C. In addition to its chemical composition, the sintered part's properties and application are to a large extent determined by its degree of porosity. Components with complicated shapes can often be made particularly cheaply from sintered metals, either ready-to-install or requiring only little finishing.

Nonmetallic inorganic materials

These materials are characterized by ion bonds (e.g., ceramic materials), mixed (heteropolar/homopolar) bonds (e.g., glass) or homopolar bonds (e.g., carbon). These kinds of bonds, in turn, are responsible for several characteristic properties: generally poor thermal and electric conductivity (the latter increases with temperature), poor luminous reflectance, brittleness and thus almost complete unsuitability for cold forming.

Ceramics

Ceramics are at least 30% crystalline in nature; most ceramics also contain amorphous components and pores. Their manufacture is similar to that of sintered metals, however nonmetallic powders or powder mixtures are used; sintering at temperatures generally higher than 1000 °C gives ceramics their characteristic properties. Ceramic structural parts are sometimes also shaped at high temperatures or even by a melting process, with subsequent crystallization.

Glass

Glass is viewed as under-cooled, frozen liquid. Its atoms are only in a short-range order. It is regarded as amorphous. Molten glass turns to solid glass at the transformation temperature T_g (T_g is derived from the former designation "glass formation temperature"). T_g is dependent on a variety of parameters and therefore not clearly determined (better: transformation range).

Nonmetallic organic materials

These materials consist mainly of compounds of the elements carbon and hydrogen, whereby nitrogen, oxygen and other elements are also often included in the structure. In general, these materials exhibit low thermal and electric conductivity, and are combustible.

Natural materials

The best-known natural materials are wood, leather, resin, natural rubber, and fibers made of wool, cotton, flax, hemp and silk. Most natural materials are used in processed or refined form, or serve as raw materials in the manufacture of plastics.

Plastics

A significant characteristic of plastics is their macromolecular structure. There are three different types of plastics: thermoplastics, thermosets (sometimes also called thermosetting plastics) and elastomers. The transformation temperature T_E for thermoplastics and thermosets lies above the temperature of application; the reverse is true for elastomers. T_E (comparable with the transformation temperature T_g of glass) is understood to mean that temperature below which intrinsic molecular motion ceases. The major importance of thermoplastics and thermosets lies in the fact that they can be shaped and molded without machining.

Thermoplastics

Thermoplastics soften and lose their dimensional stability at temperatures above T_E . Their physical properties are highly temperature-dependent. The effect of temperature can be somewhat reduced by using mixtures of thermoplastic polymers.

Thermosets

Thermosets retain their dimensional stability up to temperatures almost as high as the processing temperature due to closely-spaced cross-linking. Their mechanical properties are less temperature-dependent than those of thermoplastics. Fillers are usually added to thermosetting resins to counteract their inherent brittleness.

Elastomers

Elastomers are useful in many applications because of their elasticity, which is only present at temperatures above T_E . Elastomers are vulcanized (widely-spaced cross-linking) in order to stabilize their molecular bonds.

Composite materials

Composite materials consist of at least two physically or chemically different components. These components must be tightly bound together at a defined interface. The formation of the interface must have no negative effect on any of the bound components. Under these two conditions it is possible to bond many materials together. Composite materials exhibit combinations of properties which none of the components alone possesses. Different classes of composite materials are: Particle composite materials (e.g., powder-filled resins, hard metals, plastic-bonded magnets, cermets), Laminated composite materials (e.g., composite or sandwich panels, resin-bonded fabric), Fiber composite materials (e.g., with fiberglass, carbon-fiber, and cotton-fiber-reinforced plastics).

Magnetic materials

Materials which have ferromagnetic or ferrimagnetic properties are called magnetic materials and belong to one of two groups: metals or nonmetallic inorganic materials. They are characterized by their ability to store magnetic energy (permanent magnets), or by their good magnetic flux conductivity (soft magnets). In addition to ferromagnets and ferrimagnets, diamagnetic, paramagnetic and antiferromagnetic materials also exist. They differ from each other in terms of their permeability μ (P. 68) or the temperature-dependence of their susceptibility χ .¹⁾

$$\mu_r = 1 + \chi$$

¹⁾ Ratio of the magnetization of a substance to the magnetic field strength or excitation.

Diamagnets: Susceptibility χ_{Dia} is independent of temperature.

See P. 68 for examples.

Paramagnets: Susceptibility χ_{para} drops as temperature increases. Curie's law: $\chi_{\text{para}} = C/T$

C Curie constant, T Temperature in K. See P. 68 for examples.

Ferromagnets and ferrimagnets: Both types exhibit spontaneous magnetization which disappears at the Curie point (Curie temperature T_c). At temperatures above the Curie temperature, they behave like paramagnets. For $T > T_c$, the Curie-Weiss law is applicable to susceptibility: $\chi = C/(T - T_c)$

The saturation induction of ferromagnets is higher than it is for ferrimagnets, because all magnetic moments are aligned in parallel. In the case of ferrimagnets, on the other hand, the magnetic moments of the two sublattices are aligned antiparallel to one another. These materials are nevertheless magnetic, because the magnetic moments of the two sublattices have different magnitudes.

Antiferromagnets: Examples: MnO, MnS, FeCl₂, FeO, NiO, Cr, V₂O₃, V₂O₄.

As in the case of ferrimagnets, adjacent magnetic moments are aligned antiparallel with respect to one another. Because they are of equal magnitude, the effective magnetization of the material is zero.

At temperatures above the Néel point (Néel temperature T_N), they behave like paramagnets. For $T > T_N$, the following is applicable to susceptibility: $\chi = C/(T + \theta)$
 θ Asymptotic Curie temperature

Soft magnetic materials

The following figures are from the applicable DIN Standards. Soft-magnetic metallic materials (DIN-IEC 60 404-8-6).

Many material qualities defined in this standard relate to the materials in DIN 17 405 (DC relays) and DIN-IEC 740-2 (transformers and reactors).

Designation comprises a letter and number combination:

Code letter, Number 1, Number 2, – Number 3. The "code letter" indicates the main alloy constituent:

"A" pure iron, "C" silicon, "E" nickel, "F" cobalt.

Number 1 indicates the concentration of the main alloy element.

Number 2 defines the different curves: 1: round hysteresis loop, 2: rectangular hysteresis loop.

The significance of the Number 3 following the hyphen varies according to the individual alloy. It indicates the minimum initial permeability $\mu_a/1000$ in nickel alloys; with other alloys it designates the maximum coercive field strength in A/m. The properties of these materials are strongly geometry-dependent and highly application-specific. The material data quoted in extracts from the standard can therefore only provide an extremely general overview of the properties of these materials. Refer to P. 203 for material data.

Magnetic sheet steel and strip (formerly in DIN 46 400)

Designation: Code letter 1 Number 1 – Number 2 Code letter 2.

The first code letter is "M" for all varieties (indicates metallic materials). Number 1 is one hundred times the maximum magnetic reversal loss at 1.5 or 1.7 Tesla and 50 Hz in W/kg. Number 2 is the product's nominal depth in mm times one hundred.

Code letter 2 provides type data:

"A" cold-rolled electric sheets, no granular orientation, finish-annealed (DIN-EN 10 106).

Grain-oriented electric sheet, finish-annealed (DIN-EN 10 107): "N" standard magnetic reversal loss, "S" limited magnetic reversal loss, "P" low magnetic reversal loss, "D" cold-rolled electric sheet of unalloyed steel, not finish-annealed (DIN-EN 10 126), "E" cold-rolled steel-alloy electric sheet, not finish-annealed (DIN-EN 10 165). Materials data, P. 204.

Materials for transformers and reactors (DIN-IEC 740-2).

These materials comprise the alloy classes C21, C22, E11, E31 and E41 from the standard for soft-magnetic materials (DIN-IEC 60 404-8-6). The standard essentially contains the minimum values for core-sheet permeability for

specified core-sheet sections (YEI, YED, YEE, YEL, YUI and YM). See P. 205 for material properties.

Materials for DC relays

(DIN 17 405); see P. 206 for material properties.

Designation:

- a) Code letter "R" (relay material).
- b) Code letters for identifying alloy constituents:

Fe = unalloyed, Si = silicon steels

Ni = nickel steels or alloys.

- c) Code number for maximum coercive field strength.

- d) Code letter for stipulated delivery state: "U" = untreated, "GB" = malleable pre-annealed, "GT" = pre-annealed for deep-drawing, "GF" = final-annealed.

DIN-IEC 60 404-8-10 essentially contains the limit deviations for magnetic relay materials based on iron and steel. The designation code defined in this standard is as follows:

- Code letter "M".
- Permitted maximum value for coercive field strength in A/m.
- Code letter for material composition: "F" = pure ferric material, "T" = steel alloy, "U" = unalloyed steel.
- Code letter for delivery state: "H" = hot-rolled, "C" = cold-rolled or cold-drawn.

Example: M 80 TH.

Sintered metals for soft-magnetic components (DIN-IEC 60 404-8-9)

Designation:

- Code letter "S": for sintered materials.
- Hyphen, followed by the identifying alloy elements, i.e. Fe plus if necessary P, Si, Ni or Co.
- The maximum coercive field strength in A/m follows the second hyphen. Refer to P. 207 for material data.

Soft-magnetic ferrite cores (DIN 41 280)

Soft-magnetic ferrites are formed parts made of a sintered material with the general formula $MO \cdot Fe_2O_3$ where M is one or more of the bivalent metals Cd, Co, Ca, Mg, Mn, Ni, Zn.

Designation: The various types of magnetically soft ferrites are classified in

groups according to nominal initial permeability, and are designated by capital letters. Additional numbers may be used to further subdivide them into subgroups; these numbers have no bearing on material quality.

The coercive field strength H_c of soft ferrites is usually in the range 4...500 A/m. Based on a field strength of 3000 A/m, the induction B is in the range 350...470 mT. Refer to P. 208 for material data.

Permanent-magnet materials

(DIN 17 410, replaced by DIN-IEC 60 404-8-1)

If chemical symbols are used in the abbreviated names of the materials, they refer to the primary alloying constituents of the materials. The numbers before the forward slash denote the $(BH)_{max}$ value in kJ/m^3 and those after the slash denote one tenth of the H_{cJ} value in kA/m (rounded values). Permanent magnets with binders are indicated by a final p.

Designation by abbreviated name or material number¹⁾

DIN: Material number as defined in DIN 17 007, Parts 2 and 4.

IEC: Structure of material numbers;

Code letters:

R - Metallic permanent-magnet materials

S - Ceramic permanent-magnet materials

1st number:

indicates type of material, e.g.:

1 AlNiCo, 5 RECo

2nd number:

0: isotropic material

1: anisotropic material

2: isotropic material with binder

3: anisotropic material with binder.

3rd number:

indicates quality level.

Refer to P. 209 for material data.

¹⁾ The designation system for permanent-magnet materials is currently undergoing extensive revision. Because the discussions were still in progress at the editorial deadline, no data or comments could be provided.

Properties of solids⁸⁾

Substance		Density	Melting point ¹⁾	Boiling point ¹⁾	Thermal conductivity ²⁾	Mean specific heat capacity ³⁾	Melting enthalpy $\Delta H^4)$	Coefficient of linear expansion ³⁾
		g/cm ³	°C	°C	W/(m·K)	kJ/(kg·K)	kJ/kg	×10 ⁻⁶ /K
Aluminum	Al	2.70	660	2467	237	0.90	395	23.0
Aluminum alloys		2.60...2.85	480...655	—	70...240	—	—	21...24
Amber		1.0...1.1	≈300	Decomposes	—	—	—	—
Antimony	Sb	6.69	630.8	1635	24.3	0.21	172	8.5
Arsenic	As	5.73	—	613 ⁵⁾	50.0	0.34	370	4.7
Asbestos		2.1...2.8	≈1300	—	—	0.81	—	—
Asphalt		1.1...1.4	80...100	≈300	0.70	0.92	—	—
Barium	Ba	3.50	729	1637	18.4	0.28	55.8	18.1...21.0
Barium chloride		3.86	963	1560	—	0.38	108	—
Basalt		2.6...3.3	—	—	1.67	0.86	—	—
Beef tallow		0.9...0.97	40...50	≈350	—	0.87	—	—
Beryllium	Be	1.85	1278	2970	200	1.88	1087	11.5
Bismuth	Bi	9.75	271	1551	8.1	0.13	59	12.1
Bitumen		1.05	≈90	—	0.17	1.78	—	—
Boiler scale		≈2.5	≈1200	—	0.12...2.3	0.80	—	—
Borax		1.72	740	—	—	1.00	—	—
Boron	B	2.34	2027	3802	27.0	1.30	2053	5
Brass CuZn37		8.4	900	1110	113	0.38	167	18.5
Brickwork		>1.9	—	—	1.0	0.9	—	—
Bronze CuSn 6		8.8	910	2300	64	0.37	—	17.5
Cadmium	Cd	8.65	321.1	765	96.8	0.23	54.4	29.8
Calcium	Ca	1.54	839	1492	200	0.62	233	22
Calcium chloride		2.15	782	>1600	—	0.69	—	—
Cellulose acetate		1.3	—	—	0.26	1.47	—	100...160
Cement, set		2...2.2	—	—	0.9...1.2	1.13	—	—
Chalk		1.8...2.6	Decomposes into CaO and CO ₂	0.92	0.84	—	—	—
Chamotte (fireclay)		1.7...2.4	≈2000	—	1.4	0.80	—	—
Charcoal		0.3...0.5	—	—	0.084	1.0	—	—
Chromium	Cr	7.19	1875	2482	93.7	0.45	294	6.2
Chromium oxide	Cr ₂ O ₃	5.21	2435	4000	0.42 ⁶⁾	0.75	—	—
Clay, dry		1.5...1.8	≈1600	—	0.9...1.3	0.88	—	—
Cobalt	Co	8.9	1495	2956	69.1	0.44	268	12.4
Coke		1.6...1.9	—	—	0.18	0.83	—	—
Colophonium (rosin)		1.08	100...130	Decomposes	0.32	1.21	—	—
Common salt		2.15	802	1440	—	0.92	—	—
Concrete		1.8...2.2	—	—	≈1.0	0.88	—	—
Copper	Cu	8.96	1084.9	2582	401	0.38	205	—
Cork		0.1...0.3	—	—	0.04...0.06	1.7...2.1	—	—
Corundum, sintered		—	—	—	—	—	—	6.5 ⁷⁾
Cotton wadding		0.01	—	—	0.04	—	—	—
Diamond	C	3.5	3820	—	—	0.52	—	1.1
Foam rubber		0.06...0.25	—	—	0.04...0.06	—	—	—
Germanium	Ge	5.32	937	2830	59.9	0.31	478	5.6
Glass (window glass)		2.4...2.7	≈700	—	0.81	0.83	—	≈8
Glass (quartz glass)		—	—	—	—	—	—	0.5
Gold	Au	19.32	1064	2967	317	0.13	64.5	14.2
Granite		2.7	—	—	3.49	0.83	—	—

¹⁾ At 1.013 bar. ²⁾ At 20°C. ΔH of chemical elements at 27°C (300 K). ³⁾ At 0...100°C, see also P. 181.

⁴⁾ At the melting point and 1.013 bar. ⁵⁾ Sublimed. ⁶⁾ Powder form. ⁷⁾ At 20...1000°C. ⁸⁾ Materials, PP. 193...227.

Substance		Density	Melting point ¹⁾	Boiling point ¹⁾	Thermal conductivity ²⁾	Mean specific heat capacity ³⁾	Melting enthalpy $\Delta H^4)$	Coefficient of linear expansion ⁵⁾
		g/cm ³	°C	°C	W/(m · K)	kJ/(kg · K)	kJ/kg	×10 ⁻⁶ /K
Graphite, pure	C	2.24	≈3800	≈4200	168	0.71	—	2.7
Gray cast iron		7.25	1200	2500	58	0.50	125	10.5
Hard coal (anthracite)		1.35	—	—	0.24	1.02	—	—
Hard metal K 20		14.8	>2000	≈4000	81.4	0.80	—	5...7
Hard rubber		1.2...1.5	—	—	0.16	1.42	—	50...90 ⁵⁾
Heat-conductor alloy NiCr 8020		8.3	1400	2350	14.6	0.50 ⁶⁾	—	—
Ice (0 °C)		0.92	0	100	2.33 ⁷⁾	2.09 ⁷⁾	333	51 ⁸⁾
Indium	In	7.29	156.6	2006	81.6	0.24	28.4	33
Iodine	I	4.95	113.5	184	0.45	0.22	120.3	—
Iridium	Ir	22.55	2447	4547	147	0.13	137	6.4
Iron, pure	Fe	7.87	1535	2887	80.2	0.45	267	12.3
Lead	Pb	11.3	327.5	1749	35.5	0.13	24.7	29.1
Lead monoxide	PbO	9.3	880	1480	—	0.22	—	—
Leather, dry		0.86...1	—	—	0.14...0.16	≈1.5	—	—
Linoleum		1.2	—	—	0.19	—	—	—
Lithium	Li	0.534	180.5	1317	84.7	3.3	663	56
Magnesium	Mg	1.74	648.8	1100	156	1.02	372	26.1
Magnesium alloys		≈1.8	≈630	1500	46...139	—	—	24.5
Manganese	Mn	7.47	1244	2100	7.82	0.48	362	22
Marble	CaCO ₃	2.6...2.8	Decomposes into CaO and CO ₂		2.8	0.84	—	—
Mica		2.6...2.9	Decomposes at 700 °C		0.35	0.87	—	3
Molybdenum	Mo	10.22	2623	5560	138	0.28	288	5.4
Monel metal		8.8	1240... ...1330	—	19.7	0.43	—	—
Mortar, cement		1.6...1.8	—	—	1.40	—	—	—
Mortar, lime		1.6...1.8	—	—	0.87	—	—	—
Nickel	Ni	8.90	1455	2782	90.7	0.46	300	13.3
Nickel silver CuNi12Zn24		8.7	1020	—	48	0.40	—	18
Niobium	Nb	8.58	2477	4540	53.7	0.26	293	7.1
Osmium	Os	22.57	3045	5027	87.6	0.13	154	4.3...6.8
Palladium	Pd	12.0	1554	2927	71.8	0.24	162	11.2
Paper		0.7...1.2	—	—	0.14	1.34	—	—
Paraffin		0.9	52	300	0.26	3.27	—	—
Peat dust (mull), air-dried		0.19	—	—	0.081	—	—	—
Phosphorus (white)	P	1.82	44.1	280.4	—	0.79	20	—
Pitch		1.25	—	—	0.13	—	—	—
Plaster		2.3	1200	—	0.45	1.09	—	—
Platinum	Pt	21.45	1769	3827	71.6	0.13	101	9
Plutonium	Pu	19.8	640	3454	6.7	0.14	11	55
Polyamide		1.1	—	—	0.31	—	—	70...150
Polycarbonate		1.2	—	—	0.20	1.17	—	60...70
Polyethylene		0.94	—	—	0.41	2.1	—	200
Polystyrene		1.05	—	—	0.17	1.3	—	70
Polyvinyl chloride		1.4	—	—	0.16	—	—	70...150
Porcelain		2.3...2.5	≈1600	—	1.6 ⁹⁾	1.2 ⁹⁾	—	4...5
Potassium	K	0.86	63.65	754	102.4	0.74	61.4	83

¹⁾ At 1.013 bar. ²⁾ At 20 °C. ΔH of chemical elements at 27 °C (300 K). ³⁾ At 0...100 °C. ⁴⁾ At melting point and 1.013 bar. ⁵⁾ At 20...50 °C. ⁶⁾ At 0...1000 °C. ⁷⁾ At -20...0 °C. ⁸⁾ At -20...-1 °C. ⁹⁾ At 0...100 °C.

Properties of solids¹²⁾ (continued)

Substance	Density	Melting point ¹⁾	Boiling point ¹⁾	Thermal conduc-tivity ²⁾	Mean spe-cific heat capacity ³⁾	Melting enthalpy $\Delta H^4)$	Coefficient of linear expansion ³⁾
	g/cm ³	°C	°C	W/(m · K)	kJ/(kg · K)	kJ/kg	x10 ⁻⁶ /K
Quartz	2.1...2.5	1480	2230	9.9	0.80		8 ⁵⁾ /14.6 ⁶⁾
Radium Ra	5	700	1630	18.6	0.12	32	20.2
Red bronze CuSn5ZnPb	8.8	950	2300	38	0.67	—	—
Red lead, minium Pb ₃ O ₄	8.6...9.1	Forms PbO		0.70	0.092	—	—
Resin bonded fabric, paper	1.3...1.4	—	—	0.23	1.47	—	10...257)
Resistance alloy CuNi 44	8.9	1280	≈ 2400	22.6	0.41	—	15.2
Rhenium Re	21.02	3160	5762	150	0.14	178	8.4
Rigid foam plastic, air-filled ⁸⁾	0.015... ...0.06	—	—	0.036... ...0.06	—	—	—
Rigid foam plastic, freon-filled	0.015... ...0.06	—	—	0.02... ...0.03	—	—	—
Roofing felt	1.1	—	—	0.19	—	—	—
Rubber, raw (caoutchouc)	0.92	125	—	0.15	—	—	—
Rubidium Rb	1.53	38.9	688	58	0.33	26	90
Sand, quartz, dry	1.5...1.7	≈ 1500	2230	0.58	0.80	—	—
Sandstone	2...2.5	≈ 1500	—	2.3	0.71	—	—
Selenium Se	4.8	217	684.9	2.0	0.34	64.6	37
Silicon Si	2.33	1410	2480	148	0.68	1410	4.2
Silicon carbide	2.4	Decomposes above 3000°C 9)			1.05 ⁹⁾	—	4.0
Sillimanite	2.4	1820	—	1.51	1.0	—	—
Silver Ag	10.5	961.9	2195	429	0.24	104.7	19.2
Slag, blast furnace	2.5...3	1300... ...1400	—	0.14	0.84	—	—
Sodium Na	0.97	97.81	883	141	1.24	115	70.6
Soft rubber	1.08	—	—	0.14...0.24	—	—	—
Soot	1.7...1.8	—	—	0.07	0.84	—	—
Steatite	2.6...2.7	≈ 1520	—	1.6 ¹⁰⁾	0.83	—	8...9 ¹¹⁾
Steel, chromium steel	—	—	—	—	—	—	11
Steel, electrical sheet steel	—	—	—	—	—	—	12
Steel, high-speed steel	—	—	—	—	—	—	11.5
Steel, magnet steel AlNiCo12/6	—	—	—	—	—	—	11.5
Steel, nickel steel 36% Ni (invar)	—	—	—	—	—	—	1.5
Steel, sintered	—	—	—	—	—	—	11.5
Steel, stainless (18Cr, 8Ni)	7.9	1450	—	14	0.51	—	16
Steel, tungsten steel (18 W)	8.7	1450	—	26	0.42	—	—
Steel, unalloyed and low-alloy	7.9	1460	2500	48...58	0.49	205	11.5
Sulfur (α) S	2.07	112.8	444.67	0.27	0.73	38	74
Sulfur (β) S	1.96	119.0	—	—	—	—	—
Thermosets							
Melamin resin with cellulose fibers	1.5	—	—	0.35	—	—	≈ 60
Phenolic resin with asbestos fibers	1.8	—	—	0.70	1.25	—	15...30
Phenolic resin with fabric chips	1.4	—	—	0.35	1.47	—	15...30
Phenolic resin with wood dust	1.4	—	—	0.35	1.47	—	30...50
Phenolic resin w/o filler	1.3	—	—	0.20	1.47	—	80

1) At 1.013 bar. 2) At 20 °C. ΔH of chemical elements at 27 °C (300 K). 3) At 0...100 °C. 4) At melting point and 1.013 bar. 5) Parallel to crystal axis. 6) Perpendicular to crystal axis. 7) At 20...50 °C. 8) Rigid foam plastic from phenolic resin, polystyrene, polyethylene & similar. Values dependent on cell diameter and filler gas. 9) At 1000 °C. 10) At 100...200 °C. 11) At 20...1000 °C. 12) Materials, PP. 193...227.

Substance		Density	Melting point ¹⁾	Boiling point ¹⁾	Thermal conductivity ²⁾	Mean specific heat capacity ³⁾	Melting enthalpy $\Delta H^4)$	Coefficient of linear expansion ⁵⁾
		g/cm ³	°C	°C	W/(m · K)	kJ/(kg · K)	kJ/kg	×10 ⁻⁶ /K
Tantalum	Ta	16.65	2996	5487	57.5	0.14	174	6.6
Tellurium	Te	6.24	449.5	989.8	2.3	0.20	106	16.7
Thorium	Th	11.72	1750	4227	54	0.14	<83	12.5
Tin (white)	Sn	7.28	231.97	2270	65.7	0.23	61	21.2
Titanium	Ti	4.51	1660	3313	21.9	0.52	437	8.3
Tombac CuZn 20		8.65	1000	≈1300	159	0.38	—	—
Tungsten	W	19.25	3422	5727	174	0.13	191	4.6
Uranium	U	18.95	1132.3	3677	27.6	0.12	65	12.6
Vanadium	V	6.11	1890	3000	30.7	0.50	345	8.3
Vulcanized fiber		1.28	—	—	0.21	1.26	—	—
Wax		0.96	60	—	0.084	3.4	—	—
Wood ⁵⁾	Ash	0.72	—	—	0.16	2.1...2.9	—	in fiber direction 3...4, transverse to fiber 22...43
	Balsa	0.20	—	—	0.06		—	
	Beech	0.72	—	—	0.17		—	
	Birch	0.63	—	—	0.14		—	
	Maple	0.62	—	—	0.16		—	
	Oak	0.69	—	—	0.17		—	
	Pine	0.52	—	—	0.14		—	
	Poplar	0.50	—	—	0.12		—	
	Spruce, fir	0.45	—	—	0.14		—	
	Walnut	0.65	—	—	0.15		—	
Wood-wool building slabs		0.36...0.57	—	—	0.093	—	—	—
Zinc	Zn	7.14	419.58	907	116	0.38	102	25.0
Zirconium	Zr	6.51	1852	4377	22.7	0.28	252	5.8

¹⁾ At 1.013 bar. ²⁾ At 20°C. ΔH of chemical elements at 27°C (300 K). ³⁾ At 0...100°C.

⁴⁾ At melting point and 1.013 bar. ⁵⁾ Mean values for air-dried wood (moisture content: approx. 12%). Thermal conductivity: radial. Axial conductivity is roughly twice as high.

Properties of liquids

Substance	Density ²⁾ g/cm ³	Melting point ¹⁾ °C	Boiling point ¹⁾ °C	Thermal conductivity ²⁾ W/(m · K)	Specific heat capacity ²⁾ kJ/(kg · K)	Melting enthalpy ΔH ³⁾ kJ/kg	Evaporation enthalpy ⁴⁾ kJ/kg	Coefficient of volume expansion x10 ⁻³ /K
Acetone (CH ₃) ₂ CO	0.79	-95	56	0.16	2.21	98.0	523	-
Antifreeze-water mixture 23 % by vol.	1.03	-12	101	0.53	3.94	-	-	-
38 % by vol.	1.04	-25	103	0.45	3.68	-	-	-
54 % by vol.	1.06	-46	105	0.40	3.43	-	-	-
Benzene C ₆ H ₆	0.88	+ 5.5 ⁵⁾	80	0.15	1.70	127	394	1.25
Common-salt solution 20 %	1.15	-18	109	0.58	3.43	-	-	-
Diesel fuel	0.81...0.85	-30	150...360	0.15	2.05	-	-	-
Ethanol C ₂ H ₅ OH	0.79	-117	78.5	0.17	2.43	109	904	1.1
Ethyl ether (C ₂ H ₅) ₂ O	0.71	-116	34.5	0.13	2.28	98.1	377	1.6
Ethyl dichloride C ₂ H ₅ Cl	0.90	-136	12	0.11 ⁵⁾	1.54 ⁵⁾	69.0	437	-
Ethylene glycol C ₂ H ₄ (OH) ₂	1.11	-12	198	0.25	2.40	-	-	-
Fuel oil EL	≈ 0.83	-10	> 175	0.14	2.07	-	-	-
Gasoline/petrol	0.72...0.75	-50...-30	25...210	0.13	2.02	-	-	1.0
Glycerin C ₃ H ₅ (OH) ₃	1.26	+20	290	0.29	2.37	200	828	0.5
Hydrochloric acid 10 % HCl	1.05	-14	102	0.50	3.14	-	-	-
Kerosene	0.76...0.86	-70	> 150	0.13	2.16	-	-	1.0
Linseed oil	0.93	-15	316	0.17	1.88	-	-	-
Lubricating oil	0.91	-20	> 300	0.13	2.09	-	-	-
Mercury ⁶⁾ Hg	13.55	-38.84	356.6	10	0.14	11.6	295	0.18
Methanol CH ₃ OH	0.79	-98	65	0.20	2.51	99.2	1109	-
Methyl chloride CH ₃ Cl	0.99 ⁷⁾	-92	-24	0.16	1.38	-	406	-
m-xylene C ₆ H ₄ (CH ₃) ₂	0.86	-48	139	-	-	-	339	-
Nitric acid, conc. HNO ₃	1.51	-41	84	0.26	1.72	-	-	-

1) At 1.013 bar. 2) At 20 °C. 3) At melting point and 1.013 bar 4) At boiling point and 1.013 bar. 5) At 0 °C. 6) Setting point 0 °C. 7) At -24 °C.
8) For conversion of torr to Pa, use 13.5951 g/cm³ (at 0 °C).

Substance	Density ²⁾ g/cm ³	Melting point ¹⁾ °C	Boiling point ¹⁾ °C	Thermal conductivity ²⁾ W/(m · K)	Specific heat capacity ²⁾ kJ/(kg · K)	Melting enthalpy ΔH ³⁾ kJ/kg	Evaporation enthalpy ⁴⁾ kJ/kg	Coefficient of volume expansion x10 ⁻³ /K
Paraffin oil	—	—	—	—	—	—	—	0.764
Petroleum ether	0.66	-160	> 40	0.14	1.76	—	—	—
Rape oil	0.91	± 0	300	0.17	1.97	—	—	—
Silicone oil	0.76...0.98	—	—	0.13	1.09	—	—	—
Spirit 95 % ⁶⁾	0.81	-114	78	0.17	2.43	—	—	—
Sulfuric acid, conc.	1.83	+10.5 ⁵⁾	338	0.47	1.42	—	—	0.55
Tar, coke oven	1.2	-15	300	0.19	1.56	—	—	—
Toluene	0.87	-93	111	0.14	1.67	74.4	364	—
Transformer oil	0.88	-30	170	0.13	1.88	—	—	—
Trichloroethylene	1.46	-85	87	0.12	0.93	—	265	1.19
Turpentine oil	0.86	-10	160	0.11	1.80	—	293	1.0
Water	1.00 ⁷⁾	± 0	100	0.60	4.18	332	2256	0.18 ⁸⁾

Water vapor

Absolute pressure bar	Boiling point °C	Evaporation enthalpy kJ/kg	Absolute pressure bar	Boiling point °C	Evaporation enthalpy kJ/kg
0.1233	50	2382	25.5	225	1837
0.3855	75	2321	39.78	250	1716
1.0133	100	2256	59.49	275	1573
2.3216	125	2187	85.92	300	1403
4.760	150	2113	120.5	325	1189
8.925	175	2031	165.4	350	892
15.55	200	1941	221.1	374.2	0

- 1) At 1.013 bar.
- 2) At 20 °C.
- 3) At melting point and 1.013 bar.
- 4) At boiling point and 1.013 bar.
- 5) Setting point 0 °C.
- 6) Denaturated ethanol.
- 7) At 4 °C.
- 8) Volume expansion on freezing: 9 %.

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Properties of gases

Substance		Density ¹⁾	Melting point ²⁾	Boiling point ²⁾	Thermal conductivity ³⁾	Specific heat capacity ³⁾		Evaporation enthalpy ²⁾	
		kg/m ³	°C	°C	W/(m·K)	c _p	c _v	c _p /c _v	kJ/kg
Acetylene	C ₂ H ₂	1.17	-84	-81	0.021	1.64	1.33	1.23	751
Air		1.293	-220	-191	0.026	1.005	0.716	1.40	209
Ammonia	NH ₃	0.77	-78	-33	0.024	2.06	1.56	1.32	1369
Argon	Ar	1.78	-189	-186	0.018	0.52	0.31	1.67	163
Blast-furnace gas		1.28	-210	-170	0.024	1.05	0.75	1.40	-
i-butane	C ₄ H ₁₀	2.67	-145	-10.2	0.016	-	-	1.11	-
n-butane	C ₄ H ₁₀	2.70	-138	-0.5	0.016	-	-	-	-
Carbon dioxide	CO ₂	1.98	-57 ⁴⁾	-78	0.016	0.82	0.63	1.30	368
Carbon disulfide	CS ₂	3.41	-112	+46	0.0073	0.67	0.56	1.19	-
Carbon monoxide	CO	1.25	-199	-191	0.025	1.05	0.75	1.40	-
Chlorine	Cl ₂	3.21	-101	-35	0.009	0.48	0.37	1.30	288
City/town gas		0.56...0.61	-230	-210	0.064	2.14	1.59	1.35	-
Cyanogen (dicyan)	(CN) ₂	2.33	-34	-21	-	1.72	1.35	1.27	-
Dichlorodifluoromethane CCl ₂ F ₂ (= Freon F 12)		5.51	-140	-30	0.010	-	-	1.14	-
Ethane	C ₂ H ₆	1.36	-183	-89	0.021	1.66	1.36	1.22	522
Ethanol vapor		2.04	-114	+78	0.015	-	-	1.13	-
Ethylene	C ₂ H ₄	1.26	-169	-104	0.020	1.47	1.18	1.24	516
Fluorine	F ₂	1.70	-220	-188	0.025	0.83	-	-	172
Helium	He	0.18	-270	-269	0.15	5.20	3.15	1.65	20
Hydrogen	H ₂	0.09	-258	-253	0.181	14.39	10.10	1.42	228
Hydrogen chloride	HCl	1.64	-114	-85	0.014	0.81	0.57	1.42	-
Hydrogen sulfide	H ₂ S	1.54	-86	-61	-	0.96	0.72	1.34	535
Krypton	Kr	3.73	-157	-153	0.0095	0.25	0.15	1.67	108
Methane	CH ₄	0.72	-183	-164	0.033	2.19	1.68	1.30	557
Methyl chloride	CH ₃ Cl	2.31	-92	-24	-	0.74	0.57	1.29	446
Natural gas		≈ 0.83	-	-162	-	-	-	-	-
Neon	Ne	0.90	-249	-246	0.049	1.03	0.62	1.67	86
Nitrogen	N ₂	1.24	-210	-196	0.026	1.04	0.74	1.40	199
Oxygen	O ₂	1.43	-218	-183	0.267	0.92	0.65	1.41	213
Ozone	O ₃	2.14	-251	-112	0.019	-	-	1.29	-
Propane	C ₃ H ₈	2.00	-182	-42	0.018	-	-	1.14	-
Propylene	C ₃ H ₆	1.91	-185	-47	0.017	-	-	-	468
Sulfur dioxide	SO ₂	2.93	-73	-10	0.010	0.64	0.46	1.40	402
Water vapor at 100 °C ⁵⁾		0.60	± 0	+100	0.025	2.01	1.52	1.32	-
Xenon	Xe	5.89	-112	-108	0.0057	0.16	0.096	1.67	96

1) At 0 °C and 1.013 bar.

