

Controlling and Monitoring of the Hot-Stamping Process of Boron-Alloyed Heat-Treated Steels

Dr.-Ing. H. Engels, Dipl.-Ing. O. Schalmin, cand.-Ing. C. Müller-Bollenhagen
Innomotive Systems Europe GmbH, Bergneustadt, Germany

Abstract

Due to steadily rising crash requirements to be met by modern automotive structures, the application of ultra-high strength materials has increased. Hot-stamping is an approach to produce these structural parts. High material strengths may lead to wear problems during the trimming operations following the hot-stamping process. Depending on part geometries, the trimming operation can be integrated into the hot-stamping process. The desired mechanical and surface properties call for an analysis of the effects of process parameters on the above-mentioned part requirements. Accordingly, the feasibility analysis during prototyping has to be distinguished from the analysis of heat treatment and from the analysis of the quenching behavior inside the die. Besides standard destructive testing methods, the magnetic inductive approach seems to be apt for testing the mechanical and technological properties of the parts.

1 Introduction

While an increase in crash requirements can be observed, strong efforts are being made at the same time to reduce the weight of BIWs. It is due to this paradoxon that super-high strength materials are increasingly used for structural and security parts in body construction. Besides conventional cold stamping methods, hot-stamping of boron-alloyed steels (22MnB5) is used to produce the components mentioned above. These boron steels belong to the group of martensitic steels which stand out for their good hardenability at low cooling rates. They allow tensile strengths R_m of up to 1600 MPa, which come along with good toughness properties. Typical fields of application for this technology are e.g. A- and B-pillar reinforcements, roof rails, side-rail members and beams for crash management systems.

Given the required mechanical and surface properties, particularly when dealing with aluminated parent material, the effects of process parameters on the above-mentioned

requirements have to be analyzed in detail. A product-specific feasibility study carried out already during prototyping is just as indispensable as the examination of adequate heat treatment for a given material and a theoretic analysis of the quenching process inside the die.

To begin with, the process of hot-stamping shall be addressed in brief. A classification into direct and indirect processes can be put up.

During the trimming operations which are attached to the manufacturing chain, the preset high strengths can lead to certain problems, which shall be discussed below. Taking them into account, a partial integration of the trimming operation into the hot-stamping process shall be suggested.

Chapter 3 will cover the part-specific process parameters already mentioned, with regard to the mechanical part properties. Optimum mechanical properties can be obtained if the cooling conditions inside the die are modeled according to the TTT diagram. A theoretical approach based on the Finite Elements Method shall be outlined which allows for a thermal analysis of the cooling behavior with regard to the given assumptions and constraints.

The control and validation of process parameters requires laboratory testing of the mechanical properties of the hot-stamped parts. Besides traditional destructive testing methods, the magnetic inductive process seems to be apt to achieve this aim.

2 Hot-Stamping of Boron-Alloyed Steels

The blanks or parts are austenitized at temperatures between 900 °C and 950 °C inside a continuous feed furnace and subsequently brought into the die via a transfer unit. The blanks or parts are then stamped at high strain rates and kept under pressure inside the die after drawing depth is reached. Thereby, controlled cooling and tempering (martensitic transformation) of the material takes place, resulting in a respective increase in strength.

When using uncoated 22MnB5, the heat treatment is carried out under protective atmospheres in order to avoid oxidation (scaling) and surface decarburization. But these effects cannot be avoided during transfer between furnace and die, leading to scale formation at the blank surface due to direct contact with atmospheric oxygen. As scale is characterized by extreme hardness, processing the heated blanks will result in high tool wear. Moreover, cleaning procedures like sand blasting are necessary.

Scaling during the hot-stamping process can be largely avoided by means of surface coating (Al-Si-coating). As to its protective properties, the Al-Si-coating does not equal other coating systems (strip galvanizing), it merely provides better corrosion resistance in combination with additional surface protection measures (cataphoretic painting).

Hot-stamping technologies can be classified into two different categories, namely the direct process and the indirect process.

2.1 Direct Process

The direct process provides for the blanks to be austenitized inside a roller-hearth continuous furnace at temperatures between 900 °C and 950 °C. A transfer unit, e.g. robots or linear feeders, then brings them into the cooled die, where they are stamped at high strain rates. When reaching the bottom dead center or the draw depth, the formed parts are systematically cooled down under pressure, thus remaining inside the die for a specific amount of time according to the sheet thickness. Depending on the blank material, the parts have to be cleaned from surface scales which emerged during transfer from the furnace exit to the die. Subsequently, the parts are trimmed using a laser or the die, thereby subjecting the tools to substantial wear problems. The parts produced with the direct process have to be given a geometry which allows a production in one single forming step.

