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

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KMUTT

Overview

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

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- **Introduction**
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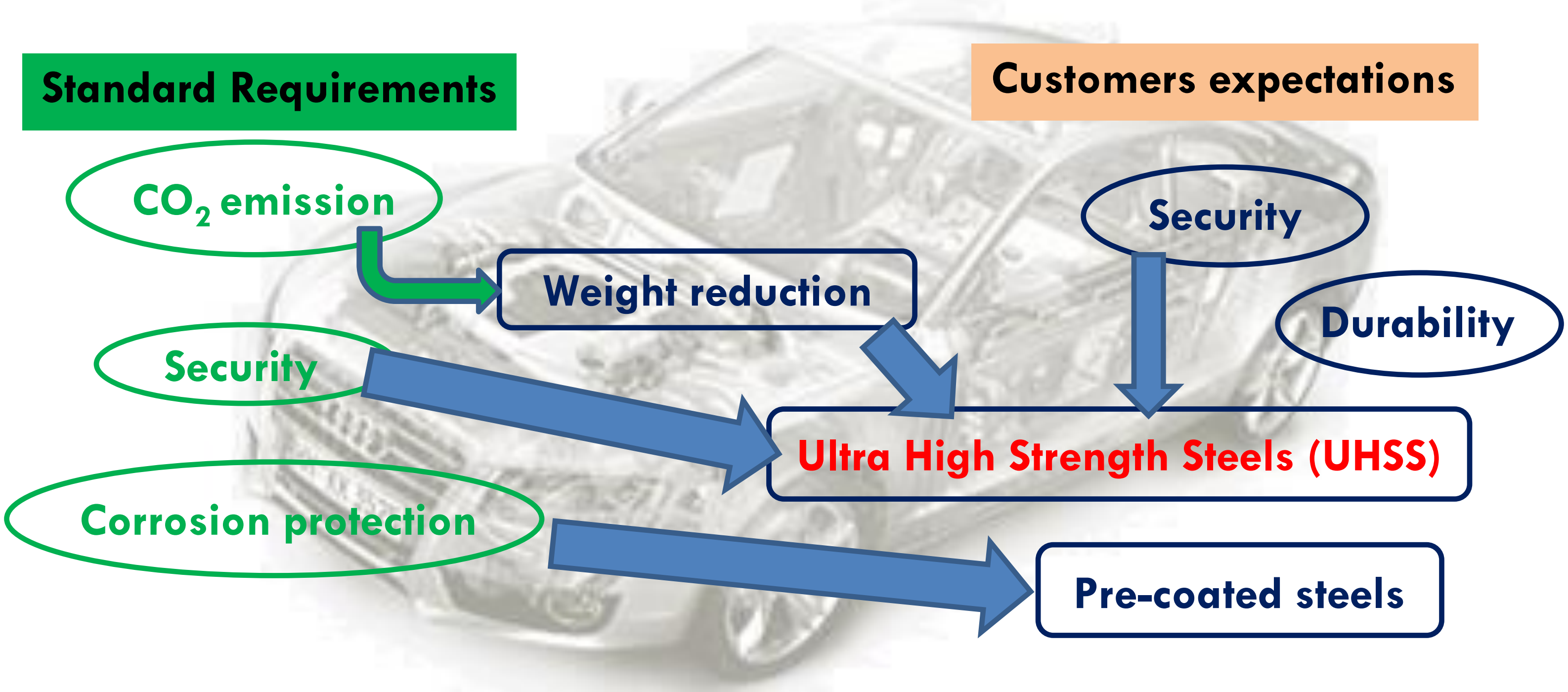
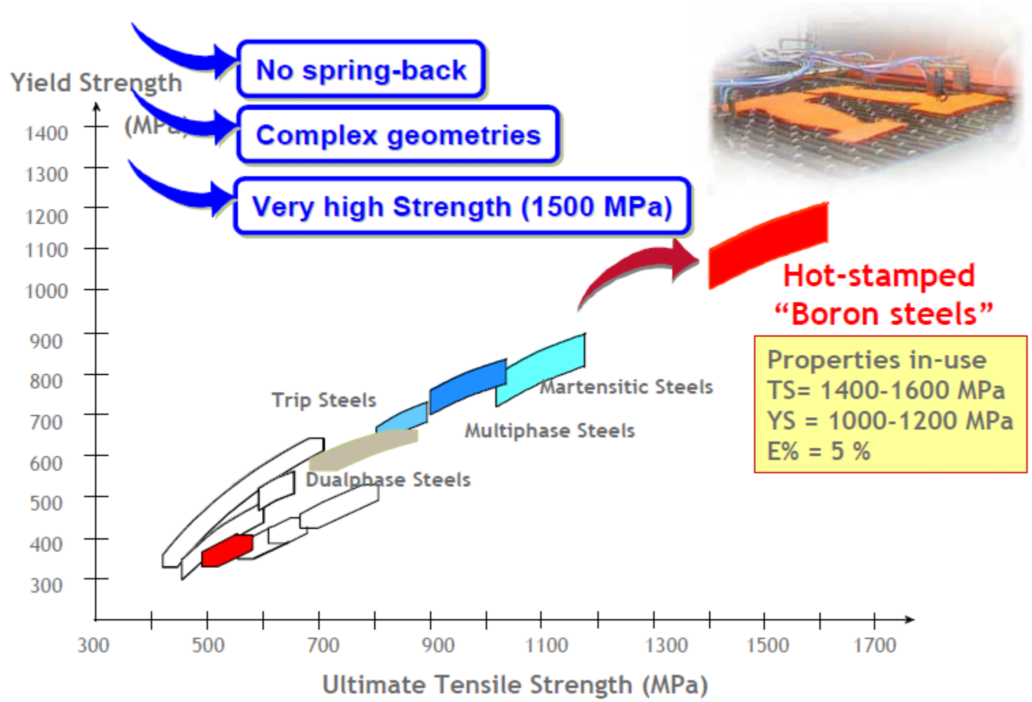
Why Hot-stamping ?



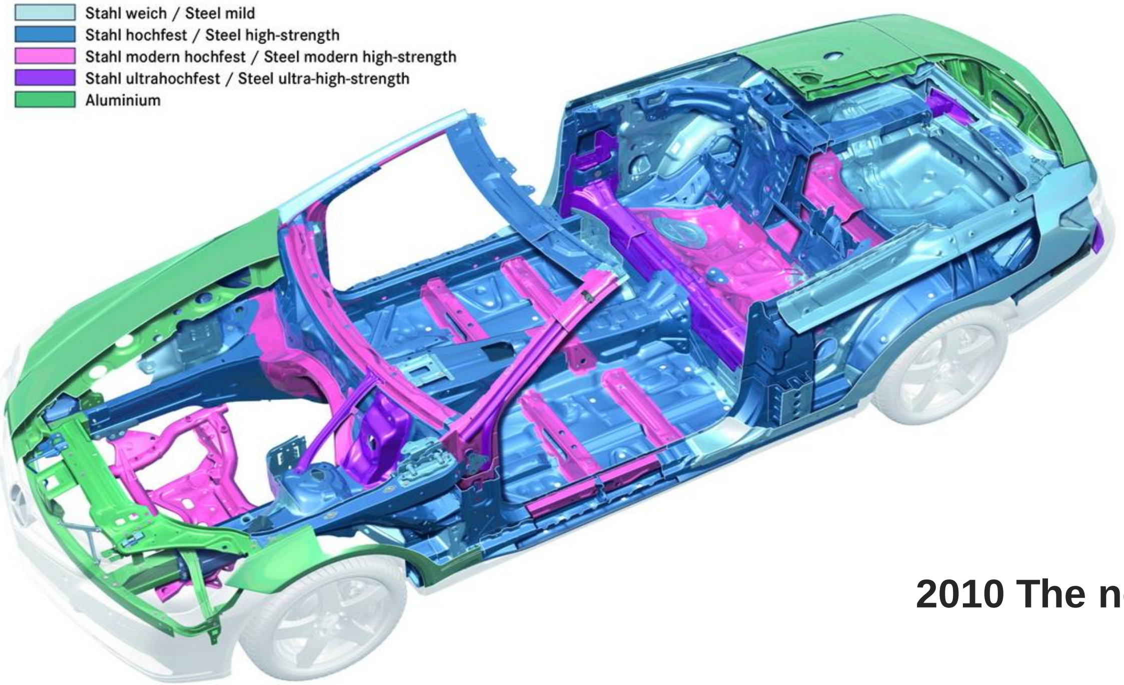
Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010