2) At 1.013 bar.

3) At 20 °C and 1.013 bar. C_p, C_v specific heat capacity at constant pressure and at constant volume.

4) At 5.3 bar.

5) At saturation and 1.013 bar, see also table "Properties of liquids".

Properties of metallic materials

Material	Standard	Abbreviation of selected types	Primary alloying constituents, mean values in % by mass	$R_m^{(1)}$ N/mm ²	$R_e^{(2)}$ N/mm ²	$A_5^{(3)}$ %	$\sigma_{0.2}^{(4)}$ Ref. value N/mm ²	Test bar dia. ⁽⁵⁾ mm	Properties, typical applications
Cast iron and malleable cast iron⁽⁶⁾ $E^{(7)}$ in 10^3 N/mm²: GG 78... 143⁽⁸⁾; GGG 160... 180; GTW and GTS 175... 195									
Lamellar graphite iron (gray cast iron)	DIN EN 1561	EN-GJL-200	Not standardized	200...300	—	—	90	30	Brittle, very good machinability.
Nodular graphite iron	DIN EN 1563	EN-GJS-400-15	Not standardized	≥ 400	≥ 250	≥ 15	200	25	More ductile than gray cast iron, good machinability.
Malleable cast iron White-heart casting Black-heart casting	DIN EN 1569	GTW-40-05 GTS-35-10	Not standardized	≥ 400 ≥ 350	≥ 220 ≥ 200	≥ 5 (A_5) ≥ 10 (A_5)	—	12 12	Ductility similar to nodular cast iron, good machinability.
Cast steel $E^{(7)}$ as steel	DIN 1681	GS-45	Not standardized	≥ 450	≥ 230	≥ 22	210	—	Heat-treatable.

Steel $E^{(7)}$ in 10^3 N/mm²: unalloyed and low-alloy steel 212, austenitic steels ≥ 190, high-alloy tool steels ≤ 230

Untreated structural steel (dia. 16...40 mm)	DIN EN 10025	S235JR E360	≤ 0.19 C	340...510 670...830	≤ 225 ≥ 355	≥ 26 ≥ 11	≥ 170 ≥ 330	—	For low-stressed parts. For higher-stressed parts.
Cold-rolled strip of soft unalloyed steels	DIN EN 10139	DC05LC	Not standardized	270...330	≤ 180	≥ 40 (A_{90})	≥ 130	—	For difficult deep-drawn parts.
Hot-galvanized strip and sheet	DIN EN 10142	DX53D	Not standardized	≤ 380	≤ 260	≥ 30 (A_{90})	≥ 190	—	For corrosion-stressed, difficult deep-drawn parts.
Free-cutting steel (dia. 16 ... 40 mm)	DIN EN 10087	11 SMn30 35 S 20	≤ 0.14 C; 1.1 Mn; 0.30 S 0.35 C; 0.9 Mn; 0.20 S	380...570 520...680	—	—	≥ 190 ≥ 260	—	Soft free-cutting steel. Free-cutting heat-treatable steel.

Hot work steel, hardened and tempered	DIN EN ISO 4957	X 40 CrMoV 5-1	0.4 C; 5 Cr; 1.3 Mo; 1 V	43...45 HRC	In the case of hard steels – hardened and tempered, case-hardened, nitration-hard- ened etc. – the material char- acteristic values measured in the tensile test are unsuitable for dimensioning of the hard components.			Wear-resistant at high temperature.
	DIN EN ISO 4957	HS6-5-2	0.85 C; 6 W; 5 Mo; 2 V; 4 Cr	61...65 HRC				
Stainless steels -Ferritic steel, annealed	17 440	X 6 Cr 17	≤ 0.08 C; 17 Cr	450...600	≥ 270	≥ 20	200...315	Non-hardenable.
				Hardness < 185 HV				
-Martensitic steel, hardened and tempered	DIN EN 10 088	X 20 Cr 13 X 46 Cr 13 X 90 CrMoV 18	0.20 C; 13 Cr 0.46 C; 13 Cr 0.9 C; 18 Cr; 1.1 Mo; 0.1 V	Hardness approx. 40 HRC Hardness approx. 45 HRC Hardness ≥ 57 HRC			Increasing wear resistance. ↓	
-Austenitic steel, quenched	17 440	X 5 CrNi 18-10 X 8 CrNiS 18-10	≤ 0.07 C; 18 Cr; 9 Ni ≤ 0.07 C; 18 Cr; 9 Ni; 0.3 S	500...700	≥ 190	≥ 45	–	Non-magnetic, non-hardenable.
				500...700	≥ 190	≥ 35		
Hard metals E = 440 000...550 000	–	–	W (Ti, Ta) carbide + Co	800...1900 HV		Sintered materials, extremely resistant to pressure and wear, but brittle; for machin- ing, cutting, forming tools.		
Extremely heavy metals E = 320 000...380 000	–	–	> 90 W; Ni & others	≥ 650	≥ 560	≥ 2	Density 17...18.5 g/cm³; for governor fly- weights, flywheel masses, counterweights.	
				240...450 HV				

1) Tensile strength.
2) Yield point (or R_{p0.2}).
3) Elongation at fracture.
4) Fatigue strength under reversed bending stresses; more precise strength values are to be calculated according to FMK Guideline "Computational verification of strength for machine components".
5) The Fatigue limits given apply to the separately cast test bar.
6) The Fatigue limits of all types of cast iron are dependent on the weight and section thickness of the cast pieces.
7) Modulus of elasticity.
8) For gray cast iron, E decreases with increasing tensile stress and remains almost constant with increasing compression stress.

Steel (continued)
Spring steel

Material	DIN	Primary alloying constituents, approx. in % by mass; E and G in N/mm ²	Diameter, mm	$R_m^{1)}$ min. N/mm ²	$Z^{2)}$ %	$\sigma_b^{3)}$ N/mm ²	$\tau_{th}^{4)}$ N/mm ²	$\tau_{zul}^{5)}$ N/mm ²	Properties Typical applications
Spring steel wire D, patented and springy drawn ⁶⁾	17 223 Sheet 1	0.8 C; 0.6 Mn; < 0.35 Si $E = 206\,000$ $G = 81\,500$	1 3 10	2230 1840 1350	40 40 30	1590 1280 930	380 ⁷⁾ 360 ⁷⁾ 320	1115 920 675	For high maximum stresses (P. 294).
Nonrusting spring steel wire	17 224	< 0.12 C; 17 Cr; 7.5 Ni $E = 185\,000$ $G = 73\,500$	1 3	2000 1600	40 40	1400 1130	— —	1000 800	For nonrusting springs.
Heat-treated valve-spring steel wire ⁸⁾	17 223 Sheet 2	0.65 C; 0.7 Mn; ≤ 0.30 Si $E = 206\,000$ $G = 80\,000$	1 3 8	1720 1480 1390	45 45 38	1200 1040 930	380 ⁸⁾ 380 ⁸⁾ 360 ⁶⁾	860 740 690	For high alternating cyclic stress.
Heat-treated, alloyed valve-spring steel wire VD Si Cr ⁶⁾	—	0.55 C; 0.7 Mn; 0.65 Cr; 1.4 Si $E = 200\,000$ $G = 79\,000$	1 3 8	2060 1920 1720	50 50 40	— — —	430 ⁸⁾ 430 ⁸⁾ 380 ⁸⁾	1030 960 860	For maximum alternating cyclic stress and higher temperatures.
Heat-treated, alloyed valve-spring steel wire VD Cr V ⁶⁾	—	0.7 C; 0.7 Mn; 0.5 Cr; 0.15 V; ≤ 0.30 S $G = 79\,000$	1 3 8	1860 1670 1420	45 45 40	— — —	470 ⁸⁾ 470 ⁸⁾ 400 ⁸⁾	930 835 710	For maximum alternating cyclic stress.
Spring steel strip Ck 85	17 222	0.85 C; 0.55 Mn; 0.25 Si $E = 206\,000$	$h \leq 2.5$	1470	—	1270	$\sigma_{th} = 640$	—	For highly stressed leaf springs.
Nonrusting spring steel strip	17 224	< 0.12 C; 17 Cr; 7.5 Ni $E = 185\,000$	$h \leq 1$	1370	—	1230	$\sigma_{th} = 590$	—	For nonrusting leaf springs.

1) Tensile strength.
2) Reduction of area at fracture.
3) Permissible bending stress.
4) Permissible lift stress for number of stress cycles $N \geq 10^7$.
5) Permissible maximum stress for temperatures to approx. 30 °C and 1...2 % relaxation in 10 hrs.; for higher temperatures, see P. 294.
6) See pp. 294 and 295 for fatigue-strength diagrams.
7) 480 N/mm² for peened springs.
8) Approx. 40 % higher for peened springs.

Vehicle-body sheet metal

Material Abbreviated name	Standard material thickness mm	$R_{p0.2}^{1)}$ N/mm ²	$R_m^{2)}$ N/mm ²	$A_{80}^{3)}$ %	Properties Typical applications
St 12	0.6...2.5	≈ 280	270...410	≈ 28	For simple drawn metal parts.
St 13		≈ 250	270...370	≈ 32	For complicated drawn metal parts.
St 14		≈ 240	270...350	≈ 38	For very complex deep-drawn parts, outer body parts (roof, doors, fenders etc.; 0.75...1.0 mm); see also DIN 1623.
ZE 260	0.75...2.0	260...340	≈ 370	≈ 28	For highly stressed supporting parts whose degree of forming is not too complicated.
ZE 340		340...420	≈ 420	≈ 24	
ZE 420		420...500	≈ 490	≈ 20	
AlMg 0.4 Si 1.2	0.8...2.5	≈ 140	≈ 250	≈ 28	For outer body parts such as front fenders, doors, engine hood, trunk lid etc.; mostly 1.25 mm; see DIN 1745.
AlMg 4.5 Mn 0.3	0.5...3.5	≈ 130	≈ 270	≈ 28	For inner reinforcements of hinged covers; for parts which are not visible; lines of stress tolerated.

1) Yield strength.
2) Tensile strength.
3) Elongation at fracture.

Nonferrous metals, heavy metals

Material Examples	Abbreviated name Examples	Composition, mean values, in % by mass	$E^{1)}$ N/mm ²	$R_m^{2)}$ min. N/mm ²	$R_{p0.2}^{3)}$ approx. N/mm ²	$\sigma_{bw}^{4)}$ approx. N/mm ²	Properties Typical applications
Wrought copper alloys (DIN EN 1652 ... 1654, 1758, 12163 ... 12168)							
High-conductivity copper	EN CW-Cu-FRTP	99.90 Cu	$128 \cdot 10^3$	200	$120^{5)}$	70	Very good electrical conductivity.
Brass	EN CW-CuZn 28 R370	72 Cu; 28 Zn	$114 \cdot 10^3$	370	320	120	Deep-drawing capability. Good cold formability. Machine parts.
	EN CW-CuZn 37 R440	63 Cu; 37 Zn	$110 \cdot 10^3$	440	400	140	
	EN CW-CuZn 39 Pb3 R430	58 Cu; 39 Zn; 3 Pb	$96 \cdot 10^3$	430	250	150	
Nickel silver	EN CW-CuNi 18 Zn 20 R500	62 Cu; 20 Zn; 18 Ni	$135 \cdot 10^3$	500	300		Corrosion-resistant.
Tin bronze	EN CW-CuSn 6 R400	94 Cu; 6 Sn	$118 \cdot 10^3$	410	300	175	Good antifriction qualities; bearing bushings, connectors.
Cast copper alloys (DIN 1705)							
Cast tin bronze	G-CuSn 10 Zn	88 Cu; 10 Sn; 2 Zn	$100 \cdot 10^3$	$260^{6)}$	$140^{6)}$	90	Corrosion-resistant, wear-resistant; gears, bearings.
Red bronze	GC-CuSn 7 ZnPb	85 Cu; 7 Sn; 4 Zn; 6 Pb	$95 \cdot 10^3$	270	130	80	
Other alloys							
Tin alloy (DIN ISO 4381)	SnSb 12 Cu 6 Pb	80 Sn; 12 Sb; 6 Cu; 2 Pb	$30 \cdot 10^3$	—	60	28	Plain bearings.
Zinc diecastings (DIN 1743)	GD-ZnAl 4 Cu 1	96 Zn; 4 Al	$85 \cdot 10^3$	$280^{6)}$	$230^{6)}$	80	Dimensionally accurate castings.
Heating-conductor alloy (DIN 17470)	NiCr 80 20 NiCr 60 15	80 Ni; 20 Cr 60 Ni; 22 Fe; 17 Cr	— —	650 600	— —	— —	High electrical resistance (P. 215).
Resistance alloy (DIN 17471)	CuNi 44 CuNi 30 Mn	55 Cu; 44 Ni; 1 Mn 67 Cu; 30 Ni; 3 Mn	— —	420 400	— —	— —	

1) Modulus of elasticity, reference values. 2) Tensile strength. 3) 0.2 % yield strength. 4) Fatigue limit under reversed bending stress. 5) Maximum.
6) For separately cast test rod.

Nonferrous metals, light metals

Material Examples	Composition, mean values in % by mass	$R_m^{(1)}$ min. N/mm ²	$R_{p0.2}^{(2)}$ min. N/mm ²	$\sigma_{bw}^{(3)}$ approx. N/mm ²	Properties Typical applications
Wrought aluminum alloys (DIN EN 458, 485, 515, 573, 754 ...), modulus of elasticity $E = 65\,000 \dots 73\,000$ N/mm ²					
ENAW-Al 99.5 O	99.5 Al	65	20	40	Soft, very good conductor, can be anodized/polished. Seawater-resistant, can be anodized. Aged artificially, seawater-resistant. Precipitation-hardened, good creep rupture properties. Maximum strength.
ENAW-AlMg 2 Mn 0.8 O	97 Al; 2 Mg; 0.8 Mn	190	80	90	
ENAW-AlSiMgMn T 6	97 Al; 0.9 Mg; 1 Si; 0.7 Mn	310	260	90	
ENAW-AlCu 4 MgSi (A) T 4	94 Al; 4 Cu; 0.7 Mg; 0.7 Mn; 0.5 Si	390	245	120	
ENAW-AlZn 5.5 MgCu T 651	90 Al; 6 Zn; 2 Mg; 2 Cu; 0.2 Cr	525	460	140	
Cast aluminum alloys ⁵⁾ (DIN EN 1706), modulus of elasticity $E = 68\,000 \dots 80\,000$ N/mm ²					
ENAC-AlSi 7 Mg 0.3 KT 6	89 Al; 7 Si; 0.4 Mg; 0.1 Ti	290	210	80	Aged artificially; highly stressed parts with good vibration strength. Highly versatile, heat-resistant. Aged artificially; simple parts with maximum strength and toughness. Thin-walled, vibration-resistant parts. Heat-resistant; complicated diecastings. Seawater-resistant; medium-stressed parts.
ENAC-AlSi 6 Cu 4 KF	89 Al; 6 Si; 4 Cu; 0.3 Mn; 0.3 Mg	170	100	60	
ENAC-AlCu 4 Ti KT 6	95 Al; 5 Cu; 0.2 Ti	330	220	90	
ENAC-AlSi 12 Cu 1 (Fe) DF	88 Al; 12 Si; 1 Cu; 1 Fe	240	140	70	
ENAC-AlSi 9 Cu 3 (Fe) DF	87 Al; 9 Si; 3 Cu; 0.3 Mn; 0.3 Mg	240	140	70 ⁶⁾	
ENAC-AlMg 9 DF	90 Al; 9 Mg; 1 Si; 0.4 Mn	200	130	60 ⁶⁾	
Magnesium alloys (DIN 1729, 9715), modulus of elasticity $E = 40\,000 \dots 45\,000$ N/mm ²					
MgAl 6 Zn F 27	93 Mg; 6 Al; 1 Zn; 0.3 Mn	270	195	—	Parts subject to medium to high stress. Aged artificially. Complicated diecastings. Chips are combustible.
GK-MgAl 9 Zn 1 wa	90 Mg; 9 Al; 0.6 Zn; 0.2 Mn	240	150	80	
GD-MgAl 9 Zn 1	90 Mg; 9 Al; 0.6 Zn; 0.2 Mn	200	150	50	
Titanium alloys (DIN 17 850, 17 851, 17 860 ... 17 864), modulus of elasticity $E \approx 110\,000$ N/mm ²					
Ti 1	99.7 Ti	290	180	—	Corrosion-resistant. Corrosion-resistant, maximum strength.
TiAl 6 V 4 F 89	90 Ti; 6 Al; 4 V	890	820	—	

¹⁾ Tensile strength. ²⁾ 0.2 % yield strength. ³⁾ Rotating bending fatigue strength. ⁴⁾ Maximum. ⁵⁾ Strength values apply to permanent mold castings and diecastings for separately cast test rods. Sand castings have slightly lower values than permanent mold castings. ⁶⁾ Flat bending fatigue strength.

Sintered metals¹⁾ for plain bearings

Material	Ma- terial code	Permissible ranges				Representative examples						
		Density ρ	Porosity $(\Delta V/V) \cdot 100$ %	Chemical composition % by mass	Radial break- ing re- sistance K^2 N/mm ²	Hard- ness HB	Density ρ	Chemical composition % by mass	Radial break- ing re- sistance K^2 N/mm ²	Com- pressive yield point $\sigma_{0.2}$ N/mm ²	Hard- ness HB ²⁾	Thermal conduc- tivity λ W/mK
Sintered iron	Sint	g/cm ³		%		HB	g/cm ³	%				
	A 00	5.6...6.0	25 ± 2.5	< 0.3 C; < 1.0 Cu;	> 150	> 25	5.9	< 0.2 others; rest Fe	160	130	30	37
	B 00	6.0...6.4	20 ± 2.5	< 2 others; rest Fe	> 180	> 30	6.3		190	160	40	43
Sintered steel containing Cu	C 00	6.4...6.8	15 ± 2.5		> 220	> 40	6.7		230	180	50	48
	A 10	5.6...6.0	25 ± 2.5	< 0.3 C; 1 ... 5 Cu;	> 160	> 35	5.9	2.0 Cu;	170	150	40	36
	B 10	6.0...6.4	20 ± 2.5	< 2 others; rest Fe	> 190	> 40	6.3	< 0.2 others; rest Fe	200	170	50	37
Sintered steel containing Cu and C	C 10	6.4...6.8	15 ± 2.5		> 230	> 55	6.7		240	200	65	42
	B 11	6.0...6.4	20 ± 2.5	0.4 ... 1.0 C; 1 ... 5 Cu;	> 270	> 70	6.3	0.6 C; 2.0 Cu;	280	160	80	28
				< 2 others; rest Fe				< 0.2 others; rest Fe				
Sintered steel containing high percentage of Cu	A 20	5.8...6.2	25 ± 2.5	< 0.3 C; 15 ... 25 Cu;	> 180	> 30	6.0	20 Cu;	200	140	40	41
	B 20	6.2...6.6	20 ± 2.5	< 2 others; rest Fe	> 200	> 45	6.4	< 0.2 others; rest Fe	220	160	50	47
Sintered steel containing high percentage of Cu and C	A 22	5.5...6.0	25 ± 2.5	0.5...2.0 C;	> 120	> 20	5.7	2.0 C ³⁾ ; 20 Cu;	125	100	25	30
	B 22	6.0...6.5	20 ± 2.5	15 ... 25 Cu;	> 140	> 25	6.1	< 0.2 others; rest Fe	145	120	30	37
				< 2 others; rest Fe								
Sintered bronze	A 50	6.4...6.8	25 ± 2.5	< 0.2 C; 9 ... 11 Sn;	> 120	> 25	6.6	10 Sn;	140	100	30	27
	B 50	6.8...7.2	20 ± 2.5	< 2 others; rest Cu	> 170	> 30	7.0	< 0.2 others; rest Cu	180	130	35	32
	C 50	7.2...7.7	15 ± 2.5		> 200	> 35	7.4		210	160	45	37
Sintered bronze containing graphite ⁴⁾	A 51	6.0...6.5	25 ± 2.5	0.5 ... 2.0 C;	> 100	> 20	6.3	1.5 C ⁴⁾ ; 10 Sn;	120	80	20	20
	B 51	6.5...7.0	20 ± 2.5	9 ... 11 Sn;	> 150	> 25	6.7	< 0.2 others; rest Cu	155	100	30	26
	C 51	7.0...7.5	15 ± 2.5	< 2 others; rest Cu	> 170	> 30	7.1		175	120	35	32

1) According to "Material Specification Sheets for Sintered Metals"; DIN 30 910, 1990 Edition.
2) Measured on calibrated bearings 10/16 dia. · 10.
3) C is mainly present as free graphite.
4) C is present as free graphite.

Sinter (PM) metals¹⁾ for structural parts

		Permissible ranges				Representative examples						
Material	Ma- terial code	Density ρ g/cm ³	Porosity ($\Delta V/V$) · 100 %	Chemical composition % by mass	Hard- ness HB	Density ρ g/cm ³	Chemical composition % by mass	Tensile strength R_m N/mm ²	Yield point $R_{p\,0.1}$ N/mm ²	Elonga- tion at break A %	Hard- ness HB	Elastic modu- lus $E \cdot 10^3$ N/mm ²
	Sint											
Sintered iron	C 00	6.4...6.8	15 ± 2.5	< 0.3 C; < 1.0 Cu;	> 35	6.6	< 0.5 others; rest Fe	130	60	4	40	100
	D 00	6.8...7.2	10 ± 2.5	< 2 others; rest Fe	> 45	6.9		190	90	10	50	130
	E 00	> 7.2	< 7.5		> 60	7.3		260	130	18	65	160
Sintered steel containing C	C 01	6.4...6.8	15 ± 2.5	0.3...0.6 C; < 1.0 Cu;	> 70	6.6	0.5 C;	260	180	3	80	100
	D 01	6.8...7.2	10 ± 2.5	< 2 others; rest Fe	> 90	6.9	< 0.5 others; rest Fe	320	210	3	100	130
	C 10	6.4...6.8	15 ± 2.5	< 0.3 C; 1...5 Cu;	> 40	6.6	1.5 Cu;	230	160	3	55	100
Sintered steel containing Cu	D 10	6.8...7.2	10 ± 2.5	< 2 others; rest Fe	> 50	6.9	< 0.5 others; rest Fe	300	210	6	85	130
	E 10	> 7.2	< 7.5		> 80	7.3		400	290	12	120	160
	C 11	6.4...6.8	15 ± 2.5	0.4...1.5 C; 1...5 Cu;	> 80	6.6	0.6 C; 1.5 Cu;	460	320	2	125	100
Sintered steel containing Cu and C	D 11	6.8...7.2	10 ± 2.5	< 2 others; rest Fe	> 95	6.9	< 0.5 others; rest Fe	570	400	2	150	130
	C 21	6.4...6.8	15 ± 2.5	0.4...1.5 C; 5...10 Cu;	> 105	6.6	0.8 C; 6 Cu;	530	410	< 1	150	100
				< 2 others; rest Fe								
Sintered steel containing Cu, Ni and Mo	C 30	6.4...6.8	15 ± 2.5	< 0.3 C; 1...5 Cu;	> 55	6.6	0.3 C; 1.5 Cu; 4.0 Ni;	390	310	2	105	100
	D 30	6.8...7.2	10 ± 2.5	1...5 Ni; < 0.8 Mo;	> 60	6.9	0.5 Mo;	510	370	3	130	130
	E 30	> 7.2	< 7.5	< 2 others; rest Fe	> 90	7.3	< 0.5 others; rest Fe	680	440	5	170	160
Sintered steel containing P	C 35	6.4...6.8	15 ± 2.5	< 0.3 C; < 1.0 Cu;	> 70	6.6	0.45 P;	310	200	11	85	100
	D 35	6.8...7.2	10 ± 2.5	0.3...0.6 P;	> 80	6.9	< 0.5 others; rest Fe	330	230	12	90	130
				< 2 others; rest Fe								
Sintered steel containing Cu and P	C 36	6.4...6.8	15 ± 2.5	< 0.3 C; 1...5 Cu;	> 80	6.6	2.0 Cu; 0.45 P;	360	290	5	100	100
	D 36	6.8...7.2	10 ± 2.5	0.3...0.6 P;	> 90	6.9	< 0.5 others; rest Fe	380	320	6	105	130
				< 2 others; rest Fe								
Sintered steel containing Cu, Ni, Mo and C	C 39	6.4...6.8	15 ± 2.5	0.3...0.6 C; 1...3 Cu;	> 90	6.6	0.5 C; 1.5 Cu; 4.0 Ni;	520	370	1	150	100
	D 39	6.8...7.2	10 ± 2.5	1...5 Ni; < 0.8 Mo;	> 120	6.9	0.5 Mo;	600	420	2	180	130
				< 2 others; rest Fe			< 0.5 others; rest Fe					

¹⁾ According to "Material Specification Sheets for Sintered Metals"; DIN 30 910, 1990 Edition.

Sintered metals¹⁾ for structural parts (continued)

Material		Permissible ranges				Representative examples						
		Density ρ	Porosity $(\Delta V/V) \cdot 100$ %	Chemical composition % by mass	Hard- ness HB	Density ρ	Chemical composition % by mass	Tensile strength R_m N/mm ²	Yield point $R_{p\,0.1}$ N/mm ²	Elonga- tion at break A %	Hard- ness HB	Elastic modu- lus $E \cdot 10^3$ N/mm ²
	Sint	g/cm ³		%		g/cm ³	%					
Stainless sintered steel AISI 316	C 40	6.4...6.8	15 ± 2.5	< 0.08 C; 10 ... 14 Ni;	> 95	6.6	0.06 C; 13 Ni;	330	250	1	110	100
	D 40	6.8...7.2	10 ± 2.5	2 ... 4 Mo; 16 ... 19 Cr; < 2 others; rest Fe	> 125	6.9	2.5 Mo; 18 Cr; < 0.5 others; rest Fe	400	320	2	135	130
AISI 430	C 42	6.4...6.8	15 ± 2.5	< 0.08 C; 16 ... 19 Cr; < 2 others; rest Fe	> 140	6.6	0.06 C; 18 Cr; < 0.5 others; rest Fe	420	330	1	170	100
AISI 410	C 43	6.4...6.8	15 ± 2.5	0.1 ... 0.3 C; 11 ... 13 Cr; < 2 others; rest Fe	> 165	6.6	0.2 C; 13 Cr; < 0.5 others; rest Fe	510	370	1	180	100
Sintered bronze	C 50	7.2...7.7	15 ± 2.5	9...11 Sn; < 2 others; rest Cu	> 35	7.4	10 Sn; < 0.5 others; rest Cu	150	90	4	40	50
	D 50	7.7...8.1	10 ± 2.5		> 45	7.9		220	120	6	55	70
Sintered aluminum containing Cu	D 73	2.45...2.55	10 ± 2.5	4...6 Cu; < 1 Mg; < 1 Si; < 2 others; rest Al	> 45	2.5	4.5 Cu; 0.6 Mg; 0.7 Si; < 0.5 others; rest Al	160	130	1	50	50
	E 73	2.55...2.65	6 ± 1.5		> 55	2.6		200	150	2	60	60

¹⁾ According to "Material Specification Sheets for Sintered Metals": DIN 30910, 1990 Edition.

Soft-magnetic metallic materials

Magnet type	Alloying constituents by mass %	Static magnetic properties										AC test data, 50 Hz ¹⁾			
		Coercive field strength $H_{c(max)}$ in A/m Thickness in mm		Minimum magnetic polarization in tesla (T) at field strength H in A/m								Measuring point $\hat{H}$ in A/m	Minimum amplitude permeability μ_r Sheet thickness in mm		
		0.4...1.5	> 1.5	20	50	100	300	500	800	1600	4000	8000		0.30...0.38	0.15...0.20
A – 240	100 Fe	240	240				1.15	1.30			1.60		Not suitable for AC applications.		
A – 120	100 Fe	120	120				1.15	1.30			1.60				
A – 60	100 Fe	60	60				1.25	1.35			1.60				
A – 12	100 Fe	12	12			1.15	1.30	1.40			1.60				
C1 – 48	0...5 Si (typical 2...4.5)	48	48			0.60	1.10	1.20			1.50				750 –
C1 – 12	0...5 Si (typical 2...4.5)	12	12			1.20	1.30	1.35			1.50				
C21 – 09	0.4...5 Si (typical 2...4.5)														
C22 – 13	0.4...5 Si (typical 2...4.5)														
E11 – 60	72...83 Ni	2	4	0.50	0.65	0.70		0.73			0.75		0.40	40000	40000
E21	54...68 Ni	Not suitable for this thickness	10	0.50	0.90	1.10		1.35			1.45		0.40	6000	6000
E31 – 06	45...50 Ni	Not suitable for this thickness	24	0.20	0.45	0.70		1.00			1.18		1.60	2900	2900
E32	45...50 Ni														
E41 – 03	35...40 Ni														
F11 – 240	47...50 Co		240				1.40		1.70	1.90	2.06	2.15	As agreed between manufacturer and buyer.		
F11 – 60	47...50 Co	60				1.80			2.10	2.20	2.25	2.25			
F21	35 Co	300							1.50	1.60	2.00	2.20			
F31	23...27 Co	300									1.85	2.00			

¹⁾ Data apply to laminated rings.

Soft-magnetic metallic materials
Magnetic steel sheet and strip

Sheet type		Nominal thickness	Density ρ	Max. cyclic magnetization loss (50 Hz) in W/kg under modulation			Magnetic polarization in tesla (T) min. at field strength H in A/m			Static coercive field strength H_c in A/m	Permeability μ max	Properties, typical applications
Abbreviated name	Material number	mm	g/cm ³	P 1.0	P 1.5	P 1.7	(B25) 2500	(B50) 5000	(B100) 10000			
M 270-35A	1.0801	0.35	7.60	1.10	2.70	—	1.49	1.60	1.70			Cyclic magnetization losses.
M 330-35A	1.0804	0.35	7.65	1.30	3.30	—	1.49	1.60	1.70			
M 330-50A	1.0809	0.50	7.60	1.35	3.30	—	1.49	1.60	1.70			
M 530-50A	1.0813	0.50	7.70	2.30	5.30	—	1.56	1.65	1.75			
M 800-50A	1.0816	0.50	7.80	3.60	8.00	—	1.60	1.70	1.78			Manufacture of magnetic circuits with alternating magnetization (e.g. motors).
M 400-65A	1.0821	0.65	7.65	1.70	4.00	—	1.52	1.62	1.72			
M1000-65A	1.0829	0.65	7.80	4.40	10.00	—	1.61	1.71	1.80			
M 800-100A	1.0895	1.00	7.70	3.60	8.00	—	1.56	1.66	1.75	≈ 100	≈ 5000	
M1300-100A	1.0897	1.00	7.80	5.80	13.00	—	1.60	1.70	1.78	≈ 100	≈ 5000	
M 660-50D	1.0361	0.50	7.85	2.80	6.60	—	1.62	1.70	1.79	≈ 300		
M1050-50D	1.0363	0.50	7.85	4.30	10.50	—	1.57	1.65	1.77			
M 800-65D	1.0364	0.65	7.85	3.30	8.00	—	1.62	1.70	1.79			
M1200-65D	1.0366	0.65	7.85	5.00	12.00	—	1.57	1.65	1.77			
							at field strength H 800 A/m (B8)					
M 097-30N	1.0861	0.30	—	—	0.97	1.50	1.75			≈ 1	≈ 30000	
M 140-30S	1.0862	0.30	—	—	0.92	1.40	1.78					
M 111-30P	1.0881	0.30	—	—	—	1.11	1.85					
M 340-50E	1.0841	0.50	7.65	1.42	3.40	—	1.54	1.62	1.72	≈ 100	≈ 5000	
M 560-50E	1.0844	0.50	7.80	2.42	5.60	—	1.58	1.66	1.76	≈ 100	≈ 5000	
M 390-65F	1.0846	0.65	7.65	1.62	3.90	—	1.54	1.62	1.72	≈ 300		
M 630-65E	1.0849	0.65	7.80	2.72	6.30	—	1.58	1.66	1.76			

Materials for transformers and reactors
Core-lamination permeability for alloy classes C21, C22, E11, E31 and E41
for core-lamination section YE11.

Minimum core-lamination permeability μ_{lam} (min)											
IEC designation	C21-09 Thickness in mm		C22-13 Thickness in mm		E11-60 Thickness in mm						
	0.3...0.38	0.15...0.2	0.3...0.38	0.15...0.2	0.3...0.38	0.15...0.2	0.1	0.05			
YEI1	-10	630	1000		14000	18000	20000	20000			
	13	800	1000		18000	20400	22400	20400			
	14	800	1000		18000	22400	25000	22400			
	16	800	1000		20000	22400	25000	22400			
	18	800	1000		22400	25000	25000	22400			
	20	800	1120		22400	25000	25000	25000			
IEC designation	22	800	1120								
	25	800	1120								
	E11-100 Thickness in mm		E31-04 Thickness in mm		E31-06 Thickness in mm						
	0.3...0.38	0.15...0.2	0.3...0.38	0.15...0.2	0.3...0.38	0.15...0.2	0.1	0.05			
	-10	18000	25000	2800	2800	3150	3150	3150	3150	4500	5000
	13	20000	28000	2800	3150	3150	3150	3150	3150	4500	5000
YEI1	14	22400	28000	2800	3150	3150	3150	3150	3150	4500	5000
	16	25000	31500	35500	2800	3150	3150	3150	3150	4500	5000
	18	25000	31500	35500	2800	3150	3150	3150	3150	4500	5000
	20	28000	35500	40000	3150	3150	3150	3150	3150	4500	5000
IEC designation	E31-10 Thickness in mm		E41-02 Thickness in mm		E41-03 Thickness in mm						
	0.3...0.38	0.15...0.2	0.3...0.38	0.15...0.2	0.3...0.38	0.15...0.2	0.1	0.05			
	-10	5600	6300	1600	1800	1800	1800	1800	2000	2500	2240
	13	6300	7100	1800	1800	1800	2000	2000	2240	2500	2240
	14	6300	7100	1800	1800	1800	2000	2000	2240	2500	2240
	16	6300	7100	1800	1800	1800	2000	2000	2240	2500	2240
YEI1	18	7100	7100	1800	1800	1800	2000	2000	2240	2500	2240
	20	7100	7100	1800	2000	2000	2000	2000	2240	2500	2240

Materials for direct-current relays

Material type		Alloying constituents	Density ¹⁾ ρ	Hard-ness ¹⁾	Rema-nence ¹⁾	Permeability ¹⁾	Specific el. resis-tance ¹⁾	Coer-sive field strength	Magnetic polarization in T (Tesla) min. at field strength H in A/m							Characteristic properties, applications		
Abbrev-iated name	Material number	by mass %	g/cm ³	HV	T (Tesla)	$\mu_{\max}$	$\Omega \cdot \text{mm}^2/\text{m}$	A/m max.	20	50	100	200	300	500	1000	4000		
Unalloyed steels																		
RFe 160	1.1011		7.85	max. 150	—	—	0.15	160	—	—	—	—	1.15	1.30	—	1.60	Low coercive field strength.	
RFe 80	1.1014				1.10	—	—	0.15	80	—	—	—	1.10	1.20	1.30	1.45		1.60
RFe 60	1.1015	—			1.20	—	—	0.12	60	—	—	—	1.15	1.25	1.35	1.45		1.60
RFe 20	1.1017				1.20	—	≈ 20 000	0.10	20	—	—	1.15	1.25	1.30	1.40	1.45		1.60
RFe 12	1.1018				1.20	—		0.10	12	—	—	1.15	1.25	1.30	1.40	1.45		1.60
Silicon steels																		
RSi 48	1.3840	2.5	7.55	130	0.50	—	0.42	48	—	—	0.60	—	1.10	1.20	—	1.50	For DC relays and similar purposes.	
RSi 24	1.3843	—	—	—	1.00	≈ 20 000	—	24	—	—	1.20	—	1.30	1.35	—	1.50		
RSi 12	1.3845	4 Si	7.75	200	1.00	≈ 10 000	0.60	12	—	—	1.20	—	1.30	1.35	—	1.50		
Nickel steels and nickel alloys																		
RNi 24	1.3911	≈ 36 Ni	8.2	130...180	0.45	≈ 5000	0.75	24	0.20	0.45	0.70	—	0.90	1.0	—	1.18		
RNi 12	1.3926	≈ 50 Ni	8.3	130...180	0.60	≈ 30 000	0.45	12	0.50	0.90	1.10	—	1.25	1.35	—	1.45		
RNi 8	1.3927	≈ 50 Ni	8.3	130...180	0.60	30 000...100 000	0.45	8	0.50	0.90	1.10	—	1.25	1.35	—	1.45		
RNi 5	2.4596	70 ... 80 Ni	8.7	120...170	0.30	≈ 40 000	0.55	5	0.50	0.65	0.70	—	—	—	—	0.75		
RNi 2	2.4595	small quantities Cu, Cr, Mo	8.7	120...170	0.30	≈ 100 000	0.55	2	0.50	0.65	0.70	—	—	—	—	0.75		

¹⁾ Standard values.