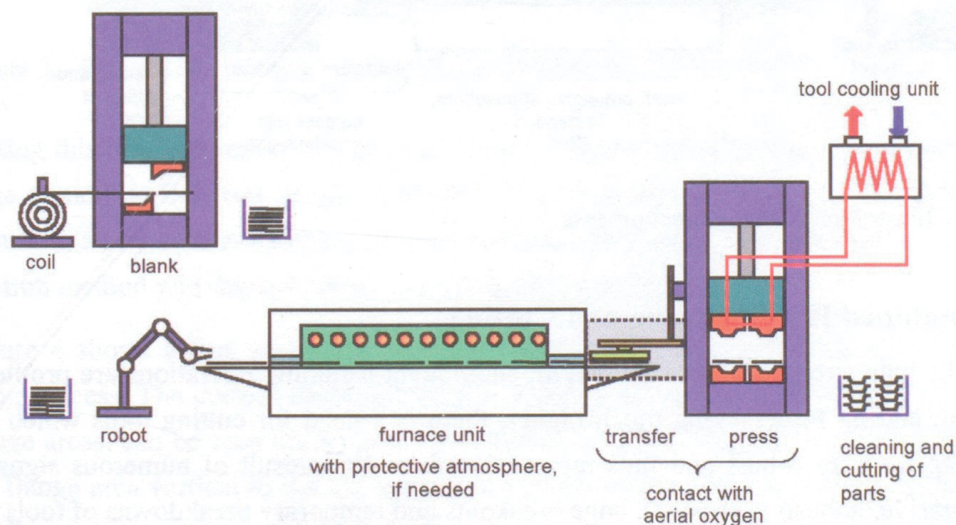


Figure 1. Illustration of the direct hot-stamping process

2.2 Indirect Process

Unlike the direct process, indirect hot-stamping provides for the parts to be deep drawn unheated and in a conventional die, followed by a partial trimming operation depending on the edge tolerance. In doing so, 90 % to 95 % of the final form are obtained. Similar to the direct process, the preformed parts are then brought into a roller-hearth continuous furnace on special charge carriers and austenitized. They are inserted into the hot-stamping die and finally gauged and tempered. The adoption of the indirect process makes it possible to realize more complex geometries, as strain hardening is abrogated by the heat treatment and re-crystallization of the cold preformed parts. The indirect process is restricted to the use of uncoated boron steels, given that a deep drawing procedure in a conventional die would lead to the ripping and flaking of an Al-Si-coating.

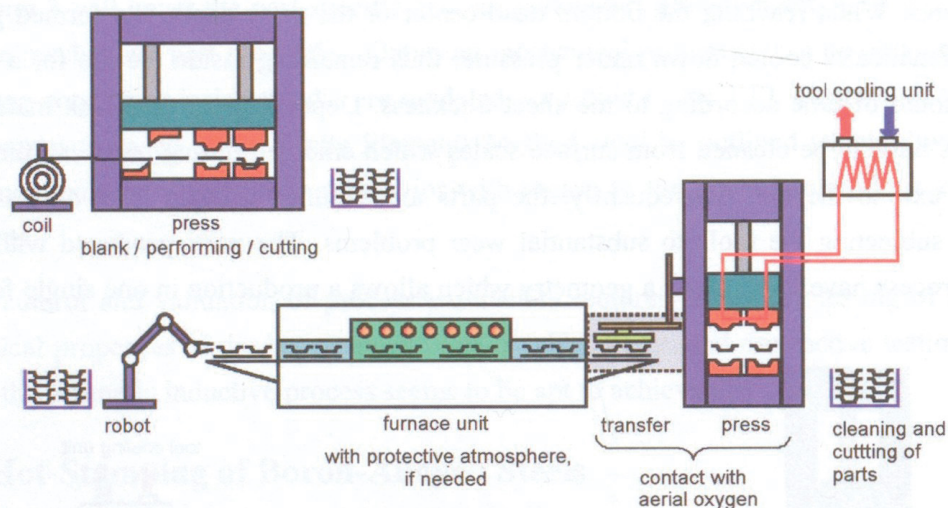


Figure 2. Illustration of the indirect process

2.3 Combined Hot-Stamping and Cutting

Due to the high strength ($R_m > 1300$ MPa), subsequent trimming operations are problematic. With cutting forces being much higher, there is a need for cutting tools which are more rugged, more robust and thus more expensive. As a result of numerous signs of wear (abrasive, adhesive, erosive), edge breakouts and temporary breakdowns of tools are likely to occur. When processing hot-dip aluminum coated parental material, the diffusion layer build up during heat treatment may complicate matters. The adhesive signs of wear shown in figure 3 are typical outcomes of this line-up. Numerous approaches to a

solution to these problems (e.g. PM steels, coating systems) are described in the literature, but will not be discussed in this article.

