

Hot Stamping of USIBOR 1500 P: Part and Process Analysis Based on Numerical Simulation

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Abstract

The amount of ultra high strength hot-stamped boron steel is rapidly increasing in automotive bodies-in-white. Indeed, this material and the related hot stamping technology allow reaching strength levels (1500 MPa) which are far above those of best-in-class cold stamping steels. Moreover, the traditional balance between high strength, low formability and high springback is outruled by hot stamping.

General market trends of hot stamping are discussed and an overview of the main parameters defining the process window of hot stamping is given. A test device has been set up to determine the formability limits of USIBOR 1500 P in hot stamping. The methodology for FE-analysis of hot stamping is presented and the flow chart of a typical feasibility study, as realised by Arcelor for its customers, is described.

1 Hot Stamping of USIBOR 1500 P

1.1 Process Description

The principle of operation of hot-stamping is intimately linked with the opportunities offered by the chemical composition of boron steels (Figure 1), resulting in a robust process window for quenching and martensitic transformation. Hot-stamping consists in heating blanks until complete austenitization (900°C to 950°C, during 4 to 10 minutes). The blanks (Figure 7) are then transferred very quickly on a press for the stamping. At high temperature (650°C to 850°C), the material has an excellent formability and thus quite complex shapes can be formed in a single stroke.

C	Mn	Si	Cr	Ti	B
0,25	1,4	0,35	0,3	0,05	0,005

Figure 1. Chemical analysis of Usibor 1500 P (Maximum- %)

The quenching (martensitic transformation, see Figure 5) is carried out just after the forming, the heat being absorbed by the closed die (cooling speed between 50°C/s and 100°C/s).

The total cycle time (transfer + stamping + cooling in the die) lies today between 15 s and 25 s. At the exit of the stamping line, the parts leave at approximately 150°C, with their final, repeatable and homogeneous mechanical properties: an ultimate tensile strength of 1400 MPa to 1600 MPa and a yield strength between 1000 MPa and 1200 MPa (Figure 2).

UTS	YS	El% (A5)	El% (ISO 20x80)	HV _{10kg}
1500 MPa	1100 MPa	9%	6%	480 HV

Figure 2. Typical mechanical properties of USIBOR 1500 P after hot-stamping and die quenching

Besides the good formability of the hot material, another main advantage of hot stamping is that the part exhibits no springback. This is a unique benefit, given the high level of mechanical properties that can be achieved on the final part.

1.2 Uncoated and Coated Boron Steel

When using uncoated boron steel (bare cold-rolled or pickled hot-rolled), an irregular and abrasive scale layer (iron oxides) forms on the blanks during transfer to the press and forming, even when protective atmospheres are used in the furnace. Moreover, it is generally impossible to avoid some superficial decarburization (up to 60 µm) which is harmful for the final properties of the parts. Thus, after hot stamping, these parts have to be shot-blasted or sand-blasted in order to get rid of the scale layer. This shot-blasting is costly and can be detrimental for the geometrical tolerances of thin parts.

Usibor 1500 P^{®1}, developed by Arcelor, is a precoated boron steel, with a metallic coating of aluminium-silicon ("Alusi": 90% of Al) of approximately 25 µm/side or

¹ USIBOR[®] is a registered trademark belonging to the Arcelor Group and protected throughout the world. Furthermore, Arcelor Group has filed numerous patents covering the principle of direct or indirect hot-stamping process of either aluminized-coated steel sheets and zinc or zinc-alloy coated steel sheets, and of the issued parts.

75 g/m²/side (Figure 3). During the heat treatment in the furnaces, this protective coating is transformed into an alloyed layer made of Fe-Al-Si, blue or gray, highly adherent on the substrate and with good corrosion properties (Figure 4).

The hot-stamped parts in Usibor 1500 P are directly ready to be painted (no scale, therefore no shot-blasting). They have excellent geometrical tolerances and don't show any decarburization (protective effect of the coating in the furnaces).

The technical and economic advantages of Usibor 1500 P are numerous for the manufacturers and the hot-stampers. The suppression of the inert atmospheres (e.g. nitrogen) in the ovens and the suppression of shot-blasting on the final parts allow saving time and money. Finally, the parts don't need any expensive protective post-coatings like zinc paintings.