Sinter metals for soft-magnetic components

Material	Characteristic alloying substances (except Fe) Mass proportions %	Sinter density ρ_s g/cm ³	Porosity p_s %	Maximum coercive field strength $H_{ci(max)}$ A/m	Magnetic polarization in Tesla (T) at field strength H in A/m				Maximum permeability $\mu_{(max)}$	Vickers hardness	Specific electrical resistance ρ $\mu\Omega m$
Abbreviated name					500	5 000	15 000	80 000			
S-Fe-175	—	6.6	16	175	0.70	1.10	1.40	1.55	2 000	50	0.15
S-Fe-170	—	7.0	11	170	0.90	1.25	1.45	1.65	2 600	60	0.13
S-Fe-165	—	7.2	9	165	1.10	1.40	1.55	1.75	3 000	70	0.12
S-FeP-150	≈0.45 P	7.0	10	150	1.05	1.30	1.50	1.65	3 400	95	0.20
S-FeP-130	≈0.45 P	7.2	8	130	1.20	1.45	1.60	1.75	4 000	105	0.19
S-FeSi-80	≈3 Si	7.3	4	80	1.35	1.55	1.70	1.85	8 000	170	0.45
S-FeSi-50	≈3 Si	7.5	2	50	1.40	1.65	1.70	1.95	9 500	180	0.45
S-FeNi-20	≈50 Ni	7.7	7	20	1.10	1.25	1.30	1.30	20 000	70	0.50
S-FeNi-15	≈50 Ni	8.0	4	15	1.30	1.50	1.55	1.55	30 000	85	0.45
S-FeCo-100	≈50 Co	7.8	3	100	1.50	2.00	2.10	2.15	2 000	190	0.10
S-FeCo-200	≈50 Co	7.8	3	200	1.55	2.05	2.15	2.20	3 900	240	0.35

Soft magnetic ferrites

Ferrite type	Initial permeability ¹⁾ μ_i $\pm 25\%$	Referenced loss factor $\tan \delta/\mu^2$		Amplitude power loss ³⁾ mW/g	Amplitude perme- ability ⁴⁾ μ_a	Curie tem- perature ⁵⁾⁶⁾ Θ_c °C	Frequency for $0.8 \cdot \mu^6$ MHz	Characteristic properties, applications
		10^{-6}	MHz					
Materials in largely open magnetic circuits								
C 1/12	12	350	100	—	—	> 500	400	Initial permeability. Compared to metallic magnetic materials, specific resistance is high: ($10^5 \dots 10^5 \Omega \cdot m$, metals $10^{-7} \dots 10^{-6} \Omega \cdot m$) therefore low eddy-current losses. Communications technol- ogy (coils, transformers).
D 1/50	50	120	10	—	—	> 400	90	
F 1/250	250	100	3	—	—	> 250	22	
G 2/600	600	40	1	—	—	> 170	6	
H 1/1200	1200	20	0.3	—	—	> 150	2	
Materials in largely closed magnetic circuits								
E 2	60 ... 160	80	10	—	—	> 400	50	
G 3	400 ... 1200	25	1	—	—	> 180	6	
J 4	1600 ... 2500	5	0.1	—	—	> 150	1.5	
M 1	3000 ... 5000	5	0.03	—	—	> 125	0.4	
P 1	5000 ... 7000	3	0.01	—	—	> 125	0.3	
Materials for power applications								
W 1	1000 ... 3000	—	—	45	1200	> 180	—	
W 2	1000 ... 3000	—	—	25	1500	> 180	—	

1) Nominal values.
2) $\tan \delta/\mu_i$ denotes the frequency-dependent material losses at a low flux density ($B < 0.1$ mT).
3) Losses at high flux density. Measured preferably at: $f = 25$ kHz, $B = 200$ mT, $\Theta = 100$ °C.
4) Permeability when subjected to a strong sinusoidal magnetic field. Measured at: $f \leq 25$ kHz, $B = 320$ mT, $\Theta = 100$ °C.
5) Curie temperature Θ_c in this table is that temperature at which the initial permeability μ_i drops to below 10% of its value at 25 °C.
6) Standard values.

Permanent-magnet materials

Material		Chemical composition ¹⁾										Density ρ ¹⁾	$(BH)_{max}^2$	Remanence B_r^2	Coercive field strength ²⁾ of the flux density		Rel. permeant ability ¹⁾ μ_p	Curie temp. ¹⁾ T_C K	Temp. coeff. of pol. lar. T_C (H_C) ¹⁾³⁾ % K	Temp. coeff. of co-erciv. T_C (H_C) ¹⁾³⁾ % K	Manufacture, processing, applications								
Abbreviated name	Material number DIN IEC	% by weight													H_{CB} kA/m	H_{CJ} kA/m													
Metallic magnets																													
Isotropic																													
AlNiCo 9/5	1.3728	R 1-0-3	11 ... 13	0 ... 5	2 ... 4	—	21 ... 28	0 ... 1	Re-	6.8	9.0	550	44	47	4.0 ... 5.0	1030	—	+ 0.03	Manufacture: Casting or sintering. Magnets with binders are pressed or injection-molded. Processing: Grinding. Application: max. 400... 500 °C.										
AlNiCo 18/9	1.3756	—	6 ... 8	24 ... 34	3 ... 6	—	13 ... 19	5 ... 9	main-	7.2	18.0	600	80	86	3.0 ... 4.0	...	— 0.02												
AlNiCo 7/8p	1.3715	R 1-2-3	6 ... 8	24 ... 34	3 ... 6	—	13 ... 19	5 ... 9	der	5.5	7.0	340	72	84	2.0 ... 3.0	1180	—	— 0.07											
Anisotropic																													
AlNiCo 35/5	1.3761	—	8 ... 9	23 ... 26	3 ... 4	0 ... 1	13 ... 16	—	Re-	7.2	35.0	1120	47	48	3.0 ... 4.5	1030	—	+ 0.03											
AlNiCo 44/5	1.3757	R 1-1-2	8 ... 9	23 ... 26	3 ... 4	0 ... 1	13 ... 16	—	main-	7.2	44.0	1200	52	53	2.5 ... 4.0	...	— 0.02												
AlNiCo 52/6	1.3759	—	8 ... 9	23 ... 26	3 ... 4	0 ... 1	13 ... 16	—	der	7.2	52.0	1250	55	56	1.5 ... 3.0	...	— 0.07												
AlNiCo 60/11	1.3763	R 1-1-6	6 ... 8	35 ... 39	2 ... 4	0 ... 1	13 ... 15	4 ... 6	7 ... 9	7.2	60.0	900	110	112	1.5 ... 2.5	1180	—	— 0.07											
AlNiCo 30/14	1.3765	—	6 ... 8	38 ... 42	2 ... 4	0 ... 1	13 ... 15	7 ... 9	7 ... 9	7.2	30.0	680	136	144	1.5 ... 2.5	...	—	— 0.07											
Pt																													
PtCo 60/40	2.5210	R2-0-1	77...78	20...23											15.5	60	600	350	400	1.1	800	— 0.01	— 0.35						
FeCoCr																													
FeCoCr 11/2	2.4570	R 3-1-3	8 ... 15	51 ... 54	0 ... 4	Remain-											—	11.0	800	24	24	2.0 ... 8.0	1000	— 0.01	— 0.02				
FeCoCr 4/1	2.4571	—	3 ... 15	51 ... 54	0 ... 6	der											—	4.0	1000	5	5	9.0 ... 25.0	1000	— 0.01	= 0				
RECo magnets of type RECo ₅																													
RECo 80/80	—	R 5-1-1	Typically MMCo ₅ (MM = ceramic-metal material)										8.1	80	650	500	800	1.05	1000	— 0.05	— 0.3								
RECo 120/96	—	R 5-1-2	Typically SmCo ₅										8.1	120	770	590	960	1.05	1000	— 0.05	— 0.3								
RECo 160/80	—	R 5-1-3	Typically (SmPr) Co ₅										8.1	160	900	640	800	1.05	1000	— 0.05	— 0.3								
RECo magnets of type RE ₂ Co ₁₇																													
RECo 165/50	—	R 5-1-11											8.2	165	950	440	500	1.1	1100	0.03	— 0.02								
RECo 180/90	—	R 5-1-13											8.2	180	1000	680	900	1.1	1100	0.03	— 0.02								
RECo 190/70	—	R 5-1-14											8.2	190	1050	560	700	1.1	1100	0.03	— 0.02								
RECo 48/60p	—	R 5-3-1											5.2	48	500	360	600	1.05	1000	— 0.05	— 0.3								

¹⁾ Standard values. ²⁾ Minimum values. ³⁾ In the range of 273 ... 373 K.

Metallic magnets (continued)																				
Material	Chemical composition ¹⁾									Density ρ ¹⁾	$(BH)_{max}^2$	Rema- nence $B_r^{2)}$	Coercive field of the flux density H_{CB} kA/m	Curie temp. ¹⁾ T_c	Rel. per- manent perme- ability ¹⁾ μ_p	Temp. coeff. of po- lar. $TC(J_s)$ ¹⁾ % K	Temp. coeff. of co- erov. $TC(H_c)$ ¹⁾ % K	Manufacture, processing, applications		
	% by weight																			
Abbreviated name	Material number	DIN	IEC	Al	Co	Cu	Nb	Ni	Ti	Fe										
CrFeCo 12/4	—	—	R 6-0-1	(no data)							7.6	12	800	40	42	5.5 ... 6.5	1125	— 0.03	— 0.04	
CrFeCo 28/5	—	—	R 6-1-1	(no data)							7.6	28	1000	45	46	3 ... 4	1125	— 0.03	— 0.04	
REFe 165/170	—	—	R 7-1-1	(no data)							7.4	165	940	700	1700	1.07	583	— 0.1	— 0.8	
REFe 220/140	—	—	R 7-1-6	(no data)							7.4	220	1090	800	1400	1.05	583	— 0.1	— 0.8	
REFe 240/110	—	—	R 7-1-7	(no data)							7.4	240	1140	850	1100	1.05	583	— 0.1	— 0.8	
REFe 260/80	—	—	R 7-1-8	(no data)							7.4	260	1180	750	800	1.05	583	— 0.1	— 0.8	
Material														Temp. coeff. of the po- larization $TK(J_s)$ % K	Temp. coeff. of coerciv. ¹⁾ $TK(H_c)$ % K	Manufacture, processing				
Abbreviated name	Material number	DIN	IEC	Density ¹⁾ ρ		$(BH)_{max}^2$		Rema- nence ²⁾ B_r		Coercive field of the flux density H_{CB} kA/m		Curie temp. ¹⁾ T_c		Rel. per- manent perme- ability ¹⁾ μ_p		Temp. coeff. of coerciv. ¹⁾ $TK(H_c)$ % K		Manufacture, processing		
Ceramic magnets																				
Isotropic																				
Hard ferrite 7/21	1.3641	S 1-0-1	4.9	6.5	125	210	1.2	723	— 0.2	0.2 ... 0.5	Manufacture: Sintering. Plastic-bound magnets are manufactured by pressing, injection- molding, rolling and extruding. Processing: Grinding.									
Hard ferrite 3/18p	1.3614	S 1-2-2	3.9	3.2	85	175	1.1													
Anisotropic																				
Hard ferrite 20/19	1.3643	S 1-1-1	4.8	20.0	320	170	190	1.1			Manufacture: Sintering. Plastic-bound magnets are manufactured by pressing, injection- molding, rolling and extruding. Processing: Grinding.									
Hard ferrite 20/28	1.3645	S 1-1-2	4.6	20.0	320	220	280	1.1												
Hard ferrite 24/23	1.3647	S 1-1-3	4.8	24.0	350	215	230	1.1												
Hard ferrite 25/22	1.3651	S 1-1-5	4.8	25.0	370	205	220	1.1												
Hard ferrite 26/26	—	S 1-1-8	4.7	26.0	370	230	260	1.1												
Hard ferrite 32/17	—	S 1-1-10	4.9	32.0	410	160	165	1.1												
Hard ferrite 24/35	—	S 1-1-14	4.8	24.0	360	260	350	1.1												
Hard ferrite 9/19p	1.3616	S 1-3-1	3.4	9.0	220	145	190	1.1												
Hard ferrite 10/22p	—	S 1-3-2	3.5	10.0	230	165	225	1.1												

¹⁾ Standard values. ²⁾ Minimum values. ³⁾ In the range of 273 ... 373 K.

Permanent-magnet materials (continued)

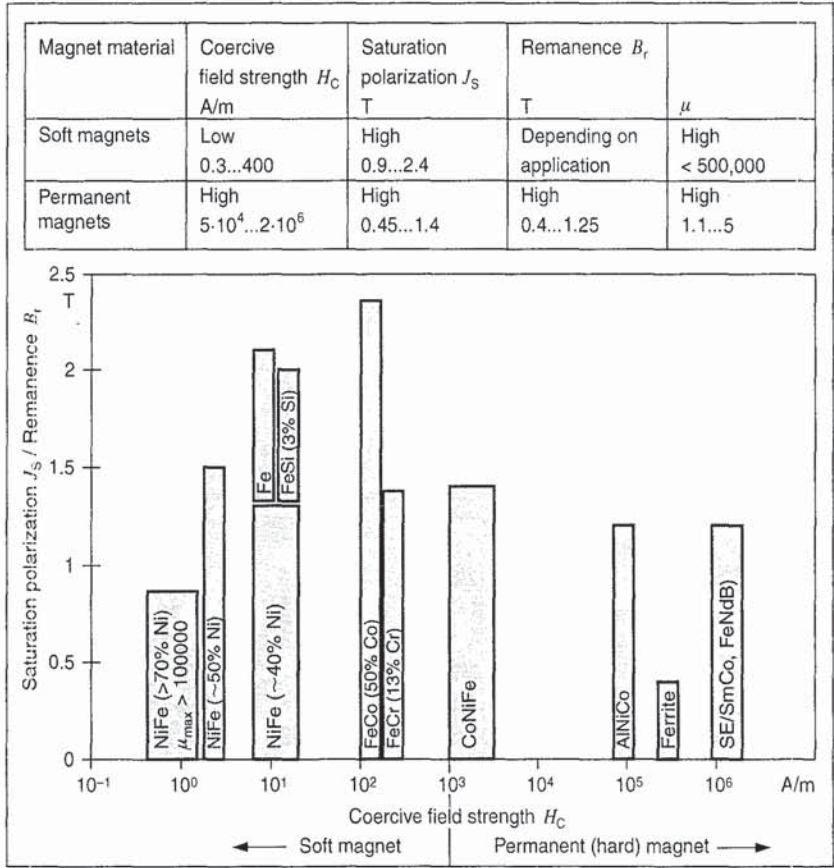
Bosch grades [BTMT] (not standardized)

Material	Density ¹⁾ ρ	$(BH)_{\max}^2)$	Remanence ²⁾ B_r	Coercive field strength ²⁾ of the flux density H_{CB}	of the polarization H_{CJ}
Abbreviated name	g/cm ³	kJ/m ³	mT	kA/m	kA/m
RBX HC 370	4.7...4.9	25	360	270	390
RBX HC 380		28	380	280	370
RBX 380K		28	380	280	300
RBX 400		30	400	255	260
RBX 400 K		31	400	290	300
RBX HC 400		29	380	285	355
RBX 420		34	420	255	270
RBX 410 K		33	410	305	330
RBX HC 410		30	395	290	340
RBX 420 S		35	425	260	270
RBX HC 400 N		28	380	280	390

1) Standard values. 2) Minimum values.

Comparison: permanent magnets and soft magnets

Range of magnetic characteristics of some crystalline materials in widespread use.



Solders and filler materials

Type of alloy	Material code	Primary alloying constituents, mean values % (by mass)	Melting range of alloy °C	Minimum workpiece temperature °C	Properties Primary applications
Soft solders (selection from DIN 1707)					
Lead-base, tin-base soft solders	L-PbSn 20 Sb 3 L-PbSn 12 Sb	20 Sn; max. 3 Sb; rest Pb 12 Sn; max. 0.7 Sb; rest Pb	186 ... 270 250 ... 295	270 295	Soft soldering in motor-vehicle body construction. Soft soldering of copper in radiator construction.
	L-PbSn 40 (Sb) L-PbSn 8 (Sb)	40 Sn; max. 0.5 Sb; rest Pb 8 Sn; max. 0.5 Sb; rest Pb	183 ... 235 280 ... 305	235 305	Tin plating: soft soldering of sheet metal parts. Soft soldering; electric motors, radiator construction.
Tin-base, lead-base soft solders	L-Sn 63 Pb L-Sn 60 Pb	63 Sn; rest Pb 60 Sn; rest Pb	183 183 ... 190	183 190	Wave soldering of printed-circuit boards. Tin plating of copper and copper alloys in the electrical industry.
	L-Sn 63 PbAg L-Sn 60 PbCu 2 L-Sn 60 PbCuP	63 Sn; max. 1.5 Ag; rest Pb 60 Sn; max. 2 Cu; rest Pb 60 Sn; max. 0.2 Cu; max. 0.004 P; rest Pb	178 183 ... 190 183 ... 190	178 190 190	Wave soldering of printed-circuit boards. Soldering (using an iron) of copper and copper alloys in the electrical industry. Dip soldering of copper and copper alloys in the electrical industry.
Special soft solders	—	57 Bi; 26 In; rest Sn	79	79	Soft soldering of heat-sensitive components; fuses.
	L-SnIn 50 L-SnAg 5	50 Sn; rest In max. 5 Ag; rest Sn	117 ... 125 221 ... 240	125 240	Soft soldering of glass/metal. Soft soldering of copper in the electrical industry and in the installation of water pipes.
	L-SnSb 5	max. 5.5 Sb; rest Sn	230 ... 240	240	Soft soldering of copper in refrigeration engineering and in the installation of water pipes.
	L-SnCu 3	max. 3.5 Cu; rest Sn	230 ... 250	250	Soft soldering of copper in the installation of water pipes.
	L-SnZn 10 L-ZnAl 5	max. 15 Zn; rest Sn max. 6 Al; rest Zn	200 ... 250 380 ... 390	250 390	Ultrasonic soft soldering of aluminum and copper without flux.

Type of alloy	Material code	Primary alloying constituents, mean values % (by mass)	Melting range of alloy °C	Minimum workpiece temperature ¹⁾ °C	Properties Primary applications
Filler metals for brazing and high-temperature brazing (selection from DIN 8513 and ISO 3677)					
Aluminum-base filler metals	L-AISI 12	12 Si; rest Al	575 ... 590	590	Brazing of Al and Al alloys with a sufficiently high melting point.
	L-AISI 10	10 Si; rest Al	575 ... 595	595	
	L-AISI 7.5	7.5 Si; rest Al	575 ... 615	615	
Silver-bearing filler metals Ag < 20 %	BCu 75AgP 643	18 Ag; 7.25 P; rest Cu	643	650	Brazing of Cu/Cu without flux.
	L-Ag 15 P	15 Ag; 5 P; rest Cu	650 ... 800	710	Brazing of steel, Cu, Ni and Ni alloys with flux.
	L-Ag 5	5 Ag; 55 Cu; 0.2 Si; rest Zn	820 ... 870	860	
Silver-bearing filler metals Ag ≥ 20 %	L-Ag55Sn	55 Ag; 22 Cu; 5 Sn; rest Zn	620 ... 660	650	Brazing of steel, Cu and Cu alloys, Ni and Ni alloys with flux.
	L-Ag44	44 Ag; 30 Cu; rest Zn	675 ... 735	730	Brazing of hard metal, steel, W, Mo and Ta with flux.
	L-Ag49	49 Ag; 16 Cu; 7.5 Mn; 4.5 Ni; rest Zn	625 ... 705	690	
	BAG 60 CuIn 605-710	60 Ag; 13 In; rest Cu	605 ... 710	710	Brazing of Cu, Ni, steel in a vacuum or under shielding gas.
	BAG 60 CuSn 600-700	60 Ag; 10 Sn; rest Cu	600 ... 720	720	
Copper-base filler metals	L-Ag 72	72 Ag; rest Cu	780	780	Brazing of steel, Ni and Co alloys, Mo, W, Ti in a vacuum or under shielding gas.
	BCu 58 AgNi 780-900	40 Ag; 2 Ni; rest Cu	780 ... 900	900	
	BAG 68 CuPd 807-810	68 Ag; 5 Pd; rest Cu	807 ... 810	810	Brazing of Cr and Cr/Ni steels in a vacuum or under shielding gas.
	BAG 54 PdCu 901-950	54 Ag; 21 Pd; rest Cu	901 ... 950	950	
	BAG 95 Pd 970-1010	95 Ag; rest Pd;	970 ... 1010	1010	
	BAG 64 PdMn 1180-1200	64 Ag; 3 Mn; rest Pd	1180 ... 1200	1200	Brazing of Cu and Cu alloys with flux. Not for Fe and Ni alloys or media containing S.
	L-Ag 56 InNi	56 Ag; 14 In; 4 Ni; rest Cu	620 ... 730	730	
	L-Ag 85	85 Ag; rest Mn	960 ... 970	960	Brazing of Cu and Cu alloys with flux. Not for Fe and Ni alloys or media containing S.
	BCu 86 SnP 650-700	6.75 P; 7 Sn; rest Cu	650 ... 700	690	

¹⁾ Depending on the process.

Filler metals for brazing and high-temperature brazing (continued)

Type of alloy	Material code	Primary alloying constituents, mean values % (by mass)	Melting range of alloy °C	Minimum workpiece temperature ¹⁾ °C	Properties Primary applications
Copper-base filler metals (continued)	L-CuP 8	8 P; rest Cu	710 ... 740	710	Brazing of Cu/Cu without flux. Not for Fe and Ni alloys or media containing S.
	L-CuZn 40	60 Cu; 0.2 Si; rest Zn	890 ... 900	900	Brazing of steel, Cu, Ni and Ni alloys with flux.
	L-CuSn 6 L-SFCu	6 Sn max; 0.4 P; rest Cu 100 Cu	910 ... 1040 1083	1040 1100	Brazing of steel in a vacuum or under shielding gas.
	BCu 86 MnNi 970-990 BCu 87 MnCo 980-1030 BCu 96.9 NiSi 1090-1100	2 Ni; 12 Mn; rest Cu 3 Co; 10 Mn; rest Cu 0.6 Si; 2.5 Ni; rest Cu	970 ... 990 980 ... 1030 1090 ... 1100	990 1020 1100	Brazing of hard metal, steel, W, Mo, Ta in a vacuum or under shielding-gas partial pressure.
Nickel-base filler metals	L-Ni6 L-Ni1 L-Ni5	11 P; rest Ni 3 B; 14 Cr; 4.5 Fe; 4.5 Si; rest Ni 19 Cr; 10 Si; rest Ni	880 980 ... 1040 1080 ... 1135	925 1065 1150	Brazing of Ni, Co and their alloys, unalloyed, low- and high-alloy steels in a vacuum or under hydrogen shielding gas.
	BAu 80 Cu 910	20 Cu; rest Au	910	910	Brazing of Cu, Ni and steel in a vacuum or under shielding gas.
	BAu 82 Ni 950	18 Ni; rest Au	950	950	Brazing of W, Mo, Co, Ni and steels in a vacuum or under shielding gas.
Active filler metals containing titanium	— — —	72.5 Ag; 19.5 Cu; 5 In; rest Ti 70.5 Ag; 26.5 Cu; rest Ti 96 Ag; rest Ti	730 ... 760 780 ... 805 970	850 850 1000	Direct brazing of non-metallized ceramics with each other or combined with steel in a vacuum or under argon protective gas.

¹⁾ Depending on the process.

Electrical properties

Electrical resistivity at 20 °C

(Resistance of a wire 1 m long with a cross section of 1 mm²)

Resistivity is highly dependent upon the purity of the metal concerned. The mean temperature coefficient α refers to temperatures between 0 and 100 °C whenever possible. Resistivity at a temperature t °C is $\rho_t = \rho_{20} [1 + \alpha (t - 20^\circ\text{C})]$. For calculation of the temperature of a winding based on the increase in resistance, see P. 136.

$$1 \Omega \text{ mm}^2/\text{m} = 1 \mu\Omega \text{ m}, 1 \text{ S m/mm}^2 = 1 \text{ MS/m (S = Siemens)}$$

Material	Electrical resistivity ρ $\mu\Omega\text{m}$	Electrical conductivity $\gamma = 1/\rho$ MS/m	Mean temperature coefficient α $\times 10^{-3}$ 1/°C	Maximum operating temperature approx. °C
Aluminum, Al 99.5 (soft)	0.0265	35	3.8	—
Aluminum alloy E-AlMgSi	< 0.0328	> 30.5	3.8	—
Bismuth	1.07	0.8	4.54	—
Brass CuZn 39 Pb 3	0.0667	15	2.33	—
CuZn 20	0.0525	19	1.60	—
Bronze CuBe 0.5, age-hardened	0.04 ... 0.05	20 ... 25	—	300
Cadmium	0.068	13	—	—
Carbon brushes, unfilled	10 ... 200	0.1 ... 0.05	—	—
metal-filled	0.05 ... 30	20 ... 0.03	—	—
Copper, soft	0.01754	57	3.9	—
hard (cold-stretched)	0.01786	56	3.9	—
Gold (fine gold)	0.023	45	4	—
Gold-chromium alloy Cr2.05	0.33	3.03	± 0.001	—
Gray cast iron	0.6 ... 1.6	0.62 ... 1.67	1.9	—
Heating-element alloy ¹⁾ CrAl 20 5	1.37	0.73	0.05	1200
NiCr 30 20	1.04	0.96	0.35	1100
NiCr 60 15	1.13	0.88	0.15	1150
NiCr 80 20	1.12	0.89	0.05	1200
Lead Pb 99.94	0.206	4.8	4	—
Magnetic steel sheet I	0.21	4.76	—	—
Magnetic steel sheet IV	0.56	1.79	—	—
Mercury	0.941	1.0386	0.9	—
Molybdenum	0.052	18.5	4.7	1600 ²⁾
Nickel Ni 99.6	0.095	10.5	5.5	—
Nickel silver CuNi 12 Zn 24	0.232	4.3	—	—
Platinum	0.106	10.2	3.923	—
Resistance alloy ³⁾ CuMn 12 Ni	0.43	2.33	± 0.01	140
CuNi 30 Mn	0.40	2.50	0.14	500
CuNi 44	0.49	2.04	± 0.04	600
Silver (fine silver)	0.016	66.5	4.056	—
Steel C 15	0.14 ... 0.16	7.15	—	—
Tantalum	0.124	8.06	3.82	—
Tungsten	0.056	18.2	4.82	—
Tin	0.114	8.82	4.4	—
Zinc	0.06	16.67	4.17	—

¹⁾ DIN 17 470. ²⁾ Under shielding gas or in a vacuum. ³⁾ DIN 17 471.

Insulating materials

Electrical properties

The properties of insulating materials are highly dependent upon the purity, homogeneity, processing and aging of the material, as well as moisture content and temperature. The following values are given as a guideline for non-aged test specimens at room temperature with average moisture content. 1 min test voltage at 50 Hz; specimen thickness: 3 mm.
Loss factor $\tan \delta$ = active power/reactive power; in USA: loss factor = $\epsilon_r \cdot \tan \delta$.

Insulating material	Relative permittivity at 800 Hz (air = 1) ϵ_r	Loss factor $\tan \delta$ at 800 Hz $\times 10^{-3}$	Loss factor $\tan \delta$ at 10^6 Hz $\times 10^{-3}$	Volume resistivity $10^n \Omega m$ values of n	Dielectric strength kV_{eff}/mm	Tracking resistance according to DIN 53 480 degree
Cellulose acetates	4.7 ... 5.8	17 ... 24	48 ... 66	11 ... 13	32	—
Epoxy casting resins and molding compounds	3.2 ... 5	2 ... 30	2 ... 60	10 ... 15	6 ... 15	KA 3 b, KA 3 c
Hard porcelain	5 ... 6.5	= 15	6 ... 12	> 9	30 ... 40	KA 3 c
Mica	5 ... 8	0.1 ... 1	0.2	13 ... 15	60	KA 3 c
Paraffin waxes	1.9 ... 2.3	< 0.3	< 0.3	13 ... 16	10 ... 30	—
Phenolic resin molding compounds with inorganic filler	5 ... 30	30 ... 400	50 ... 200	6 ... 11	5 ... 30	KA 1
Phenolic resin molding compounds with organic filler	4 ... 9	50 ... 500	50 ... 200	6 ... 10	5 ... 20	KA 1
Polyamides	8 ... 14	20 ... 200	20 ... 200	6 ... 12	10 ... 50	KA 3 b, KA 3 c
Polycarbonates	3 ... 7	1.0	10	14 ... 16	25	KA 1
Polyester casting resins and molding compounds	3 ... 7	3 ... 100	6 ... 60	8 ... 14	6 ... 25	KA 3 c
Polyethylene	2.3	0.2 ... 0.6	0.2 ... 0.6	> 15	= 80	KA 3 c
Polymethyl methacrylate	3.1 ... 3.4	40	20	> 13	30	KA 3 c
Polypropylene	2.3	< 0.5	< 0.5	> 15	—	KA 3 b
Polystyrene	2.5	0.1	0.1	14	40	KA 2, KA 1
Polytetrafluorethylene	2	0.1 ... 0.5	0.1 ... 0.5	13 ... 15	50	KA 3 c
Polyvinyl chloride	3.3 ... 6.5	15 ... 150	10 ... 100	10 ... 14	15 ... 50	KA 3 b
Quartz glass	3.5 ... 4.2	0.5	0.2	14 ... 16	25 ... 40	KA 3 c
Silicones	5 ... 8	= 4	= 4	10 ... 14	20 ... 60	KA 3 c
Soft rubber	2 ... 14	0.2 ... 100	—	2 ... 14	15 ... 30	KA 1 ... KA 3 c
Stearite	5.5 ... 6.5	1 ... 3	0.3 ... 2	10 ... 12	20 ... 45	KA 3 c
Titanium ceramic	12 ... 10 000	—	0.05 ... 100	—	2 ... 30	—
Transformer oil, dry	2 ... 2.7	= 1	= 10	11 ... 12	5 ... 30	—

Properties of non-metallic materials

Ceramics

Materials	Composition	$\rho^1)$ g/cm ³	$\sigma_{\text{ba}}^2)$ MN/m ²	$\sigma_{\text{a}}^3)$ MN/m ²	$E^4)$ GN/m ²	$\alpha^5)$ 10 ⁻⁶ /K	$\lambda^6)$ W/mK	$c^7)$ kJ/kg · K	$\rho^8)$ $\Omega \cdot \text{cm}$	$\epsilon_r^9)$	$\tan \rho^{10})$ 10 ⁻⁴
Aluminum nitride	AlN > 97 %	3.3	250 ... 350	1100	320 ... 350	5.1	100 ... 220	0.8	> 10 ¹⁴	8.5 ... 9.0	3 ... 10
Aluminum oxide	Al ₂ O ₃ > 99 %	3.9 ... 4.0	300 ... 500	3000 ... 4000	380 ... 400	7.2 ... 8.6	20 ... 40	0.8 ... 0.9	> 10 ¹¹	8 ... 10	2
Aluminum titanate	Al ₂ O ₃ · TiO ₂	3.0 ... 3.2	20 ... 40	450 ... 550	10 ... 20	0.5 ... 1.5	< 2	0.7	> 10 ¹¹	—	—
Beryllium oxide	BeO > 99 %	2.9 ... 3.0	250 ... 320	1500	300 ... 340	8.5 ... 9.0	240 ... 280	1.0	> 10 ¹⁴	6.5	3 ... 5
Boron carbide	B ₄ C	2.5	300 ... 500	2800	450	5.0	30 ... 60	—	10 ⁻¹ ... 10 ²	—	—
Cordierite e.g. KER 410, 520	2MgO · 2Al ₂ O ₃ · 5SiO ₂	1.6 ... 2.1	40 ... 200	300	70 ... 100	2.0 ... 5.0	1.3 ... 2.3	0.8	> 10 ¹¹	5.0	70
Graphite	C > 99.7 %	1.5 ... 1.8	5 ... 30	20 ... 50	5 ... 15	1.6 ... 4.0	100 ... 180	—	10 ⁻³	—	—
Porcelain e.g. KER 110 – 2 (non-glazed)	Al ₂ O ₃ 30 ... 35 % balance SiO ₂ + glassy phase	2.2 ... 2.4	45 ... 60	500 ... 550	50	4.0 ... 6.5	1.2 ... 2.6	0.8	10 ¹¹	6	120
Silicon carbide hot-pressed HP-SiC	SiC > 99 %	3.1 ... 3.2	450 ... 650	> 1500	420	4.0 ... 4.5	100 ... 120	0.8	10 ³	—	—
Silicon carbide pressureless- sintered SSiC	SiC > 98 %	3.1 ... 3.2	400 ... 450	> 1200	400	4.0 ... 4.5	90 ... 120	0.8	10 ³	—	—
Silicon carbide reaction-sintered SiSiC	SiC > 90 % + Si	3.0 ... 3.1	300 ... 400	> 2200	380	4.2 ... 4.3	100 ... 140	0.8	10 ... 100	—	—
Silicon nitride gas-pressure sintered GPSN	Si ₃ N ₄ > 90 %	3.2	800 ... 1400	> 2500	300	3.2 ... 3.5	30 ... 40	0.7	10 ¹²	—	—

Ceramic materials (continued)

Material	Composition	$\rho^1)$ g/cm ³	$\sigma_{\text{BE}}^{2)}$ MN/m ²	$\sigma_{\text{BE}}^{3)}$ MN/m ²	$E^4)$ GN/m ²	$\alpha_t^{5)}$ 10 ⁻⁶ /K	$\lambda^6)$ W/mK	$c^7)$ kJ/kg · K	$\rho_D^{8)}$ $\Omega \cdot \text{cm}$	$\epsilon_r^9)$	$\tan \delta^{10)}$ 10 ⁻⁴
Silicon nitride hot-pressed HPSN	Si ₃ N ₄ > 95 %	3.2	600 ... 900	> 3000	310	3.2 ... 3.5	30 ... 40	0.7	10 ¹²	—	—
Silicon nitride reaction-sintered RBSN	Si ₃ N ₄ > 99 %	2.4 ... 2.6	200 ... 300	< 2000	140 ... 160	2.9 ... 3.0	15 ... 20	0.7	10 ¹⁴	—	—
Steatite e.g. KER 220, 221	SiO ₂ 55...65 % MgO 25 ... 35 % Al ₂ O ₃ 2 ... 6 % Alk. oxide < 1.5 %	2.6 ... 2.9	120 ... 140	850 ... 1000	80 ... 100	7.0 ... 9.0	2.3 ... 2.8	0.7 ... 0.9	> 10 ¹¹	6	10...20
Titanium carbide	TiC	4.9	—	—	320	7.4	30	—	7 · 10 ⁻⁵	—	—
Titanium dioxide	TiO ₂	3.5 ... 3.9	90 ... 120	300	—	6.0 ... 8.0	3 ... 4	0.7 ... 0.9	—	40 ... 100	8
Titanium nitride	TiN	5.4	—	—	260	9.4	40	—	3 · 10 ⁻⁵	—	—
Zirconium dioxide partially stabilized, PSZ	ZrO ₂ > 90 % Rest Y ₂ O ₃	5.7 ... 6.0	500 ... 1000	1800 ... 2100	200	9.0 ... 11.0	2 ... 3	0.4	10 ⁸	—	—
Standards		DIN EN 623 Part 2	DIN EN 843 Part 1	pr EN 993 Part 5	DIN EN 843 Part 2	DIN EN 821 Part 1	DIN EN 821 Part 2	DIN EN 821 Part 3	DIN VDE 0335 Parts 2 and 3		

The characteristic values for each material can vary widely, depending on raw material, composition and manufacturing process. The material data relate to the information provided by various manufacturers.
The designation "KER" corresponds to DIN EN 60672-1.

