Hot stamping of ultra high strength steel:
A key technology for lightweight automotive design

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Overview

- Introduction
- Material and coating
- Heating
- Forming and quenching
- Thermo-mechanical behavior
- Subsequent processing
- Hot stamped parts with tailored properties
Overview

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Why Hot-stamping?

Standard Requirements

- CO₂ emission
- Security
- Corrosion protection

Customers expectations

- Weight reduction
- Security
- Durability
- Ultra High Strength Steels (UHSS)
- Pre-coated steels

Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010
Main properties after hot stamping

- No spring-back
- Complex geometries
- Very high Strength (1500 MPa)

Hot-stamped "Boron steels"

Properties in-use:
- TS = 1400-1600 MPa
- YS = 1000-1200 MPa
- E% = 5%

Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010
Steel sheet concept for automotive parts

2010 The new Mercedes-Benz E-Class

Steel sheet concept for automotive parts

- Ultra High Strength Steel
- Extra High Strength Steel
- Very High Strength Steel
- High Strength Steel
- Mild Steel / Forming grades
- Aluminium

2011 Volvo V70 Body Structure

Steel sheet concept for automotive parts

Audi A3
Karosseriematerialien
Materials in the body structure
04/12

- **Ultrahochfeste Stähle (warmumgeformt)**
  Ultra-high strength steels (hot-formed)
- **Höchstfeste Stähle**
  Higher strength steels
- **Hochfeste Stähle**
  High-strength steels
- **Weiche Stähle**
  Soft steels
- **Aluminium-Blech**
  Sheet aluminium
- **Aluminium-Profil**
  Aluminium section

2012 Audi A3 body Structure

Source: http://carskeleton.blogspot.com/2012_04_01_archive.html
Steel sheet concept for automotive parts

Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010
Hot Stamping Demand

Source: Neugebauer et al. 2012

Increase by a factor of 2.8
Variants of hot stamping process

**Direct hot stamping**
- Blank
- Austenitization
- Transfer
- Forming and quenching
- Part

**Indirect hot stamping**
- Blank
- Cold pre-forming
- Austenitization
- Transfer
- Calibration and quenching
- Part

Source: Karbasian and Tekkaya 2010
Direct hot stamping

Advantages:
- Saving cost of pre-forming
- Accelerating production rate
- Blank is flat which not only saves heating area and energy, but also can be heated by a variety of heating methods.

Disadvantages:
- It cannot be used for forming automobile parts with complex shapes.
- Laser cutting facilities are needed.
- Design of cooling system for stamping dies is more complex.

Source: P. Hu, N. Ma, L.Z. Liu and Y.G. Zhu 2013
Indirect hot stamping

Advantages:

• Producing parts with complex shape is possible.
• Ensuring the martensitic microstructure of the blank followed by complete quenching.
• Blank can be previously processed by trimming, flanging, punching and other processing after being pre-formed so that it will be easier for processing after it is quenched.

Source: P. Hu, N. Ma, L.Z. Liu and Y.G. Zhu 2013
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22MnB5

**Chemical composition**
(in percent by weight)

<table>
<thead>
<tr>
<th>Element</th>
<th>min.</th>
<th>max.</th>
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</thead>
<tbody>
<tr>
<td>C</td>
<td>0.220%</td>
<td>0.250%</td>
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<tr>
<td>Mn</td>
<td>1.200%</td>
<td>1.400%</td>
</tr>
<tr>
<td>Si</td>
<td>0.200%</td>
<td>0.300%</td>
</tr>
<tr>
<td>P</td>
<td>0.020%</td>
<td>0.050%</td>
</tr>
<tr>
<td>S</td>
<td>0.005%</td>
<td>0.050%</td>
</tr>
<tr>
<td>Al</td>
<td>0.020%</td>
<td>0.050%</td>
</tr>
<tr>
<td>Ti</td>
<td>0.020%</td>
<td>0.050%</td>
</tr>
<tr>
<td>Cr</td>
<td>0.110%</td>
<td>0.200%</td>
</tr>
<tr>
<td>B</td>
<td>0.002%</td>
<td>0.0035%</td>
</tr>
<tr>
<td>Mo</td>
<td>0.100%</td>
<td>0.100%</td>
</tr>
<tr>
<td>Cu</td>
<td>0.100%</td>
<td>0.100%</td>
</tr>
<tr>
<td>Ni</td>
<td>0.100%</td>
<td>0.100%</td>
</tr>
</tbody>
</table>