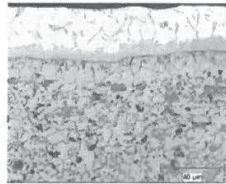


Figure 3. Structure of the Al-Si coating before hot-stamping (Usibor 1500 P)

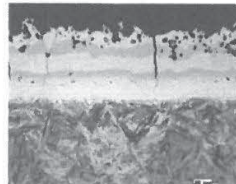


Figure 4. Structure of the alloyed layer Al-Fe-Si after hot-stamping

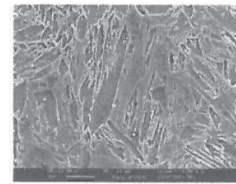


Figure 5. Martensitic structure after hot-stamping (SEM picture)

1.3 Market Trends

Hot stamping with die-quenching of flat boron steel appeared at the end of the nineties for some rather simple automotive parts like door-beams or bumper beams. Today, this forming process shows an exceptional development and growth for several kinds of structural parts (Figure 6). The technical and organizational difficulties inherent to the introduction of such a breakthrough material and technology are outweighed by the opportunities offered to the car designers in their struggle for crashworthiness, weight saving and control of cost /1/, /2/. The huge majority of the car manufacturers are specifying hot-stamped parts for their new vehicles. New hot-stampers appear on the market and several new lines are being built throughout the world /3/.

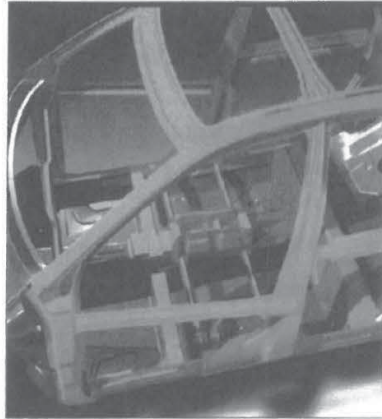


Figure 6. Applications of hot stamped structural parts in the BIW

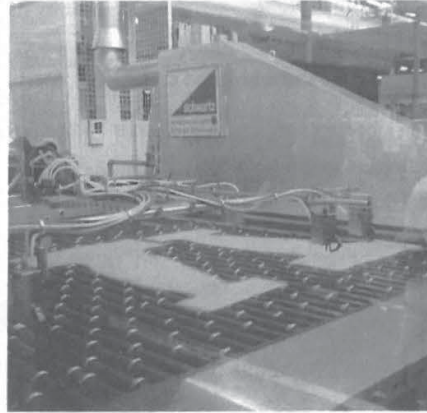


Figure 7. B-pillar blanks at the exit of the furnace just before hot-stamping
(source: VW)

The automotive parts concerned today by hot-stamping are numerous: front or rear bumpers beams, A-pillars (or reinforcements), B-pillars (or reinforcements), roof-rails, A-frames, sills, side-rail members, tunnels, floor-reinforcements, door-beams... Some new concepts are in development like hot-stamped patchworks or hot-stamped tailor-welded-blanks (laser TWB).

The estimated total consumption of flat boron steels for hot-stamping and die quenching was about 60.000 – 80.000 t/year in Europe in 2004. In 2008-2009, this consumption will strongly increase in Europe, up to 300.000 t/year (see Figure 8). The same trend is observed in Japan and in North-America. More than 20 new hot-stamping lines will be built between 2004 and 2009. Some OEMs, like VW, have strongly invested in this technology.

	2004	2009
Hot-stamping lines in Europe	15	40
Hot-stampers in Europe (incl. OEMs)	3	9
Hot stamped B-pillars in European car models	7	20
Hot-stamped B-pillars in European car models produced in Usibor 1500 P	0	11

Figure 8. Forecast growth of hot stamping in Europe

Thanks to its many advantages (corrosion, no shot-blasting, no protective atmosphere in the furnaces, no post-coating...), the precoated solution, Usibor 1500 P, is more and more specified and used in the new European and US cars. For example, Usibor 1500 P is used for the pillars and sills of the new VW Passat (Figure 9 and Figure 10) and of the Mercedes Class S, for A-pillars of Landrover cars, bumper-beams of the Ford Mustang... A similar trend can be observed in Japan.