1) Density.
2) Flexing strength.
3) Cold compressive strength.
4) Modulus of elasticity.
5) Coefficient of thermal expansion RT ... 1000 °C.

6) Thermal conductivity at 20 °C.
7) Specific heat.
8) Specific electrical resistivity at 20 °C and 50 Hz.
9) Relative permittivity.
10) Dielectric loss factor at 25 °C and 10 MHz.

Laminates

Type	Type of resin	Filler	$\vartheta_{\text{G}}^{(1)}$ ° C	$\sigma_{\text{BS}}^{(2)}$ min. N/mm ²	$\alpha_k 10^3$ min. kJ/m ²	CTI ⁽⁴⁾ min. grade	Properties, applications
Paper-base laminates (DIN 7735, Part 2 / VDE 0318, Part 2)							
Hp 2061	Phenolic resin	Paper web	120	150	5	CTI 100	For mechanical loading. For electrical loading; base material FR 2 for printed-circuit boards. Particularly resistant to tracking; decorative laminates. Good electrical and mechanical properties; flame-resistant; base material FR 3 for printed-circuit boards.
Hp 2063	Phenolic resin	Paper web	120	80	2.5	CTI 100	
Hp 2262	Melamine resin	Paper web	90	100	—	CTI 600	
Hp 2361.1	Epoxy resin	Paper web	90	120	2	CTI 100	
Fabric-base laminates (DIN 7735, Part 2 / VDE 0318, Part 2)							
Hgw 2072	Phenolic resin	Glass-fiber fabric	130	200	40	CTI 100	High mechanical, electrical and thermal strength. Good workability, good sliding and wear behavior; especially good material for gears and bearings. Optimum mechanical and electrical properties; base material FR 4 for printed-circuit boards. For high service temperature.
Hgw 2082	Phenolic resin	Fine-weave cotton fabric	110	130	10	CTI 100	
Hgw 2083	Phenolic resin	Superfine-weave cotton fabric	110	150	12	CTI 100	
Hgw 2372.1	Epoxy resin	Glass-fiber fabric	120	350	50	CTI 200	
Hgw 2572	Silicone resin	Glass-fiber fabric	180	125	25	CTI 400	
Glass-mat-base laminates (DIN 7735, Part 2 / VDE 0318, Part 2)							
Hm 2472	Unsaturated polyester resin	Glass-fiber mat	130	200	60	CTI 500	Good mechanical and electrical properties, particularly resistant to tracking.

1) Limit temperature according to VDE 0304, Part 2, for service life of 25,000 h.
2) Flexural strength according to DIN 53 452
3) Notched impact strength in accordance with DIN 53 453.
4) Tracking resistance according to DIN IEC 112, Comparative Tracking Index (CTI).

Plastic molding compounds

Chemical name	Material code (ISO 1043/ DIN 7728)	$t_g^{(1)}$ °C	$E^{(2)}$ N/mm ²	$\alpha_{kl}^{(3)}$ min. kJ/m ²	Resistance at 20° to ⁴⁾ Gas-oline Benzene Diesel fuel	Alcohol Mineral oil	Properties, applications
Thermoplastics (Selection from DIN 7740 ... 7749; DIN 16 771 ... 16 781)							
Acrylnitrile-butadien-styrene	ABS	80	2000	5 ... 15	0	+	High gloss, some types transparent; tough housings.
Fluorinated hydrocarbons	FEP PFA	250/205 260	600 650	⁶⁾ ⁶⁾	+	+	Extreme reduction in rigidity as temperature increases, resistant to chemicals; used for coatings, sliding parts and seals.
Polyamide 11, 12	PA 11, 12	140/120	1500	20 ... 40	+	0	Tough, hard and resistant to abrasion, low coefficient of friction, good attenuation of sound, approx. 1 ... 3% water absorption required for good toughness, PA 11/12 have much lower water absorption.
Polyamide 6	PA 6	170/120	2500	40 ... 90	+	+	Impact-resistant machine housings.
Polyamide 66	PA 66	190/120	2800	10 ... 20	+	+	
Polyamide 6 + GF ⁵⁾	PA 6-GF	190/120	5000	8 ... 14	+	+	Rigid machine housings/components, remains rigid at elevated temperatures (engine-bay components). Lower water absorption than standard PA.
Polyamide 66 + GF ⁵⁾	PA 66-GF	200/120	6000	6 ... 12	+	+	
Polyamide 6T/6I/66 + GF45	PA 6T/6I/66 + GF45	285/185	14 000	8 ... 12	+	+	Wear-resistant, chemically resistant, rigidity decreases above 60 °C, hydrolysis above 70 °C.
Polyamide 6/6T + GF ⁵⁾	PA 6/6T-GF	250/170	10 000	6 ... 12	+	+	
Polyamide MXD6 + GF50	PA MXD6 + GF50	240/170	15 000	8 ... 12	+	+	Higher rigidity than PBT without GF.
Polybutylene terephthalate	PBT	160/120	1700	2 ... 4	+	+	Tough and rigid over wide temperature range, transparent.
Polybutylene terephthalate + GF ⁵⁾	PBT-GF	180/120	5000	5 ... 9	+	+	
Polycarbonate	PC	130/125	2500	20 ... 30	+	0	Very rigid structural parts.
Polycarbonate + GF ⁵⁾	PC-GF	130	4500	6 ... 15	+	+	Acid-resistant containers and pipes, films.
Polyethylene	PE	80	1000	⁶⁾	0	+	

Polyethylene terephthalate	PET	180/120	2000	2 ... 7	+	+	+	+	+	+	+	+	+	+	Wear-resistant, chemically resistant, rigidity decreases above 60 °C, hydrolysis above 70 °C in water.
Cyclo-olefine copolymers	COC	160	3000	1.7 ... 2	-	-	-	-	-	-	-	-	-	-	Highly transparent, weatherproof.
Liquid crystal polymers + GF 5)	LCP-GF	300/240	15 000	8 ... 16	+	+	+	+	+	+	+	+	+	+	Highly resistant to thermal deformation, high impact strength, low bond strength, for extremely thin-walled components.
Polyethersulfon + GF 5)	PES-GF	220/180	9000	6 ... 10	+	+	0	+	+	+	+	+	+	+	High continuous service temperature, temperature has no more than a minor influence on properties.
Polyether etherketon + GF 5)	PEEK	320/250	9000	6.5 ... 10	+	+	+	+	+	+	+	+	+	+	High-strength components for high temperatures, good sliding characteristics and low wear.
Polyethylene terephthalate + GF 5)	PET-GF	200/120	7000	5 ... 12	+	+	+	+	+	+	+	+	+	+	Higher rigidity than PETP without GF.
Polymethylmethacrylate	PMMA	80	3000	1.5 ... 2.5	+	-	-	-	-	-	-	-	-	-	Transparent and in all colors, weatherproof; diffusers, lenses.
Polyoxymethylene	POM	125/120	2000	5 ... 7	+	+	0	+	+	+	+	+	+	+	Sensitive to acid-induced stress cracking; precision moldings.
Polyoxymethylene + GF	POM-GF	140/120	6000	3 ... 5	+	+	0	+	+	+	+	+	+	+	
Polyphenylene ether + SB 7)	(PPE + S/B)	120/100	2500	4 ... 14	0	-	-	-	-	-	-	-	-	-	Resistant to hot water, flame-retardant.
Polyphenylene sulfide + GF 40	PPS-GF	270/240	13 000	4 ... 7	+	+	+	+	+	+	+	+	+	+	High resistance to heat, inherently flame-retarding; for engine-bay components.
Polypropylene	PP	130/110	1500	6 ... 10	x	+	0	+	+	+	+	+	+	+	Household articles, battery cases, cover hoods.
Polypropylene + GF 5)	PP-GF	130/110	4000	4 ... 8	x	+	0	+	+	+	+	+	+	+	Fan impellers.
Polystyrene	PS	80	2500	2 ... 3	-	-	-	-	-	-	-	-	-	-	Molded parts; transparent and coated in all colors.
Polyvinyl chloride, plasticized	PVC-P	80/70	200	6)	-	-	-	-	-	-	-	-	-	-	Artificial leather, flexible caps, cable insulation, tubing and hoses, seals.
Polyvinyl chloride, unplasticized	PVC-U	70/60	3000	2 ... 30	+	+	-	-	-	-	-	-	-	-	Weatherproof exterior parts, pipes, parts for galvanotechnical equipment.

1) Maximum service temperature, short term (1 h)/long-term (5000 h).
2) Modulus of elasticity, approx. standard values.
3) Notched impact strength in accordance with DIN 53 453.
4) + good resistance, x limited resistance, 0 low resistance, - no resistance.
5) GF Glass fiber (25 ... 35 % by weight).
6) No fracture.
7) Polymer mixture of polyphenylene ether and styrene/butadiene.

Chemical name	Material code (ISO 1043/ DIN 7728)	$t_g^1)$ °C	$E^2)$ N/mm ²	$\alpha_{10}^3)$ min. kJ/m ²	Resistance at 20° to ⁴⁾				Properties, applications
					Gas-oline	Ben-zene	Die-sel fuel	Alco-hol	Mi-ne-ral oil
Styrene-acrylonitrile	SAN	90	3000	1.5 ... 2.5	0	—	x	0	+
Styrene-butadiene	S/B	60	1500	4 ... 14	—	—	—	x	+
Non-cross-linked plastics which can be processed only by molding and sintering:									
Polyimide	PI	320/290	3100	2	+	+	+	+	+
Polytetrafluorethylene	PTFE	300/240	400	13 ... 15	+	+	+	+	+

1) Maximum service temperature, short term (1 h)/long-term (5000 h). 2) + 3) Polyamides, saturated by air humidity at 23 °C and 50 % rel. humidity
2) Modulus of elasticity, approx. standard values. 4) + good resistance, x limited resistance, — no resistance.
3) Notched impact strength in accordance with DIN 53 453.

Type	Type of resin	Filler	$t_g^1)$ °C	$\alpha_{BS}^2)$ min. N/mm ²	$\alpha_{10}^3)$ min. kJ/m ²	CTI ⁴⁾ min. grade	Properties, applications
Thermosetting plastics (selection from DIN 7708, 16 911, 16 912)							
11.5	Phenol	Rock flour	200/170	50	3.5	CTI 150	For parts subject to thermal loading, high resistance to glow heat, good heat dissipation, little dimensional change in humid atmosphere. Good electrical properties for types 11.5 and 13.5.
13.5 ¹³⁾		Mica	200/170	50	3.0	CTI 150	
31 and 31.5	Wood flour		160/140	70	6	CTI 125	Types 30.5 and 31.5 for parts with high electrical loads.

1) Maximum service temperature, short-term (100 h)/continuous (20,000 h). 4) Tracking resistance according to DIN IEC 112 method for determining
2) Flexing strength. Comparative Tracking Index (CTI).
3) Impact strength. ¹³⁾ Not used in new parts (asbestos ban).

Type	Type of resin	Filler	$t_g^{1)}$ °C	$\sigma_{50}^{2)}$ min. N/mm ²	$\alpha_n^{3)}$ min. kJ/m ²	CTI ⁴⁾ min. grade	Properties, applications
Thermosetting plastics (selection from DIN 7708, 16 911, 16 912)							
51	Phenol	Cellulose ⁵⁾	160/140	60	5	CTI 150	Somewhat greater water absorption than types 11 ... 16. For parts with good insulating properties in low-voltage range. Type 74 has high impact strength.
71		Cotton fibers ⁵⁾	160/140	60	6	CTI 150	
74		Cotton fabric shreds ⁵⁾	160/140	60	12	CTI 150	
83		Cotton fibers ⁶⁾	160/140	60	5	CTI 150	Tougher than type 31.
—		Glass fibers, short	220/180	110	6	CTI 150	High mechanical strength, resistant to glow heat.
—	Melamine	Glass fibers, long	200/180	120	7.5	CTI 150	
150		Wood flour	160/140	70	6	CTI 600	Resistant to glow heat, high-grade electrical properties, high shrinkage factor.
181	Melamine-phenol	Cellulose	160/140	80	7	CTI 250	For parts subject to electrical and mechanical loads.
801 and 803	Polyester	Glass fibers, inorganic fillers	220/170	60	22	CTI 600	Types 801, 804: low molding pressure (large-area parts manufacture); types 803, 804 glow-heat resistant.
802 and 804			220/170	55	4.5	CTI 600	
870	Epoxy	Rock flour	240/200	50	5	CTI 500	Types 870 and 871 as low-pressure plastics for encapsulating metal parts and electronic components. Low softening temperatures, low shrinkage factor.
871		Glass fibers, short	230/200	80	8	CTI 500	
872		Glass fibers, long	220/190	90	15	CTI 500	
—	Silicone	Glass fibers, short	340/180	55	2	CTI 600	High temperature resistance, high-grade electrical properties.

1) Maximum service temperature, short-term (100 h)/continuous (20,000 h).

2) Flexing strength.

3) Impact strength.

4) Tracking resistance according to DIN IEC 112 method for determining

Comparative Tracking Index (CTI).

5) With or without addition of other organic fillers.

6) And/or wood flour.

Material	Code ⁷⁾	Range of application ⁸⁾ °C	Shore A hardness	Tensile strength ⁹⁾ N/mm ²	Ultimate elongation ⁹⁾ %	Resistance to ¹¹⁾ Weath- ering	Gasoline	Diesel fuel	Mine- ral oil	Highly non-flammable hydraulic fluids HF ¹²⁾				
										A	B	C	D	
Rubbers														
Polyacrylate rubber	ACM	- 20 ... + 150	55 ... 90	5 ... 13	100 ... 350	x	+	x	+	x	x	x	x	-
Acrylnitrile butadiene rubber	NBR	- 30 ... + 120	35 ... 100	10 ... 25	100 ... 700	x ¹⁰⁾	- ¹⁰⁾	x	+	x	x	+	x	-
Butyl rubber	IIR	- 40 ... + 125	40 ... 85	7 ... 17	300 ... 600	x ¹⁰⁾	x ¹⁰⁾	-	-	-	-	+	+	x
Chloroprene rubber	CR	- 40 ... + 110	20 ... 90	7 ... 25	100 ... 800	x	x ¹⁰⁾	x	x	0	0	+	+	-
Chlorinated polyethylene	CM	- 30 ... + 140	50 ... 95	10 ... 20	100 ... 700	+	+	0	0	x	x	+	+	-
Chlorosulfonated polyethylene	CSM	- 30 ... + 140	50 ... 85	15 ... 25	200 ... 500	+	+	-	0	0	x	+	+	-
Epichlorohydrin rubber	ECO	- 40 ... + 135	50 ... 90	6 ... 15	150 ... 500	+	+	x	+	x	x	-	-	-
Ethylene acrylate rubber	EAM	- 40 ... + 185	50 ... 75	7 ... 14	200 ... 500	+	+	0	0	0	x	x	x	-
Ethylene propylene rubber	EPDM	- 50 ... + 150	20 ... 85	7 ... 17	150 ... 500	+	+	-	-	-	-	+	+	+
Fluorcarbon rubber	FKM	- 25 ... + 250	40 ... 90	7 ... 17	100 ... 350	+	+	+	+	+	+	-	+	+
Fluorsilicon rubber	FMQ	- 60 ... + 200	40 ... 70	4 ... 9	100 ... 400	+	+	x	+	+	+	-	+	+
Hydrogenated nitrile rubber	HNBR	- 20 ... + 150	45 ... 90	15 ... 35	100 ... 600	+	+	x	+	+	+	+	+	-
Natural rubber	NR	- 55 ... + 90	20 ... 100	15 ... 30	100 ... 800	0 ¹⁰⁾	- ¹⁰⁾	-	-	-	-	+	+	-
Polyurethane elastomer	AU EU	- 25 ... + 80	50 ... 98	20 ... 50	300 ... 700	x	x	-	-	0	-	-	-	-
Silicone rubber	VMQ	- 60 ... + 200	20 ... 80	4 ... 9	100 ... 400	+	+	-	0	x	+	+	+	+
Styrene butadiene rubber	SBR	- 50 ... + 110	30 ... 100	7 ... 30	100 ... 800	0 ¹⁰⁾	- ¹⁰⁾	-	-	-	-	+	+	-

7) DIN ISO 1629.
8) Not continuous-service temperature.
9) Depending upon composition of compound.
10) Can be improved by adding protective agents.
11) + good resistance, x limited resistance, 0 low resistance, - no resistance.
12) A oil-in-water emulsion; B water-in-oil emulsion;
C polyglycol-water solution; D synthetic liquids.

Material	Code ⁷⁾	Range of application ⁸⁾ °C	Shore A hardness (D)	Tensile strength ⁹⁾ N/mm ²	Ultimate elongation ⁹⁾ %	Resistance to ¹¹⁾ Weathering	Ozone	Gasoline	Diesel fuel	Mineral oil
Thermoplastic elastomers										
Blend/olefin with non-linked to fully cross-linked rubber	TPE-O ¹⁴⁾	- 40 ... + 100 (120)	45A ... 50D	3 ... 15	250 ... 600	+	+	0	0	0
Blend/styrene block polymers	TPE-S ¹⁴⁾	- 60 ... + 60 (100)	30A ... 90A	3 ... 12	500 ... 900	+	+	-	-	-
Polyester elastomer	TPE-E ¹⁴⁾	- 50 ... + 150	40D ... 80D	9 ... 47	240 ... 800	0 ¹⁰⁾	x	x	+	+
Polyester urethane	TPE-U ¹⁴⁾	- 40 ... + 100	70A ... 70D	15 ... 55	250 ... 600	0 ¹⁰⁾	+	0	x	+
Polyetherblockamide	TPE-A ¹⁴⁾	- 40 ... + 80	75A ... 70D	30 ... 60	300 ... 500	0 ¹⁰⁾	+	x	+	x

7) DIN ISO 1629.
8) Not continuous-service temperature.
9) Depending upon composition of compound.
10) Can be improved by adding protective agents.
11) + good resistance, x limited resistance, 0 low resistance, - no resistance.
14) No ISO standard to date.

Plastics abbreviations with chemical names and trade names³⁾

Code	Chemical name	Trade names
ABS	Acrylonitrile butadiene styrene	Cycolac, Novodur, Ronfalin, Terluran
ACM	Polyacrylate rubber	Cyanacryl, Hycar
EAM ¹⁾	Ethylene acrylate rubber	Vamac
APE ¹⁾	Ethylene propylene rubber	Arylef, APEC
ASA	Acrylate styrene acrylonitrile	Luran S
AU	Polyurethane elastomers	Urepan
CA	Cellulose acetate	Bergacell, Tenite
CAB	Cellulose acetate butyrate	Cellidor, Tenite
CM	Chlorinated polyethylene	Bayer CM, CPE
CR	Chloroprene rubber	Baypren, Neoprene
CSM	Chlorosulfonated polyethylene	Hypalon
ECO	Epichlorohydrin rubber	Herclor, Hydrin
EP	Epoxy	Araldite
EPDM	Ethylene propylene rubber	Buna AP, Dutral, Keltan, Nordel, Vistalon
EU	Polyurethane elastomers	Adiprene C
FPM	Fluorcarbon rubber	DAI-EL, Fluorel, Tecnoflon, Viton
HNBR ¹⁾	Hydrogenated nitrile rubber	Therban, Zetpol
IR	Isoprene rubber	Cariflex IR, Natsyn
MF	Melamine-formaldehyde	Bakelite, Resinol, Supraplast, Resopal
MPF	Melamine/phenol-formaldehyde	Supraplast, Resiplast
MVQ	Silicone rubber	Rhodorsil, Silastic, Silopren
NBR	Nitrile butadiene rubber	Buna N, Chemigum, Hycar, Perbunan
PA 46 ¹⁾	Polyamide 46	Stanyl
PA 6-3-T	Amorphous polyamide	Trogamid T
PA 6	Polyamide 6 (polymers of ε-caprolactam)	Akulon, Durethan B, Grilon. Nivionplast, Perlon, Renyl, Sniamid, Technyl, Ultramid B, Wellamid
PA 66	Polyamide 66 (polymers of hexamethylene diamide and adipic acid)	Akulon, Durethan B, Grilon. Nivionplast, Perlon, Renyl, Sniamid, Technyl, Ultramid B, Wellamid
PA X ¹⁾	X = partially aromatic polyamides	Ultramid T ⁴⁾ , Amodel 1... ⁵⁾ , Amodel 4... ⁶⁾ , Grivory GV ⁷⁾ , Grivory HTV ⁸⁾ , Zytel HTN ⁹⁾ , IXEF ¹⁰⁾
PA 11	Polyamide 11 (polymers of 11-aminoundecanoic acid)	Rilsan B
PA 12	Polyamide 12 (polymers of dodecalactam)	Grilamid, Rilsan A, Vestamid
PAI	Polyamide imide	Torlon
PAN	Polyacrylonitrile	Dralon, Orlon
PBTP	Polybutylene terephthalate	Crastin, Pocan, Ultradur, Vestodur, Celanex
PC	Polycarbonate	Makrolon, Orgalan, Sinvet, Lexan
PA 612	Polyamide 612 (polymers of hexamethylene diamine and dodecanoic acid)	Zytel
COC ¹⁾	Cyclo-olefin copolymers	Topas
LCP	Liquid crystal polymers	Vectra, Zenite
PA 6/66	Copolyamide 6/66	Ultramid C, Technyl, Grilon TSV
SPS ¹⁾	Syndiotactic polystyrene	Questra, Xarec
PK ¹⁾	Polyketon	Carilon

Code	Chemical name	Trade names
LFT ¹⁾	Long-fiber reinforced thermoplastic	Celstran
(PC + ABS)	Blend of polycarbonate + ABS	Bayblend, Cycoloy
(PC + ASA)	Blend of polycarbonate + ASA	Terblend S
(PC-PBT)	Blend of polycarbonate + PBT	Xenoy
PE	Polyethylene	Hostalen, Lupolen, Stamylen, Vestolen
PEEK	Polyether ether ketone	Victrex "PEEK"
PEI	Polyether imide	Ultem
PES	Polyether sulphone	Victrex "PES", Ultrason E
PETFE ¹⁾	Ethylene tetrafluorethylene copolymer	Hostafion ET, Tefzel
PETP	Polyethylene terephthalate	Arnite, Crastin, Mylar, Rynite, Impet
PF	Phenol-formaldehyde	Bakelite, Supraplast, Vyncolite
PFA	Perfluoralkoxyethylene	Teflon PFA
PFEP ¹⁾	Fluorinated ethylene-propylene copolymer	Teflon FEP
PI	Polyimide	Kapton, Kerimid, Kinel, Vespel
PMMA	Polymethyl methacrylate	Degalan, Diakon, Lucryl, Perspex, Plexiglas, Vedril
PCM	Polyoxymethylene, polyformaldehyde (a polyacetal)	Delrin, Hostaform, Ultraform
PP	Polypropylene	Daplen, Hostalen PP, Moplen, Stamylen P, Starpylen, Vestolen
(PPE + SB)	Blend of polyphenylene ether + SB	Noryl, Luranyl
(PPE + PA)	Blend of polyphenylene ether + PA	Noryl GTX, Ultranyl, Vestoblend
PPS	Polyphenylene sulfide	Fortron, Ryton, Tedur
PS	Polystyrene	Edistir, Hostyren, Lustrex
PSU	Polysulphone	Udel, Ultrason S
PTFE	Polytetrafluorethylene	Fluon, Hostafion, Teflon
PUR	Polyurethane	Lycra, Vulkollan
PVC-P	Polyvinyl chloride, plasticized	Trosiplast, Vestolit, Vinoflex
PVC-U	Polyvinyl chloride, unplasticized	Trovidur, Hostalit, Vinidur, Vestolid
PVDF	Polyvinylidene fluoride	Dyflor, Kynar, Solef
PVF	Polyvinyl fluoride	Tedlar
SAN	Styrene acrylnitrile	Kostil, Luran, Tyril
SE	Styrene butadiene	Hostyren, Lustrex
SER	Styrene butadiene rubber	Buna Hüls, Buna S, Cariflex S
TPE-A ¹⁾	Polyether blockamide	Pebax, Vestamid E
TPE-E ¹⁾	TPE ²⁾ polyester base	Arnitel, Hytrel, Riteflex
TPE-O ¹⁾	TPE ²⁾ olefin base	Leraflex, Santoprene
TPE-S ¹⁾	TPE ²⁾ styrene base	Cariflex, Evoprene, Kraton
TPE-11 ¹⁾	Polyester urethane	Desmopan, Elastollan
UF	Urea-formaldehyde	Bakelite, Pollopas
UP	Unsaturated polyester	Keripol, Leguval, Palatal

¹⁾ Material code not yet standardized.

²⁾ TPE: Thermoplastic rubber.

³⁾ ISO 1043/DIN 7728 (Thermoplastics, thermosetting plastics), ISO 1629 (Rubbers).

Material codes

⁴⁾ PA 6/6T

⁸⁾ PA 6I/6T

⁴⁾ - ¹⁰⁾ are standardized

⁵⁾ PA 6T/6I/66

⁹⁾ PA 6T/MPMDT

⁶⁾ PA 6T/66

¹⁰⁾ PA MXD 6

⁷⁾ PA 66 + PA 6I/6T

Automotive paints, structure of solid-color coatings

Layer	Layer thickness in μm	Structure	Composition				
			Binders	Solvents	Pigments	Extenders	Additives and SC
1	20...25	KTL	Epoxy resins Polyurethane	Water, small amounts of water- miscible organic solvents	Anorganic (organic)	Anorganic extenders	Surface-active substances, anti-crater agents, 20% SC
2a	approx. 35	Primer	Polyester, melamine, urea & epoxy resins	Aromatic compounds, alcohols	Anorganic and organic	Anorganic solids	e.g. wetting agents, surface-active substances 58...62% SC
2b	approx. 35	Water extender	Water-soluble polyester, polyurethane & melamine resins	Water, small amounts of water- miscible organic solvents			43...50% SC
2c	approx. 20	Thin-film water extender	Water-soluble polyurethane & melamine resins	Water, small amounts of water- miscible organic solvents		Anorganic extenders	e.g. wetting agents, surface-active substances 32...45% SC
3a	40...50	Solid-color top coat	Alkyd & melamine resins	Esters, aromatic compounds, alcohols		—	e.g. leveling & wetting agents
3b	10...35 (color-specific)	Water-borne solid-color base coat	Water-soluble polyester, polyurethane, polyacrylate & melamine resins	Small amounts of water-miscible co-solvents		—	Wetting agents 20...40% SC
4a	40...50	Conven- tional clear coat	Acrylic & melamine resins	Aromatic compounds, alcohols, esters	—	—	e.g. leveling agents and light stabilizers 45% SC
4b	40...50	2C-HS	HS acrylate resin polyisocyanates	Esters, aromatic compounds	—	—	e.g. leveling agents and light stabilizers 58% SC
4c	40...50	Powder- slurry clear coat	Urethane-modified epoxy/carboxy system	—	—	—	e.g. light stabilizers 38% SC

Structure of metallic coatings

Layer	Layer thickness in μm	Structure	Composition				Additives and SC	Application
			Binders	Solvents	Pigments	Extenders		
1	20...25	KTL	Epoxy resin polyurethane	Water, small amounts of water- miscible organic solvents	Anorganic (organic)	Anorganic extenders	Surface- active substances, anti-crater agents, 20% SC	ET
2a	approx. 35	Extender melamine, urea & epoxy resins	Polyester, alcohols	Aromatic compounds, alcohols	Anorganic and organic	Anorganic extenders	e.g. wetting agents, surface- active substances 58...62% SC	PZ ESTA-HR
2b	approx. 35	Water extender	Water-soluble polyester, polyurethane & melamine resins	Water, small amounts of water- miscible organic solvents			43...50% SC	PZ ESTA-HR
2c	approx. 20	Thin-film water exten- der		Water, small amounts of water- miscible organic solvents			e.g. wetting agents, surface- active substances 32...45% SC	PZ ESTA-HR
3a	10...15	Metallic base coat		Esters, aromatic compounds	Aluminum particles, mica particles	—	15...30% SC	PZ ESTA-HR
3b	10...15	Water-solu- ble metallic base coat	Water-soluble polyester, polyurethane, polyacrylate & melamine resins	Small amounts of water-miscible co-solvents	Aluminum and mica particles organic and anorganic pigments	—	Wetting agent	PZ ESTA-HR
4a	40...50	Conven- tional clear coat	Acrylic & melamine resins	Aromatic compounds, alcohols, esters	—	—	e.g. leveling agents and light stabilizers 45% SC	PZ ESTA-HR
4b	40...50	2C-HS	HS acrylate resin, polyisocyanates	Esters, aromatic compounds	—	—	e.g. leveling agents and light stabilizers 58% SC	
4c	40...50	Powder- slurry clear coat	Urethane-modified epoxy/carboxy system	—	—	—	e.g. light stabilizers 38% SC	

Acronyms: DS High film build, ESTA-HR Electrostatic high rotation, ET Electrophoretic coating, SC (FK) Solids content or non-volatiles, KTL Cathodic deposition, PZ Pneumatic spray, 2C-HS 2-component high-solid (high levels of non-volatile matter).

Lubricants

Terms and definitions

Lubricants provide mutual insulation for components in a state of relative motion. The lubricant's function is to prevent direct contact between these components, thereby reducing wear and minimizing, or optimizing, friction. Lubricants serve as coolants, sealants and corrosion inhibitors, and can also reduce operating noise. The lubricant can be solid, consistent, liquid or gaseous in form. Specific lubricants are selected with reference to design characteristics, materials combinations, the operating environment and the stress factors encountered at the friction surface.

Additives

Additives are substances mixed into the lubricant in order to improve specific properties. These substances modify either the lubricant's physical characteristics (e.g. viscosity index improvers, pour-point depressors) or its chemical properties (e.g. oxidation inhibitors, corrosion inhibitors). In addition, the properties of the friction surfaces themselves can be modified with additives which change the friction characteristics (friction modifiers), protect against wear (anti-wear agents), or provide protection against scoring and seizure (extreme-pressure additives). Great care must be exercised in order to ensure that the additives are correctly matched with each other and with the base lubricant.

AFC (Anti-Friction-Coating)

Solid lubricant combinations which a binding agent holds in place on the friction faces.

ATF (Automatic Transmission Fluid)

Special-purpose lubricants specifically formulated to meet stringent requirements for operation in automatic transmissions.

Ash (DIN 51575, 51803)

The mineral residue which remains after oxide and sulfate incineration.

Bingham bodies

Materials whose flow characteristics differ from those of Newtonian liquids.

Bleeding (Oil separation, DIN 51817)

Separation of the base oil and the thickener in a lubricating grease.

Cloud point (DIN ISO 3015)

The temperature at which mineral oil becomes opaque due to the formation of paraffin crystals or precipitation of other solids.

Consistency (DIN ISO 2137)

A measure of the ease with which lubricating greases and pastes can be deformed.

Doped lubricants

Lubricants containing additives for improving specific properties (e.g. aging stability, wear protection, corrosion protection, viscosity-temperature characteristics).

Dropping point (DIN ISO 2176)

Temperature at which a lubricating grease attains a specified viscosity under defined conditions.

EP Lubricants (Extreme Pressure)

See high-pressure lubricants.

Fire point/flash point (DIN ISO 2592)

The lowest temperature (referred to 1013 hPa) at which a gaseous mineral product initially flashes (fire point), or continues to burn for at least 5 secs (burning point).

Flow pressure (DIN 51805)

According to Kesternich, the gas pressure required to press a consistent lubricant through a standardized test nozzle. The flow pressure is an index of a lubricant's starting flow characteristics, particularly at low temperatures.

Friction modifiers

Polar lubricant additives which reduce friction in the mixed-friction range and increase bearing capacity after adsorption on the surface of the metal. They also inhibit stick-slip behavior.

Gel-type greases

Lubricants with inorganic gelling agents (e.g. Bentonites, Aerosiles, silica gels).

Graphite

Solid lubricant with layer-lattice structure. Graphite provides excellent lubrication when combined with water (e.g. high atmospheric humidity) and in carbon-dioxide atmospheres or when combined with oils. It does not inhibit friction in a vacuum.

High-pressure lubricants

Contain additives to enhance load-bearing capacity, to reduce wear and to reduce scoring (generally provide good performance in steel-to-steel and steel-to-ceramic applications).

Induction period

The period which elapses before substantial changes occur in a lubricant (e.g. aging of an oil containing an oxidation inhibitor).

Inhibitors

Lubricant protection additives (e.g. oxidation and corrosion inhibitors).

Low-temperature sludge

Products of oil degradation which form in the engine crankcase due to incomplete combustion and condensation at low engine load. Low-temperature sludge increases wear and can cause engine damage. Modern high-quality engine oils inhibit its formation.

Metal soaps

Reaction products from metals or from their compounds with fatty acids. They are used as thickeners for grease and as friction modifiers.

Mineral oils

Mineral oils are distillates or raffinates produced from petroleum or coal. They consist of numerous hydrocarbons in various chemical combinations. Classification is according to the predominant component: paraffin-based oils (chain-shaped saturated hydrocarbons), naphthene-based oils (closed-chain saturated hydrocarbons, generally with 5 or 6 carbon atoms per ring) or aromatic oils (e.g.

alkylbenzene). These substances are distinguished by major variations in their respective chemical and physical properties.