**Mechanical properties**

1) YS – 1000 MPa
TS – 1500 MPa
Elongation – < 6%

**Microstructure**
(delivery state, untreated):
The 22MnB5 steel in cold formed state usually has a ferritic-pearlitic microstructure with carbide precipitations, and a typical grain size of > 10 ASTM.

**After hot stamping:**
YS – 1000 MPa
TS – 1500 MPa
Elongation – < 6%
Microstructure – Martensite

Source: Salzgitter Flachstahl 22MnB5 Edition: 07/07
Ultra High Strength Steels (UHSS)

Source: Karbasian and Tekkaya 2010 and Geiger 2008
Ultra High Strength Steels (UHSS)

<table>
<thead>
<tr>
<th>Steel</th>
<th>Al</th>
<th>B</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>N</th>
<th>Ni</th>
<th>Si</th>
<th>Ti</th>
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</thead>
<tbody>
<tr>
<td>20MnB5</td>
<td>0.04</td>
<td>0.001</td>
<td>0.16</td>
<td>0.23</td>
<td>1.05</td>
<td>-</td>
<td>0.01</td>
<td>0.40</td>
<td>0.034</td>
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<tr>
<td>22MnB5</td>
<td>0.03</td>
<td>0.002</td>
<td>0.23</td>
<td>0.16</td>
<td>1.18</td>
<td>0.005</td>
<td>0.12</td>
<td>0.22</td>
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<td>8MnCrB3</td>
<td>0.05</td>
<td>0.002</td>
<td>0.07</td>
<td>0.37</td>
<td>0.75</td>
<td>0.006</td>
<td>0.01</td>
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<td>27MnCrB5</td>
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<td>0.002</td>
<td>0.25</td>
<td>0.34</td>
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<td>0.004</td>
<td>0.02</td>
<td>0.21</td>
<td>0.042</td>
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<td>37MnB4</td>
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<td>0.001</td>
<td>0.33</td>
<td>0.19</td>
<td>0.81</td>
<td>0.006</td>
<td>0.02</td>
<td>0.31</td>
<td>0.046</td>
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</table>

<table>
<thead>
<tr>
<th>Steel</th>
<th>Martensite start temperature in °C</th>
<th>Critical cooling rate in K/s</th>
<th>Yield stress in MPa</th>
<th>Tensile strength in MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>As delivered</td>
<td>Hot stamped</td>
</tr>
<tr>
<td>20MnB5</td>
<td>450</td>
<td>30</td>
<td>505</td>
<td>967</td>
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<tr>
<td>22MnB5</td>
<td>410</td>
<td>27</td>
<td>457</td>
<td>1010</td>
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<tr>
<td>8MnCrB3</td>
<td>-</td>
<td>-</td>
<td>447</td>
<td>751</td>
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<td>27MnCrB5</td>
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<td>20</td>
<td>478</td>
<td>1097</td>
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<tr>
<td>37MnB4</td>
<td>350</td>
<td>14</td>
<td>580</td>
<td>1378</td>
</tr>
</tbody>
</table>

* There is no possibility to have fully martensitic microstructure.

Source: Karbasian and Tekkaya 2010
Uncoated 22MnB5 sheet

First applied for automotive parts by company HARDTECH (today GESTAMP-HARDTECH) in Sweden

Coldstamping
(Could be eliminated for simple parts)

Heating
Protective Gas Atmosphere

Hot Stamping

Sand blasting

Scale formation on uncoated material

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
Pre-coated USIBOR1500P is used for direct hot stamping. It is metallic coating, that first realized by TKS-SOFEDIT and developed for the first serial hot stamping by ARCELOR MITTAL. The coating is generated in a continuous hot-dip galvanizing process and consists of 10% Si, 3% Fe and 87% Al.