Figure 9. Hot-stamped parts made in Usibor 1500 P in the VW Passat (source: VW)



Figure 10. B-pillar of the VW Passat

2 Main Influencing Process Parameters

When designing a hot stamping process, and choosing the corresponding machine technology, particular attention has to be paid to factors directly influencing the part quality, the cycle time and the process stability. All three factors significantly impact the cost effectiveness of the process.

2.1 Transfer Time

The transfer time between the furnace and the die has to be reduced as much as possible. Indeed, the temperature loss of the blank can be as high as several tens of °C/s, depending on the blank thickness, and a too low forming temperature can cause troubles:

- Reduced formability of the material (see 3.3)
- Local occurrence of phase transformation during forming, leading to discontinuities in material behaviour and potential strain localization
- High friction or even galling in bending areas (e.g. die radius)
- Powdering of the alloyed Al-Fe coating

2.2 Heat Treatment

The heat treatment of the blank in the furnace should be conducted so as to respect the kinetics of the austenitic transformation /4/ and of the intermetallic alloying reaction between the AlSi-coating and the iron substrate of the blank. A too rapid heating of the blanks can cause the melting of the AlSi-coating and deposition of metal onto the rolls. A too short dwell time in the furnace bears the risk of incomplete alloying of the coating and thus adhesion between the residual Al-layer and the tool material, leading to build-up and galling. Recommendations are given by Arcelor concerning the process-windows for heat-treatment of Usibor 1500P.

2.3 Forming Speed

The forming speed should be high enough to limit the heat exchange between the blank and the tool during forming. Strain rate effects on the material behaviour need also to be considered.

2.4 Die Design

As in any forming process, the die design is a key know-how for an efficient production process, requiring both high technical expertise and at the same time good practical skills on the shop floor. This issue is particularly crucial for hot stamping, as an additional difficulty has to be handled: heat transfer. The die has to absorb and evacuate a significant amount of energy (up to 100 kW) through integrated cooling devices. This puts high stress especially on the surface layers of the tool which are submitted to a thermal gradient in the order of 25°C/mm.

As far as the tool material is concerned, a compromise must be found between good wear resistance over a wide range of temperature and good thermal conductivity. Standard cold forming steels (e.g. X160CrMoV12), plastic mould steels and hot work steels can be found in industrial hot stamping tools. An increasing content of alloying elements (Cr, Mo, V) has a positive effect on the hardness but rapidly pulls the heat conductivity under 20 W/m/K. That is why concepts with local segments made of different tool materials can be a good solution for tailoring the properties to the needs.

Coatings (e.g. TiAlN or CrVN) may help to increase the resistance against abrasive wear and galling /5/. Exploratory R&D-work is ongoing for developing alternative tool materials based on non-ferrous-alloys with much higher heat conductivity.

3 Formability of USIBOR 1500 P

3.1 Introduction

In cold sheet metal forming, it is usual to describe the formability of a material by its forming limit curve. Its experimental determination and conditions of validity or applicability have been widely studied and feasibility studies by FEA are nowadays based on the comparison between the computed strain distribution and the FLD, complemented by some other criteria (e.g. wrinkling). Quite a lot of knowledge is today available to interpret strain distributions on stamped parts with respect to the FLD, and to cope with conditions where the FLD is not strictly applicable (bending, cut edge, etc.).

If we want to keep the same formalism for hot stamping, at least one other dimension (temperature) needs to be added to the strain state (ϵ_1, ϵ_2), and it has to be checked in which manner strain rate, strain and temperature histories as well as strain or temperature gradients influence the local necking or fracture. Work is in progress to develop and study the experimental, theoretical and numerical aspects of the formability in the hot stamping process.

3.2 Failure Analysis

Different hot stamping tests have been carried out to analyse the necking and the fracture of a failed part. During hot stamping, strain localisation usually happens in quite hot areas of the blank, transmitting forming load between relatively cool areas, e.g. in vertical walls between the punch nose and the die radius. Strain localization is intimately linked to temperature and thus ductility gradients around the considered zone.