Molybdenum disulfide (MoS_2)

A solid lubricant with layer-lattice structure. Only low cohesive forces are present between the individual layers, so their mutual displacement is characterized by relatively low shear forces. A reduction in friction is only obtained when MoS_2 is applied in suitable form to the surface of the metal (e.g. in combination with a binder such as MoS_2 anti-friction coating).

Multigrade oils

Engine and transmission oils with good resistance to viscosity-temperature change (high viscosity index VI). These oils are formulated for year-round use in motor vehicles; their viscosity ratings extend through several SAE grades.

Penetration (DIN ISO 2137)

Depth (in 10^{-1} mm) to which a standardized cone penetrates into a consistent lubricant within a defined period and at a specified temperature. The larger the number, the softer the lubricant.

Polar substances

Dipolar molecules are easily adsorbed onto metal surfaces. They enhance adhesion and bearing capacity, thus reducing friction and wear. This category includes, for example, esters, ethers, polyglycols and fatty acids.

Pour point (DIN ISO 3016)

The lowest temperature at which an oil continues to flow when cooled under defined conditions.

Rheology

Science dealing with the flow characteristics of materials. These are generally represented in the shape of flow curves.

Coordinate plotting:

Shear stress $\tau = F/A$ ($\text{N/m}^2 = \text{Pa}$)

F force, A surface area

against

Shear rate $D = v/y$ (s^{-1})

(linear shear rate)

v velocity, y thickness of lubricating film.

Dynamic viscosity

$$\eta = \tau/D \text{ (Pa} \cdot \text{s)}$$

The formerly-employed unit "centiPoise" (cP) is equal to the unit (mPa · s).

Kinematic viscosity

$$\nu = \eta/\rho \text{ (mm}^2\text{/s)}$$

ρ density (kg/m³).

The formerly-employed unit "centiStokes" (cSt) is equal to the unit (mm²/s).

Newtonian fluids

These display a linear relationship between τ and D in the shape of a straight line through zero, with the slope increasing as a function of viscosity.

All materials not characterized by this kind of flow behavior are classified as non-Newtonian fluids.

Intrinsically viscous flow behavior

Decrease in viscosity with increasing shear rate (e.g. liquid grease, multigrade oil with VI improvers).

Dilatant flow behavior

Increase in viscosity with increasing shear rate.

Plastic flow behavior

Formability of an intrinsically viscous fluid supplemented by yield value (e.g. lubricating greases).

Thixotropy

A characteristic of those non-Newtonian fluids that display an increase in viscosity proportional to shear time, and only gradually recover their original viscosity once shearing ceases.

Rheopexy

A characteristic of those non-Newtonian fluids that display a reduction in viscosity proportional to shear time, and only gradually recover their original viscosity once shearing ceases.

Stribeck curve

Portrays friction levels between two liquid- or grease-lubricated bodies separated by a narrowing gap (e.g. lubricated plain or roller bearings) as a function of sliding speed.

Solid-body friction

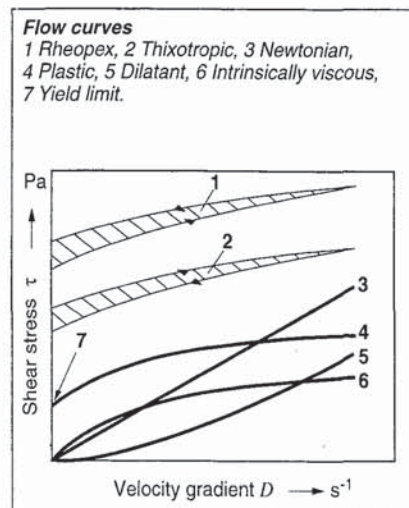
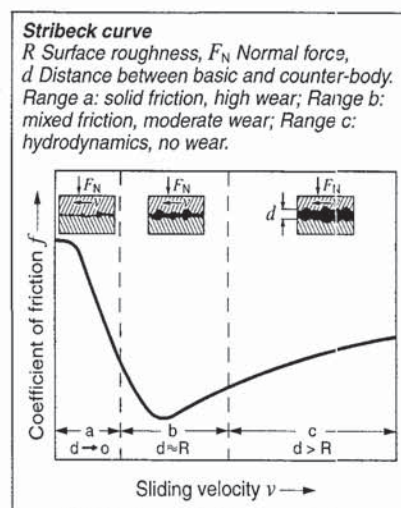
The height of the lubricant layer is lower than that of the roughness protrusions in the material's surface.

Mixed friction

The height of the lubricant layer is approximately equal to that of the roughness protrusions

Hydrodynamics

Complete separation between primary and opposed body (virtually frictionless condition).



Viscosity (DIN 1342, DIN 51550)
Defines the internal friction of substances. It indicates the degree of resistance (internal friction) with which the substance's molecules oppose displacement forces (see Rheology).

Viscosity index (VI) (DIN ISO 2909)
The viscosity index VI is a mathematically-derived number expressing the change in a mineral-oil product's viscosity relative to its temperature. The greater the VI, the lower the effect of temperature on the viscosity.

Viscosity classification
Classification of oils in specific viscosity ranges. ISO viscosity classifications (DIN 51519, see Table 1).
SAE viscosity grades (DIN 51511, SAE J300, DIN 51512, SAE J306c, see Tables 2 and 3).

Yield point (DIN 13342)
The minimum shear stress at which a substance begins to flow. Above the yield point, the rheological characteristics of plastic substances are the same as those of liquids.

Table 1. Viscosity classes for industrial lubricating oils to ISO 3448 (DIN 51519)

ISO viscosity class	Medium viscosity at 40 °C mm ² /s	Kinematic viscosity limits at 40 °C mm ² /s	
		min.	max.
ISO VG 2	2.2	1.98	2.42
ISO VG 3	3.2	2.88	3.52
ISO VG 5	4.6	4.14	5.06
ISO VG 7	6.8	6.12	7.48
ISO VG 10	10	9.00	11.0
ISO VG 15	15	13.5	16.5
ISO VG 22	22	19.8	24.2
ISO VG 32	32	28.8	35.2
ISO VG 46	46	41.4	50.6
ISO VG 68	68	61.2	74.8
ISO VG 100	100	90.0	110
ISO VG 150	150	135	165
ISO VG 220	220	198	242
ISO VG 320	320	288	352
ISO VG 460	460	414	506
ISO VG 680	680	612	748
ISO VG 1000	1000	900	1100
ISO VG 1500	1500	1350	1650

Table 2. SAE viscosity grades for engine oils/transmission lubricants (SAE J300, Dec. 95)

SAE viscosity grade	Viscosity (ASTM D 5293) mPa · s at °C	Limit pumping viscosity (ASTM D 4684) with no yield point mPa · s at °C	Kinematic viscosity (ASTM D 445) mm ² /s at 100 °C		Viscosity under high shear (ASTM D 4683, CEC L-36-A-90, ASTM D 4741) mPa · s at 150 °C and 10 ⁶ s ⁻¹
	max.	max.	min.	max.	min.
0 W	3250 at -30	60000 at -40	3.8	—	—
5 W	3500 at -25	60000 at -35	3.8	—	—
10 W	3500 at -20	60000 at -30	4.1	—	—
15 W	3500 at -15	60000 at -25	5.6	—	—
20 W	4500 at -10	60000 at -20	5.6	—	—
25 W	6000 at -5	60000 at -15	9.3	—	—
20	—	—	5.6	< 9.3	2.6
30	—	—	9.3	< 12.5	2.9
40	—	—	12.5	< 16.3	2.9 (0W-40, 5W-40, 10W-40)
40	—	—	12.5	< 16.3	3.7 (15W-40, 20W-40, 25W-40, 40)
50	—	—	16.3	< 21.9	3.7
60	—	—	21.9	< 26.1	3.7

Table 3. SAE viscosity grades for transmission lubricants (SAE J306c, March 85)

SAE viscosity grade	Maximum temperature °C for dynamic viscosity at 150,000 mPa · s (ASTM D2983)	Kinematic viscosity mm²/s at 100 °C (ASTM D 445)	
		min.	max.
70 W	-55	4.1	-
75 W	-40	4.1	-
80 W	-26	7.0	-
85 W	-12	11.0	-
90	-	13.5	24.0
140	-	24.0	41.0
250	-	41.0	-

Worked penetration (DIN ISO 2137)
Penetration of a grease sample after it is warmed to 25 °C and processed in a grease kneader.

Engine oils

Engine oils are employed primarily to lubricate contiguous components in relative motion within the internal-combustion engine. The oil also removes heat generated by friction, carries particles removed by friction away from the source, washes out contaminants and holds them in suspension, and protects metals against corrosion. The most common engine oils are mineral oils treated with additives (HD oils: Heavy Duty for extreme operating conditions). Higher stress-resistance requirements combined with extended oil-change intervals have led to widespread application of fully and semi-synthetic oils (e.g. hydro-crack oils). The quality of an engine oil is determined by its origin, the refining processes used on the mineral oil (except in the case of synthetic oils) and the additive composition.

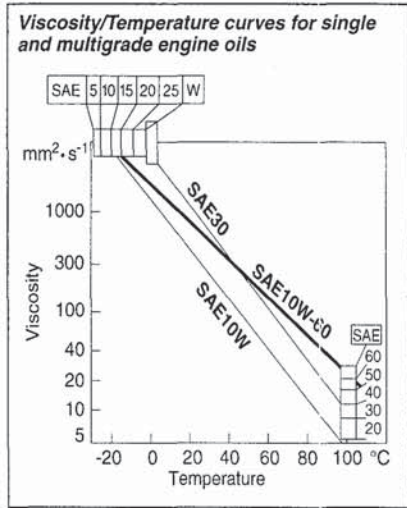
- Additives are classified according to their respective functions:
- Viscosity-index (VI) improvers,
 - Pour-point improvers,
 - Oxidation and corrosion inhibitors,
 - Detergent and dispersant additives,
 - Extreme-pressure (EP) additives,

- Friction modifiers,
- Anti-foaming agents.

Oil is subjected to considerable thermal and mechanical stresses in the IC engine. The data on the oils' physical properties provide information on their operating range, but are not indicative of their other performance characteristics.

There thus exist several different procedures for evaluating engine oils (see comparison of engine-oil performance categories):

- ACEA (Association des Constructeurs Européens de l'Automobile) standards, replaced the CCMC standards (Comité des Constructeurs d'Automobiles du Marché Commun) at the beginning of 1996,
 - API Classification (American Petroleum Institute)
 - MIL Specifications (Military),
 - Manufacturer's specifications.
- The approval criteria include the following:
- Sulfate-ash content,
 - Zinc content,
 - Engine type (diesel or spark-ignition engines, naturally-aspirated or forced-induction engines),
 - Load on power-transmission components and bearings,
 - Wear-protection properties,
 - Oil operating temperature (in oil pan),



- Combustion residue and chemical stress exerted upon the oil by acidic combustion products,
- The oil's detergent and residue-scavenging properties,
- Its suitability for use with gasket and sealing materials.

ACEA (CCMC) Specifications

Engine oils for gasoline engines

A1-98: Special high-lubricity oils with reduced viscosity at high temperatures and high shear.

A2-96: Conventional and high-lubricity engine oils without any restriction on viscosity class. Higher requirements than CCMC G4 and API SH.

A3-98: Oils of this category meet higher requirements than A2-96 and CCMC G4 and G5.

Engine oils for passenger-car diesel engines

B1-98: Corresponding to A1-98 for low friction losses and, consequently, reduced fuel consumption.

B2-98: Conventional and high-lubricity engine oils compliant with the current minimum requirements (higher than those of CCMC PD2).

B3-98: Exceeds B2-98.

B4-98: Corresponds to B2-98, particularly suitable for VW TDI engines.

Engine oils for commercial-vehicle diesel engines

E1-96: Oils for naturally aspirated and turbocharged engines with normal intervals between oil changes.

E2-96: Derived from MB Specification Sheet 228.1. Primarily for engine designs predating the Euro-II standard.

E3-96: For Euro-II engines, derived from MB Specification Sheet 228.3. In comparison with the predecessor category CCMC D5, these oils evince a significant improvement in soot dispersion capability and a much reduced tendency to thicken.

E4-98: Currently the highest quality category for diesel engines compliant with the Euro-I and Euro-II standards and with high requirements, particularly for extended intervals between oil changes (according to manufacturer's specification). Based to a large extent on MB 228.5.

API Classifications

S Classes (Service) for gasoline engines.
C Classes (Commercial) for diesel engines.

SF: For engines produced in the 80s.

SG: For engines built since 1989, with more stringent sludge test, improved oxidation stability and friction protection.

SH: Since mid-1993, corresponds to API SG quality level, but with more stringent process requirements for oil quality testing.

SJ: Since October 1996, more tests than API SH.

CC: Engine oils for non-turbocharged diesel engines with low stress factors.

CD: Engine oils for non-turbocharged and turbocharged diesels, replaced by API CF in 1994.

CD-2: API CD requirements, plus additional requirements relevant to 2-stroke diesel engines.

CF-2: Oils with special 2-stroke properties (since 1994).

CE: Oils with CD performance characteristics, with supplementary test operation in American Mack and Cummins engines.

CF: Replaced API CD in 1994. Specially for indirect injection, even if the sulfur content of the fuel is >0.5%.

CF-4: As API CE, but with more stringent test procedure in single-cylinder Caterpillar turbo-diesel engines.

CG-4: For diesel engines operating under very stringent conditions. Exceeds API CD and CE. Fuel sulfur <0.5%. Required for engines compliant with post-1994 emission-control regulations.

SAE viscosity grades

(DIN 51511, SAE J300, DIN 51512, SAE J306c)

The SAE (Society of Automotive Engineers) classifications are the internationally-accepted standard for defining viscosity. The standard provides no information on the quality of the oil. A distinction is drawn between single-grade and multi-grade oils. Multigrade oils are the type in widespread use today.

Two series are employed for the designation (see Table 2) with the letter "W" (Winter) being used to define specific cold-flow properties. The viscosity grades including the letter "W" are rated according to max-

imum low-temperature viscosity, maximum viscosity pumping temperature and the minimum viscosity at 100°C; viscosity grades without the "W" are rated only according to viscosity at 100°C.

Multigrade oils

Multigrade oils are characterized by a less pronounced proportional relationship between temperature and viscosity. They reduce friction and wear, can be used all year round, and provide rapid lubrication for all engine components in cold starts.

High-lubricity oils

Lubricating oils with multigrade properties, low viscosity at low temperatures, and special anti-friction additives. Extremely low engine friction under all operating conditions reduces fuel consumption.

Transmission lubricants

Specifications for transmission lubricants are defined by the type of transmission and the stresses to which it is subjected through the entire range of operating conditions. The requirements (high pressure resistance, high viscosity stability relative to temperature, high resistance to aging, good anti-foaming properties, compatibility with gaskets and seals) can only be satisfied by lubricants treated with special additives. The use of unsuitable and qualitatively inferior oils typically results in damage to bearings and gear-tooth flanks.

The viscosity must also suit the specific application. Viscosity grades for vehicular transmissions are defined in DIN 51512 and SAE J 306 (see Table 3).

Synthesized oils are being increasingly used to meet special requirements (e.g. poly- α -olefines). Advantages over standard mineral lubricants include superior temperature-viscosity properties and increased aging resistance.

API Classifications for transmission lubricants

GL1-GL3: Outdated, no longer of practical significance.

GL4: Transmission lubricants for moder-

ately-stressed hypoid-gear transmissions and for transmissions which operate at extreme speeds and impact loads, high rotational speeds and low torques, or low rotational speeds and high torques.

GL5: Transmission lubricants for highly-stressed hypoid-gear transmissions in passenger cars and in other vehicles where they are exposed to impact loads at high rotational speeds, and at high rotational speeds and low torques, or low rotational speeds and high torques.

MT-1: Non-synchromeshed manual transmissions in American trucks.

Lubricants for automatic transmissions (ATF: Automatic Transmission Fluid)

Automatic transmissions differ from their manually shifted counterparts in the way that they transfer torque; positive mechanical and hydrodynamic force transfer being supplemented by friction coupling arrangements. Thus the friction response of automatic-transmission fluids is extremely important. Applications are basically classified according to the friction characteristics:

General Motors: Superseded classifications: Type A, Suffix A, DEXRON®, DEXRON®B, DEXRON®II C, DEXRON®II D, DEXRON® II E (valid through 1994).

DEXRON® III. Valid since 1 January, 1994. Features more stringent requirements for oxidation stability and consistency in frictional coefficient.

Ford: MERCON® (valid since 1987).

Other manufacturers: In accordance with operating instructions.

Lubricating greases

Lubricating greases are thickened lubricating oils. A great advantage that greases enjoy over oil is that they do not drain from the contact location. Complicated measures designed to seal them in place are therefore unnecessary (e.g. application in wheel bearings and moving systems such as ABS, alternators, ignition distributors, windshield-wiper motors, servo motors). Table 4 provides a general overview of the components in a consistent lubricating grease as blended from three basic components – base oil, thickener and additive.

Mineral oils are usually employed as the basic oil component, although full-synthetic oils have recently become more common as a replacement (e.g. due to more stringent requirements for aging resistance, cold-flow properties, viscosity-temperature characteristics). Thickeners are used as a binder for the base oil; metal soaps being generally employed. They bind the oil in a sponge-like soap structure (micelle) via occlusion and Van der Waals forces. The higher the proportion of thickener in the grease (depends upon the type of thickener), the greater the grease's consistency (depth of penetration of a test cone into the grease sample) and the higher the NLGI classification (see Table 5).

The additives serve to modify physical and chemical properties of the grease to achieve specific objectives (such as improvement of anti-oxidation properties, increased load capacity (EP additives), and reduction of friction and wear). Solid lubricants (e.g. MoS₂) are also added to lubricating greases (for instance for lubricating constant-velocity joints in motor vehicles). Specific lubricating greases are selected with reference to their physical characteristics and their effects upon the sliding surface, and to minimize interaction between the grease and the contact materials.

Example:
Mutually antagonistic effects with polymers:

- Formation of stress cracks,
- Consistency changes,
- Polymer degradation,
- Swelling, shrinkage, brittleness.

Thus, for example, mineral-oil greases and greases based on synthetic hydrocarbons should not come into contact with elastomers used together with brake fluid (polyglycol base), as this could provoke substantial swelling.

In addition, greases with varying compositions should not be mixed (changes in physical properties, grease liquefaction due to drop-point reduction).

The correct lubricating grease can substantially enhance the performance potential of products with sliding contact-surfaces (e.g. transmissions, friction and roller bearings, actuator and control systems).

Table 5. Consistency classifications for lubricating greases (DIN 51 813)

NLGI grade	Worked penetration as per DIN ISO 2137 in units (0.1 mm)
000	445 ... 475
00	400 ... 430
0	355 ... 385
1	310 ... 340
2	265 ... 295
3	220 ... 250
4	175 ... 205
5	130 ... 160
6	85 ... 150

Table 4. Composition of lubricating greases

Base oils	Thickeners	Additives
Mineral oils - Paraffinic - Naphthenic - Aromatic	Metal soaps (Li,Na,Ca,Ba,Al) Normal Hydroxi- Complex	Oxidation inhibitors Fe, Cu ions, sequestering agents Corrosion inhibitors Extreme-pressure additives (EP additives)
Poly-α-olefines Alkyl aromatics Esterols Polyalcohols Silicones Phenyletherols Perfluoropolyethers	Polyureas PE Bentonites Silica gels	Wear-protection additives (anti-wear additives) Friction reducers (friction modifiers) Adhesion improvers Detergents, dispersants VI improvers Solid lubricants

Whatever the friction pairing, the multiplicity of lubricant components can be used to develop a high-performance lubricant.

Fuels

Characteristics

Net and gross calorific values

The specific values for the net (formerly: low) and gross (formerly: high, or combustion) calorific values, or H_u and H_o respectively, provide an index for the energy content of fuels. Only the net calorific value H_u (combustion vapor) is significant in dealing with fuels with which water is produced as a byproduct of combustion.

Oxygenates, fuel constituents which contain oxygen, such as alcohols, ether, and fatty-acid methyl ester have a lower calorific value than pure hydrocarbons, because their bound oxygen does not contribute to the combustion process. Power comparable to that achievable with conventional fuels can thus only be attained at the cost of higher consumption rates.

Calorific value of air-fuel mixture

The calorific value of the combustible air-fuel mixture determines the engine's output. Assuming a constant stoichiometric ratio, this figure remains roughly the same for all liquid gases and fuels (approx. 3500 ... 3700 kJ/m³).

Fuels for spark-ignition engines (gasoline/petrol)

The minimum requirements for these types of fuels are contained in various national and international standards. European Standard EN228 defines the unleaded fuels which have been introduced within Europe ("Euro-Super"). DIN EN228 contains the corresponding German specifications along with supplementary descriptions of unleaded regular and super premium ("Super-Plus") fuels. In the USA, fuels for spark-ignition engines are defined in ASTM D439 (American Society for Testing and Materials). Fuels for spark-ignition engines are hydrocarbon compounds which may contain supplements in the form of oxygenous organic components or other additives to improve performance.

A distinction is made between regular and premium (super-grade) gasolines. Premium gasoline has higher anti-knock qualities and is formulated for use in high-compression engines. Volatility ratings vary according to region and whether the fuel is intended for summer or winter use.

Unleaded gasoline (EN 228)

Unleaded fuel is indispensable for vehicles equipped with catalytic converters for treating exhaust gases, as lead would damage the noble metals (e.g. platinum) in the catalytic converter and render it inoperative. It would also destroy the Lambda sensors employed to monitor exhaust gas composition for closed-loop control.

Unleaded fuels are a special mixture of high-grade, high-octane components (e.g. platformates, alkylates and isomerisates). The anti-knock qualities can be effectively increased with non-metallic additives such as methyl tertiary butyl ether (MTBE) in concentrations of 3...15% and/or alcohol mixtures (methanol 2...3%, and higher alcohols). As of the year 2000, the maximum lead content is limited to 5 mg/L.

Leaded gasoline

In Europe, sales of leaded gasoline are prohibited as of the year 2000, although for a transitional period it will still be available in exceptional cases.

Leaded fuel is still available in some countries, although their number is steadily decreasing.

Density

European Standard EN228 limits the fuel density range to 720...775 kg/m³. Because premium fuels generally include a higher proportion of aromatic compounds, they are denser than regular gasoline, and also have a slightly higher calorific value.

Anti-knock quality (octane rating)

The octane rating defines the gasoline's anti-knock quality (resistance to pre-ignition). The higher the octane rating, the greater the resistance to engine knock. Two differing procedures are in international use for determining the octane rat-

Table 1. Essential data for unleaded gasoline, European Standard EN 228 (valid since 1 January 2000)

Requirements	Unit	Specification
Anti-knock quality		
Premium, min.	RON/MON	95/85
Regular, min. ¹⁾	RON/MON	91/82.5
Super Plus ¹⁾	RON/MON	98/88
Density	kg/m ³	720 ... 775
Sulfur, max.	mg/kg	150
Benzene, max.	% volume	1
Lead, max.	mg/l	5
Volatility		
Vapor pressure, summer, min./max.	kPa	45/60
Vapor pressure, winter, min./max.	kPa	60/90 ¹⁾
Evaporated vol. at 70 °C, summer, min./max.	% volume	20/48
Evaporated vol. at 70 °C, winter, min./max.	% volume	22/50
Evaporated vol. at 100 °C, min./max.	% volume	46/71
Evaporated vol. at 150 °C, min./max.	% volume	75/—
Final boiling point, max.	°C	210
VLI transitional period ³⁾ , max. ²⁾		1150 ¹⁾

¹⁾ National values for Germany, ²⁾ VLI = Vapor Lock Index, ³⁾ spring and fall.

ing; these are the Research Method and the Motor Method.

RON, MON

The number determined in testing using the Research Method is the Research Octane Number, or RON. It serves as the essential index of acceleration knock.

The Motor Octane Number, or MON, is derived from testing according to the Motor Method. The MON basically provides an indication of the tendency to knock at high speeds.

The Motor Method differs from the Research Method by using preheated mixtures, higher engine speeds and variable ignition timing, thereby placing more stringent thermal demands on the fuel under examination. MON figures are lower than those for RON.

Octane numbers up to 100 indicate the volumetric content in percent of C₈H₁₈ iso-octane (trimethyl pentane) contained in a mixture with C₇H₁₆ n-heptane at the point where the mixture's knock-resistance in a test engine is identical to that of the fuel being tested. Iso-octane, which is extremely knock-resistant, is assigned the octane number 100 (100 RON and MON), while n-heptane, with low-resistance to pre-ignition, is assigned the number 0.

Increasing the anti-knock quality

Normal (untreated) straight-run gasoline displays little resistance to knock. Various refinery components must be added to obtain a fuel with an octane rating which is adequate for modern engines. The highest-possible octane level must also be maintained throughout the entire boiling range. Cyclic hydrocarbons (aromatics) and branched chains (iso-paraffins) provide greater knock resistance than straight-chain molecules (n-paraffins).

Additives based on oxygenous components (methanol, ethanol, methyl tertiary butyl ether (MTBE)) have a positive effect on the octane number, but can lead to difficulties in other areas (alcohols raise the volatility level and can damage fuel-system components).

Volatility

Gasolines must satisfy stringent volatility requirements to ensure satisfactory operation. The fuel must contain a large enough proportion of highly volatile components to ensure good cold starting, but the volatility must not be so high as to impair operation and starting when the engine is hot (vapor lock). In addition, environmental considerations demand that evaporative losses be held low. Volatility

is defined in various ways.

EN228 defines 10 different volatility classes distinguished by various levels of vapor pressure, boiling-point curve and VLI (Vapor Lock Index). To meet special requirements stemming from variations in climatic conditions, countries can incorporate specific individual classes into their own national standards.

Boiling curve

Individual ranges on the boiling curve exercise a particularly pronounced effect on operating behavior. They can be defined according to volumetric fuel evaporation at three temperatures. The volume which evaporates up to 70 °C must be adequate to ensure good cold starting, (particularly important for old carburetor-type engines), but not so large as to promote formation of vapor bubbles when the engine is hot. The percentage of vaporized fuel at 100 °C determines the engine's warm-up qualities, as well as its acceleration and response characteristics once it has reached normal operating temperature. The vaporized volume up to 150 °C should be high enough to minimize dilution of the engine's lubricating oil, especially with the engine cold.

Vapor pressure

Fuel vapor pressure as measured at 38 °C/100 °F in accordance with prEN 13016-1 is primarily an index of the safety with which the fuel can be pumped into and out of the vehicle's tank. The Reid method is an alternative method of measuring fuel vapor pressure. All specifications place limits on this vapor pressure. Germany, for example, prescribes maxima of 60 kPa in summer and 90 kPa in winter. In the case of modern fuel-injected (EFI) engines though, when troubleshooting vapor-lock malfunctions, it is more important to know the vapor pressure at higher temperatures (80, 100 °C). Research procedures are in place, and a definitive standard is currently being prepared. Fuels to which methanol is added are characterized by a pronounced rise in vapor pressure at high temperatures.

Vapor/liquid ratio

This specification provides an index of a

fuel's tendency to form vapor bubbles. It is based on the volume of vapor generated by a specific quantity of fuel at a set temperature. A drop in pressure (e.g. when driving over a mountain pass) accompanied by an increase in temperature will raise the vapor/liquid ratio and with it the probability of operating problems. ASTM D439, for example, defines specific vapor/liquid ratios for gasolines.

Vapor Lock Index (VLI)

This parameter is the sum of the Reid vapor pressure (in kPa x 10), and that proportion of the fuel that vaporizes up to a temperature of 70 °C. Both components in the equation are absolute data, the latter being derived from the boiling-point curve prior to multiplication by a factor of 7. The VLI provides more useful information on the fuel's influence on starting and operating a hot engine than that supplied by conventional data.

The correlation between VLI and vapor/liquid ratio is good in the case of fuels that contain no alcohol additives.

Sulfur

Direct-injection systems for gasoline engines require fuels with a low sulfur content on account of their exhaust-emission control systems. The byproducts of sulfur combustion would render the catalytic converters inoperative. Consequently, and also on account of the target reduction in SO₂ emissions, the sulfur content of fuels will have to be further reduced in future; figures in the range < 10 ppm are desirable.

Additives

Along with the structure of the hydrocarbons (refinery components), it is the additives which determine the ultimate quality of a fuel. The packages generally used combine individual components with various attributes.

Extreme care and precision are required both when testing additives and in determining their optimal concentrations. Undesirable side-effects must be avoided. To obtain optimal results, the quantities used remain the province of the manufacturer, who can add the correct ratios in the desired concentrations when

filling the tanker at the refinery. Vehicle operators should refrain from adding supplementary additives of their own.

Anti-aging additives

These agents are added to fuels to improve their stability during storage, and are particularly important when the fuel also contains cracked components. They inhibit oxidation due to atmospheric oxygen and prevent catalytic reactions with metal ions (metal deactivators).

Intake-system contamination inhibitors

The entire intake system (injectors, intake valves) must be kept free of contamination and deposits for several reasons. A clean intake tract is essential for maintaining the factory-defined A/F ratios, as well as for trouble-free operation and minimal exhaust emissions. To achieve this end, effective detergent agents should be added to the fuel.

Corrosion protection

Moisture entrained with the fuel can lead to corrosion in the fuel system. An extremely effective remedy is afforded by anti-corrosion additives designed to form a protective layer below the film of water.

Environmentally compatible gasolines

Environmental authorities and legislative bodies are imposing increasingly stringent regulations for fuels to ensure low evaporation and pollutant emissions (ecologically sound fuels, reformulated gasoline). As defined in the regulations, these fuels' salient characteristics include reduced vapor pressure along with lower levels of aromatic components, benzene and sulfur, and special specifications for the final boiling point. In the USA, additives designed to prevent deposit formation in the intake tract are also mandatory.

Diesel fuels

Diesel fuels contain a multiplicity of individual hydrocarbons with boiling points ranging from roughly 180°C to 370°C.

They are the product of graduated distillation of crude oil. The refineries are adding increasing amounts of conversion products to the diesel fuel; these "cracked components" are derived from heavy oil by breaking up (cracking) large molecules. Specifications for diesel fuels are defined in national standards, while European Standard EN 590 applies throughout Europe. The most important specifications in this standard are listed in Table 2.

Ignition quality, cetane number, cetane index

Because the diesel engine dispenses with an externally-supplied ignition spark, the fuel must ignite spontaneously (auto-ignition) and with minimal delay (ignition lag) when injected into the hot, compressed air in the combustion chamber. Ignition quality is an expression of the fuel's suitability for spontaneous auto-ignition in a diesel engine. The higher the cetane number, the greater the fuel's tendency to ignite. The cetane number 100 is assigned to n-hexadecane (cetane), which ignites very easily, while slow-burning methyl naphthalene is allocated the cetane number 0. The cetane number is determined using a test engine. A cetane number in excess of 50 is desirable for optimal operation in modern engines (smooth operation, emissions). High-quality diesel fuels contain a high proportion of paraffins with elevated CN ratings. Conversely, the aromatic compounds found in cracked components have a detrimental effect on ignitability.

Yet another indication of ignitability is provided by the cetane index, which can be calculated on the basis of density and various points on the boiling curve. In contrast to the cetane number, this index does not reflect the positive influence of "ignition enhancers" on the fuel's ignitability.

Cold-flow properties, filtration

Precipitation of paraffin crystals at low temperatures can result in fuel-filter blockage, ultimately leading to interruption of the fuel flow. Under unfavorable conditions paraffin particles can start to form at temperatures of 0°C or even higher. Spe-

cial selection and manufacturing procedures are thus necessary for winter diesel fuels in order to ensure trouble-free operation during cold seasons of the year. Normally, flow improvers are added to the fuel at the refinery. Although these do not actually prevent paraffin precipitation, they severely limit the growth of the crystals, which remain small enough to pass through the pores in the filter material. Other additives can be used to maintain the crystals in a state of suspension, extending the filtration limit downward even further.

Suitability for cold-weather operation is defined with reference to a standardized procedure for determining the "limit of filtration". This is known as the CFPP, or Cold Filter Plugging Point. European Standard EN 590 defines CFPPs for various classes. Individual classes are then selected according to the country and season (summer/winter) in which the fuel is to be used.

At one time owners frequently improved the cold response of diesel fuel by adding kerosene or regular gasoline to the contents of their vehicles' fuel tanks. Fuels conforming to modern standards have rendered this measure unnecessary, and it is no longer recommended by vehicle manufacturers.

Flash point

The flash point is the temperature at which the quantities of vapor which a combustible fluid emits into the atmosphere are sufficient to allow a spark to ignite the vapor-air mixture above the fluid. Safety considerations (transport, storage) dictate that diesel fuels must meet the requirements for Class A III (flash point $> 55^{\circ}\text{C}$). Less than 3% gasoline in the diesel fuel is sufficient to lower the flash point to such an extent that ignition becomes possible at room temperature.

Boiling range

The boiling range affects several parameters of major importance in determining the diesel fuel's operating characteristics. Extending the boiling range downward to embrace lower temperatures improves the fuel's cold-operation properties, but at the price of a reduction in the cetane num-

ber. Particularly critical is the negative effect on the fuel's lubrication properties, with the attendant increase in the risk of wear to injection-system components. In contrast, raising the final temperature at the upper end of the boiling range, although desirable from the standpoint of efficient utilization of petroleum resources, also results in higher soot emissions as well as carbon deposits (combustion residue) in the injection nozzles.

Density

There is a reasonably constant correspondence between a diesel fuel's calorific value and its density; higher densities have a higher calorific value. Assuming constant injection-pump settings (and thus constant injection volume), the use of fuels with widely differing densities in a given system will be accompanied by variations in mixture ratios stemming from fluctuations in calorific value. Higher densities provoke increased particulate emissions, while lower densities lead to reductions in engine output.

Viscosity

Leakage losses in the injection pump result if viscosity is too low, and this in turn results in lower power, while on the other hand high viscosity has a detrimental effect on fuel atomization. The viscosity of diesel fuels, therefore, is limited to a narrow bandwidth.

Lubricity

The hydrodynamic lubricity of diesel fuels is not as important as that in the mixed-friction range. The introduction of environmentally compatible, hydrogenation-desulfurized fuels resulted in huge wear problems with distributor injection pumps in the field. Lubricity enhancers have to be added to the fuel to avoid these problems. Lubricity is tested using a high-frequency reciprocating rig (HFRR). Minimum lubricity is defined in EN 590.

Sulfur

Diesel fuels contain chemically bonded sulfur, with the actual quantities depending upon the quality of the crude petroleum and the components which are added at the refinery. Cracked compo-

nents are generally characterized by especially high sulfur contents, but these can be reduced with hydrogen treatment at the refinery. The sulfur converted to sulfur dioxide (SO_2) during combustion in the engine is undesirable due to its environmentally harmful acidic reactions. For this reason, the legal limits placed on sulfur levels in diesel fuels have been progressively tightened in recent years. As of 1 January, 2000, the European limit is 350mg/kg. Reducing particulate mass (sulfate in the soot) is another reason why vehicles with oxidation catalytic converters require fuel with a low sulfur content. The same applies in terms of avoiding damage to the converters used for removing nitrogen from the exhaust gas (NO_x treatment). Sulfur contents < 10 ppm are desirable.

Carbon-deposit index (carbon residue)

The carbon-deposit index describes the fuel's tendency to form residues on the injection nozzles. The mechanisms of deposit formation are complex and not easily described.