Main properties after hot stamping



Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010

Steel sheet concept for automotive parts

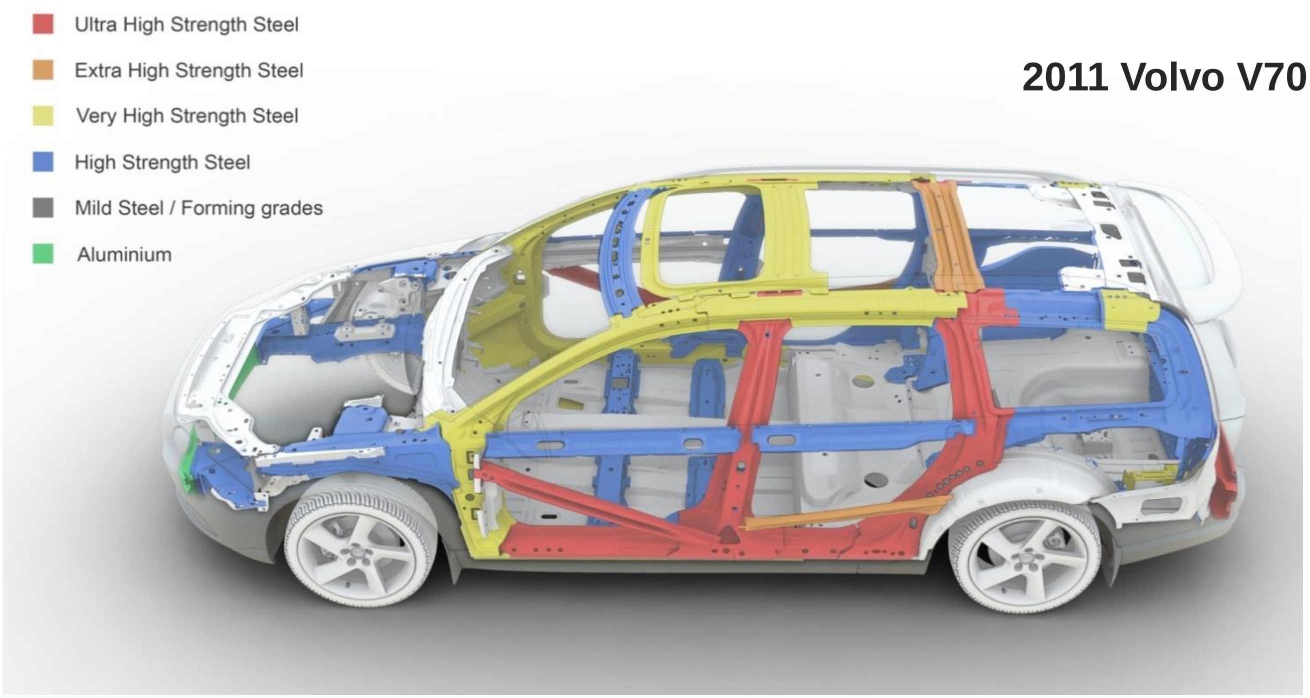


2010 The new Mercedes-Benz E-Class

Source: http://mercedes-benz-blog.blogspot.com/2010/03/new-mercedes-benz-e-class-cabriolet_2785.html

Steel sheet concept for automotive parts

2011 Volvo V70 Body Structure



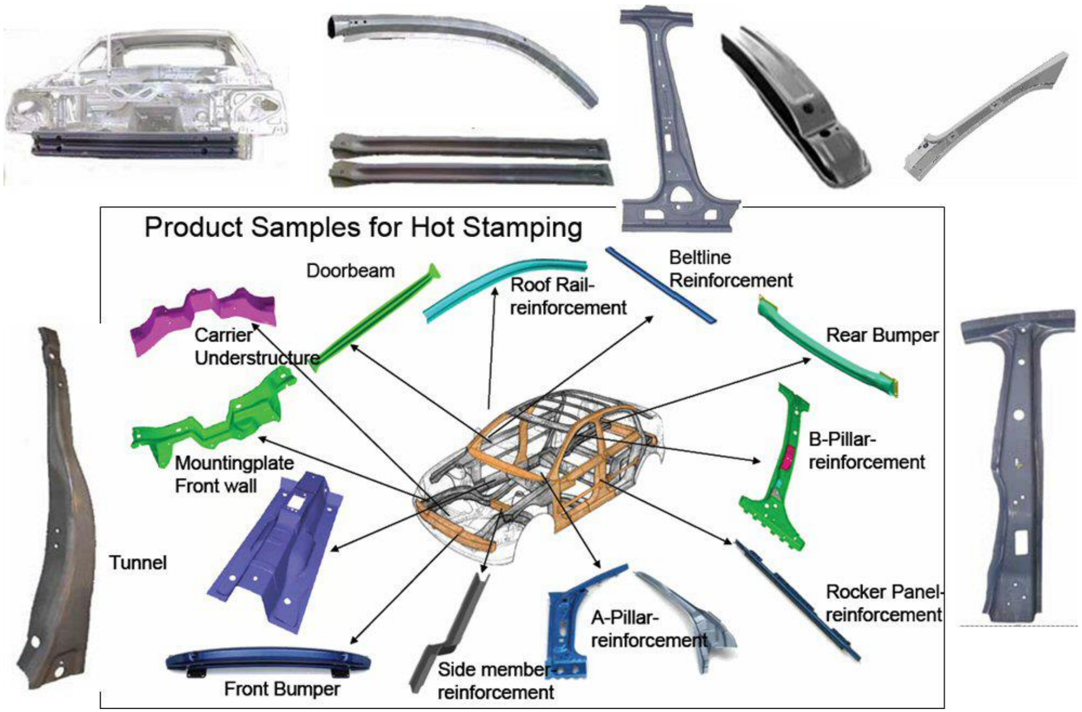
Source: http://boronextrication.com/tag/list-of-vehicles-with-boron-and-uhss