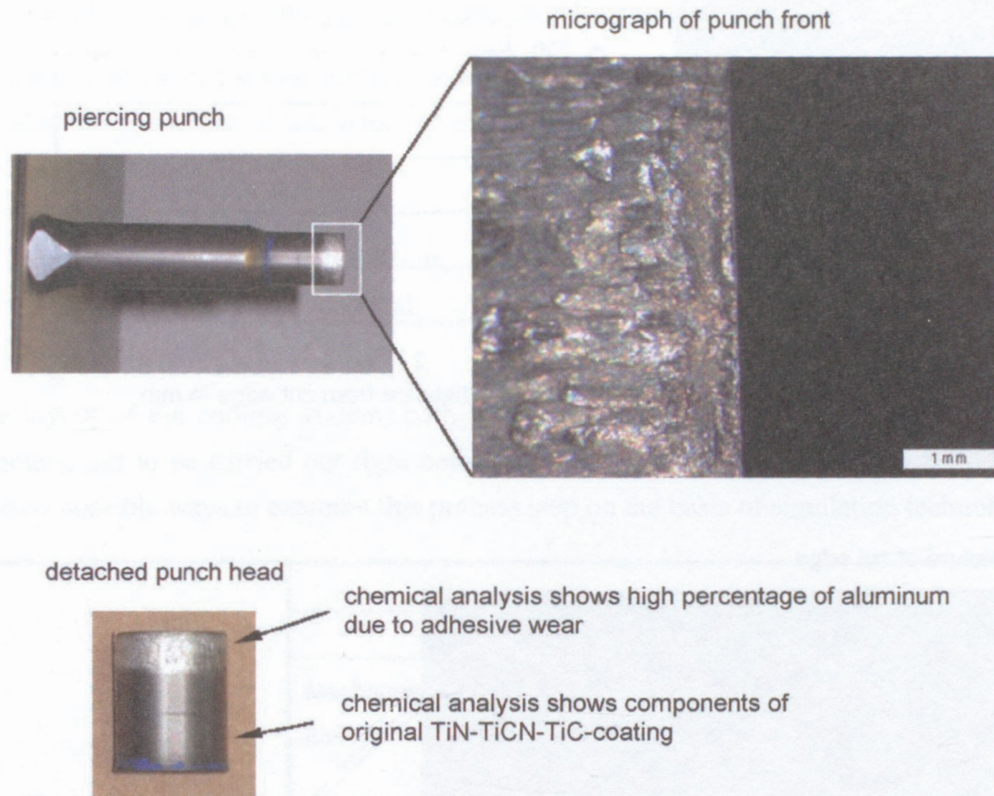


Figure 3. Pictures of a piercing punch, processed Material: USIBOR 1500 P

Taking this into account, it is suggested to merge the two process steps, hot-stamping and edge trimming, into one single operation. This will cut production and tool costs, as trimming after the hot-stamping process becomes redundant. The feasibility of this production method will depend on the part geometry, though.

Figure 4 shows a part which has been the result of a combined hot-stamping and trimming process. The cut-off waste and the hot stamped part, which has been trimmed in the flange areas, can be seen on the left. The distribution of the Vickers hardness HV_{30} across the flange area vertical to the cut edge shows constant hardness values. The lower part of the figure shows a picture of the cut edge.