The components (particularly the cracking constituents) which the diesel fuel contains at the end of vaporization exercise a not inconsiderable influence on deposit formation.

Additives

Additives, long a standard feature in gasolines, have attained increasing significance as quality improvers for diesel fuels. The various agents are generally combined in additive packages to achieve a variety of objectives. As the total concentration of the additives generally lies < 0.1 %, the fuel's physical characteristics – such as density, viscosity and boiling range – remain unchanged.

Flow improvers: Flow improvers are polymers whose application is generally restricted to winter (see Cold-flow properties).

Cetane improvers: Cetane improvers are added to promote good ignition response; they are in the form of alcohol-derived esters of azotic acid. These agents improve the fuel's combustion properties, with

positive effects upon noise and particulate emissions.

Detergent additives: Detergent additives help clean the intake system to ensure efficient mixture preparation and inhibit the formation of carbon deposits on the injection nozzles.

Corrosion inhibitors: Corrosion inhibitors resist corrosion on metallic components (when fuel-borne moisture is entrained into the system).

Anti-foaming agents: Anti-foaming agents prevent the fuel foaming, so it is easier to refuel the vehicle.

Environmentally compatible diesel fuels

Some countries and regions (including Sweden and California) are promoting reductions in exhaust emissions by providing fiscal incentives for the use of "ecologically sound/environmentally compatible" fuels and/or making their use mandatory. In these fuels the final boiling point and the aromatic content are reduced, while sulfur is virtually eliminated. Introduction of these fuels was accompanied by serious problems stemming from component wear and elastomer damage in fuel-injection systems. Special additives are required to prevent this type of damage.

Alternative fuels

Coal hydrogenation

The essential raw materials are coal and coke. These emerge from initial processing in the form of water gas ($\text{H}_2 + \text{CO}$), while subsequent catalytic conversion produces hydrocarbons. These, in turn, provide the basic materials for the production of gasoline and diesel fuel. The byproducts are liquefied petroleum gas (LPG) and paraffin. Fischer-Tropsch synthesis has acquired particular significance in South Africa, where it is in widespread use in large industrial installations.

Properties of liquid fuels and hydrocarbons

Substance	Density kg/l	Main constituent % by weight	Boiling temperature °C	Latent heat of evaporation kJ/kg ¹⁾	Specific calorific value MJ/kg ¹⁾	Ignition tempera- ture °C	Theoretical air requirement kg/kg	Ignition limit Lower Upper % by vol. of gas in air
Spark-ignition engine fuel, Regular	0.715...0.765	86 C, 14 H	25...215	380...500	42.7	≈ 300	14.8	≈ 0.6 ≈ 8
Premium	0.730...0.780	86 C, 14 H	25...215	—	43.5	≈ 400	14.7	— ≈ 8
Aviation fuel	0.720	85 C, 15 H	40...180	—	43.5	≈ 500	—	≈ 0.7 ≈ 8
Kerosene	0.77...0.83	87 C, 13 H	170...260	—	43	≈ 250	14.5	≈ 0.6 ≈ 7.5
Diesel fuel	0.815...0.855	86 C, 13 H	180...360	≈ 250	42.5	≈ 250	14.5	≈ 0.6 ≈ 7.5
Crude oil	0.70...1.0	80...83 C, 10...14 H	25...360	222...352	39.8...46.1	≈ 220	—	≈ 0.6 ≈ 6.5
Lignite tar oil	0.850...0.90	84 C, 11 H	200...360	—	40.2...41.9	—	13.5	— —
Bituminous coal oil	1.0...1.10	89 C, 7 H	170...330	—	36.4...38.5	—	—	— —
Pentane C ₅ H ₁₂	0.63	83 C, 17 H	36	352	45.4	285	15.4	1.4 7.8
Hexane C ₆ H ₁₄	0.66	84 C, 16 H	69	331	44.7	240	15.2	1.2 7.4
n-Heptane C ₇ H ₁₆	0.68	84 C, 16 H	98	310	44.4	220	15.2	1.1 6.7
Iso-octane C ₈ H ₁₈	0.69	84 C, 16 H	99	297	44.6	410	15.2	1 6
Benzene C ₆ H ₆	0.88	92 C, 8 H	80	394	40.2	550	13.3	1.2 8
Toluene C ₇ H ₈	0.87	91 C, 9 H	110	364	40.6	530	13.4	1.2 7
Xylene C ₈ H ₁₀	0.88	91 C, 9 H	144	339	40.6	460	13.7	1 7.6
Ether (C ₂ H ₅) ₂ O	0.72	64 C, 14 H, 22 O	35	377	34.3	170	7.7	1.7 36
Acetone (CH ₃) ₂ CO	0.79	62 C, 10 C, 28 O	56	523	28.5	540	9.4	2.5 13
Ethanol C ₂ H ₅ OH	0.79	52 C, 13 H, 35 O	78	904	26.8	420	9	3.5 15
Methanol CH ₃ OH	0.79	38 C, 12 H, 50 O	65	1110	19.7	450	6.4	5.5 26

Viscosity at 20 °C in mm²/s (= cSt, P. 27): gasoline = 0.6; diesel fuel = 4; ethanol = 1.5; methanol 0.75.

¹⁾ Values per l = values per kg x density in kg/l. See P. 25 for conversion tables.

Properties of gaseous fuels and hydrocarbons

Substance	Density at 0°C and 1013 mbar kg/m ³	Main constituents % by weight	Boiling temp. at 1013 mbar °C	Specific calorific value		Ignition temperature °C	Theoretical air requirement kg/kg	Ignition limit	
				Fuel MJ/kg ¹⁾	A/F mixture MJ/m ³ ¹⁾			Lower	Upper
Liquefied gas	2.25 ²⁾	C ₃ H ₈ , C ₄ H ₁₀ 50 H, 8 CO, 30 CH ₄ 76 C, 24 H	-30 -210 -162	46.1 ≈ 30 47.7	3.39 ≈ 3.25 —	≈ 400 ≈ 560 —	15.5 10 —	1.5 4 —	15 40 —
Municipal gas	0.56...0.61 ≈ 0.83								
Natural gas	—								
Water gas	0.71	50 H, 38 CO 28 CO, 59 N, 12 CO ₂ 46 CH ₄ , 54 CO ₂	— -170 —	15.1 3.20 27.2 ³⁾	3.10 1.88 3.22	≈ 600 ≈ 600 —	4.3 0.75 —	6 ≈ 30 —	72 ≈ 75 —
Blast-furnace gas	1.28								
Sewage gas) ³⁾	—								
Hydrogen	0.090	100 H	-253	120.0	2.97	560	34	4	77
Carbon monoxide	1.25	100 CO	-191	10.05	3.48	605	2.5	12.5	75
Methane	0.72	75 C, 25 H	-162	50.0	3.22	650	17.2	5	15
Acetylene	1.17	93 C, 7 H 80 C, 20 H 86 C, 14 H	-81 -88 -102	48.1 47.5 14.1	4.38 — —	305 515 425	13.25 17.3 14.7	1.5 3 2.75	80 14 34
Ethane	1.36								
Ethene	1.26								
Propane	2.0 ²⁾	82 C, 18 H 86 C, 14 H 83 C, 17 H 86 C, 14 H 52 C, 13 H, 35 O	-43 -47 -10; +1 ⁴⁾ -5; +1 ⁴⁾ -25	46.3 45.8 45.6 45.2 28.8	3.35 — 3.39 — 3.43	470 450 365 — 235	15.6 14.7 15.4 14.8 9.0	1.9 2 1.5 1.7 3.4	9.5 11 8.5 9 18.6
Propene	1.92								
Butane	2.7 ²⁾								
Di-	2.5								
methyl ether	2.05 ⁵⁾								

1) Values per m³ = values per kg x density in kg/m³. See P. 25 for conversion tables.
2) Density of liquefied gas 0.54 kg/l, density of liquefied propane 0.51 kg/l, density of liquefied butane 0.58 kg/l.
3) Purified sewage gas contains 95% CH₄ (methane) and has a heating value of 37.7 MJ/kg.
4) First value for isobutane, second value for n-butane or n-butene.
5) Density of liquefied dimethylether: 0.667 kg/l.

Table 2. Essential data for diesel fuels, European Standard EN 590 (valid since 1 January 2000)

Requirements	Unit	Specification
Flame point, min.	°C	55
Water, max.	mg/kg	200
Sulfur content, max.	mg/kg	350
Lubricity, "wear scardiameter" max.	µm	460
For temperate climates:		
Density (at 15 °C), min./max.	kg/m³	820/845
Viscosity (at 40 °C), min./max.	mm²/s	2/4.5
Cetane number, min.	–	51
Cetane index, min.	–	46
up to 250 °C, distilled, max.	% volume	65
up to 350 °C, distilled, min.	% volume	85
up to 360 °C, distilled, min.	% volume	95
CFPP¹) in 6 classes A...F, max.	°C	+5 ... –20
For arctic climates (in 5 classes 0 ... 4):		
Density (at 15 °C), min./max.	kg/m³	800/845 ... 800/840
Viscosity (at 40 °C), min./max.	mm²/s	1.5/4 ... 1.2/4
Cetane number, min.	–	49 ... 47
Cetane index, min.	–	46 ... 43
up to 180 °C, distilled, max.	% volume	10
up to 340 °C, distilled, min.	% volume	95
CFPP¹), max.	°C	–20 ... –44

¹) Filtration limit.

Liquefied Petroleum Gas (LPG)

The two major components of LPG are butane and propane. It is in limited use as a fuel for motor vehicles. LPG is a byproduct of the petroleum-refining process, and can be liquefied under pressure. LPG is distinguished by a high octane number (RON >100).

CNG (Compressed Natural Gas)

This usually assumes the form of compressed methane, and is suitable for obtaining ultra-low emissions from combustion engines. Due to its high H/C ratio (relative to other fuels), CNG also produces less CO₂. CNG is being tested in both diesel and spark-ignition engines. Soot production is virtually zero when this fuel is combusted in the diesel cycle. The vehicles must be specially adapted for operation on this type of alternative fuel.

Alcohol fuels

Methanol, ethanol, and their various byproducts (e.g. ether) are the main contenders as alternative fuels for spark-ignition

engines, being the focus of both discussion and actual application. Methanol can be derived from the plentiful hydrocarbon reserves represented by coal, natural gas, and heavy oils, etc. In certain countries (such as Brazil, but also in the USA), biomass (sugar cane, wheat) is distilled to produce ethanol for use as an engine fuel and fuel additive.

Methanol additives ≤3 % by volume are permissible in many countries. Methanol, however, should be used only in conjunction with solubilizers. Fuels with higher concentrations (15...85 %) have been subjected to large-scale testing (flexible fuel).

Ethanol fuel mixtures are commercially available in countries with high agricultural yield (e.g. E22 in Brazil).

Both calorific value and other factors differ from those of conventional fuels, so special vehicle modifications are sometimes required.

Dimethylether (DME)

This is a synthetic product with a high

cetane number, producing little soot and reduced nitrogen oxide when combusted in diesel engines. Its calorific value is low, on account of its low density and high oxygen content. It is a gas-phase fuel, so the fuel-injection equipment has to be modified. Other ethers (dimethoxymethane, di-n-pentylether, and others) are also being tested.

Emulsions

Emulsions of water and alcohols in diesel fuels are undergoing testing by a number of different institutes. Water and alcohols (particularly methanol) are difficult or impossible to mix with diesel. Emulsifiers are required to keep the mixture stable and prevent it from de-emulsifying. Corrosion-inhibiting measures are also necessary. Soot and nitrogen-oxide emissions can be reduced by these emulsions, but to date their use has been restricted to certain fleet applications; there has been no broad-based testing for a variety of injection systems.

Fatty-acid methyl ester (FAME)

Fatty-acid methyl ester is the generic term applied to all vegetable and animal oils and greases transesterified with methanol, including rapeseed (RME), soy, and sunflower methyl esters, among others. The use of vegetable oils for combustion in diesel engines is a field of investigation because it would allow agricultural areas to be used for the production of regenerative energy. Considerable problems arise with pure vegetable oils, due to their high viscosity and severe tendency to cause nozzle coking; oils transesterified with methanol are free of these difficulties.

Fatty-acid methyl esters are used in pure form and as additives for diesel fuel ($\leq 5\%$). In concentrations as low as 1...2% they boost the lubricity of the fuels. A definitive standard for these substances is now in preparation. This standard will have to lay down characteristics, stability and maximum permissible contaminants in order to ensure trouble-free operation of the injection equipment and engines. FAME fuels are uneconomical in comparison with conventional fuels and their use will require subsidization.

Antifreeze and brake fluid

Brake fluids

Brake fluid is the hydraulic medium employed to transmit actuation forces within the braking system. Compliance with stringent requirements is essential to ensure reliable brake-system operation. These requirements are defined in various standards of similar content (SAE J 1703, FMVSS 116, ISO 4925). The performance data contained in FMVSS 116 (Federal Motor Vehicle Safety Standard), mandatory in the US, also serve as an international reference. The US Department of Transportation (DOT) has defined specific ratings for salient characteristics (Table 1).

Requirements

Equilibrium boiling point

The equilibrium boiling point provides an index of the brake fluid's resistance to thermal stress. The heat encountered in the wheel cylinders (with the highest temperatures in the entire braking system) can be especially critical. Vapor bubbles can form at temperatures above the brake fluid's instantaneous boiling point, resulting in brake failure.

Wet boiling point

The wet boiling point is the fluid's equilibrium boiling point subsequent to moisture absorption under specified conditions (approx. 3.5%). Hygroscopic (glycol-based) fluids respond with an especially pronounced drop in boiling point. The wet boiling point is tested to quantify the response characteristics of used brake fluid. Brake fluid absorbs moisture, mostly by diffusion through brake-system hoses. This is the main reason why it should be replaced every 1...2 years. The illustration shows the reductions in boiling point that result from moisture absorption in two different brake fluids.

Table 1. Brake fluids

Reference standard for testing	FMVSS 116			SAE J1703
Requirements/Date	DOT3	DOT4	DOT5	Nov. 1983
Dry boiling point min. °C	205	230	260	205
Wet boiling point min. °C	140	155	180	140
Cold viscosity at -40 °C mm ² /s	1500	1800	900	1800

Viscosity

To ensure consistent reliability throughout the braking system's extended operating range (-40 °C...+100 °C), the viscosity should remain as constant as possible, with minimal sensitivity to temperature variations. Maintaining the lowest possible viscosity at very low temperatures is especially important in ABS/TCS/ESP systems.

Compressibility

The fluid should maintain a consistently low level of compressibility with minimal sensitivity to temperature fluctuations.

Corrosion protection

FMVSS 116 stipulates that brake fluids shall exercise no corrosive effect on those metals generally employed in braking systems. The required corrosion protection can be achieved only by using additives.

Elastomer swelling

The elastomers employed in a particular brake system must be able to adapt to the type of brake fluid being used. Although a small amount of swelling is desirable, it is imperative that it not exceed approximately 10%. Otherwise, it has a negative effect on the strength of the elastomer components. Even minute levels of mineral-oil contamination (such as mineral-oil-based brake fluid, solvents) in glycol-based brake fluid can lead to destruction of rubber components (such as seals) and ultimately lead to brake-system failure.

Chemical composition

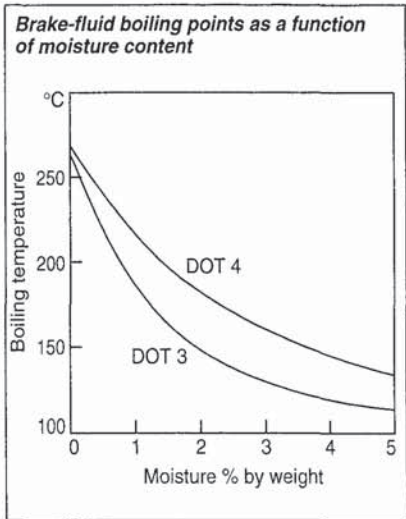
Glycol-ether fluids

Most brake fluids are based on glycol-ether compounds. These generally consist of monoethers of low polyethylene glycols. Although these components can be used to produce a brake fluid which conforms to the DOT 3 requirements, their undesirable hygroscopic properties cause this fluid to absorb moisture at a relatively rapid rate, with an attendant swift reduction in the boiling point.

If the free OH (hydroxyl) groups are partially esterified with boric acid, the result is a superior DOT 4 (or "DOT4+", "Super DOT4", "DOT5.1") brake fluid capable of reacting with moisture to neutralize its effects. As the DOT 4 brake fluid's boiling point drops much more slowly than that of a DOT 3 fluid, its service life is longer.

Mineral-oil fluids (ISO 7308)

The great advantage of mineral-oil-based fluids is the fact that they are not hygroscopic, so the boiling point does not drop owing to moisture absorption. The mineral and synthetic oils for this fluid must be selected with utmost care. Viscosity-index improvers are generally added to



achieve the desired relationship between viscosity and temperature.

The petroleum industry can also supply a range of further additives to improve other brake-fluid properties. It should be noted that mineral-oil-based fluids should never be added to braking systems designed for glycol ether (or vice versa), as this destroys the elastomers.

Silicone fluids (SAE J1705)

Because silicone fluids – like mineral oils – do not absorb moisture, they formerly saw occasional use as brake fluids. The disadvantages of these products include considerably higher compressibility and inferior lubrication, both of which reduce their suitability for use as hydraulic fluid in many systems. A critical factor with brake fluids based on silicone or mineral oils is the absorption of free water in a fluid state, as the water forms vapor bubbles when it heats up to more than 100°C and freezes when it cools to less than 0°C.

Coolants

Requirements

The cooling system must dissipate that part of the engine's combustion heat that is not converted into mechanical energy. A fluid-filled cooling circuit transfers the heat absorbed in the cylinder head to a heat exchanger (radiator) for dispersal into the air. The fluid in this circuit is exposed to extreme thermal loads; it must also be formulated to ensure that it does not attack the materials within the cooling system (corrosion).

Owing to its high specific heat and its correspondingly substantial thermal-absorption capacity, water is a very good cooling medium. Its disadvantages include its corrosive properties and limited suitability for application in cold conditions (freezing).

This is why additives must be mixed with the water for satisfactory performance.

Table 2. Ice flaking and boiling points for water-glycol mixtures

Glycol Vol. %	Ice flaking point °C	Boiling point °C
10	-4	101
20	-9	102
30	-17	104
40	-26	106
50	-39	108

Antifreeze

It is possible to lower the coolant's freezing point by adding ethylene glycol. When glycol is added to form a mixture with water the resulting coolant no longer freezes at a given temperature. Instead, ice crystals are precipitated in the fluid once the temperature drops to the flaking point. At this temperature the fluid medium can still be pumped through the cooling circuit. Glycol also raises the coolant's boiling point (Table 2).

In their owner's manuals automobile manufacturers usually specify various optional antifreeze mixture ratios for different levels of low-temperature frost protection.

Additives

Coolants must include effective additives to protect the glycol against oxidation (with formation of extremely corrosive byproducts) and to protect metallic cooling-system components against corrosion. Common additives include:

- Corrosion inhibitors: silicates, nitrates, nitrites, metal salts of organic acids, benzthiazole derivatives,
- Buffers: borates,
- Antifoaming agents: silicones.

Many of these additives are subject to aging deterioration, leading to a gradual reduction in coolant performance. The manufacturers have responded to this fact by granting official approval exclusively for coolants of proven long-term stability.

Names of chemicals

Hazard codes: E = explosive, O = flammable, F = readily flammable, F₊ = highly flammable, C = caustic, X_n = slightly toxic, X_i = irritant, T = toxic, T₊ = highly toxic.

Commercial name English (hazard code)	German	French	Chemical name	Chemical formula
(Glacial) acetic acid (C) Acetic ether; vinegar naphtha (F) Aerosil (fumed silica)	Eisessig (Essigessenz) Essigester (Essigäther) Aerosil ₁	Acide acétique glacial Ether acétique	Acetic acid Ethylacetate Silicon dioxide in extremely fine particles	CH ₃ COOH CH ₃ COOC ₂ H ₅ SiO ₂
Ammonia liquor (X _n , C)	Salmiakgeist	Ammoniaque hydroxide	Aqueous solution of ammonium hydroxide	NH ₄ OH in H ₂ O
Anon; pimelic ketone (X _n) Aqua fortis (C)	Anon Scheidewasser	Anone Eau forte	Cyclohexanone Nitric acid (50 % aqueous solution)	C ₆ H ₁₀ O HNO ₃ in H ₂ O
Aqua regia (C, T ₊)	Königswasser	Eau régale	Mixture of nitric acid and hydrochloric acid	HNO ₃ + HCl (1 + 3)
Bitter almond oil (T) Bleach (C) Chloride of lime Blue vitriol Borax (tincal) Butoxyl [®] Butter of tin (C)	Bittermandelöl Chlorkalk Kupfervitrol Borax (Tinkal) Butoxyl [®] Zinnbutter	Essence d'amandes amères Chlorure de chaux Vitriol bleu Borax (tincal) Beurre d'étain	Benzaldehyde Calciumchloride-hypochlorite Copper sulphate pentahydrate Sodium tetraborate (3-methoxybutyl) acetate Tin tetrachloride	C ₆ H ₅ CHO Ca(OCl)Cl CuSO ₄ · 5H ₂ O Na ₂ B ₄ O ₇ · 10H ₂ O CH ₃ COO(CH ₂) ₂ CH(OCH ₃)CH ₃ SnCl ₄ · 5H ₂ O
Calcium carbide (F) Calomel (X _n) Carbitol acetate ^{™ 1)} Carbitol ^{™ 1)} (solvent)	Karbid Kalomel Carbitolacetat [®] Carbitol [®] , Dioxitol [®]	Carbure de calcium Calomel Carbitol	Calcium carbide Mercury(II) chloride Diethylene glycol ethylether acetate Diethylene glycol monoethylether	CaC ₂ Hg ₂ Cl ₂ CH ₃ COOCH ₂ CH ₂ OCH ₂ CH ₂ OC ₂ H ₅ HOCH ₂ CH ₂ OCH ₂ CH ₂ OC ₂ H ₅

Carbolic acid (T) Caustic potash (C) Caustic soda (C) Cellosolve™ ¹⁾ (solvent) Cellosolve™ ¹⁾ acetate	Karbonsäure Ätzkali Ätznatron Cellosolve®, Oxitol® Cellosolveacetat®	Acide carbolique Potasse caustique Soude caustique	Phenol Potassium hydroxide Sodium hydroxide Ethylene glycol monoethylether Ethylene glycol ethylether acetate Calcium carbonate Sodium salt of the p-toluene- sulfonic acid chloroamide 2-chloro 1,3-butadiene 1,1,1-trichloroethane	C ₆ H ₅ OH KOH NaOH HOCH ₂ CH ₂ OC ₂ H ₅ CH ₃ COOCH ₂ CH ₂ OC ₂ H ₅ CaCO ₃ Na[CH ₃ C ₆ H ₄ SO ₂ NCI] · 3H ₂ O CH ₂ =CCICH=CH ₂ Cl ₃ CCH ₃
Chalk Chloramine-T (X) Chloroprene (F, X _n) Chlorothene™ ¹⁾ ; ("1,1,1"); (X _n) Methylchloroform	Kreide Chloramin T Chloropren Chlorothene® Methylchloroform	Craie Chloramine-T Chloroprène Chlorothène	Calcium carbonate Sodium salt of the p-toluene- sulfonic acid chloroamide 2-chloro 1,3-butadiene 1,1,1-trichloroethane	CaCO ₃ Na[CH ₃ C ₆ H ₄ SO ₂ NCI] · 3H ₂ O CH ₂ =CCICH=CH ₂ Cl ₃ CCH ₃
Chromic anhydride (C, O, X) Cinnabar Colophony; rosin Corrosive sublimate (T) Cryolite (X _n)	Chromsäure Zinnober Kolophonium Sublimat Kryolith	Anhydride chromique Cinabre; vermillon Colophane Sublimé corrosif Cryolite	Chromium trioxide (chromic acid anhydride) Mercury (II) sulfide Naturally occurring abietic acid Mercury (II) chloride Sodium hexafluoroaluminate	CrO ₃ HgS C ₁₉ H ₂₉ COOH HgCl ₂ Na ₃ [AlF ₆]
Decalin Diane Diisobutylene (F) DMF (X _n) DMSO Dry ice	Dekalin Bisphenol A; Diphenylolpropan Diisobutylen DMF DMSO Trockeneis	Décaline Diisobutylène DMF DMSO Carboglace	Decahydro naphthalene Dihydroxyphenyl propane-2,2 2,4,4-trimethyl pentenes 1 and 2 N,N-dimethyl formamide Dimethyl sulfoxide (Solid) carbon dioxide	C ₁₀ H ₁₈ (CH ₃) ₂ C(C ₆ H ₄ (OH)-4) ₂ (CH ₃) ₃ CCH ₂ C(CH ₃)=CH ₂ and (CH ₃) ₃ C-CH=C(CH ₃) ₂ HCON(CH ₃) ₂ (CH ₃) ₂ SO CO ₂
English red Epsomite, bitter salt	Polierrot Bittersalz (Magnesiumvitriol)	Rouge d'Angleterre Epsomite	Iron (III) oxide Magnesium sulfate	Fe ₂ O ₃ MgSO ₄ · 7H ₂ O

¹⁾ methyl-, propyl-, i-propyl-, butyl-c.: names for analogous ethers containing the above mentioned groups instead of ethyl-.

Names of chemicals (continued)

Commercial name		French	Chemical name	Chemical formula
English	German			
Fixing salt; (hypo) Fluorspar; fluorite Formalin (T) Freon™(es)	Fixiersalz ("Antichlor") Flußspat; Fluorit Formalin® Freon®(e); Frigen®(e)	Sel fixateur Spath fluor; fluorine Formol Fréon(es); Frigène(s)	Sodium thiosulfate Calcium fluoride Aqueous solution of formaldehyde Compounds of C, H, F, Cl, (Br)	$\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ CaF_2 H_2CO in H_2O Numerical characterization ²⁾
	Glauber's salt; mirabilite Glycol (X) Golden antimony sulphide Green vitriol	Sel de Glauber Glycol Sulfre doré d'antimoine Vitriol vert; couperose verte	Sodium sulphate 1,2-ethanediol Antimony (V)-sulfide Iron (II) sulfate	$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ $\text{HOCH}_2\text{CH}_2\text{OH}$ Sb_2S_5 $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$
Halone(s) Halon™ Halothane Hartshorn salt Hexalin Hexone (F) Hydrochloric acid (C) Hydrofluoric acid (T, C) Hydrogen peroxyde	Halon(e) Halon® Halothan Hirschhornsalz Hexalin® Hexon; MIBK Salzsäure Flußsäure Perhydrol®	Halon(s) Sel volatil d'Angleterre Hexaline Esprit de sel (Acide fluorhydrique) Eau oxygénée	Compounds of C, F, Cl, Br Polymer from tetrafluorethylene 2-bromine 2-chlorine 1,1,1-tetrafluoroethane Ammonium hydrogen carbonate + ammonium carbonate Cyclohexanol (also: hexahydronaphthalene) 4-methylpentanone 2 (Methylisobutylketon) Aqueous solution of hydrogen chloride Aqueous solution of hydrogen fluoride Hydrogen dioxide	Numerical characterization ³⁾ $(\text{C}_2\text{F}_4)_n$ $\text{F}_3\text{CCHClBr}$ $(\text{NH}_4)\text{HCO}_3 + (\text{NH}_4)_2\text{CO}_3$ $\text{C}_6\text{H}_{11}\text{OH}$ $(\text{C}_{10}\text{H}_{18})$ $(\text{CH}_3)_2\text{CHCH}_2\text{COCH}_3$ HCl in H_2O HF in H_2O H_2O_2
Laughing gas (O) Lead sugar (X ₆)	Lachgas ("Stickoxydul") Bleizucker	Gaz hilarant Sel de Saturne	Nitrous oxide Lead acetate	N_2O $\text{Pb}(\text{CH}_3\text{COO}) \cdot 3\text{H}_2\text{O}$

Lead vinegar (X _n)	Bleissig	Eau blanche; vinaigre de plomb	Aqueous solution of lead acetate and lead hydroxide	Pb(CH ₃ COO) ₂ · Pb(OH) ₂
Libavius' fuming spirit (C)	Spiritus fumans Libavii		Tin (IV) chloride	SnCl ₄
Lime saltpeter	Salpeter, Kalk-; Norge-	Salpêtre	Calcium nitrate	Ca(NO ₃) ₂ · 4H ₂ O
Liquid gas (F)	Flussiggas	Gaz liquéfié	Propane, isobutane, n-butane	C ₃ H ₈ + C ₄ H ₁₀
Lunar caustic (C)	Höllenstein; "lapis infernalis"	Pierre infernale	Silver nitrate	AgNO ₃
Marble	Marmor	Marbre	Calcium carbonate	CaCO ₃
Microcosmic salt	Phosphorsalz		Sodium ammonium hydrogenphosphate	NH ₄ NaHPO ₄ · 4H ₂ O
Mine gas (F)	Grubengas; Sumpfgas	Grisou; gaz des marais	Methane	CH ₄
Minium	Mennige	Minium	Lead (II) orthoplumbate	Pb ₃ O ₄ (Pb ₂ PbO ₄)
Mohr's salt	Mohr'sches Salz	Sel de Mohr	Iron (II) ammonium sulfate	(NH ₄) ₂ [Fe(SO ₄) ₂] · 6H ₂ O
Mordant rouge; mordant salt ⁴⁾	Tonerde, essigsäure Meta®	Mordant d'alun	Basic aluminium acetate	(CH ₃ COO) ₂ AlOH
Mota (X _n)		Alcool solidifié	Tetramethyltetraoxacyclooctane (metaldéhyde)	(CHCHCH ₃) ₄ O ₄
Muthmann's liquid	Muthmann's Flüssigkeit		1.1.2.2-tetrabromethane	Br ₂ CHCHBr ₂
Nitroglycerin (E, F)	Nitroglycerin	Nitroglycérine	Glycerol trinitrate	CHONO ₂ (CH ₂ ONO ₂) ₂
Nitrolim; lime nitrogen	Kalkstickstoff	Chaux azotée	Calcium cyanamide	CaCN ₂
Norway saltpeter	Salpeter, Ammon-	Nitrate d'ammonium	Ammonium nitrate	NH ₄ NO ₃

²⁾ Numerical codes for freons (fluorine-chlorine derivatives of methane and ethane, CH₄ and C₂H₆):

Number in hundreds column = number of carbon atoms - 1
Number in tens column = number of hydrogen atoms + 1
Number in ones column = number of fluorine atoms

The missing atoms for valence saturation are chlorine atoms. Examples: F 113 = C₂F₃Cl₃; F 21 = CHFCl₂

³⁾ Numerical codes for halones (fully halogenated hydrocarbons):

Number in thousands column = number of C atoms
Number in hundreds column = number of F atoms
Number in tens column = number of Cl atoms
Number in ones column = number of Br atoms

Examples: halone 1211 = CF₂ClBr; halone 2402 = C₂F₄Br₂

⁴⁾ Mordanting agent, for instance for dyeing textiles red. See Hawley's Condensed Chemical Dictionary, 11th ed. 1987, "Aluminium acetate".

Names of chemicals (continued)

Commercial name		German	French	Chemical name	Chemical formula
English					
Oleum (C)		Oleum ("Vitriolöl")	Oléum	Sulfuric acid + disulfuric acid	$H_2SO_4 + H_2S_2O_7$
Oxalic acid (X_n)		Kleesäure	Acide oxalique	Oxalic acid	$(COOH)_2 \cdot 2H_2O$
Phosgene (T) Phosphine (T_+) Picric acid (T, E) Potash Potash alum Potassium chlorate (O, X_n) Potassium metabisulphite Pyrolusite (X_n)		Phosgen Phosphin Pikrinsäure Pottasche Alaun, Kali- Knallsalz Kaliummetabisulfit Braunstein	Phosgène Phosphine (sel de phosphore) Acide picrique Potasse Alun de potassium Sel de Berthollet Métabisulfite de potassium Pyrolusite	Carbonic acid dichloride Hydrogen phosphide 2,4,6-trinitrophenole Potassium carbonate Potassium aluminum sulfate Potassium chlorate potassium disulfite Manganese dioxide	$COCl_2$ PH_3 $C_6H_2(NO_2)_3OH$ K_2CO_3 $KAl(SO_4)_2 \cdot 12H_2O$ $KClO_3$ $K_2S_2O_5$ MnO_2
Quicklime; burnt lime; caustic lime Red prussiate of potash Rochelle salt; salt of Seignette		Kalk, gebrannter Blutlaugensalz, rotes; Kaliumferricyanid Seignettesalz (Natronweinstein)	Chaux vive Ferricyanure de potassium Sel de Seignette	Calcium oxide Potassium hexacyanoferrate (III) potassium sodium tartrate	CaO $K_3[Fe(CN)_6]$ $(CHOH)_2COOKCOONa$
Sal ammoniac (X_n) Saltpeter Silica gel with indicator Slaked lime Soda crystals Soda niter; Chile saltpeter		Salmiak (Salmiaksalz) Natronsalpeter Salpeter, Kali- Blaugel (Silicagel) Kalk, gelöschter Soda (Kristall-) Salpeter, Chile;	salmiac Salpêtre Gel bleu Chaux éteinte Soude (cristaux de) Salpêtre du Chili	Ammonium chloride Potassium nitrate Porous silicon dioxide with humidity indicator Calcium hydroxide Sodium carbonate Sodium nitrate	NH_4Cl KNO_3 SiO_2 with cobalt compound $Ca(OH)_2$ $Na_2CO_3 \cdot 10H_2O$ $NaNO_3$

Sorrel salt; potassium binoxalate Sulphuric ether (F) Tetrachloroethylene (X _n) Tetrachloromethane (T)	Kleesalz Schwefelether Per Tetra ("Tetraform")	Sel d'oseille Ether sulfurique Tétrachloroéthylène Tetrachlorométhane	Potassium tetraoxalate Diethyl ether Tetrachloroethylene (perchloroethylene) Perchloromethane	(HOCCOOK) · (COOH) ₂ · 2H ₂ O C ₂ H ₅ OC ₂ H ₅ Cl ₂ C=CCl ₂ CCl ₄
Tetralin (O, C) Tin foil Tin salt TNT; trotyl (E) Trichloroethylene (X _n)	Tetralin Stanniol Zinnsalz TNT Tri	Tétraline Papier d'étain Sel d'étain TNT; tolite Trichloréthylène	1.2.3.4-tetrahydronaphthalene Foil tin Tin (II) chloride 2.4.6-trinitro toluene Trichlorethene	C ₁₀ H ₁₂ Sn SnCl ₂ · 2H ₂ O C ₆ H ₂ (NO ₂) ₃ CH ₃ Cl ₂ C=CHCl
Urea Urotropine Vichy salt; baking soda	Harnstoff Urotropin Bullrichsalz®; Natron (Natriumbicarbonat)	Urée Urotropine Sel de Vichy	Carbonic acid diamide 1.3.5.7-Tetra acadamantane Sodium hydrogen carbonate	CO(NH ₂) ₂ (CH ₂) ₆ N ₄ NaHCO ₃
Waterglass Yellow prussiate of potash	Wasserglas (Kali- bzw. Natron-) Blutlaugensalz, gelbes; Kaliumferrocyanid GB-Ester; Polysolvan O®	Verre soluble Ferrocyanure de potassium	Aqueous solution of potassium or sodium silicates Potassium hexacyanoferrate (II) Glycol acid butyl ester (hydroxic acetic acid butylester)	M ₂ SiO ₃ + M ₂ Si ₂ O ₅ (M = K or Na) K ₄ [Fe(CN) ₆] HOCH ₂ COOC ₄ H ₁₀

Corrosion and corrosion protection

Corrosion is the attrition of metal as a result of electrochemical reactions with substances in the environment. As it proceeds, metal atoms oxidize to form non-metallic compounds in a process emanating from the affected material's surface. In thermodynamic terms, the process can be viewed as an entropic transition from an ordered, high-energy state into a less-ordered state of lower energy and consequently greater stability.