Steel sheet concept for automotive parts

2012 Audi A3 body Structure

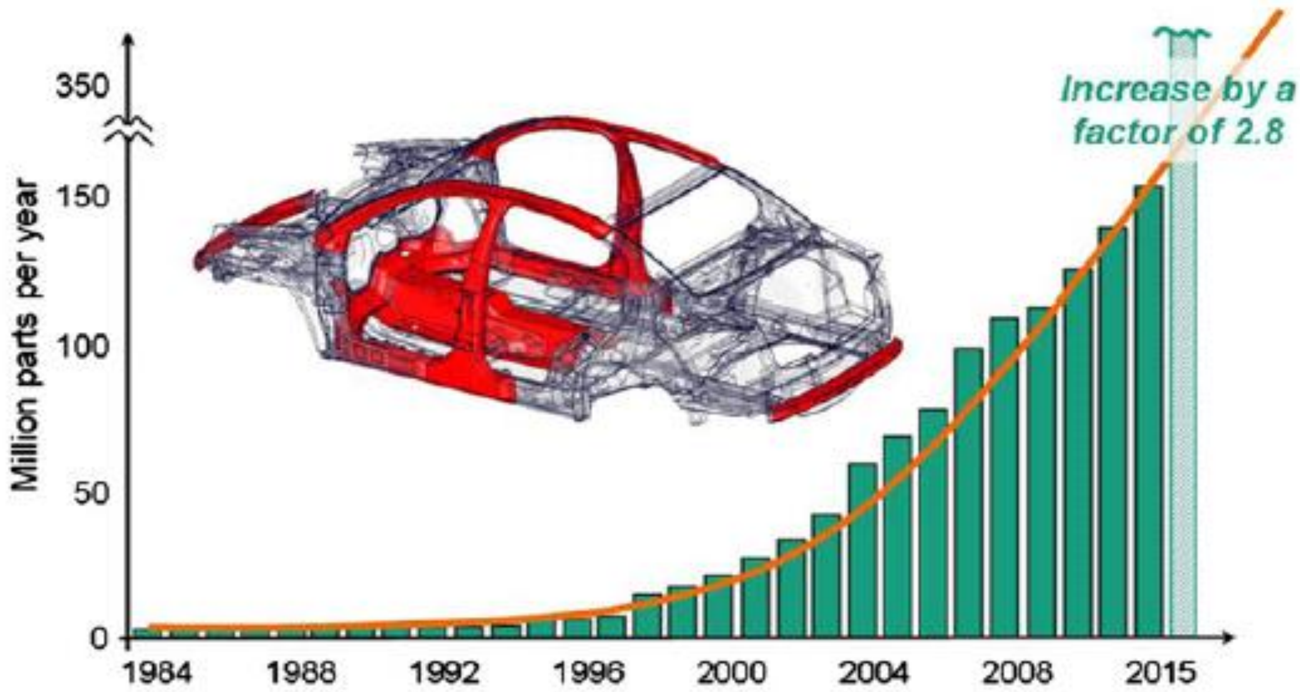
Source: http://carskeleton.blogspot.com/2012_04_01_archive.html

Steel sheet concept for automotive parts



Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010

Hot Stamping Demand

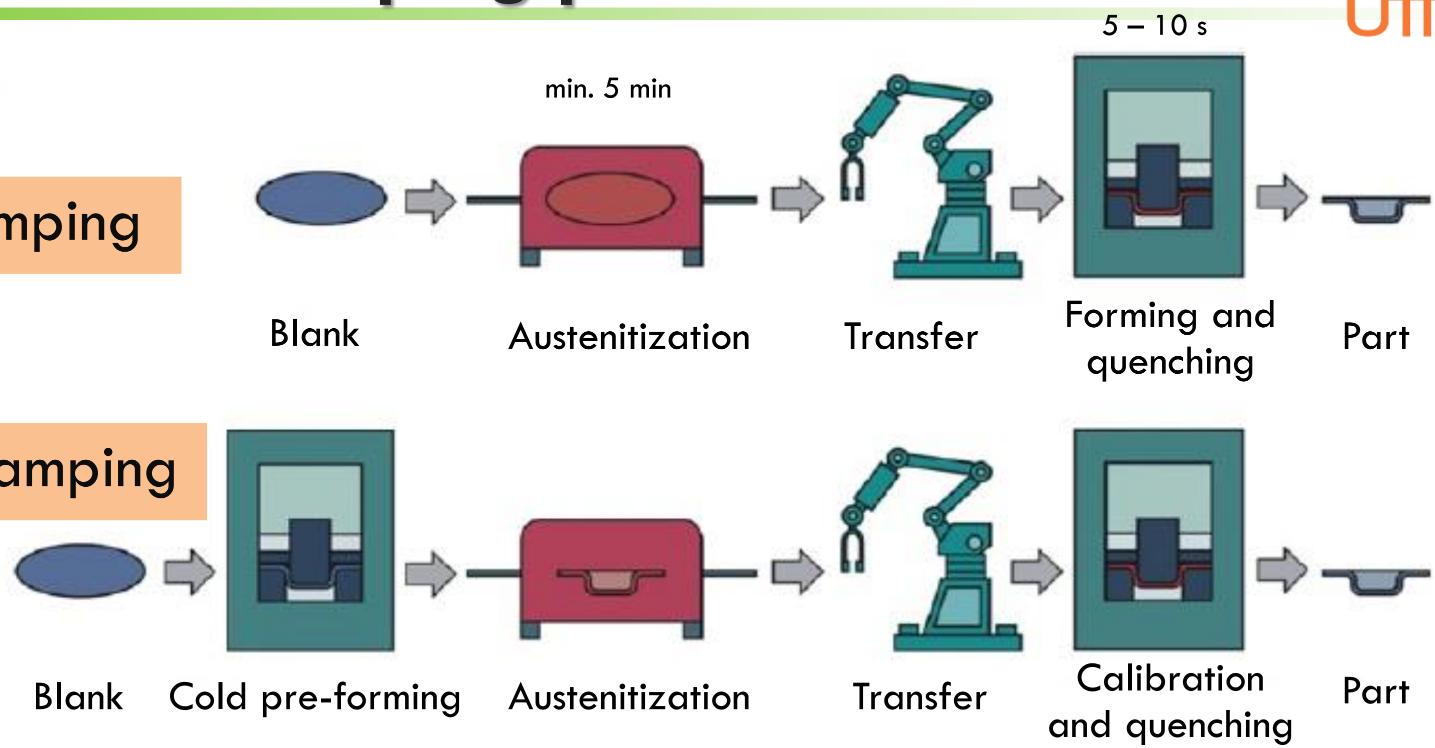


Source: Neugebauer et al. 2012

Variants of hot stamping process

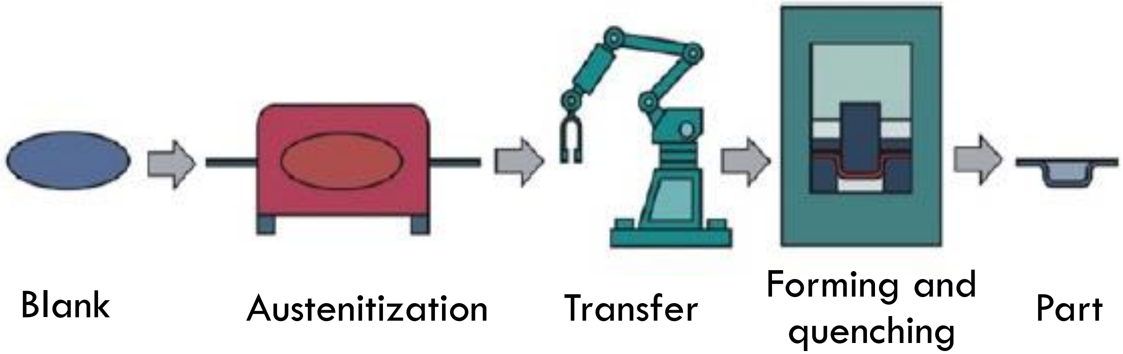
Direct hot stamping

Indirect hot stamping



Source: Karbasian and Tekkaya 2010

Direct hot stamping



Advantages:

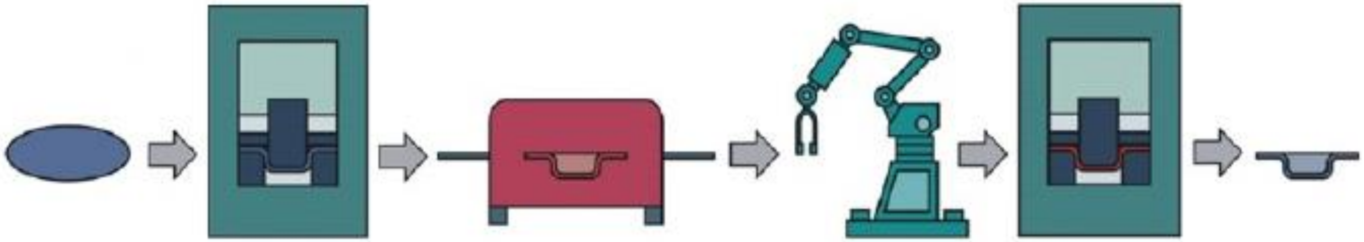
- Saving cost of pre-forming
- Accelerating production rate
- Blank is flat which not only saves heating area and energy, but also can be heated by a variety of heating methods.