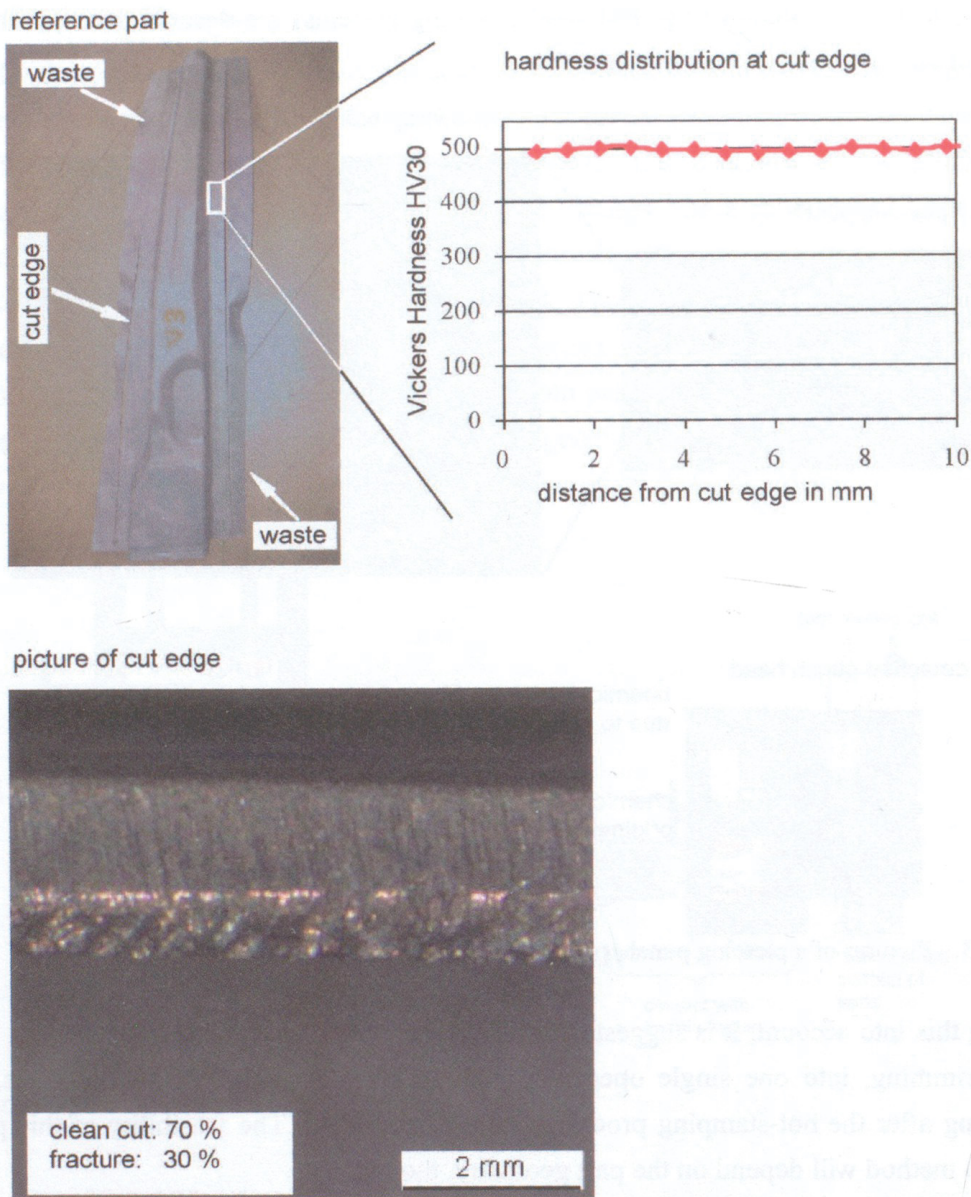


Figure 4. Part produced in a combined hot-stamping and trimming process

3 Part-Specific Process Parameters

As already explained above, the hot-stamping process aims at producing high-strength structural parts with defined mechanical and surface properties. Table 1 is a list of part characteristics and their dependency on the process constraints. Among these constraints are most notably the yield point $R_{p0.2}$, the tensile strength R_m and the elongation at frac-

ture A_{80} (flat tensile specimen). They are directly impacted by the chosen temperature profile of the furnace and the transfer from furnace to die, as well as by the cooling process inside the die. The cooling process itself correlates to the following parameters:

- Design layout of the tool cooling system,
- Material properties of active tool elements in regard to heat transfer
- Flow conditions,
- Forming temperature,
- Temperature of the cooling medium,
- Pressing force / forming load and
- Dwell time inside the die.

The layout of the cooling system, both constructive and with regard to the process parameters, has to be carried out right before the actual tool construction. Chapter 3.2 will discuss possible ways to examine this process step on the basis of simulation technology.

	Part characteristics		
	Mechanical properties	Surface properties	
		22MnB5+AS diffusion layer	22MnB5, oxidation, surface decarburization
Heat treatment			
Temperature profile	X	X	
Protective atmosphere			X
Stamping and tempering			
Transfer time t_T between furnace and die	X		X
Cooling realized according to TTT diagram	X		

Table 1. Part-specific process parameters

3.1 Heat Treatment

The heat treatment of uncoated boron steel is carried out under a protective atmosphere in order to avoid oxidation and surface decarburization. Besides so-called endo- and exo-gases, a nitrogen atmosphere with natural gas added at a 95:5 ratio is being used. This is a non-explosive mixture providing light carburization effects.

When using hot-dip aluminum coated boron steels, it is crucial to look for a correctly shaped diffusion layer with regard to layer thickness, porosity and roughness, as this layer will decisively impact the corrosion and welding properties of the hot stamped parts. The diffusion process is affected by the preset temperature profile of the heating facility.

Thus, these are the parameters which have to be taken into account when setting the temperature profile:

- the heating rate,
- the total processing time,
- the maximum austenitizing temperature and
- the material thickness.