Corrosion processes are always inter-phase reactions. An example of this type of reaction is metal scaling, i.e. oxidation in hot gases. The following deals exclusively with the corrosion that occurs at the phase limit between the metal and aqueous phases, generally referred to as electrochemical corrosion.

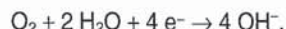
Corrosive attack

Two distinct reactions occur in every corrosive attack: in the anodic subprocess – the directly visible corrosive effect – the difference in respective potentials causes the metal to oxidize as described in the reaction equation



freeing an equivalent number of electrons. The metal ions thus formed can either be dissolved in the electrolyte, or can precipitate out on the metal after reacting with constituents in the attacking medium.

This anodic subprocess can continue only as long as the electrons it produces are consumed in a second process. This second subprocess is a cathodic subreaction in which oxygen is reduced to hydroxyl ions in neutral or alkaline media, in accordance with the reduction equation



These hydroxyl ions, in turn, are able to react with the metal ions, whereas in acidic media the hydrogen ions are reduced via the formation of free hydrogen, which escapes as a gas according to the following formula:



When two different metals moistened by the same fluid are in mutual electrical contact, the cathodic subprocess occurs at the more noble metal while the anodic subprocess progresses at the baser material. This is called contact corrosion.

However, it is also possible for both reactions to occur on the same metal in a process termed "free corrosion". Anodic and cathodic subprocesses can alternate continuously at the metal/solution interface with statistically random time and location distributions for the individual subprocesses.

Each of the individual subreactions corresponds to a partial current/voltage curve. The total current is the sum of the two currents I_a and I_c :

$$I_{\text{total}} = I_a + I_c$$

The two partial current/voltage curves combine to produce the cumulative current/voltage curve.

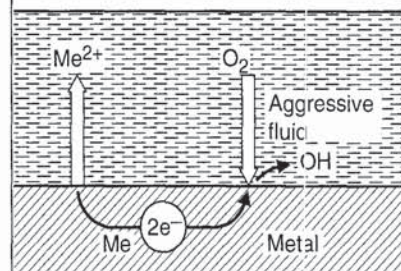
If no voltage is supplied externally, i.e., in free corrosion, the system assumes a state in which the anodic and cathodic partial currents are precisely balanced:

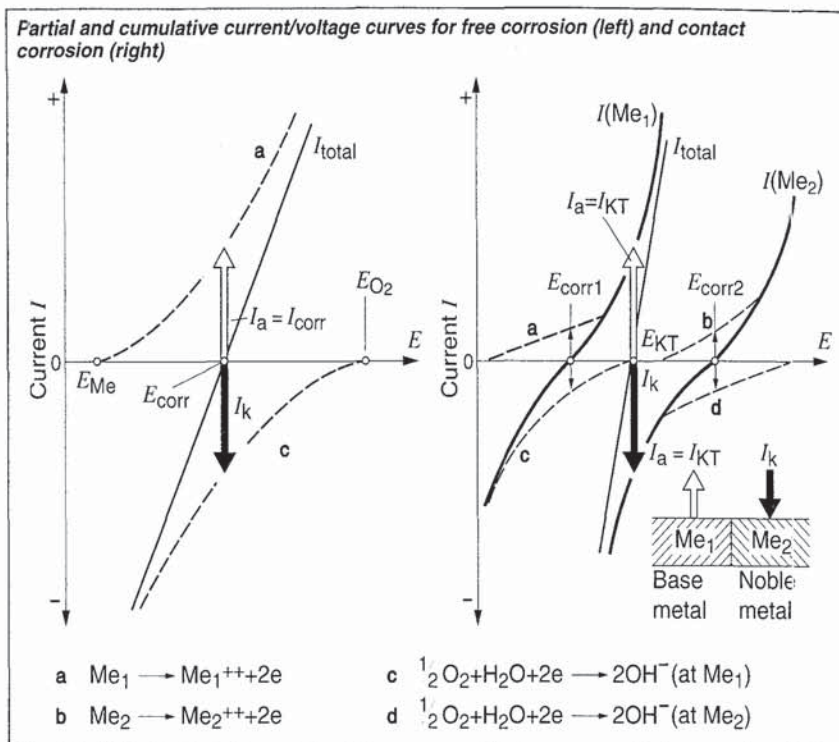
$$I_a = -I_c = I_{\text{corr}}$$

The anodic current is called the corrosion current I_{corr} , while the corresponding potential at which this current compensation

Free corrosion at the metal/corrosive-medium phase boundary

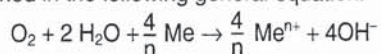
In an aggressive fluid, oxygen is reduced at the corroding metal and corrosion products are simultaneously formed.





occurs is called the "open-circuit potential" E_{corr} .

The open-circuit potential is a mixed potential in which there is no equilibrium; matter is converted continuously, as defined in the following general equation:



The above is essentially applicable for contact corrosion, although the interrelationships are more complicated. In addition to pairs of partial current/voltage curves for each of the two metals and the resulting two cumulative current/voltage curves, the resultant total current/voltage curve for the entire system must be considered as a value which can be measured externally.

Electrochemical series of metals

Metals are often ranked in "electrochemical series of metals" corresponding to

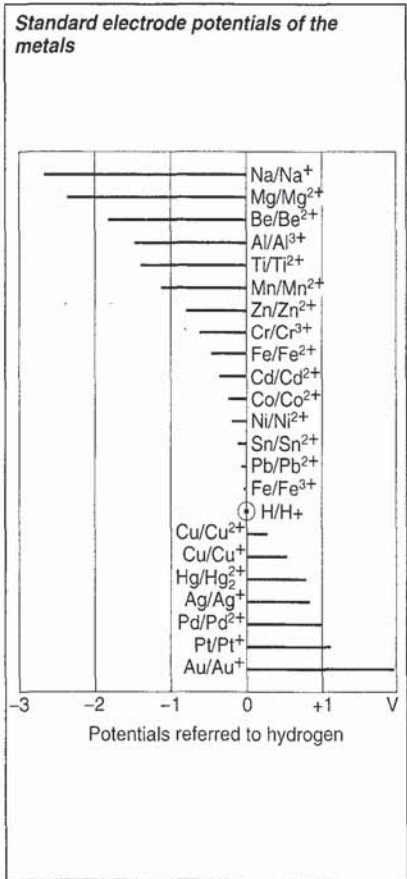
consecutively higher "standard potentials." Here, the term "standard potential" indicates that the specified values apply to standard conditions, especially to the activities (in the electrochemically active part of the concentration) of the dissolved metal ions and hydrogen in a concentration of 1 mol/l at a hydrogen pressure of 1 bar at 25°C. Such conditions are seldom found in practice; in fact, most solutions are virtually free of ions from the metal in question.

It should be emphasized that the table ("Standard electric potentials of the metals") is limited to thermodynamic values, and does not reflect the effects of corrosion kinetics, for example as encountered in the formation of protective layers. For instance, lead is shown as a base metal; as such it should dissolve in sulfuric acid. Although the "practical" and "technical" electrochemical series of metals do not have this disadvantage, their practical application range remains restricted. In contrast, electrochemical corrosion measurements provide unambiguous data.

For general reference purposes, the following relationships between electrical potential and corrosion susceptibility can be specified for metals with no application of external voltages provided that the metal's response is not affected by secondary reactions such as complexing reactions or the formation of protective layers:

Very base metals (potential less than - 0.4 V), e.g. Na, Mg, Be, Al, Ti and Fe, corrode in neutral aqueous solutions, even in the absence of oxygen.

Base metals (potential between - 0.5 and 0 V), e.g. Cd, Co, Ni, Sn and Pb, corrode in neutral aqueous solutions in the presence of oxygen, and corrode in acids to produce hydrogen even in the absence of oxygen.



Semi-noble metals (potential between 0 and + 0.7 V), e.g. Cu, Hg and Ag, corrode in all solutions only if oxygen is present.

Noble metals (potentials above + 0.7 V), e.g. Pd, Pt and Au, are generally stable.

These response patterns can vary sharply when external voltage is applied to the metals. The variations are exploited in the field of electrochemical corrosion protection (see corresponding section).

Types of corrosion

General surface corrosion

Uniform removal of material over the entire contact surface between the material and the attacking medium. This is a very frequent type of corrosion in which the material penetration rate (removal depth) can be calculated per unit of time based on the corrosion current.

Pitting corrosion

Limited localized attack by a corrosive medium which penetrates the material by forming holes, or pits, whose depth is almost always greater than their diameter. Practically no material is removed from the surface outside the pitted areas. Pitting corrosion is frequently caused by halogenide ions.

Crevice corrosion

Corrosive attack primarily occurring in narrow crevices, caused by concentration differences in the corrosive medium, e.g., as a result of long oxygen diffusion paths. This type of corrosion generates potential differences between the crevice's extremities, leading to intensified corrosion in more poorly ventilated areas.

Stress corrosion cracking

Corrosion stemming from the simultaneous concerted action of a corrosive medium and mechanical tensile stress (which can also be present as internal stress in the object itself). Intercrystalline or transcrystalline fissures form, in many

cases without the appearance of visible corrosion products.

Vibration corrosion cracking

Corrosion caused by the simultaneous effects of a corrosive medium and mechanical fatigue stress, e.g., caused by vibrations. Transcrystalline fissures are formed, frequently without visible deformation.

Fretting corrosion

Corrosion caused by the simultaneous effect of a corrosive medium and mechanical friction; sometimes called frictional oxidation.

Intercrystalline and transcrystalline corrosion

Types of corrosion characterized by selective formation along the grain boundaries or roughly parallel to the deformation plane in the grain's interior.

Dezincification

Selective dissolution of zinc from brass, leaving behind a porous copper structure. Denickelification and dealuminification are analogous processes.

Rust formation

Formation of ferriferrous oxide and hydroxide corrosion products on iron and steel.

Corrosion testing

Electrochemical corrosion-testing procedures

In electrochemical testing procedures, in addition to determining the relationship between potentials and object materials during the corrosion reaction, above all the corrosion currents are measured. In the case of uniform surface corrosion, these are then used for the precise definition of the periodic weight and thickness losses. The relevant conversion factors are listed in Table 2.

These electrochemical processes thus represent a valuable supplement to non-electrochemical methods.

The rate of free corrosion is defined based on the polarization resistance (slope of the total-current/voltage curve). Testing entails subjecting the metal to minimal, alternating anodic and cathodic pulses.

Electrochemical Impedance Spectroscopy (EIS) is employed to examine corrosion mechanisms. This alternating-current technique determines the AC resistance (impedance) and the phase angle of an electrochemical test object as a function of frequency. A low-amplitude sinusoidal alternating voltage is superimposed on the working electrode's potential, and the current response is measured. After measurement, the system is approximated in the form of an equivalent network. By way of example, the illustration captioned "Evaluation of EIS data" shows the equivalent network for the metal/coating/medium system.

The parameter-fit method is used to fit the equivalent networks to the experimental data. The impedance elements (resis-

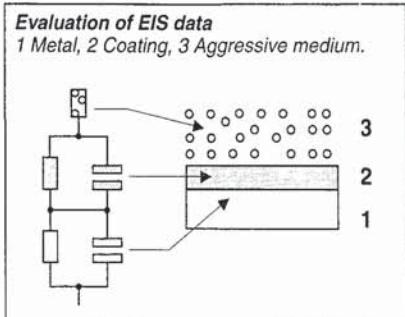


Table 1. Overview of selected standardized non-electrochemical corrosion-testing procedures

Standard	Type of corrosion-testing procedure
DIN ¹⁾ EN ISO 196 (replaces DIN 50911)	Testing of copper and copper alloys; mercury nitrate test
DIN EN ISO 3651 (replaces DIN 50914)	Testing intercrystalline corrosion in stainless steels
DIN EN ISO 4628-3 (draft) DIN 53210	Evaluation of degradation of paint coatings, Part 3: evaluation of degree of rusting Designation of degree of rusting of paint surfaces and similar coatings (will be replaced by DIN EN ISO 4628-3)
DIN EN ISO 8565 (repl. DIN 50917-1)	Corrosion tests in atmosphere; natural weathering tests
DIN EN ISO 11306 (repl. DIN 50917-2)	Corrosion of metals; testing under natural conditions; testing in sea water
DIN 50016	Method of test in damp, alternating atmosphere
DIN 50017	Condensation water test atmospheres
DIN 50018	Testing in a saturated atmosphere in the presence of sulfur dioxide
DIN 50021	Salt spray testing
DIN 50900 -1...3	General terms, electrochemical terms, terms of corrosion testing
DIN 50905 -1...4	Corrosion testing; principles, corrosion characteristics under uniform corrosion attack, corrosion characteristics under non-uniform and localized corrosion attack without mechanical stress
DIN 50 915	Testing intercrystalline stress corrosion in non-alloy and low-alloy steels
DIN 50919	Testing contact corrosion in electrolyte solutions
DIN 50920 -1	Testing corrosion in flowing liquids
DIN 50922	Testing resistance of metallic materials against stress corrosion cracking
DIN 50928	Testing and evaluating protection of coated metallic materials against aqueous corrosive media
DIN 51213	Testing metallic wire coatings (tin, zinc)
N42AP 206	Climatic tests; testing in constant condensate climate
N42AP 209	Climatic tests; cyclic humidity tests
N42AP 213	Climatic tests; industrial-climate tests

1) Deutsches Institut für Normung e.V.

tances, capacitances, inductances) are assigned physical properties. Direct conclusions can then be drawn about various characteristics, such as the effectiveness of corrosion-protection measures, porosity, thickness, a coating's ability to absorb water, the effectiveness of inhibitors, the rate of corrosion of the base metal, and so on.

The Scanning Reference Electrode Technique (SRET) is used for detecting corrosion in its early stages and for examining local corrosion processes.

Pit, gap, and intercrystalline corrosion are examples of local processes that can significantly impair mechanical properties and even result in failure in extreme cases. A high local rate of corrosion and a change in local potential are typical of these processes.

The illustration captioned "SRET principle" is a diagrammatic view of the equipotential lines at a local, active corrosion point. A sensor consisting of two offset platinum tips measuring the micropotential changes above a rotating probe is used to pick up the signal.

Data is recorded automatically on a PC using the appropriate software for analysis and presentation in the form of 2D graphics.

SRET is used to examine pitting corrosion, activation and repassivation, to detect defects in organic coatings and at welds, and to trace delamination, etc.

To measure contact corrosion, the current which flows between the two affected metals is measured directly with both immersed in the same corrosive medium.

The degradation rates determined through electrochemical measurements closely reflect those obtained in field testing. In addition to the small amount of corrosive medium required, another advantage of electrochemical procedures over non-electrochemical methods is that they provide quantitative data on corrosion rates.

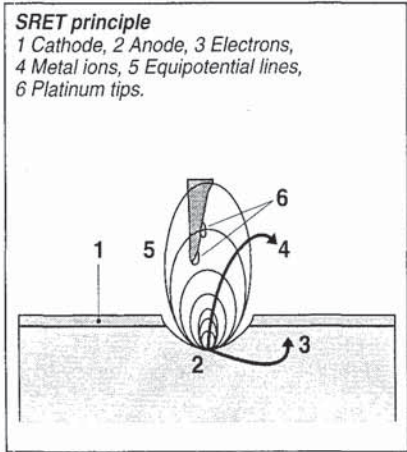


Table 2. Loss of mass and thickness due to surface corrosion of various metals with a corrosion current density of 1 $\mu\text{A}/\text{cm}^2$

Metals	Relative atomic mass	Density g/cm^3	Loss of mass $\text{mg}/(\text{cm}^2 \cdot \text{year})$	Loss of thickness $\mu\text{m}/\text{year}$
Fe	55.8	7.87	9.13	11.6
Cu	63.5	8.93	10.40	11.6
Cd	112.4	8.64	18.40	21.0
Ni	58.7	8.90	9.59	10.8
Zn	65.4	7.14	10.70	15.0
Al	27.0	2.70	2.94	10.9
Sn	118.7	7.28	19.40	26.6
Pb	207.2	11.30	33.90	30.0

Table 3. Degree of rusting and proportion of rust penetrations and visible sub-rusting at the surface to DIN EN ISO 4628-3

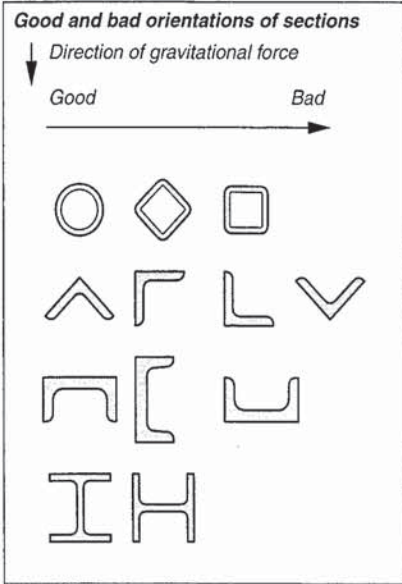
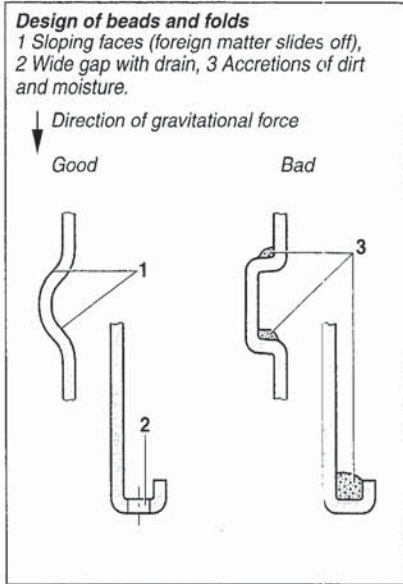
Degree of rusting	Rust surface in %
R _i 0	0
R _i 1	0.05
R _i 2	0.5
R _i 3	1
R _i 4	8
R _i 5	40 ... 50

Non-electrochemical corrosion-testing procedures
Non-electrochemical test procedures rely on determining the weight loss by weighing, or defining the rust level. DIN EN ISO 4628-3 (formerly DIN 53210) defines 5 different rust categories according to rust coverage or surface perforation (Table 3).
The corrosion tests have been defined to reflect actual field requirements. In addition to the standard DIN corrosion-testing procedures (Table 1), processes have evolved to reflect specific requirements,

e.g. motor-vehicle testing. These tests provide reliable indices of projected service life under normal operating conditions by using short-term exposure in extremely harsh conditions to simulate long-term stresses in the real world. (These tests include operating exposure to climatic factors, splash-water tests of air/fuel mixture systems).

Corrosion protection

The manifestations and mechanisms of corrosion are many and varied, so widely differing methods can be adopted to protect metals against corrosion attack. Corrosion protection means intervening in the corrosive process with the object of reducing the rate of corrosion in order to prolong the service life of the components.
Corrosion protection can be achieved by applying four basic principles:
– Measures in planning and design: the choice of suitable materials and the suitable structural design of components,
– Measures that intervene in the corrosive process by electrochemical means,



- Measures that separate the metal from the corrosive medium by protective layers or coatings, and
- Measures that influence the corrosive medium, for example the addition of inhibitors to the medium.

Corrosion protection by means of suitable structural design

Selecting suitable materials which feature optimum resistance to corrosion under the expected conditions can be of considerable assistance in avoiding corrosion damage. When the costs that would otherwise be incurred for upkeep and repair are factored into the long-term cost of ownership equation, a more expensive material can often be the more cost-effective alternative.

Design measures, too, are of major importance. A great deal of skill and expertise goes into design, particularly regarding the connections between parts that are made of the same material or different materials.

Corners and edges of sections are difficult to protect, and this is where corrosion can easily attack. Favorable orientation can reduce corrosion.

Beads and folds can trap dirt and moisture. Suitable surfaces and drain openings can help avoid this problem.

Welds, which generally modify the microstructure for the worse, are another weak point. In order to avoid crevice corrosion, welds have to be smooth and free of gaps.

Contact corrosion can be avoided by joining same or similar metals, or by installing washers, spacers or sleeves to ensure that both metals are electrically insulated.

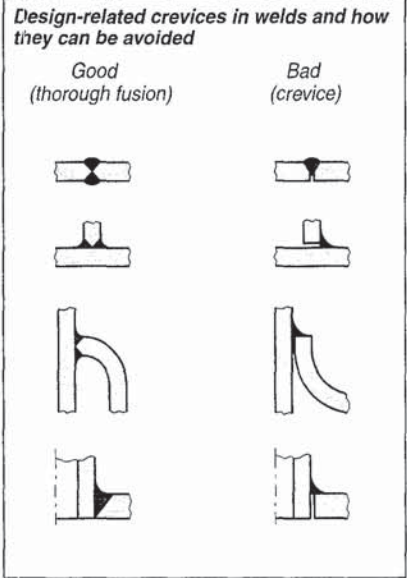
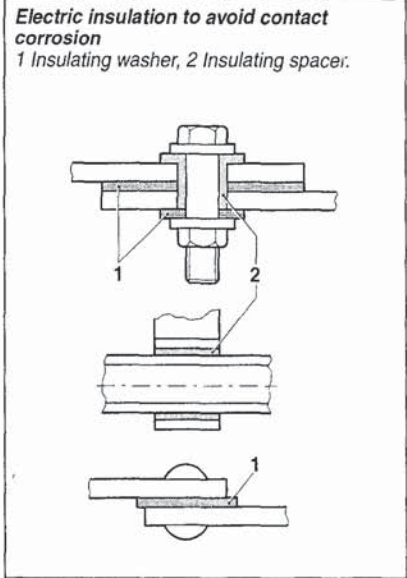
Electrochemical processes

The schematic current/voltage curves for a metal suitable for passivation coating show how these processes work. The current-density values arranged in ascending order on the y-axis represent anodic currents corresponding to the corrosion reaction defined in the equation



In contrast, the descending current-density values represent cathodic currents with the reaction equation progressing from right to left. The diagram indicates that external voltage can be applied to suppress corrosion. There are two basic ways of doing this:

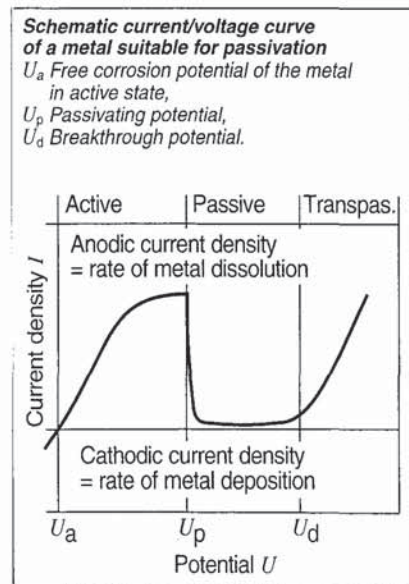
For cathodic protection the potential is shifted so far toward the left that no an-



odic currents flow, leading to $U < U_a$. As an alternative to applying voltage from an external source, it is also possible to shift the potential by using a base metal to act as a "sacrificial" reactive anode.

Another option is to shift the potential of the threatened electrode into the passive range, i.e., into the potential range between U_p and U_d . This is called anodic protection. The anodic currents which flow in the passive range are less than those in the active range by exponential powers of between 3 and 6, depending upon the type of metal and the corrosive medium. The result is excellent protection for the metal.

However, the potential should not exceed U_d , as oxygen would be produced in this transpassive range, potentially leading to higher rates of oxidation. Both of these effects would cause the current to increase.



Coatings

Coatings inhibit corrosion by forming protective films applied directly to the metal to be protected, where they resist attack by the corrosive medium. These protective coatings should be neither porous nor electrically conductive. Because adequate application depths are also essential, considerable difficulties may be encountered when attempts are made to apply these substances in systems with close dimensional tolerances.

Inorganic nonmetallic coatings

Protective coatings can be formed interactively with the material to be protected. The formation of stable oxide coatings can be promoted in many metals by alloying in small amounts of foreign metals, such as silicon in the case of cast iron, or molybdenum with chrome-nickel steels. Phosphates, chromates and silicates can also produce coatings. Examples are found in the automotive industry, where these substances are employed in body panel manufacture ("phosphate coating") and in cooling systems.

Diffusion process

Surface treatment can be selectively combined with surface hardening by using the diffusion process to thermochemically carburize, carbonitride or chromate the metal, or treat it with boron or vanadium. The metal can also be oxidized, nitrated or sulfided without hardening.

Browning

Browning is used to produce coatings for limited protection over a short period of time. A ferrous material is browned by dipping it in hot concentrated sodium hydroxide containing NaNO_2 .

Anodizing

Anodizing applications are restricted to aluminum. This anodic oxidation process in electrolytes containing sulfuric, chromic, or oxalic acids generally produces very durable coatings, which can be further stabilized and colored by chromating. Cadmium and magnesium surfaces can also be chromated.

Enameling

Enameling furnishes high levels of corrosion protection, particularly on unalloyed steel. On the negative side, enamel coatings are brittle and thus particularly susceptible to impact and thermal shock. In addition, they are subject to consistent internal compressive stress, and tensile stress factors (e.g. when the yielding point of the carrier material is exceeded) cause fissures in the relatively inflexible enamel. To improve enamel bonding, an intermediate layer consisting of a base material is first fused to the metal; this intermediate layer is then covered with the actual silica-based protective coating.

Glass ceramics

Glass ceramics do not display the disadvantages of enamel under mechanical or thermal loading. They are applied to the material in the form of a semi-crystalline coating using controlled crystallization of thermodynamically unstable glasses. Subsequent heat treatment establishes roughly 50 % crystallinity.

Metallic coatings

Numerous options are available for applying foreign metals or metal compounds to base materials. In many cases, corrosion protection is combined with enhanced wear resistance and with the formation of decorative surfaces. Standard procedures, suitable metals and application ranges are listed in Table 4. It should be noted though that not every metal is suitable for every type of protection (e.g. aluminum applied to base materials in thermal spray processes provides no protection against wear).

Electroplating (electrolytic deposition)

In electrolytic plating, metals suspended in ionized metallic-salt solutions are deposited on conductive bases in a cathodic reaction. Under controlled conditions it is possible to produce alloys and dispersion coatings (layers of finely dispersed additives) of a type not amenable to duplication in fusion processes. Most metals are deposited from suspensions in aqueous solutions. In contrast, aluminum – an extremely base metal – can only be applied using water-free organic or molten saline solutions.

Table 4. Uses of inorganic protective coatings

Method of application	Type of metal	Primarily used for
Chemical deposition	Ni (NiB, NiP, NiPCu), Cu, dispersion coatings (NiB + SiC, NiP + SiC).	Corrosion protection, protection against wear, decorative surfaces.
Vapor deposition	Al, Au, Ta.	Corrosion protection
Electroplating (external power source)	Ag, Al, Au, Cd, Cr, Ni, Sn, Zn, ZnNi, ZnNiP.	Corrosion protection, decorative surfaces
Plating	Al, Cu, Ni, Pb, Ti, Zr and their alloys, stainless steels.	Corrosion protection
Hot immersion (including "hot-dip galvanization")	Al, Pb, Sn, Zn.	Corrosion protection
Thermal spraying	Al and alloys, Cr, Ni, NiCr, NiCrBSi, Ti, borides, carbides, oxides.	Corrosion protection, protection against wear.

Chemical deposition

The basic principles are the same as in the electroplating process, but the electrons required for reduction do not come from an external power source. Instead, they are furnished by an added reducing agent (usually sodium hypophosphite or sodium boranate). This is why phosphorus and boron are present in most nickel coatings.

Hot immersion priming

The most common immersion process is the hot-dip galvanizing of iron and steel; this process is also the one most frequently used in the automotive industry. Here the pretreated (pickled and wetted with flux) material is immersed in the molten coating metal to produce alloy layers; this process progresses at the phase limit in accordance with solubility conditions in the phase diagrams. The alloy layers promote bonding between the coating and the base material. This process allows substantially greater layer depths than electroplating methods.

Evaporation

Due to its high cost, the evaporation process is limited to special applications, particularly in applying thin coatings to objects with limited surface areas (substrates). These thin layers often require additional protection from supplementary inorganic or organic coatings (example: headlight reflectors). The coating material (metal) is heated by an electric current and evaporated in an intense vacuum. It condenses on the substrate, forming a fine metal coating.

Thermal spraying

In thermal spraying, the coating material (usually in powdered form) is melted by a plasma ("plasma spraying") or an arc as it leaves the spray gun. Because this process entails accepting a certain amount of inconsistency and porosity in the final coating, thick layers (150 to 200 μm) are required to ensure effective corrosion protection.

Plating

Plating is the joining of two or more metal layers at high temperature and/or under

high pressure. These metal layers do not separate under normal stress. Plating methods are divided into rolling, transfer and mechanical cladding. The materials are joined by using diffusion processes, bonding with alloying techniques, or mechanical interlocking. The application materials are several millimeters in thickness.

Organic coatings

Thermoplastics, elastomers and duromers are the primary types of organic protective coatings. They are used in the automobile industry in paints, whirl-sintered compounds, interior coatings, fiber-reinforced resins and fillers. How well these coatings protect the underlying material depends not only on the individual plastic, but also on the binder, anti-aging agent, UV stabilizers and the type of filler and pigment used. Organic coatings can be used alone or together with one of the inorganic coatings mentioned above.

Painting

Depending upon individual requirements, paint can be applied with brushes and rollers, using compressed-air or high-pressure sprays, and by immersion processes (with and without electrophoresis), and with electrostatic spray painting. An adhesion-promoting primer coat is applied to the pretreated metal surface with subsequent application of the actual protective coat on top of the primer. Solvent evaporation and/or oxygen absorption then promote formation of a homogenous, continuous surface layer.

Powder coating

Powdered plastics, which are very difficult to transform into a liquid phase at room temperature, can be applied using powder coating processes. The powder can either be fused onto the preheated parts, flame-sprayed or electrostatically sprayed. Heat treatment can be employed to form homogenous sealed layers as required. Powder coating processes are usually more economical than painting processes, while environmental and occupational safety are both less of a problem.

Internal rubber and plastic coatings

Rubber and plastic coatings are frequently used to protect the insides of transport and storage tanks, vessels and pipes. Prelinked natural and synthetic rubber, and pretreated thermoplastic films are applied with interlacing adhesives; final linkage takes place either catalytically or by applying heat after the coatings have been applied to the bare carrier materials.

Plasma polymerization

Plasma polymerization is a process in which a gaseous-discharge plasma promotes polymerization of organic monomers on the object material. This type of polymer film represents a suitable coating for any metal. The result is an organic layer without gas enclosures or the volatile components frequently found in solid polymers.

Inhibitors

Inhibitors are substances added to the corrosive medium in low concentrations (up to a maximum of several hundred ppm) for absorption at the surface of the protected metal. Inhibitors drastically reduce the rate of corrosion by blocking either the anodic or the cathodic subprocess (frequently blocking both subprocesses simultaneously). Organic amines and amides of organic acids are the most frequent inhibitors. In automotive applications, for example, inhibitors are used in fuel additives; they are also added to antifreeze in order to inhibit corrosion damage in the coolant circuit.

Vapor-phase inhibitors provide only temporary protection for metallic products during storage and shipping. They must be easy to apply and remove.

The drawback of vapor-phase inhibitors is that they are potentially injurious to health.

Vapor-phase inhibitors (VPI), or volatile corrosion inhibitors (VCI), are organic substances of moderate vapor pressure. They are frequently enclosed in special-purpose packing materials or as solvents in liquids or emulsions with oil. The inhibitors evaporate or sublimate over the

course of time, and are adsorbed as monomolecules on the metal, where they inhibit either anodic or cathodic corrosion subreactions, or both at once. Dicyclohexylamin nitrite is a typical example.

For optimal effectiveness, the inhibitor should form a sealed coating extending over the largest possible surface area. This is why they are generally enclosed in packing materials such as special paper or polyethylene foil. An airtight edge seal is not required; the packing can be opened briefly for inspection of contents. The duration of the packing's effectiveness depends on the tightness of the seal and the temperature (normally approx. 2 years, but less in environments substantially hotter than room temperature).

Standard commercial vapor-phase inhibitors are generally a combination of numerous components capable of providing simultaneous protection for several metals or alloys. Exceptions: cadmium, lead, tungsten and magnesium.

Heat treatment of metallic materials

Heat treatment is employed to endow metallic tools and components with the specific qualities required either for subsequent manufacturing processes or for actual operation. The heat-treating process includes one or several time and temperature cycles. First, the parts to be treated are heated to the required temperature, where they are maintained for a specific period before being cooled back down to room temperature (or below in some processes) at a rate calculated to achieve the desired results.

The process modifies the microstructure to achieve the hardness, strength, ductility, wear resistance, etc., required to withstand the stresses associated with static and dynamic loads. The most significant industrial processes are summarized in Table 1 (see DIN EN 10 052 for terminology).

Hardening

Hardening procedures produce a martensitic microstructure of extreme hardness and strength in ferrous materials such as steel and cast iron.

The parts being treated are heated to the austenitizing, or hardening temperature, at which they are maintained until an

Table 2. Standard austenitizing temperatures

Type of steel	Quality specification	Austenitizing temperature °C
Unalloyed and low-alloy steels	DIN EN 10 083-1 DIN 17 211 DIN 17 212	780...950
< 0.8% by mass of C		
≥ 0.8% by mass of C	—	780...820
Cold- and hot-working tool steels	DIN 17 350	950...1100
High-speed steels		1150...1230
Cast iron	—	850...900

austenitic structure emerges, and until an adequate quantity of carbon (released in the decay of carbides, such as graphite in cast iron) is dissolved in the treated material. The material is then quenched or otherwise cooled back to room temperature as quickly as possible in order to obtain a maximum degree of conversion to a martensitic microstructure (the time-temperature transformation chart for the specific steel in question contains the reference figures for the necessary cooling rate).

The austenitizing temperature varies according to the composition of the material in question (for specific data, consult the DIN Technical Requirements for Steels). Table 2 above furnishes reference data. See DIN 17 022, Parts 1 and 2, for practical information on hardening procedures for tools and components.

Table 1. Summary of heat-treatment processes

Hardening	Austempering	Tempering	Thermo-chemical treatment	Annealing	Precipitation hardening
Through hardening	Isothermic transformation in the bainite stage	Tempering of hardened parts	Carburizing	Stress-relief	Solution treatment and aging
Surface hardening		Hardening and tempering above 550 °C	Carbonitriding	Recrystallization annealing	
Hardening of carburized parts (case-hardening)			Nitriding	Soft annealing, spheroidization	
			Nitrocarburizing	Normalizing	
			Boron treatment	Homogenizing	
			Chromating		

Not all types of steel and cast iron are suitable for hardening. The following equation describes the hardening potential for alloyed and unalloyed steels with mass carbon contents of between 0.15 and 0.60%, and can be applied to estimate the hardness levels achievable with a completely martensitic microstructure:

Max. hardness = 35 + 50 · (%C) ± 2 HRC

If the microstructure does not consist entirely of martensite, then the maximum hardness will not be reached.