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

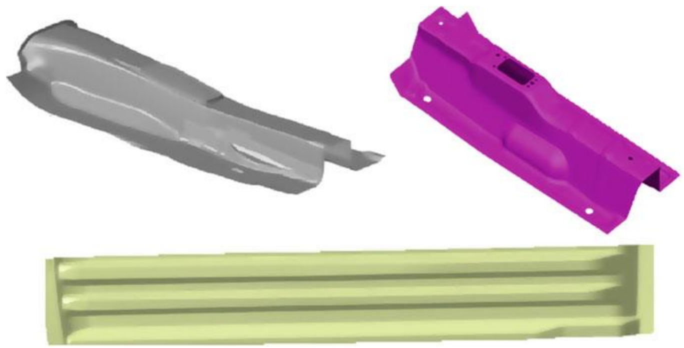
Indirect hot stamping



Blank | Cold pre-forming | Austenitization | Transfer | Calibration and quenching | Part

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

KMUTT

Chemical composition
(in percent by weight)

	min.	max.
C	0,220%	0,250%
Mn	1,200%	1,400%
Si	0,200%	0,300%
P		0,020%
S		0,005%
Al	0,020%	0,050%
Ti	0,020%	0,050%
Cr	0,110%	0,200%
B	0,002%	0,0035%
Mo		0,100%
Cu		0,100%
Ni		0,100%

Mechanical properties [1)]

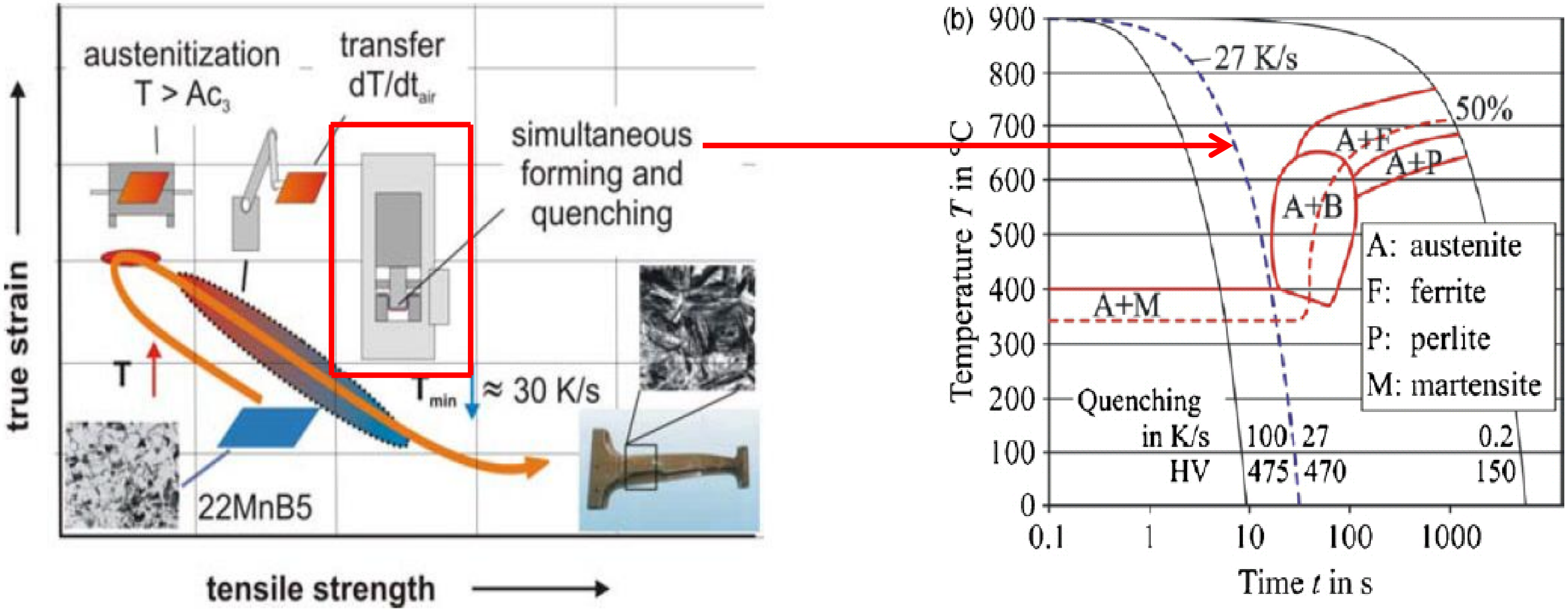
Yield strength $R_{p\,0,2}$
310 – 400 MPa
Tensile strength R_m
480 – 580 MPa
Total elongation A_{80}
≥20 %

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)

Steel	Al	B	C	Cr	Mn	N	Ni	Si	Ti
20MnB5	0.04	0.001	0.16	0.23	1.05	–	0.01	0.40	0.034
22MnB5	0.03	0.002	0.23	0.16	1.18	0.005	0.12	0.22	0.040
8MnCrB3	0.05	0.002	0.07	0.37	0.75	0.006	0.01	0.21	0.048
27MnCrB5	0.03	0.002	0.25	0.34	1.24	0.004	0.01	0.21	0.042
37MnB4	0.03	0.001	0.33	0.19	0.81	0.006	0.02	0.31	0.046

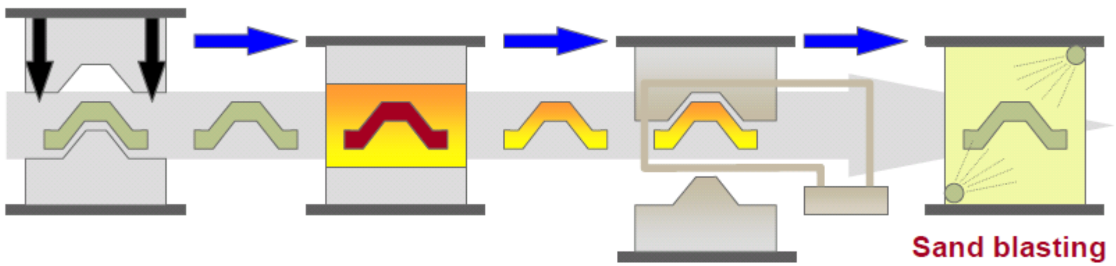
Steel	Martensite start temperature in °C	Critical cooling rate in K/s	Yield stress in MPa		Tensile strength in MPa	
			As delivered	Hot stamped	As delivered	Hot stamped
20MnB5	450	30	505	967	637	1354
22MnB5	410	27	457	1010	608	1478
8MnCrB3	–*	–*	447	751	520	882
27MnCrB5	400	20	478	1097	638	1611
37MnB4	350	14	580	1378	810	2040