Figure 5 shows a cross-section polish of the diffusion layer of a hot-dip aluminum coated boron steel. Five phases which differ in their layer thickness and chemical composition can easily be distinguished.

phase number	layer thickness, μm	Al	Fe	Si	Cr	Mn
		Volume-%				
1	5 – 9	7,2	89,2	1,9	0,3	1,4
2	< 1 μm	unmeasurable				
3	11 – 18	51,4	45,9	1,9	0,1	0,7
4	3 – 8	33,9	54,3	10,6	0,3	0,9
5	5 - 11	53,2	44,1	1,9	0,2	0,6

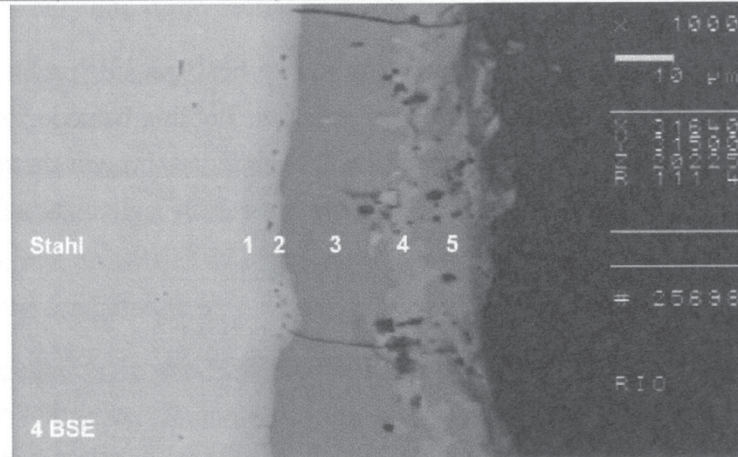


Figure 5. SEM micrograph of a cross-section polish of the diffusion layer

3.2 Simulation of the Cooling Behavior During the Hot-Stamping Process

A holistic simulation of the hot-stamping process has to provide a theoretic representation of the mere forming process and the cooling behavior as well as of the collateral structural changes. The whole process can be divided into two steps.

The first step sees the forming of the hot blank. During the forming process, local temperature gradients occur at the points of contact between lower die or punch and blank or part, respectively. Furthermore, a limited structural change takes place.

When the second step begins, the forming process has finished, with the tool being at its bottom dead center. It is only now that the actual structural change results in a martensitic microstructure due to the reached cooling speed in accordance with the TTT diagram. The present article will thus concentrate on the examination of cooling conditions on the basis of simulation technology.

A homogeneous distribution of part hardness and of the correlated mechanical properties can only be achieved if cooling conditions are equal at every point of the die. The heat quantity absorbed by the die during the cooling process is normally removed by means of

a cooling medium. The cooling medium is introduced to the effective areas via corresponding channels inside the die. Basically, the heat quantity is transferred in two ways. Between part and upper or lower die, heat transfer is carried out as thermal conduction. If the surface is in contact with a fluid, what takes place is called heat transmission via convection. This mechanism is valid for the heat removal from the effective areas of the die by means of a cooling medium.

The mathematic approximate solution of the above heat transfer problem by means of FEM makes it possible to generate forecasts about the cooling behavior of a part at every single point of its geometry. Furthermore, insights obtained through thermal analysis can be incorporated into the design of the cooling system during tool construction.

The general equation for transient heat conduction is /1/

$$\rho c_p \frac{\partial \vartheta}{\partial t} = \lambda \left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2} \right), \quad (1)$$

whereas the thermal conductivity λ is defined as a material constant depending on temperature.

Newton described the convective process defining the heat transmission coefficient as follows /1/

$$\alpha = \frac{\dot{q}}{\vartheta_{\text{Medium}} - \vartheta_{\text{Kontaktfläche}}}. \quad (2)$$

Using the general equation

$$\dot{q} = -\lambda \left(\frac{\partial \vartheta}{\partial n} \right)_{\text{Kontaktfläche}}, \quad (3)$$

the heat transmission coefficient α can be defined as

$$\alpha = \frac{-\lambda \left(\frac{\partial \vartheta}{\partial y} \right)_{\text{Kontaktfläche}}}{\Delta \vartheta}. \quad (4)$$

The heat transmission coefficient α is a parameter which depends on the material properties (λ , c_p), on the parameters (p , $\dot{V}$, w) and on the geometry. Experimentally obtained data is required to generate α .

The predominant flow inside the cooling channels in the case of forced convection can be of laminar or turbulent nature. Heat transfer in turbulent flow is higher than in laminar

flow, as superposition of speeds enables an additional heat exchange upright to the main flow direction.