In Figure 11a, we observe a cross section of a fractured zone: the thinning appears in both a concentrated and continuous manner close to the fracture region. In addition, it seems to be symmetrical with respect to the blank middle line. On the tip of the fractured zone (Figure 11b), the intragranular microvoids are characteristic of a ductile fracture.

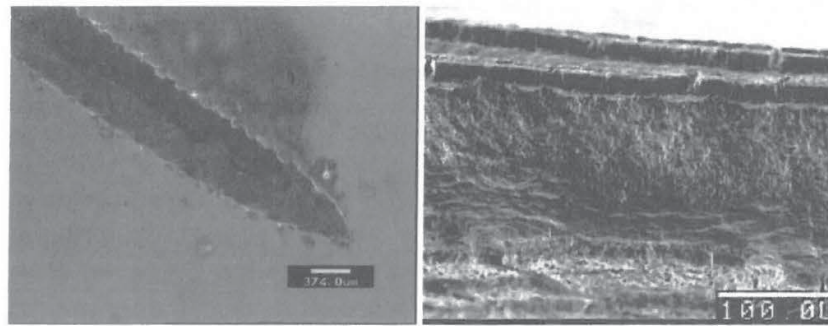


Figure n° 11a and 11b. Binocular cross section (left) and SEM front view (right) of the fracture zone

3.3 Formability Tests

To get experimental formability data, hot stamping tests have been carried out with a modified Nakazima test. The temperature and strain distribution measurements have been made using respectively pyrometers and pattern recognition systems. In parallel, a numerical model of the hot stamping process has been developed with the FE-software Forge2[®] and Forge3[®]. The strain distributions obtained from numerical simulations have been compared to the strains given by Aramis[®] or Asame[®].

The experimental determination of formability limits has to accurately handle several effects such as heat transfer (anisothermal process), phase transformation (unstable austenitic structure), stress triaxiality (bending strains), strain rate sensitivity (viscoplastic behaviour) and strain path (blank shape and friction). These parameters are changed by varying the process time, the initial blank temperature, the thickness and the blank shape in order to analyse their respective influence on the formability. Only the influence of the blank shape and the blank initial temperature will be detailed in the following.

We have carried out several hot stamping tests by varying either the initial temperature of the blank (Figure 12) or the blank width (Figure 13). Each stamped blank is then analysed and classified according to the blank damage.

3.3.1 Temperature

Varying the initial blank temperature from 600°C to 800°C allows us to analyse the influence of temperature on formability: the higher the initial blank temperature, the

higher the maximum punch stroke. According to these experimental results and for the given process conditions, a 27 mm stroke is feasible only if the initial blank temperature is higher than 720°C. Below this temperature, necking and fracture in the critical zone of the blank are strongly probable.

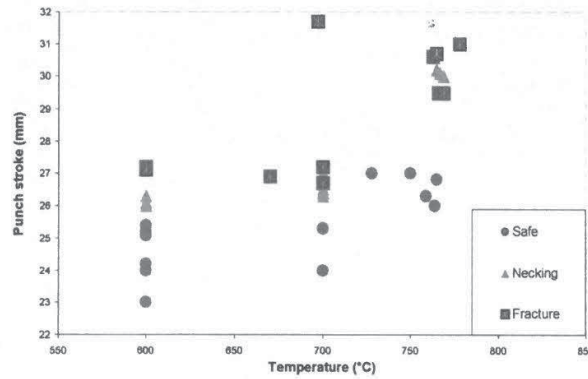


Figure 12. Influence of the initial blank temperature on the limiting punch stroke

3.3.2 Strain State

In Figure 13, we visualise the punch stroke as a function of the blank width for safe, necked or fractured blanks. The formability is strongly dependent on the blank width: the larger the blank width, the lower the critical punch stroke. This observation is mainly due to the shifting of the strain state in the critical region towards uniaxial tension with decreasing blank width.