* 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

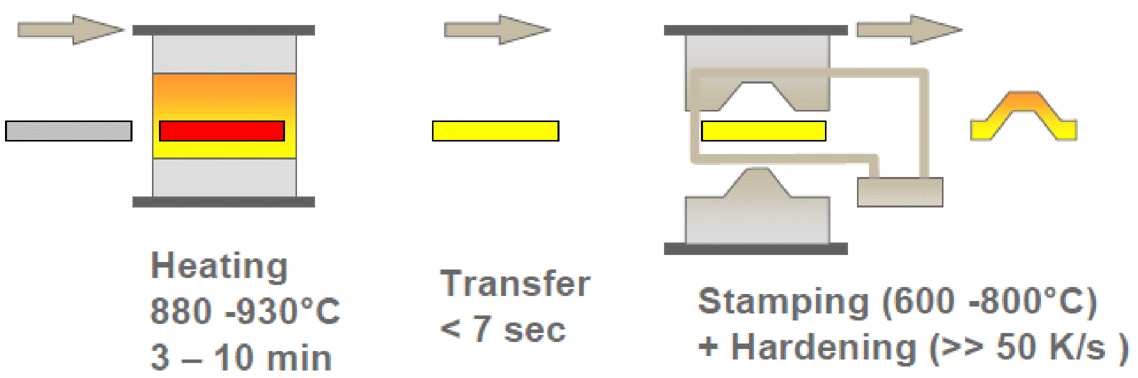


Scale formation on uncoated material

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010

Al-Si coating

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

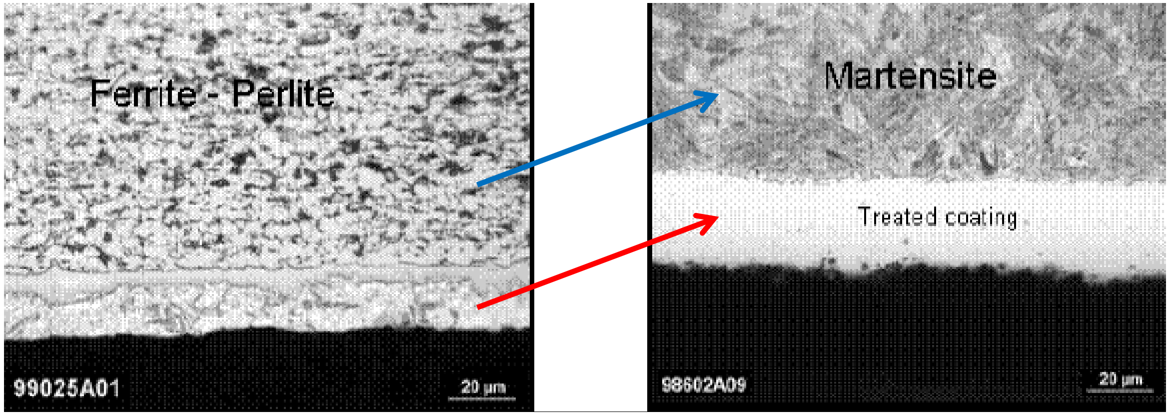
- Quenching speed in the dies (average): >50°C/s
- Water quenching: post-tempering may be necessary
- Final temperature of the part: < 200°C after die-quenching.

Trimming

- Laser trimming or die trimming

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010

Effect of heat treatment

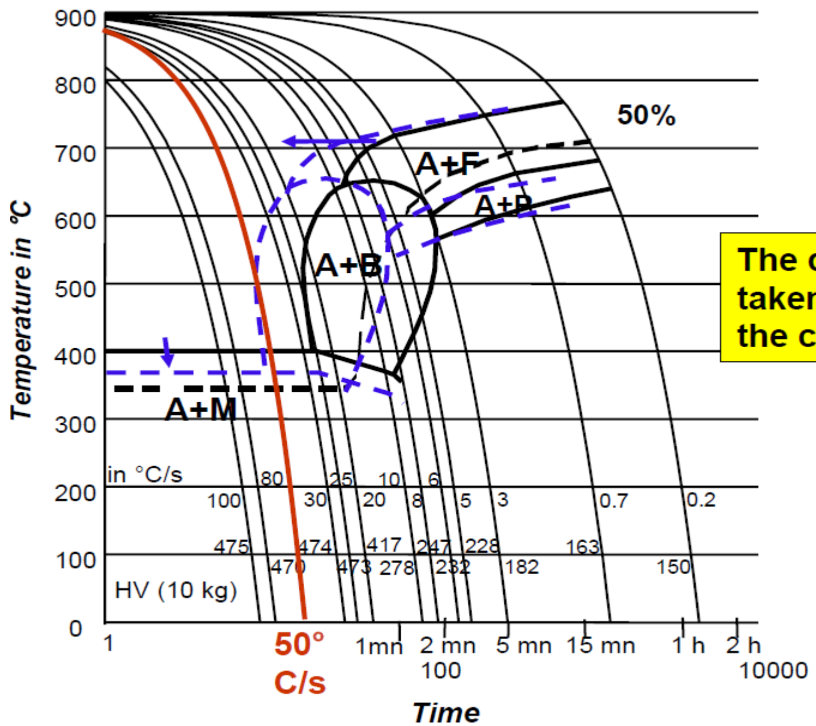


As delivered | After hot stamping

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

Source: ArcelorMittal, Hot Stamping with USIBOR1500P® 2010

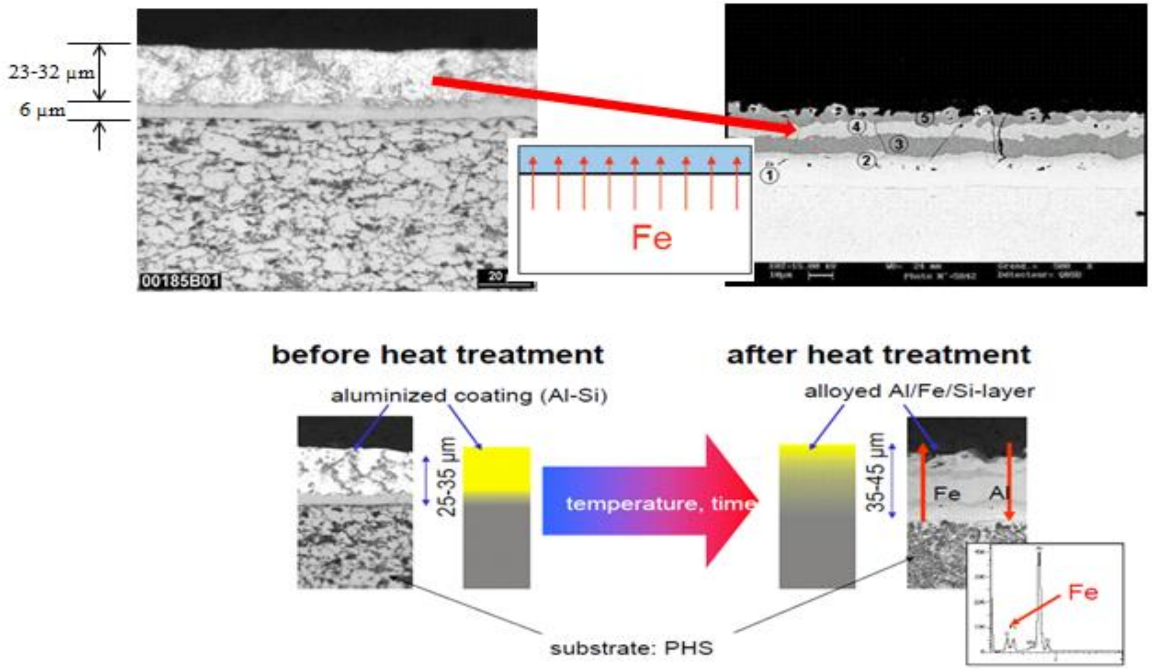
CTT diagram with and without deformation



The degree of deformation has to be taken into account when calculating the cooling performance.