If the derivatives in relation (1) are replaced by finite differences, the transient heat conduction can be numerically calculated by means of the Schmidt-Binder operation. The influence of convection can be calculated by means of a difference method as well. Equation (5) considers only one-dimensional heat conduction

$$mc_p \frac{dT(t)_i}{dt} = \frac{\lambda A}{s} (T(t)_{i+1} - T(t)_i) - \frac{\lambda A}{s} (T(t)_i - T(t)_{i-1}). \quad (5)$$

The FEM allows for a calculation of a three-dimensional comparative model which considers the temperature dependency of the thermal properties of steels involved in the process. The thermal properties of structural states which exist during the cooling process thus depend on the temperature as well.

The cooling simulation is conducted using LS-DYNA, an explicit and implicit FEM software. LS-DYNA is very common in the automobile industry and is successfully applied to perform explicit impact calculations.

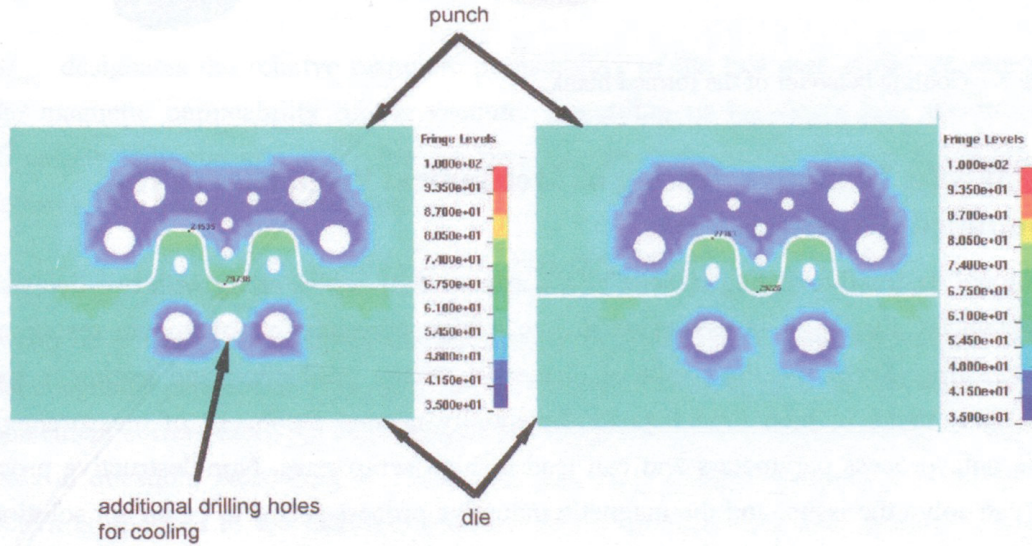


Figure 6. Visualization of temperature distribution inside the die during a cooling process

By means of thermal analysis, drillings during the development phase of the die can be judged by their cooling capacity. The die on the left in figure 6 provides five drill holes,

while the one on the right provides only four. In this case, the additional drilling hole results in a decreased cooling capacity, apart from a lower total flow rate.

Insufficient cooling rates as well as high temperature differences can be detected and corrected. Technical calculation is indispensable when developing a controllable hot-stamping process. The calculations allow for miscellaneous options to optimize the forming process with regard to cooling and thus to production efficiency.

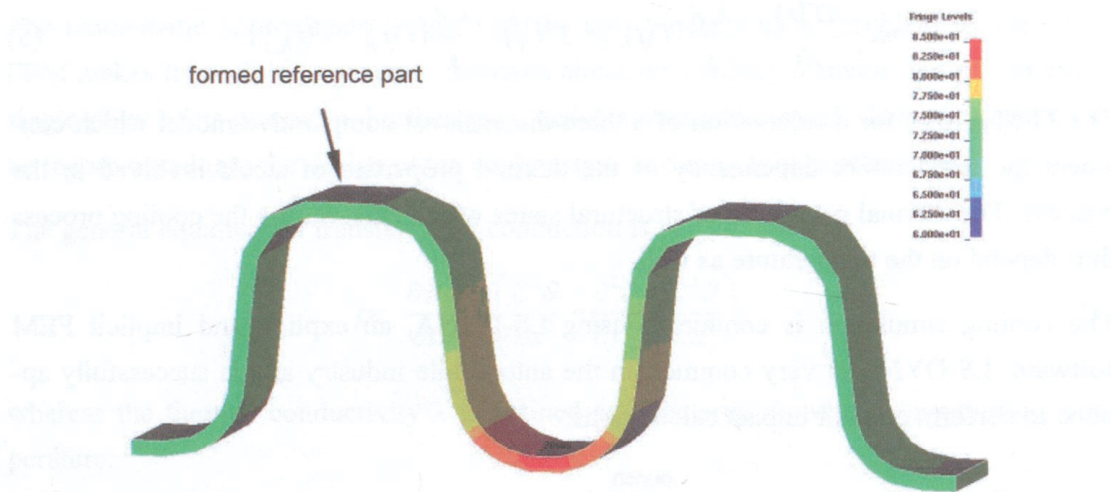


Figure 7. Cooling behavior of the formed blank.