- No cold forming
- No scale formation
- No sandblasting
- Excellent geometrical accuracy
- Very good corrosion protection

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
Process parameters recommended by AM for USIBOR1500P

Heat treatment
- Austenitization and coating alloying: 880 – 930°C, 4 – 10 min
- Heating rate: < 12°C/s
- Atmosphere in the furnace: air, no combustion gas

Transfer time furnace - press
- About 7 seconds

Quenching
- Quenching speed in the dies (average): > 50°C/s
- Water quenching: post-tempering may be necessary
- Final temperature of the part: < 200°C after die-quenching.

Trimming
- Laser trimming or die trimming

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
Effect of heat treatment

Austenitization + Stamping + Quenching leads to a martensitic structure and significant increase of tensile properties and hardness.

Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010
The degree of deformation has to be taken into account when calculating the cooling performance.

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
During heat treatment, Fe diffuses in the Al-Si layer. Complex Al-Si-Fe intermetallic layers & growth is formed in coating thickness. This layer has higher melting point and prevents the formation of scales.

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
Effect of heat treatment

Time dependent change in coating aspect and properties

Dwell time, furnace temperature, degree of deformation and cooling speed determine the final part quality.

- total coating layer increases
- inter diffusion layer increases
- porosities increase

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
Effect of heat treatment

- Porosity
- Oxides at the surface
  → inhomogeneous current flow - poor mechanical stability of coating (collapse)
  → Unstable welding parameters

- Less porosity
- Less oxides
  → homogenous current flow - good mechanical stability of coating
  → stable welding parameters

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
Drawbacks of Al-Si coating

This Al-Si coating provides enhanced anticorrosion properties. On the other hand, it has the following drawbacks:

- High raw material cost

- A process window of 5 – 7 minutes is required in the heat treatment to allow the Al-Si material to diffuse into the steel matrix and thereby to achieve its anticorrosion effect.

- During the heat treatment of Al-Si-coated sheet metal, a fusion phase occurs, which results in intense thermochemical attack on the ceramic conveying rollers of the roller hearth furnace.

- Al-Si-coated blanks cannot be processed by the indirect method, since the coating with lower forming limits would get damaged in the pre-forming step.

Source: Practical Handbook of Thermo-processing Technology VW-Kassel 2011
**USIBOR with Zn containing coatings**

**GI process**
- only for indirect process
- expensive shot blasting is needed
- risk of Zn LME cracking
- additional line investment necessary

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
Hot stamping process with GA coating

- direct and indirect process possible
- compatible with existing hot stamping lines
- No sand blasting necessary
- Sacrificial corrosion protection

Development of USIBOR1500P GA (Zinc/ Iron or “galvannealed” coating)

Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010
Comparison between coated and uncoated part (tunnel) after hot stamping

Source: Practical Handbook of Thermo-processing Technology VW-Kassel 2011
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Influence of austenitization temperature and time

(a) Vickers hardness

- As delivered: $s_0 = 1.75 \text{ mm}$
- Austenitization temperature $T_v$ in °C
  - 860°C (5.5 min)
  - 900°C (4 min)
  - 950°C (3 min)

(b) Vickers hardness vs. Sheet thickness $s_0$ in mm

- Austenitization time $t_v$ in min
  - 2.25 min
  - 2.75 min
  - 3 min
  - 4 min

Source: Karbasian and Tekkaya 2010
Heating system

Roller Hearth Furnace  Double-decker  Multi-chamber

In mass production ✓

Conduction  Resistance Heating  Rotary Hearth Furnace  Induction Heating

Prototyping – Try-out  Under Development

Over 80% of all heating systems in hot stamping applications are roller-hearth furnaces. Furnaces of this type can be run with or without protective gas.

Source: Practical Handbook of Thermo-processing Technology Schwartz 2011
Note: Furnace length is essential due to two factors:

1. For AlSi-coated sheet metal, a process window of at least 300 seconds is specified for allowing the coating to diffuse far enough into the steel matrix so that it can deliver its subsequent corrosion protection properties plus good weldability. (Equipment used only for uncoated blanks can be built up to 30% shorter than roller-hearth furnaces used also for AlSi-coated blanks.)