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010

Diffusion process in Al-Si coating layer

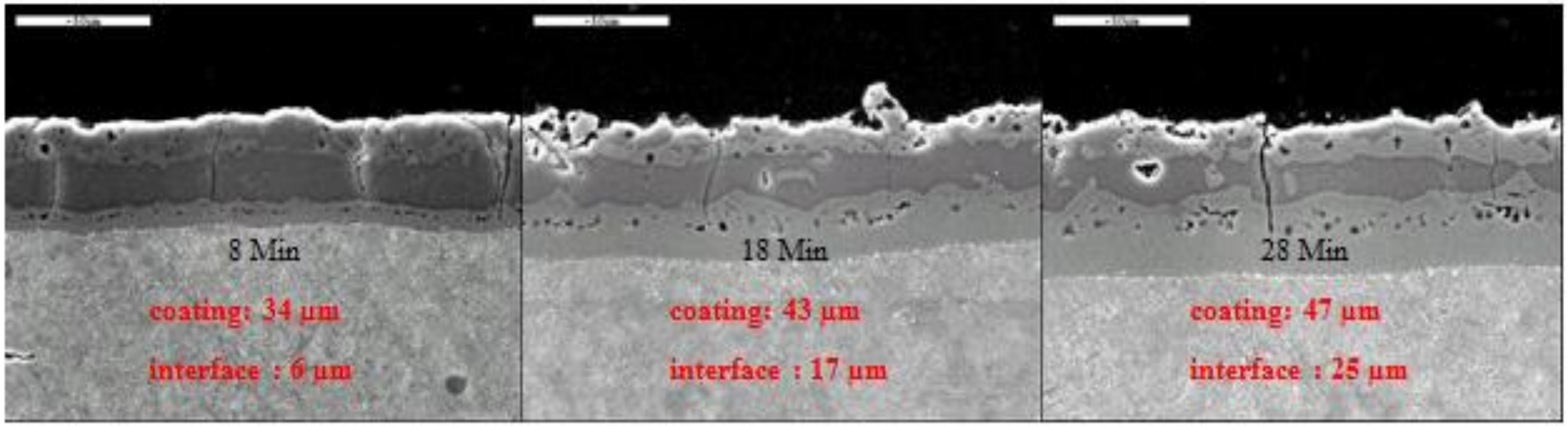


During heat treatment, Fe diffuses in the Al-Si layer. Complex Al-Si-Fe intermetallic layers & growth is formed in coating thickness. This layer has higher melting point and prevents the formation of scales.

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010

Effect of heat treatment

Time dependent change in coating aspect and properties

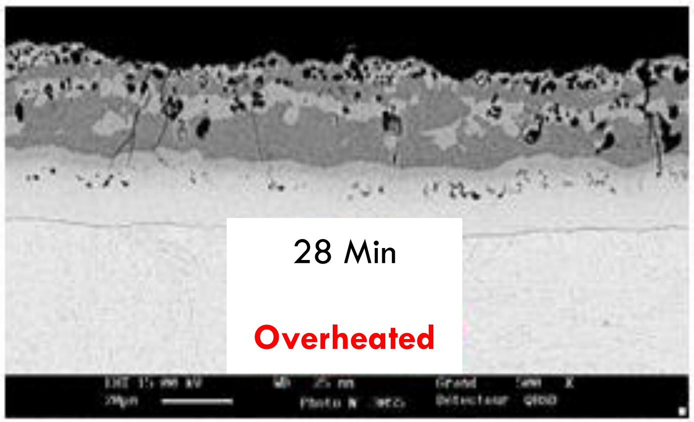


- total coating layer increases
- inter diffusion layer increases
- porosities increase

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

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010

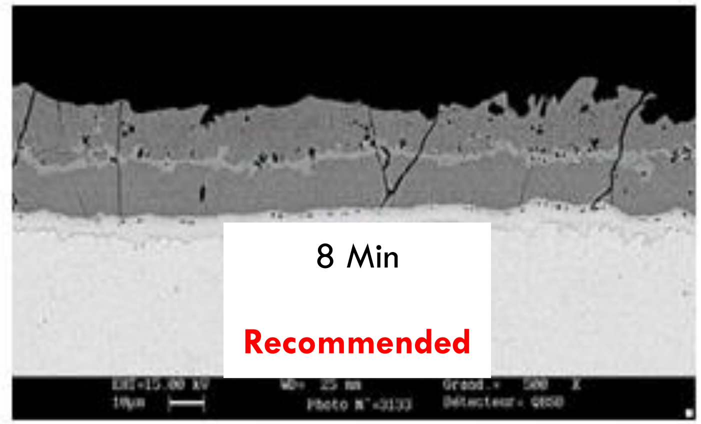
Effect of heat treatment



- 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

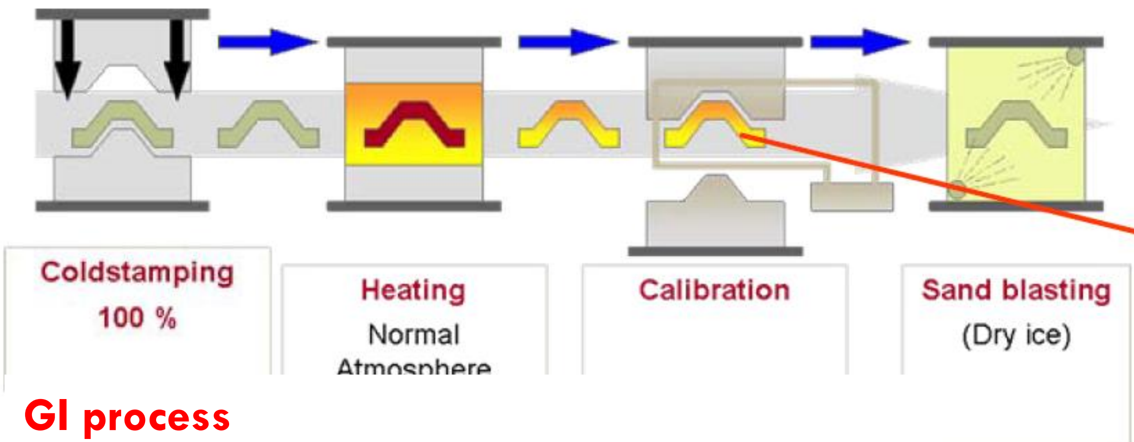
• A process window of 5 – 7 minutes is required in the heat treatment to allow the Al-Si material to diffuse into the steel matrix and thereby to achieve its anticorrosion effect.

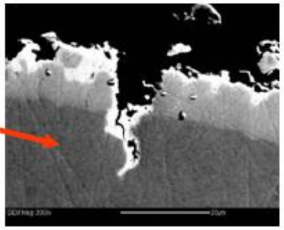
• During the heat treatment of Al-Si-coated sheet metal, a fusion phase occurs, which results in intense thermochemical attack on the ceramic conveying rollers of the roller hearth furnace.