4 Magnetic Inductive Testing of Mechanical Properties of Hot Stamped Structural Parts

Traditional destructive testing (tensile test, hardness test) comes along with two decisive disadvantages. Firstly, it is expensive due to a high consumption of human resources during testing. Secondly, the temporal distance between production and testing is too high. This results in high time lags for potentially needed feedbacks of measurement results onto process parameters and can lead to high scrap rates. Non-destructive processes can solve the issue, and the magnetic inductive process seems to be an apt solution in this case.

4.1 The Operating Principle of Magnetic Inductive Testing

The operating principle of the eddy current method, which is called 'magnetic inductive process' when talking about the low frequency range, shall now be described. Figure 8 gives a schematic illustration of such a measuring device, in this particular case a probe

coil. If a coil is operated with the stimulus current $\vec{J}$ (figure 8, yellow winding), it generates a magnetic field with the field strength $\vec{H}$, which causes an induction $\vec{B}$ in the test part according to the equation $\vec{B} = \mu_0 \mu_{rel} \vec{H} = \mu \vec{H}$.

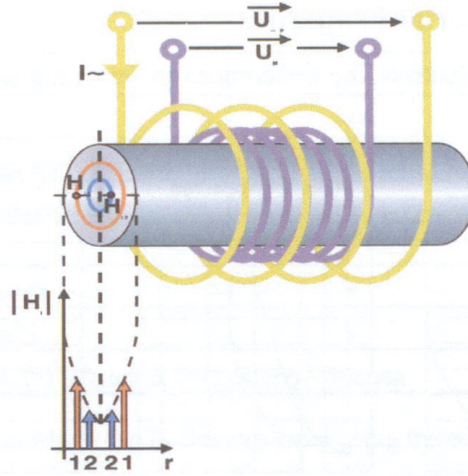


Figure 8. Magnetic inductive testing with a probe coil /3/

μ_{rel} designates the relative magnetic permeability of the test part, while μ_0 represents the magnetic permeability of the vacuum. According to Faraday's law, the induction $\vec{B}$ causes eddy currents inside the test part. For the eddy current density in the test part follows from Maxwell's equations:

$$\text{rot } \vec{J}_W = -i\sigma\mu_0\mu_{rel}2\pi f\vec{H}$$

It can be noticed that the eddy current density depends on the electrical conductivity σ , the magnetic permeability μ_{rel} and the measurement frequency f . In this case, the displacement current has been neglected due to the good electrical conductivity of the materials in question. According to Lenz' rule, the eddy currents generate a magnetic field which is opposed to the external magnetic field. By measuring the superposition of the external and the eddy current magnetic field, information about the test material can be retrieved from this cumulative field. For the most part, the impedance (reactance and effective resistance) of the secondary coil (red in figure 8) is measured. Since the impedance depends on the variation of the magnetic field and thus as well on the eddy current density inside the test part, the measurement results depend on the parameters μ_{rel} , σ , f and on the geometry of the test part. The magnetic inductive process provides for a compari-

son of the part's properties with those of reference parts which have been analyzed earlier. Thus, the measuring device has to be calibrated systematically before the test on the basis of good and bad parts.

4.2 Hysteresis and Material Properties

The hysteresis curves can illustrate the differences in ferromagnetic properties (Figure 9, middle):

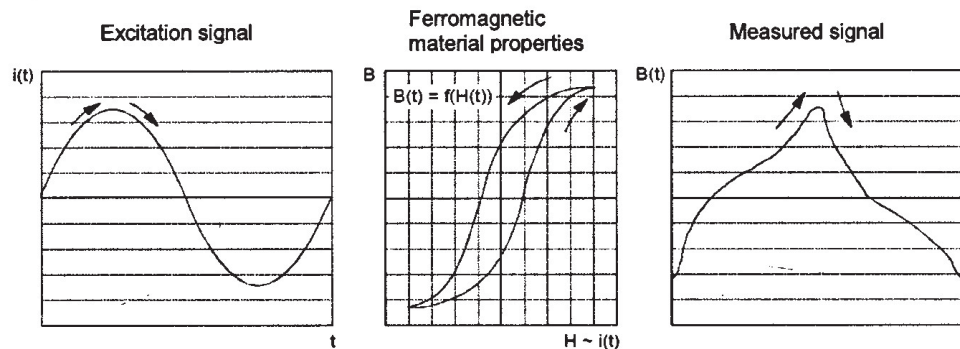


Figure 9. Hysteresis curve causing a signal distortion /5/

It demonstrates the course of the magnetic induction B of a test part in an increasing and in a decreasing magnetic field H and thus defines some important magnetic parameters. Figure 9, middle, illustrates that the hysteresis curve causes the distortion between exciting signal and measured signal.