When the carbon content exceeds 0.6% by mass, it may be assumed that the material's structure contains untransformed austenite (residual austenite) in addition to the martensite. This condition prevents the maximum hardness from being achieved, and the wear resistance will be lower. In addition, residual austenite is metastable, i.e. there exists a potential for subsequent transformation to martensite at temperatures below room temperature or under stress, with changes in specific volume and internal stress as the possible results. Low-temperature follow-up procedures or tempering operations at over 230 °C can be useful in cases where residual austenite is an unavoidable product of the hardening procedure.

The surface and core hardnesses remain virtually identical in components with material thicknesses up to approx. 10 mm. Beyond this point the core hardness is lower; there is a hardness progression or gradient. The rate of the progression depends upon the hardening response (testing described in DIN 50 191), which is a function of the material's composition (Mo, Mn, Cr). This factor requires particular attention with parts which do not cool well (thick parts and/or slow or graduated cooling processes designed to minimize the risk of cracks and/or distortion).

DIN 50 150 defines the method for using hardness as the basis for estimating tensile strength R_m ; this method can only be applied in cases where the surface and core hardnesses are virtually identical:

$R_m \approx (34...37.7) \cdot \text{Rockwell C hardness number in N/mm}^2$ or
 $R_m \approx (3.2...3.35) \cdot \text{Vickers hardness number in N/mm}^2$.

The specific volume of the martensitic microstructure is approximately 1.0 % greater than that of the original material. In addition, stresses result from the rearrangement of the microstructure and from contraction during cooling. As the latter phenomenon does not take place at a uniform rate in all sections of the part, it produces variations in shape and dimensions; tensile stresses near the surface and pressure tension at the core are the common result.

Surface hardening

The process is especially suited for integration within large-scale manufacturing operations, and can be adapted to fit the rhythm of the production line.

Heating and hardening are restricted to the surface, thereby minimizing alterations in shape and dimensions. Heating is generally provided by high- or medium-frequency alternating current (inductive hardening) or by a gas burner (flame hardening). Friction (friction hardening) and high-energy beams (e.g. electron or laser beams) can also provide the heat required for austenitizing. Table 3 provides a summary of the specific heat energies for the individual procedures.

These methods can be used to treat both linear and flat surfaces, meaning that the parts can be heated either while stationary or in motion. The heat source itself can also be moved. Rotation is the best way of dealing with radially symmetrical parts, as it ensures concentric hardening. Either immersion or spraying arrange-

Table 3. Comparison of power densities when heating with different sources

Energy source	Normal power density W/cm²
Laser beam	10³...10⁴
Electron beam	10³...10⁴
Induction (MF, HF, HF pulse)	10³...10⁴
Flame heating	10³...6 · 10³
Plasma beam	10⁴
Molten salt (convection)	20
Air/gas (convection)	0.5

ments can be applied for quenching.

Heat rise is rapid, so the temperatures must be 50...100 °C higher than those used in furnace heating so as to compensate for the shorter dwell period. The procedure is generally employed with low-alloy or unalloyed steels with mass carbon contents of 0.35...0.60 % (consult DIN 17 212 for list of suitable steels). However, surface hardening processes can also be applied with alloyed steels, cast iron and rolling-bearing steels. The parts can be heat-treated to provide a combination of improved base strength and high surface hardness, making them suitable for high-stress applications (recessed edges, bearing surfaces, cross-sectional transitions).

Surface hardening generally results in internal compression stresses along the edge. This leads to increased fatigue resistance, especially when notched parts are exposed to inconstant vibration stress (see illustration).

The relationship defined above can be employed to estimate the potential surface hardness. There is a substantial reduction in hardness between the surface and the unhardened core region. The hardening depth R_{ht} – the depth at which 80 % of the Vickers surface hardness is found – can be derived from the hardness progression curve (see DIN 50 190, Part 2).

Austempering

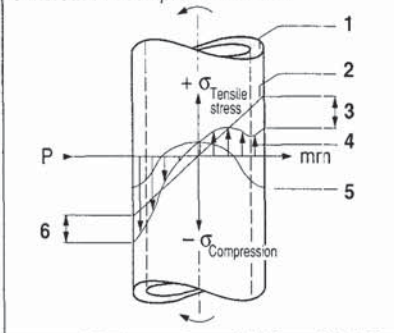
The object of this process is to achieve a bainite microstructure. This microstructure is not as hard as martensite, but does display greater ductility as well as smaller changes in specific volume.

After austenitizing (see hardening), the parts for austempering are first cooled to a temperature of 200...350 °C (depending upon the exact composition of the material) at the required rate. The parts are then held at this temperature until the microstructure's transformation into bainite has been completed. The parts can then be cooled to room temperature (no special procedure required).

Austempering is an excellent alternative for parts whose geometrical configuration makes them sensitive to distortion

Cyclically alternating stress according to surface-layer hardening

+ σ Tensile stress, – σ Compression;
1 Case layer, 2 Bending stress,
3 Reduction of tensile stress,
4 Resulting tension, 5 Intrinsic stress
6 Increase in compression stress.



and/or cracks, or in which high ductility is required together with substantial hardness, or which should combine hardness with a low level of residual austenite.

Draw tempering

Parts emerge from the hardening process in a brittle state; they must be tempered to increase their ductility in order to reduce the risk of damage associated with excessive internal tension, such as delayed cracking after hardening or splintering during grinding. This tempering process is based on the elimination of carbides, a phenomenon accompanied by an increase in ductility, albeit at the price of reductions in hardness.

The parts are heated in the draw to a temperature of between 180 and 650 °C; they are then held there for at least one hour before being allowed to cool to room temperature. Depending upon the specific composition of the material, tempering at temperatures in excess of 230 °C may result in any residual austenite being transformed into bainite and/or martensite.

Tempering at temperatures as low as 180 °C is enough to reduce the hardness of unalloyed and low-alloy steels by approx. 1...5 HRC. The individual materials respond to higher temperatures with specific characteristic hardness loss. The graph at the right shows a characteristic

tempering curve for typical types of steel. The graph illustrates the fact that the hardness of high-alloy steels remains constant until the temperature exceeds 550 °C, after which it drops.

The mutual relationships between tempering temperature on the one side, and hardness, strength, yield point, fracture contraction and ductility on the other, can be taken from the tempering diagrams for the various steels (see DIN EN 10 083).

Tempering of hardened parts is accompanied by a reduction in specific volume. In some cases, tempering can also induce changes in the progressive variation in internal tension at different depths in the parts.

It must be remembered that steels alloyed with manganese, chromium, manganese and chromium, chrome-vanadium, and chromium and nickel should not be tempered at temperatures of 350...500 °C, as brittleness could result. When these types of materials are cooled from higher tempering temperatures, the transition through this critical range should also be effected as rapidly as possible (see DIN 17 022, Parts 1 and 2 for additional information).

Quench and draw

This type of quench and draw process combines hardening and tempering at temperatures above 500 °C. This procedure is designed to achieve an optimal relationship between strength and ductility. It is applied in cases where extreme ductility or malleability is required.

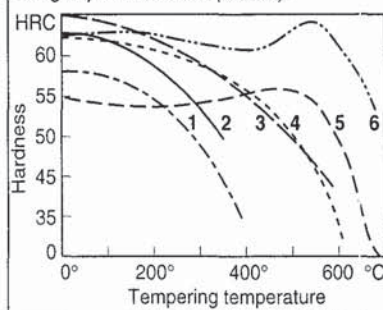
Particular care must be devoted to avoiding brittleness in the quench and draw operation (see above).

Thermochemical treatment

In thermochemical treatment, the parts are annealed in agents which emit specific elements. These diffuse into the surface layer of the parts being treated and modify their composition. This results in very specific properties. Of particular importance for this process are the elements carbon, nitrogen and boron.

Tempering response of various types of steel

- 1 Non-alloyed tempering steel (C45),
- 2 Non-alloyed cold-working tool steel (C80W2),
- 3 Low-alloyed cold-working tool steel (105WCr6),
- 4 Alloyed cold-working tool steel (X165CrV12),
- 5 Hot-working tool steel (X40CrMoV51),
- 6 High-speed tool steel (S6-5-2).



Carburizing, carbonitriding, case hardening

Carburizing increases the carbon content in the surface layer, while carbonitriding supplements the carbon enrichment with nitrogen. This process is generally carried out in molten salt, granulate, or gas atmospheres at temperatures ranging from 850...1000 °C. The actual hardening is performed subsequently, either by quenching directly from the carburizing/carbonitriding temperature (direct hardening), or by allowing the parts to cool to room temperature (single hardening), or by allowing them to cool to a suitable intermediate temperature (e.g. 620 °C) prior to reheating (hardening after isothermal conversion). This process produces a martensitic surface layer, while the degree of martensite at the core is a function of hardening temperature, hardenability and part thickness.

Specific temperatures can be selected for either surface hardening in the upper layers with higher carbon content (case refining), or for the non-carburized core (core refining) (see DIN 17 022, Part 3).

Carburizing and carbonitriding produce a characteristic carbon declivity, with levels dropping as the distance from the surface increases (carbon curve). The distance between the surface and the point at which the mass carbon content is still

0.35% is normally defined as the carburization depth $At_{0.35}$.

The length of the carburizing or carbonitriding process depends upon the required carburization depth, the temperature and the atmosphere's carbon-diffusion properties. A reasonable approximation is possible:

$$At = K \cdot \sqrt{t} - D/\beta \text{ in mm}$$

Depending on temperature and carbon levels, K lies between 0.3 and 0.6 during carburization in a gas atmosphere, for example; the correction factor D/β is generally 0.1...0.3 mm; the time t in h must be inserted.

Generally, the objective is to achieve a carbon gradient with a concentration of at least 0.60% mass carbon content, the ultimate goal being a surface hardness of 750 HV (corresponding to 65 HRC). Higher concentrations of carbon can lead to residual austenite and/or carbide diffusion, which could have negative effects on the performance of case-hardened parts in actual use. Control of the atmosphere's carbon level, and thus the part's ultimate carbon content, is thus extremely important.

The gradient defining the relationship between hardness and depth corresponds to the carbon concentration curve. The hardness gradient is used to define the case depth E_{ht} . DIN 50 190, Part 1 defines this as the maximum distance from the surface before the hardness drops below 550 HV.

The case-hardened part generally exhibits compression tension at the surface, and tensile stresses at the core. As with surface-hardened materials, this distribution pattern provides enhanced resistance to vibration loads.

In carbonitriding, nitrogen is also absorbed; it serves to improve the material's tempering properties, increase its durability and enhance its wear resistance. The positive effects are especially pronounced with non-alloyed steels. For additional, more detailed information on case-hardening procedures consult DIN 17 022, Part 3, and Information Sheet 452 of the Steel Information Center, Düsseldorf.

Nitriding and nitrocarburizing

Nitriding is a thermal treatment process (temperature range: 500...600 °C) which can be used to enrich the surface layer of virtually any ferrous material with nitrogen. In nitrocarburizing, a certain amount of carbon is diffused into the material at the same time.

The nitrogen enrichment is accompanied by precipitation hardening. This strengthens the surface layer, enhancing the material's resistance to wear, corrosion and alternating cyclic stress.

Because the process employs relatively low temperatures, there are no volumetric changes of the kind associated with transformations in the microstructure, so that changes in dimensions and shape are minute.

The nitrided region consists of an outer layer, several millimeters in depth, and a transitional white layer, the hardness of which may be anywhere from 700 to over 1200 HV, depending upon the composition of the material. Still deeper is a softer diffusion layer extending several tenths of a millimeter. The thickness of the individual layers is determined by the temperature and duration of the treatment process. The process produces a hardness gradient (similar to that which results from surface and case-hardening); this gradient furnishes the basis for determining the nitriding depth N_{ht} . DIN 50 190, Part 3 defines this as the depth from the surface at which the hardness is still 50 HV above the core hardness.

The material's resistance to wear and corrosion is essentially determined by the white layer, which contains up to 10 mass components of nitrogen in %. The nitriding depth and the surface hardness determine the material's resistance to alternating cyclic stress (for additional details, see DIN 17 022, Part 4, and Information Sheet 447 from the Steel Information Center, Düsseldorf).

Boron treatment

This is a thermochemical treatment method which employs boron to enrich the surface layer of ferrous materials. Depending upon duration and temperature (normally 850...1000 °C), an iron-boron white layer of 30 µm...0.2 mm in

depth and with a hardness of 2000...2500 HV is produced.

Boron treatment is particularly effective as a means of protecting against abrasive wear. However, the comparatively high process temperature leads to relatively large changes in shape and dimensions, meaning that this treatment is only suitable for applications in which large tolerances can be accepted.

Annealing

Annealing can be applied to optimize certain operational or processing characteristics of parts. With this method, the parts are heated to the required temperature and maintained there for an adequate period before being cooled to room temperature. Table 1 lists the various processes used in specific individual applications.

Stress-relief

Depending upon the precise composition of the parts, this operation is carried out at temperatures ranging from 450...650°C. The object is to achieve the maximum possible reduction in internal stress in components, tools and castings by inducing physical deformation.

After an oven time of 0.5...1 h, the parts are cooled back to room temperature; this cooling should be as gradual as possible to prevent new stresses from forming.

Recrystallization annealing

Recrystallization annealing is applied with parts that have been formed using non-cutting procedures. The goal is to restructure the grain pattern in order to prevent increased hardening, thereby facilitating subsequent machining work.

The temperature requirement depends upon the composition of the material and the degree of deformation: it lies between 550...730°C for steel.

Soft annealing, spheroidization

Soft annealing is intended to facilitate the machining and/or shaping of workpieces which have hardened owing to deformation processes or other heat treating procedures.

The temperature requirement is determined by the material's composition. It is in a range of 650...720°C for steel, and lower for nonferrous materials.

Spheroidizing of cementite is applied when a microstructure with a granular carbide pattern is desired. If the initial structure is martensite or bainite, the result will be an especially homogeneous carbide distribution.

Normalizing

Normalizing is carried out by heating the parts to austenitizing temperature and then allowing them to gradually cool to room temperature. In low-alloy and non-alloyed steels, the result is a structure consisting of ferrite and perlite. This process is essentially employed to reduce grain size, reduce the formation of coarse grain patterns in parts with limited reshaping, and to provide maximum homogeneity in the distribution of ferrite and perlite.

Precipitation hardening treatment

This process combines solution treatment with aging at ambient temperature. The parts are heated and then maintained at temperature to bring precipitated structural constituents into a solid solution, and quenched at room temperature to form a supersaturated solution. The aging process comprises one or several cycles in which the material is heated and held at above-ambient temperatures (hot aging). In this process, one or several phases, i.e. metallic bonds between certain base alloys, are formed and precipitated in the matrix.

The precipitated particles enhance the hardness and strength of the base microstructure. The actual characteristics are determined by the temperature and duration of the aging process (option of mutual substitution); exceeding a certain maximum will usually reduce the strength and hardness of the final product.

Precipitation hardening is mostly applied for nonferrous alloys, but some hardenable steels (maraging steels) can also be processed.

Hardness

Hardness testing

Hardness is the property of solid materials that defines their resistance to deformation. In metallic materials the hardness is used to assess mechanical properties such as strength, machinability, malleability, and resistance to wear. DIN 50 150 defines guidelines for converting hardness to tensile strength. Measurement processes are practically nondestructive.

The test data are generally derived from the size or depth of the deformation produced when a specified indenter is applied at a defined pressure.

A distinction is made between static and dynamic testing. Static testing is based on measurement of the permanent impression left by the indenter. Conventional hardness tests include the Rockwell, Vickers and Brinell procedures. Dynamic testing monitors the rebound of a test tool accelerated against the surface of the test specimen.

Another option for obtaining an index of surface hardness is to scratch the surface with a hard test tool and then measure the groove width. The table (next page) compares the standard application ranges for the Rockwell, Vickers and Brinell hardness tests.

Rockwell hardness
(DIN EN 10 109)

This method is particularly suitable for large-scale testing of metallic workpieces. A steel or diamond indenter is positioned vertically against the surface of the test specimen and a minor load applied prior to application of the full test pressure (major load) for a period of at least 30 s. The Rockwell hardness is the resulting penetration depth *e* in mm (see Table 1).

The test surface should be smooth (depending on hardness range, *R*_{max} ≤ 1.2...3.4 μm) and as flat as possible. If the specimen's radius of curvature is less than 20 mm then the results must be scaled using the correction factor for the individual resistance level.

Selection of the individual test procedures enumerated in Table 1 is based upon either the specimen's thickness or the case depth of the hardened surface layer (refer to Figs. A.1...A.3 in DIN EN 10 109). The abbreviation for the selected test method should be appended to the numerical data when specifying hardness, e.g., 65 HRC, 76 HR 45 N. The Rockwell C procedure's error range is approx. ±1 HRC.

Advantages of the Rockwell test method include minimal specimen preparation and rapid measurement; this test process can also be completely automated.

Table 1. Rockwell test methods

Abbreviation	Indenter	Minor load N	Total test force N	Hardness number (<i>e</i> indenter penetration depth)	
HRC	Diamond cone	98 ± 2	1471 ± 9	100 - <i>e</i> / 0.002	20...70
HRA			588 ± 5		60 ... 381
HRB	Steel ball		980 ± 6.5	130 - <i>e</i> / 0.002	35 ... 100
HRF			588 ± 5		60 ... 100
HR15N HR30N HR45N	Diamond cone	29.4 ± 0.6	147 ± 1 294 ± 2 441 ± 3	100 - <i>e</i> / 0.001	66 ... 32 39...84 17...75
HR15T HR30T HR45T	Steel ball	3 ± 0.06	15 ± 0.1 30 ± 0.2 45 ± 0.3		50 ... 34 10 ... 34 0 ... 75

Any tester vibration, or shifting and movement of either the test probe or the specimen itself can lead to testing errors, as can an uneven support surface or a damaged indenter.

Brinell hardness (DIN EN 10003)

This procedure is used for metallic materials of low to medium hardness. The test tool (indenter) is a hard-metal or hardened-steel ball. It is applied to the surface of the specimen at an individually specified force *F* for at least 15 s¹⁾. Microscopic examination of the resulting deformation diameter *d* provides the basis for calculating the Brinell hardness. These data can be correlated with standard charts or calculated as follows:

Brinell hardness = $\frac{0.204 \cdot F}{\pi \cdot D \cdot (D - \sqrt{D^2 - d^2})}$ HB

- F* Force in N
- D* Ball diameter in mm
- d* Indentation diameter in mm

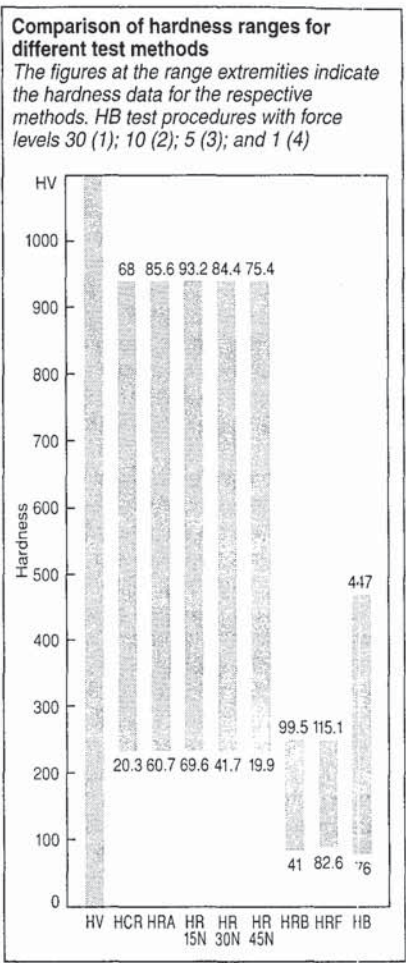
Test pressures range from 9.81 to 29,420 N. Results obtained using spheres of different diameters are only conditionally comparable, and any comparisons should be based on testing at identical force levels. Testing should always be performed using the largest possible spherical sphere, while load factors should be

¹⁾ At least 30 s for lead, zinc, etc.

Table 2. Application of the Brinell hardness test

Material	Brinell hardness	Load factor 0.102 <i>F</i> / <i>D</i> ²
Steel; nickel and titanium alloys		30
Cast iron ¹⁾	< 140	10
	≥ 140	30
Copper and copper alloys	< 35	5
	35 to 200	10
	< 200	30
Light metals and their alloys	< 35	2.5
	35 to 80	5
		10
		15
	> 80	10
		15
Lead and tin		1
Sintered metals	see EN 24498-1	

¹⁾ Ball nominal diameters of 2.5, 5 or 10 mm are specified for testing cast iron.



selected to obtain an indentation diameter of $(0.24 \dots 0.6) \cdot D$. Table 2 lists the recommended load factors and ball diameters for a variety of materials as laid down in DIN EN 10 003.

In the Brinell hardness designation the numeric data are accompanied by the procedure code, the material of the ball (W for hard metal, S for steel) and the ball diameter. The final element is the test force (in N) multiplied by a factor of 0.102. Example: 250 HBW 2.5/187.5.

To prevent test errors stemming from deformation of the ball itself, testing at hardness factors in excess of 450 HB is to be carried out exclusively with a hard-metal ball.

High test pressures producing deformations extending over a relatively wide surface area can be employed to gather data on materials with inconsistent structures. An advantage of the Brinell method is the relatively high degree of correlation between the Brinell hardness factor and the steel's tensile strength.

The range of application for the Brinell test method is limited by specifications for the thickness of the test specimen (cf. DIN EN 10 003) and by the ball material. The required preparations and ensuing test procedures are more complex than those used for Rockwell testing. Potential error sources are the test's reliance on visual evaluation of the impact area's diagonal length and the possibility of inconsistencies in the impression itself.

Vickers hardness (DIN 50 133)

This test method can be used for all metallic materials, regardless of hardness. It is especially suitable for testing minute and thin specimens, while the potential application range extends to include surface and case-hardened parts as well as nitrided workpieces and parts carburized in nitrogen-based atmospheres.

The test tool is a square-based diamond pyramid with an apical angle of

136°. This is applied to the surface of the test specimen at the specified force *F*.

The diagonal *d* of the rhomboidal cavity remaining after the tool's removal is measured using a magnifying glass to obtain the basis for calculating the Vickers hardness, which can be read from tables or calculated as follows:

Vickers hardness = $0.189 \cdot F/d^2$ HV

F Applied force in N
d Diagonal of impression in mm

Table 3 gives an overview of the graduated force levels defined in DIN 50 133.

In the formula for Vickers hardness data, the actual test figure is accompanied by the abbreviation HV, the force in N (multiplied by a factor of 0.102) and, following a slash, the force application period (if other than the standard 15 s) in seconds, e.g.: 750 HV 10/25.

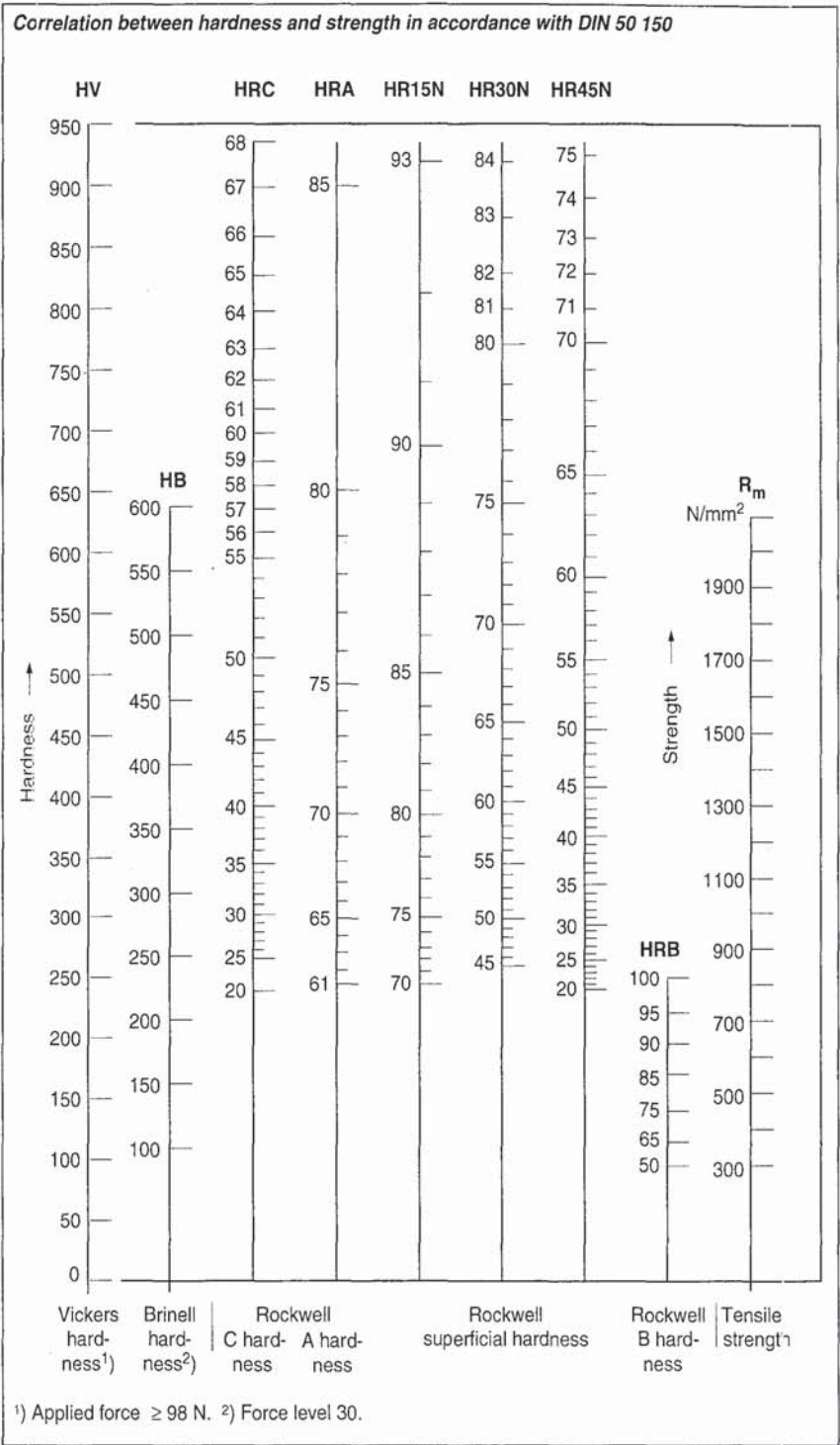
The test specimen's surface should be smooth ($R_{max} \leq 0.005 \cdot d$) and flat. DIN 50 133 stipulates that correction factors be used to compensate for any error stemming from surface curvature. Test pressure levels are selected with reference to either the thickness of the test specimen itself or of its hardened outer layer (cf. Fig. 2 in DIN 50 133). Practical experience indicates an error range of approximately ± 25 HV. Although the geometrical configurations are similar, hardness data vary as a function of applied-force levels.

A major advantage of this test method is that there are virtually no limitations on using it to assess thin parts or layers. It allows the use of extremely small force levels to determine the hardness of individual structural sections. The Brinell and Vickers numbers correlate up to approximately 350 HV.

However, a certain minimal degree of surface consistency is necessary to ensure accurate results. Vickers testing furnishes roughly the same accuracy levels as the Brinell method, although the mea-

Table 3. Vickers hardness force increment

Abbreviation	HV0.2	HV0.3	HV0.5	HV1	HV2	HV3	HV5	HV10	HV20	HV30	HV50	HV100
Applied force N	1.96	2.94	4.9	9.8	19.6	29.4	49	98	196	294	490	980



surement process is extremely sensitive to movement of the test set-up. The test tools are more expensive than the balls used in Brinell testing.

Knoop hardness

This process closely resembles the Vickers procedure. It is the method of choice for testing thin-layer hardness in the Anglo-Saxon world.

The test tool is designed to leave an impression in the form of a thin, elongated rhombus. The extended diagonal d is seven times longer than the short one and is the only one that is actually measured. The applied force is less than 9.8 N. Hardness ratings are available from standard charts, or may be calculated as follows:

$$\text{Knoop hardness} = 1.451 \cdot F/d^2 \text{ HK}$$

F Applied load in N

d Long diagonal in mm

The diagonal, which is roughly 2.8 times longer than in the Vickers method, provides more accurate results with visual assessment procedures. The penetration depth is 1/3 less than in the Vickers method, allowing evaluation of surface hardness in thin parts and layers. By making Knoop impressions in different directions, even material anisotropies can be detected.

Disadvantages of this method include pronounced sensitivity to misaligned specimen surfaces, which must be absolutely perpendicular to the force-application axis, and the fact that the maximum force is restricted to 9.8 N. There are no special German standards for this procedure. Test results cannot be correlated with those of the Vickers test, on account of this lack of standardization.

Shore hardness

This method is primarily used for hardness testing on rubber and soft plastics. The test tool is a steel pin of 1.25 mm diameter; this is forced against the surface of the test specimen by a spring. The subsequent change in the spring length (spring travel) furnishes the basis for determining Shore hardness.

In the Shore D method a pretensioned spring exerts a force of 0.55 N. The tip of the steel pin has the shape of a frustrum (for testing hard rubber). The spring rate c is 4 N/mm.

In the Shore A method, measurement uses a conical steel pin with a rounded tip and no pretension. The spring rate c is 17.8 N/mm. Each 0.025 mm of spring travel corresponds to 100 Shore units.

Ball impression hardness

(DIN 53 456)

This is the standard test for determining hardness levels in elastomers, and is also employed with hard rubber substances. The test tool is a hardened steel ball 5 mm in diameter. It is applied with a minor load of 9.81 N to the surface of the test specimen which must be at least 4 mm thick. Subsequent graduated rises in force provide application pressures of 49, 132, 358 and 961 N. After 30 s the penetration depth is measured and indicated on an analog display. The test load F should be selected to provide a penetration depth h of between 0.15 and 0.35 mm.

Ball impression hardness is defined as the ratio of the applied load to the deformed area in the test surface. It can be read from tables or calculated as follows:

$$\text{Ball impression hardness} = \frac{0.21 \cdot F}{1.25 \cdot \pi \cdot (h - 0.04)} \text{ N/mm}^2$$

F Applied load in N

h Penetration depth in mm

Scleroscope hardness

This dynamic measurement method is specially designed for heavy and large metal pieces. This process is based on the measurement of the rebound height (energy of impact) of a steel indenter (hammer) featuring a diamond or hard metal tip; this is dropped from a stipulated height onto the surface of the test specimen. The rebound serves as the basis for determining the hardness.

The method is not standardized and there is no direct correlative relationship with any other hardness testing method.

Tolerances

Correlations

In the absence of special supplementary definitions, envelope analysis is mandatory for all individual form elements in prints based on standardized DIN definitions for tolerances and fits (e.g. Independence Principle from ISO 8015). The envelope concept is based on the Taylor gauge test, which specifies that maximum intolerance material mass shall not penetrate the geometric envelope at any point.

Because it is not possible to produce geometrically ideal workpieces, dimension limits (dimensional tolerances) are defined for production.

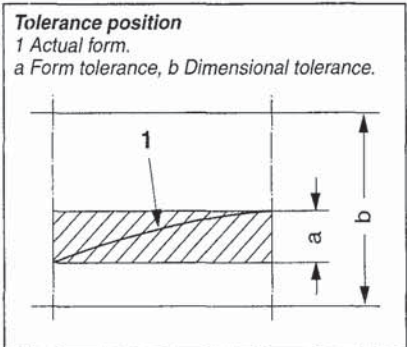
DIN 7167 includes all tolerances of form, including tolerances of parallelism, position and planar regularity as well as dimensional tolerances. The geometrical tolerance may lie anywhere within the dimensional tolerance (see diagram).

For the following tolerances of position the envelope dimension at maximum material dimension is not defined:

Tolerances of perpendicularity, slope, symmetry, coaxiality and concentricity. For these tolerances of position either direct specifications on the drawing or the general tolerances are necessary.

No generally applicable correlative data are defined for the relationship between dimensional tolerance and peak-to-valley height (general formula: $R_z \leq 0.5 \cdot T$).

ISO International Organization for Standardization.



ISO system for limit allowances and fits

ISO tolerance classes are indicated by letters (for basic allowances) and numbers (for basic tolerance grades). The definitions are:

- The **letters** A to Z indicate the position of the tolerance range relative to the base line; small letters for shafts; capital letters for bores.
- The **numbers** 01 to 18 indicate the magnitude of the tolerance grade.

The ISO tolerance ranges for shafts and bores can be combined as desired to give fits; the standard bore and standard shaft systems of fits are preferred.

Standard bore: The basic allowances for all holes are identical, and different fits are obtained by selecting the appropriate shaft sizes.

Standard shaft: The basic allowances for all shafts are identical, and different fits are obtained by selecting the corresponding bore dimensions.

Most common clearance, transition and interference fits can be defined using the following selection of ISO tolerances from ISO 286.

Example for tolerance class: H7
Basic allowance
Tolerance grade

Tolerances of form and position

Tolerances of form and position should be specified only where required (e.g. in response to functional requirements, interchangeability and possible production conditions).

An element's geometrical and positional tolerances define the zone within which it must be located (surface, axis or generating line).

Within the tolerance zone the tolerated element may have any desired form or directional orientation. The tolerance applies to the entire length or surface of the tolerated element.

Symbols are employed when entering the tolerances in prints (see table).

Symbols for tolerated properties

Properties		Symbols
Straightness	1)	
Flatness		
Roundness (circularity)		
Cylindricity		
Profile of any line		
Profile of any surface		
Parallelism	2)	
Perpendicularity		
Slope		
Position	3)	
Concentricity, coaxiality		
Symmetry		
Path	4)	
Overall path		

1) Tolerances of form, 2) Tolerances of direction,
3) Tolerances of location,
4) Running tolerances.

Geometrical deviations

The term “geometrical deviation” refers to all disparities between the actual surface and its ideal geometrical configuration. Critical considerations may be restricted to dimensional deviations, surface irregularities or undulations, or may encompass the entire potential deviation range, depending upon the specified application. To help distinguish between the different types of geometrical deviation DIN 4760 defines a classification system including examples of deviation types and their possible sources:

1st order geometrical deviations

Formal deviations are 1st order geometrical irregularities which can be detected when an entire surface area is examined. Usually, the general relationship between formal deviation intervals and depth is > 1000:1.

Supplementary symbols

Description		Symbols
Identification of the tolerated element	direct	
	with letter	
Identification of the reference	direct	
	with letter	
Reference point		
Theoretically precise dimension		
Projected tolerance zone		
Maximum material condition		

2nd to 5th order geometrical deviations

Undulations, or waviness, are geometrical irregularities of the 2nd order. These essentially periodic irregularities are defined using a representative section of the actual surface area on the geometrical element under investigation. Roughness consists of geometrical irregularities of orders 3 through 5. It is characterized by periodic or irregular formal deviations in which the deviation intervals are a relatively low multiple of their depth.

Surface parameters

Stylus instruments are employed to record sectioning planes of surface profiles, registering vertically, horizontally, and as a function of the two components in combination. The characteristics are derived from the unfiltered primary profile (P profile), the filtered roughness profile (R profile), and the filtered waviness profile (W