• 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





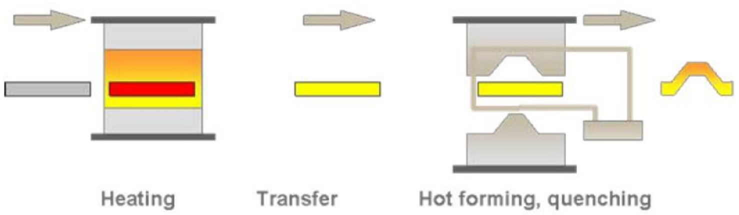
Risk of Zn LME cracking
if deformation at the hot stage

GI process

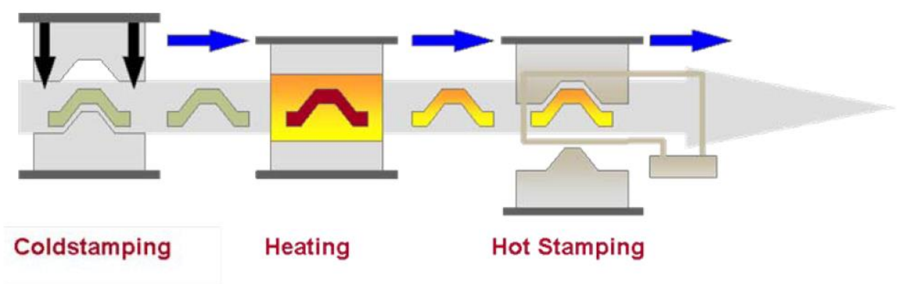
- only for indirect process
- expensive shot blasting is needed
- risk of Zn LME cracking
- additional line investment necessary

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010

Hot stamping process with GA coating



Direct (cheapest) hot stamping process



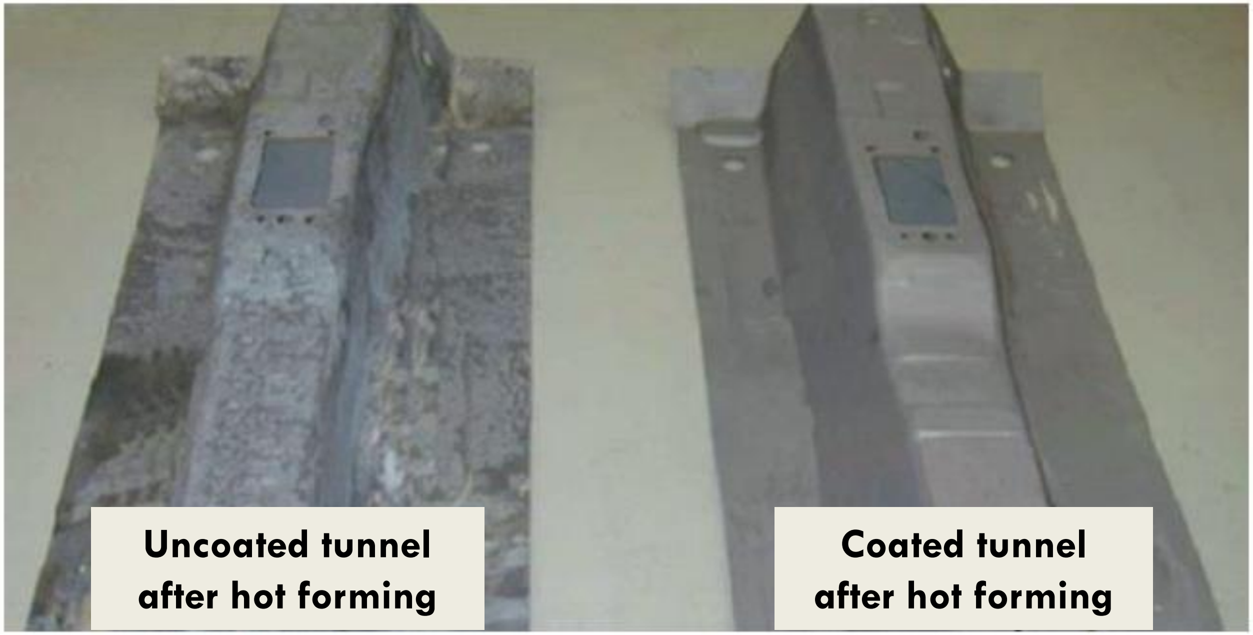
Indirect hot stamping process, <u>only if part is not feasible with direct process</u>

- 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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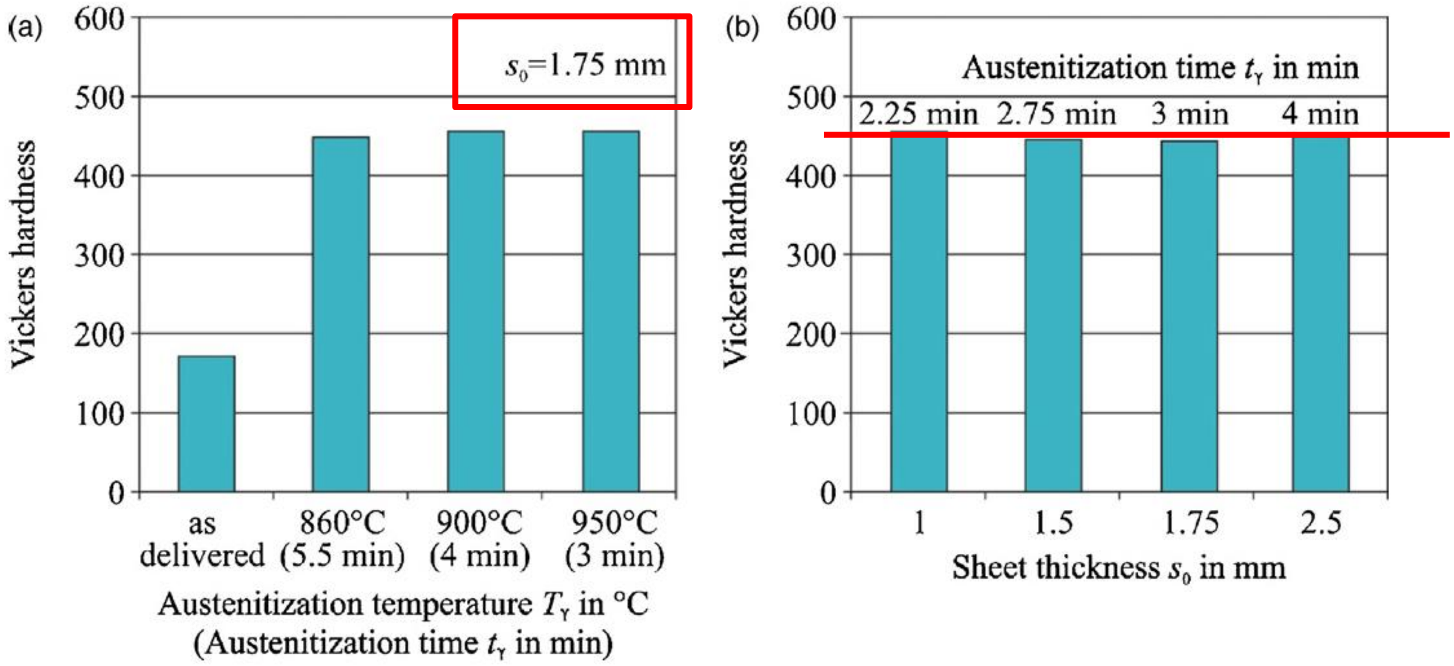
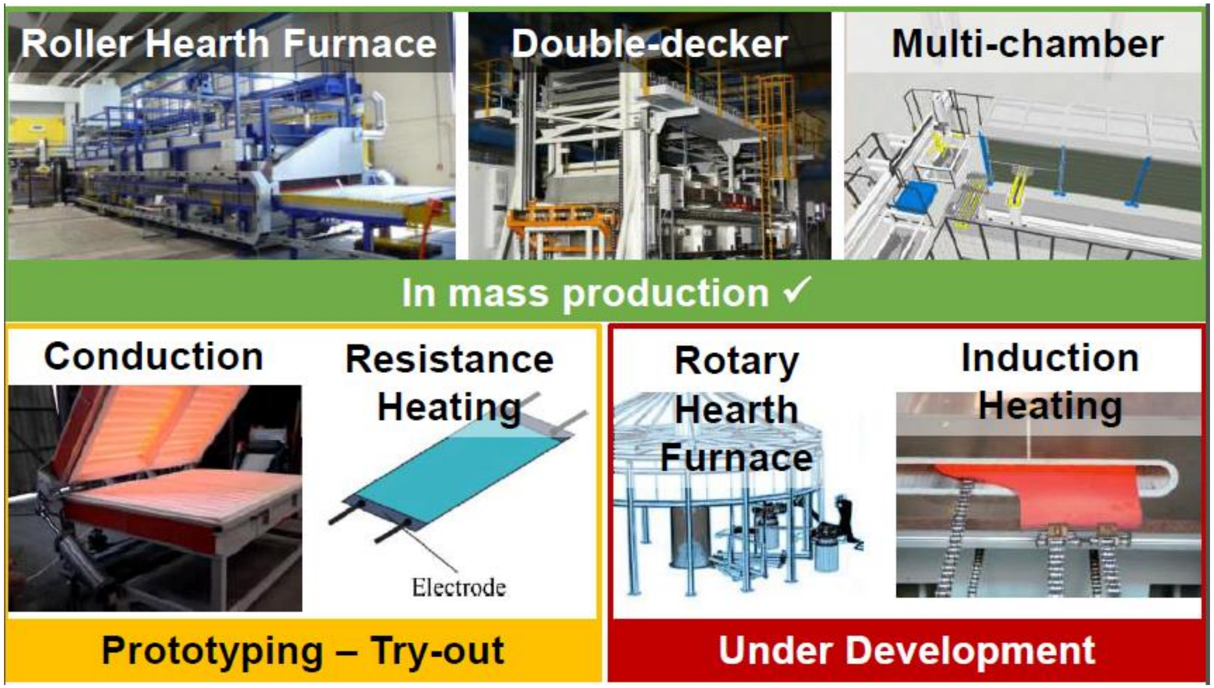
Influence of austenitization temperature and time