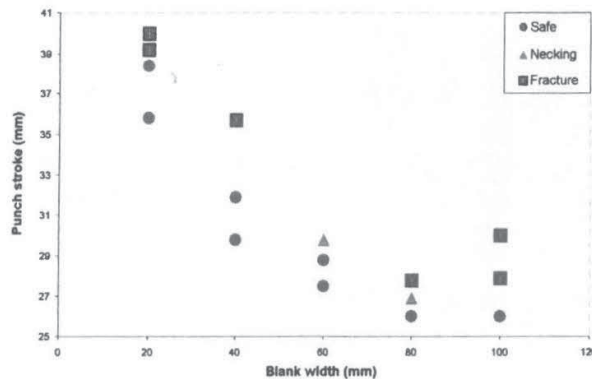


Figure 13. Influence of the blank width on the limiting punch stroke

4 Steps of a Numerical Feasibility Analysis for Hot Stamping

Generally speaking, a FE-based feasibility study for a hot stamped component is a sequence of calculation runs with increasing accuracy, but also with increasing complexity and time to result.

4.1 One-Step Calculation

By standard commercial one-step solvers, a strain distribution can be calculated on the CAD-geometry of the part. This information is helpful to detect severe forming difficulties and to suggest changes in the part geometry.

Of course, as neither material behaviour, nor heat exchange nor addendum surfaces are taken into consideration, the diagnosis relies mainly on the expertise and accumulated knowledge of the designer.

The shape of the initial blank is an important output of this calculation and first cost calculations can be started based on it.

4.2 Isothermal FE-Analysis

Switching to standard finite element simulation software for forming calculations is the next step. Plastic material flow and friction are modelled but the heat transfer is not considered. The flow curve describing the rheology of the material, and especially the

hardening behaviour, needs to be carefully adapted to the temperature level of the process.

In fact, the added value of such an isothermal calculation also highly depends on collected knowledge and detection of analogies with previous cases, and it is often merely a model check performed to prepare a smooth run of the anisothermal calculation. Satisfying accuracy can be reached for shallow parts (e.g. door beams or roof stiffeners), thick gauges and very high forming speeds.

4.3 Coupled Thermo-Mechanical Calculation

For complex structural parts, a full thermo-mechanical calculation is very helpful to make a final validation of the geometry of the part and of the forming process layout. It takes into account the coupling effects between the deformation of the material and the heat transfer and reacts very sensitively to contact conditions with the cold dies /6/, /7/. Indeed, temperature and strain gradients are accurately modelled, including their mutual influences, which is not the case for the isothermal calculation. Figure 14 demonstrates with the example of a B-pillar (first calculations motivating part and process modifications) that the isothermal calculation generally underestimates the strain level in the critical zones, can be misleading on the predicted location of the split and does not always allow for a conservative assessment of the feasibility for a complex part.

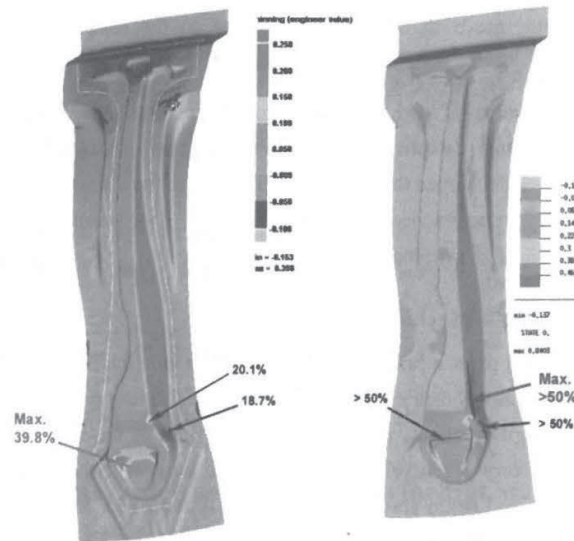


Figure 14. Comparison of the calculated thickness reduction for a B-pillar with an isothermal calculation (at 700°C, left) and with an thermo-mechanical calculation (right)

Because of the high sensitivity of the forming process to temperature gradients, it is of interest to include in the simulation the waiting phase (blank lying on the lower die while the upper die approaches) /8/. For certain applications, even the quenching phase (closed die) can be simulated in order to follow the martensitic transformation and estimate the cycle time after which the part can be safely withdrawn from the die.

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