2. Cold-rolling creates residual stresses in the sheet metal. These may cause the blank to become distorted when heated rapidly. Accordingly, the temperatures in the front zones of the roller-hearth furnaces must not be set too high.

Source: Practical Handbook of Thermo-processing Technology Schwartz 2011
It was found that a very strong **thermochemical reaction** occurs when the AlSi-coated sheet metal comes into direct contact with the ceramic conveying rollers during the heat treatment. This effect calls for relatively frequent roller replacements which may impact plant availability.

**Thermochemical attack on a conveying roller**

Source: Practical Handbook of Thermo-processing Technology Schwartz 2011
Roller hearth furnace ➔ Direct process

Relying on the sol-gel process, a suspension was developed for application to the conveying rollers by spray-coating. (0-sample = uncoated roller sample)

Area of transition between coated and uncoated rollers after heat-treatment of approx. 40,000 AlSi-coated blank. Coated rollers were made from a non-oxidic, aluphobic ceramic material.

Source: Practical Handbook of Thermo-processing Technology Schwartz 2011
Roller hearth furnace ➞ Indirect process

Source: Practical Handbook of Thermo-processing Technology Schwartz 2011
Roller hearth furnace → Indirect process

- In indirect process, pre-formed parts must pass through the furnace on product support trays to accommodate their complex shape.

- Since the parts are heat-treated in their uncoated state, a furnace of this type needs to run with a controlled atmosphere (i.e., protective gas) in order to prevent oxidation of the part surface (scale formation).

- A return conveyor for the product trays in a closed loop is required.

Source: Practical Handbook of Thermo-processing Technology Schwartz 2011
Disadvantages:

- Up to 50% more heating power (trays must be heated and cooled down during each press cycle)

- The trays are high-wear components. (a fairly short service life due to the cyclic thermal loads

Advantages:

- Trays may be used for AlSi-coated blanks so that thermochemical attack on the ceramic rollers is avoided.

- Highly complex geometry can be subjected to a heat treatment process prior to hot stamping. However, this geometry is limited by the tray dimensions.

Source: Practical Handbook of Thermo-processing Technology Schwartz 2011
Conductive heating

In this process, the decrease in temperature of the blank before forming is prevented by direct heating the sheet into die sets by means of the electrical resistance.

- Inhomogeneous temperature along the length of component.
- By industrial application, this heating method is difficult for blanks with complex geometries.

Source: Mori et al. 2009
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Forming

- tool steel
- die design and construction
- die coating
- process parameters
- die maintenance

Tool design for the hot stamping process

Source: Karbasian and Tekkaya 2010
Heat transfer from the drawn part to the tool depends on surface scaling effects and gap between part and tool surface.

Heat conductivity of the tool material depends on choice of tool material.

Design of the cooling ducts is defined by size location and distribution of the cooling ducts.

Temperature and type of coolant affect the heat transfer. Temperature difference between coolant and tool affects the heat transfer.

Source: Naganathan and Altan 2010
Heat transfer from drawn part to tools

- depends on surface scaling effects and gap between part and tool surface

Source: Geiger et al. 2008, Lechler 2009
Heat conductivity of tool material

Thermal conductivity - depends on choice of tool material

Introduction of extreme high thermal conductivity tool steels enabled the reduction of cycle time by reducing the holding time. Die materials like HTCS-117 (Ni, Cr and Mo die steel) reduced closed die cycle times from 10-15 s to 4-6 s. Now with the introduction of HTCS-130 (High thermal conductivity tool steel originally developed for aluminum die casting), HTCS-150 and HTCS-170, the cycle time is further reduced to 2-3 s.

Comparison of heat conductivity by 44 HRC

Temperature 100°C
Design of cooling ducts

Convection coefficient - defined by size location and distribution of the cooling ducts

Source: Hoffmann et al. 2007, Shapiro 2009
Current Practice: Cast-in or drilled cooling channels

- Cooling holes can be drilled. (Machining restriction must be considered in the design of hole position.)
- Providing cooling holes as pipes in the casting mold.
- Using lasered blank segments that are screwed and form the tool surface with integrated cooling holes.