The unequal magnetization of ferromagnetic materials which can be observed in the hysteresis curve is due to elementary magnets which are aligned homogeneously in the so-called Weiß districts of the material. If the material is brought into the effective area of a light magnetic field, the elementary magnets in Weiß districts which are aligned favorable to the effective direction of the field will change their orientation into field direction. If the magnetizing force is increased, more and more energy will be needed to align other elementary magnets into field direction, until finally all of them show into the same direction (saturated magnetization state). Similar to other mechanical properties, this effect depends on the crystal lattice structure, on imperfections, on inclusions etc. Different materials, or even equal materials with different properties may show different permeabilities and conductivities which can be demonstrated by means of magnetic induction (see table 2).

Material properties	Conductivity σ	Permeability μ
Chemical composition	++	+
Mixed crystal composition	+	+
Structure, grain size	-	++
Precipitations	-	++
Inclusions, voids	-	+
Inner splits	+	++
Lamellar tearing, anisotropism	-	+
Stress corrosion cracking	+	+
Deformation	-	+
Δ -ferrite in austenite	+	++
Dendrite in steel	-	-
(-) No influence, (+) Influence, (++) Strong influence		

Table 2. Material properties which can be demonstrated using the eddy current system, Becker /6/

Strength and hardness are determined by material properties as well (structure, grit size, alloy). Therefore, these values can be checked indirectly as well using the magnetic inductive process. To some extent, statistical correlation analysis or neural networks can enable a combination of mechanical and magnetic part properties and thus allow for a quantitative determination of strength and hardness values. This is the case e.g. in thin sheet production, where strength and hardness can be determined online /7/. But this does not aim primarily at the determination of strength and hardness values, but on a review of the heat treatment process and of the structural state. Even tensile and hardness tests can only check these values indirectly.

4.3 Testing the Applicability of the Process

In order to test whether the magnetic inductive process is appropriate to ensure the hot-stamping process, some experiments with A₈₀ tensile bars made from 22MnB5 were carried out. Based on these bars lasered from hot-stamped automotive structures, the influence of disturbances and the traceability of different heat treatment processes were examined using a magnetic inductive multi-frequency test. As a result, the following disturbances were found to have major influence: part geometry, relative shifting of the part with regard to the coil, and part temperature. Different heat treatments and structural states may be recognized using the eddy current test.

Moreover, it could be observed that an exploitation of harmonic waves can reduce the influence of the disturbances mentioned above to a significant degree. Precisely the complex geometries of automotive structures which are partially subjected to tolerances (radii, cut-outs, flowing edges etc. have less impact on the harmonic wave than on the fundamental wave. Harmonic waves result from distortion of the exciter signal due to the non-linearity of the hysteresis curve (see Figure 9). Higher-frequency parts of the harmonic waves emerge, in which the measure signal can be splitted using the fourier series /5/.

The performed tests have shown that the magnetic inductive process is a non-destructive testing device which can be realized. With regard to the benefit of measuring results being immediately available, an integration of this testing method into the hot-stamping process could be considered.

References

- /1/ Richter, H. Wärmeübertragung. Skript, FH Giessen-Friedberg, 2003
- /2/ Strelow, O. FH Giessen-Friedberg
- /3/ Institut Dr. Foerster GmbH & Co KG, Reutlingen
- /4/ Zielke, R. Verbesserung der lateralen Auflösung der Wirbelstromprüfung durch Entwicklung magnetooptischer Sensorsysteme. Dissertation, Dortmund, 2004
- /5/ Weber, W. Zerstörungsfreie Prüfung dickwandiger austenitischer Rohre und Rohrbögen mit fortschrittlicher Wirbelstromtechnik. Dissertation, Hannover, 2002
- /6/ Becker, R. Über die Prüfung auf Fehler in metallischen Werkstoffen und Bauteilen mittels eines zerstörungsfreien Mehrfrequenz-Wirbelstrom-Prüfverfahrens. Dissertation, Saarbrücken, 1980
- /7/ Reimche, W. Online-Materialcharakterisierung und Überwachung relevanter
Heutling, B. Bandeigenschaften von feuerverzinktem Stahlblech im
Bach, F.-W. Produktionsfluss mit einem Harmonischen-Messsystem. In:
DACH-Jahrestagung Salzburg, 2004