Proposed: near-surface cooling channels

Source: Kolleck et al. 2010
Die design

The heat transfer between component and dies plays an important role.

The heat conductivity within the tool can be considerably influenced by the choice of the tool material.

Another important factor with respect to heat drain is the design of the cooling ducts, which is defined by the size, location, and distribution of the cooling ducts. The heat drain can be accelerated by using a coolant with a low temperature, in order to increase the temperature difference between the coolant and the tool and therefore the resulting heat flux.

Source: Steinbeiss 2007
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Thermal characteristics

\[ q = h_{\text{conv}} A (T - T_\infty) + h_{\text{rad}} A (T_1^4 - T_2^4) + h_{\text{cond}} A (T_2 - T_1) \]

Heat transfer coefficients:

- Convection: \( h_{\text{conv}} = f(T) \)
- Conduction: \( h_{\text{cond}} = f(p,T) \)
- Radiation: \( h_{\text{rad}} = f(T) \)

Source: Karbasian and Tekkaya 2010
Phase transformation behavior

- The transformation from austenite (FCC) into martensite (BCT) causes an increase in volume, which influences the stress distribution during quenching.

- Volume fraction of different phases, residual stresses and distortion of the work piece after cooling.

Source: Karbasian and Tekkaya 2010
Flow behavior

Source: Merklein and Lechler 2006
Forming limit curve

Source: Karbasian and Tekkaya 2010
Friction coefficient

Deep drawing
Pin-on-disc
Drawing
Strip drawing
Strip drawing under bending

Source: Karbasian and Tekkaya 2010
Microstructure evolution

As delivered
Ferrite + pearlite

Austenitized
Martensite + bainite

Hot stamped

Temperature (°C)

Critical cooling rate \( \approx 30 \, ^\circ C/s \)

0 200 400 600 800 1000

1 10 100

Time (s)

Austenite
Ferrite
Bainite
Martensite
Pearlite

Source: Karbasian and Tekkaya 2010 and ArcelorMittal 2012
FE simulation performance

Isothermal

Thermo-mechanical

Thermo-mechanical calculation is necessary to validate the feasibility

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010
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Laser cutting

- Due to the contactless trimming laser, cutting does not cause any tool wear or any failure on the cutting edge in contrast to other cutting methods.
- There are nearly no limits with regard to the shape of the parts to be trimmed.
- The achievable tolerances are influenced by the stiffness of the laser machine and the holding fixture of the part.
- The laser cutting time depends on the part geometry and the movement of the laser machine.

- So et al. (2009) showed that in the blanking process, the quality of the sheared surface and dimension precision are influenced by certain process parameters, such as punch speeds, blanking angles, punch-die clearances, tool cutting edge geometries, and mechanical properties of the material. No influence of the punch speed on the sheared geometries and the blanking forces are observed.

- Picas et al. (2008) showed that the high hardness of the punch induces low wear of the cutting edge, but it becomes strongly sensitive to high loads during its application, since considerable micro-fractures occur along the cutting edge. An optimal toughness-hardness compromise must be found to improve the mechanical behavior of tools.

Warm cutting

- Cutting parts during quenching at elevated temperatures
- A reduced cutting force and an optimized cutting edge through a short process chain
- Selective heat treatment of the parts during quenching for avoiding martensite structure. **Locally differentiated heat treatments** can be performed by employing tool materials with different thermal conductivities designed for improvement of posterior cutting.

Developed Blanks

- The most cost-effective cutting method is pre-developed blanking.

- This method requires a certain blank design to achieve the desired part outline after forming.

- The tolerances that can be achieved are smaller than with cutting after hot forming.

Combining techniques

Trimming: Combining Techniques

No impact on cycle time,
Reducing the need for laser trimming.

- Red = Hot cutting
- Green = Blank development
- Blue = Laser cutting

Source: Karbasian and Tekkaya 2010, Josefsson 2010
Zn-Fe coating

- The best resistance spot welding results are produced with the double-pulse technology in combination with a DC source.

x-tec®

- The test of second and third generation x-tec® anti scaling coatings by the integration of magnesium particles has shown the suitability of the coatings for resistance spot welding.
- Applied atmosphere inside the furnace while heating the blanks has a great influence on the spot-weldability. Heating in air (with O₂ content) causes the formation of oxide layers so that spot welding cannot be applied.

Zn-Fe coating

- The best resistance spot welding results are produced with the double-pulse technology in combination with a DC source.

Source: Karbasian and Tekkaya 2010, World auto steel 2014
Laser and gas metal arc welding

- For laser and gas metal arc welding, the cross-sections of the joints of the tested combinations show that the x-tec® coating had no influence on the welding behavior. No pores or other defects were detected inside the joints.

- This coating will flexibly work also with different substrates, e.g. H430LA for manufacturing tailor welded blanks.

Source: Karbasian and Tekkaya 2010, Braun and Fritzsche 2009
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Fully martensitic transformation during hot stamping leads to a part with tensile strength of up to 1500 MPa and low elongation of about 5%. But an improved crash performance of a vehicle structural component, such as B-pillar, can be achieved by introducing regions which have an increased elongation for improved energy absorption.

Source: ThyssenKrupp 2012, Eller et al. 2010
Tool tempering

Source: Maikranz-Valentin 2007, Karbasian and Tekkaya 2010
Blank tempering

Source: Maikranz-Valentin 2007, Karbasian and Tekkaya 2010
Tailor rolled blanks

Source: mubea.com, Hover 2011
Tailored welded blanks

Source: ThyssenKrupp and ArcelorMittal
Hot stamped part with tailored properties

Cold Forming
8.7 kg
Reinf. t=2 mm (1.5 kg) Mat. H360

Hot Forming
6.4 kg
t=2.25 mm (7.2 kg) Mat. DP600

Tailored Rolled
4.5 kg
t=2 mm Mat. BTR165

Tailored Welded
4.9 kg
1.2 mm
1.75 mm
2.2 mm
1.75 mm
1.2 mm

Partial Hardening
6.4 kg
1.5 mm
2.1 mm
1.5 mm
2.0 mm

Weight potential per vehicle
- 4.6
- 8.4 kg
- 7.6 kg
- 4.6 kg

Benteler Design Variation

Source: Benteler Automotive 2010
Applications

B-pillar $s = 1.85 \text{ mm}$

Bumper beam $s = 2.30 \text{ mm}$

Windscreen upright $s = 1.20 \text{ mm}$

Door reinforcement $s = 1.00 \text{ mm}$

Tunnel $s = 1.0 \text{ mm}$

Source: Karbasian and Tekkaya 2010
Crash test

VW Passat incorporating hot-forming hardened steel parts. After the crash test at 75 km/h, the doors could be opened without problems.

Source: Practical Handbook of Thermo-processing Technology VW-Kassel 2011
The goal of hot-forming is to heat a steel to temperatures high enough to
- increase forming parameters to allow successful forming of difficult stampings
- quench stamped part to form very high strength martensite
- avoid springback problems associated with higher strength steels.

Steel usually utilized is a 22MnB5 grade with yield strength of 340 MPa, tensile strength of 480 MPa and 20-30% total elongation.

Heating above 850°C reduces the tensile strength to 100 MPa and increases the total elongation to 50-60%. The steel is formed in dies under this condition.

The forming die is chilled to provide a quenching action while the stamping is still held in the die. The quenching action:
- transforms the steel microstructure to martensite
- The stamping shape is retained with almost zero springback.

Press speed is approximately two strokes per minute to allow sufficient quenching.

The reduced forming strength may allow for multiple stampings in one die without over loading press capacity.

The very high final strength of the stamped part severely limits post forming operations. No additional forming should be attempted. Trimming, cutting, and piercing equipment must be built to overcome the strength of the final stamping. Laser welding is often used.

Source: World auto steel 2014
THANK YOU