Source: Karbasian and Tekkaya 2010

Heating system



Source: DieDe 2009, Veit 2010, Karbasian 2010, Bader 2011, Billur and Altan 2012

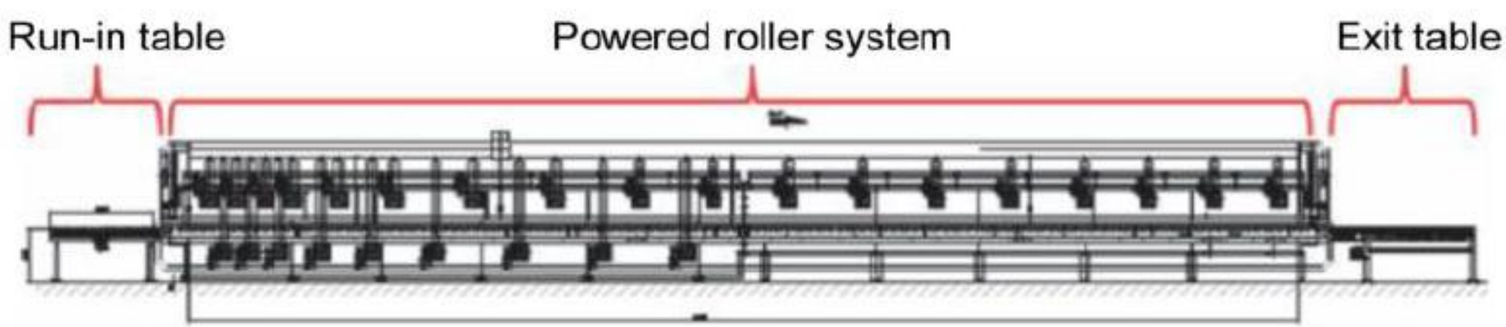
Roller hearth furnace ➡ Direct process

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.

Roller hear furnace heated by means of

- electricity
- gas
- hybrid power (gas/electricity combined)

30 – 40 m



Source: Practical Handbook of Thermo-processing Technology Schwartz 2011

Roller hearth furnace ➡ Direct process

- No need of product trays
- Sheet metal is placed directly on the conveying rollers and passes through the furnace in this manner.

Note: Furnace length is essential due to two factors:

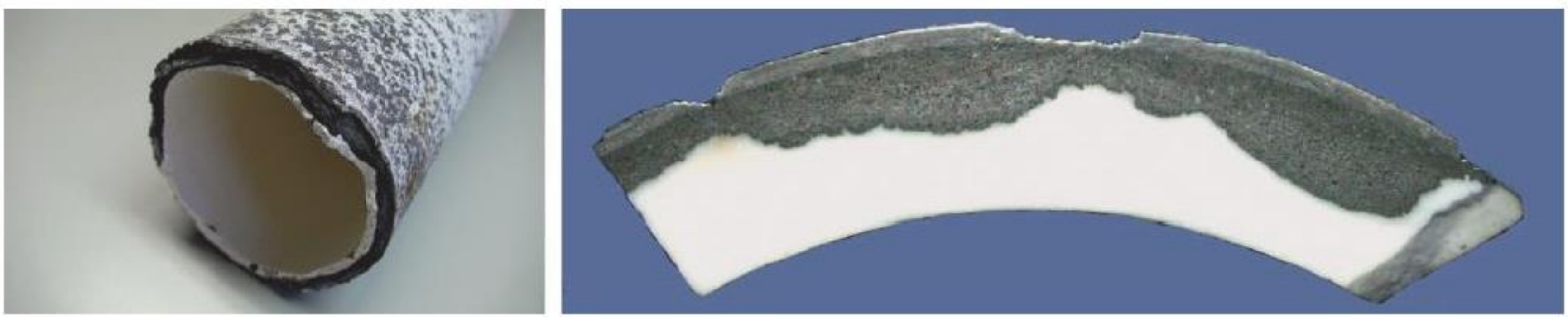
1. For AlSi-coated sheet metal, a process window of at least 300 seconds is specified for allowing the coating to diffuse far enough into the steel matrix so that it can deliver its subsequent corrosion protection properties plus good weldability. (Equipment used only for uncoated blanks can be built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

Roller hearth furnace ➡ Direct process

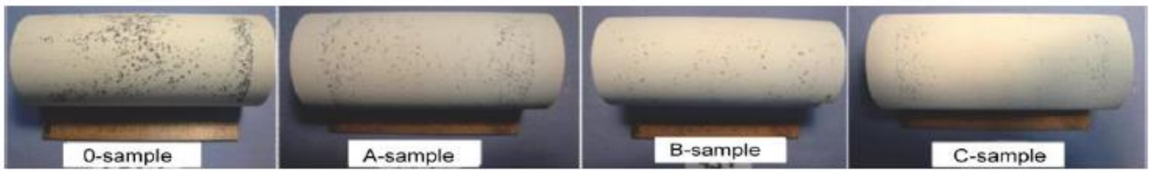
It was found that a very strong **thermochemical reaction** occurs when the AlSi-coated sheet metal comes into direct contact with the ceramic conveying rollers during the heat treatment. This effect calls for relatively frequent roller replacements which may impact plant availability.



Thermochemical attack on a conveying roller

Source: Practical Handbook of Thermo-processing Technology Schwartz 2011

Roller hearth furnace ➡ Direct process

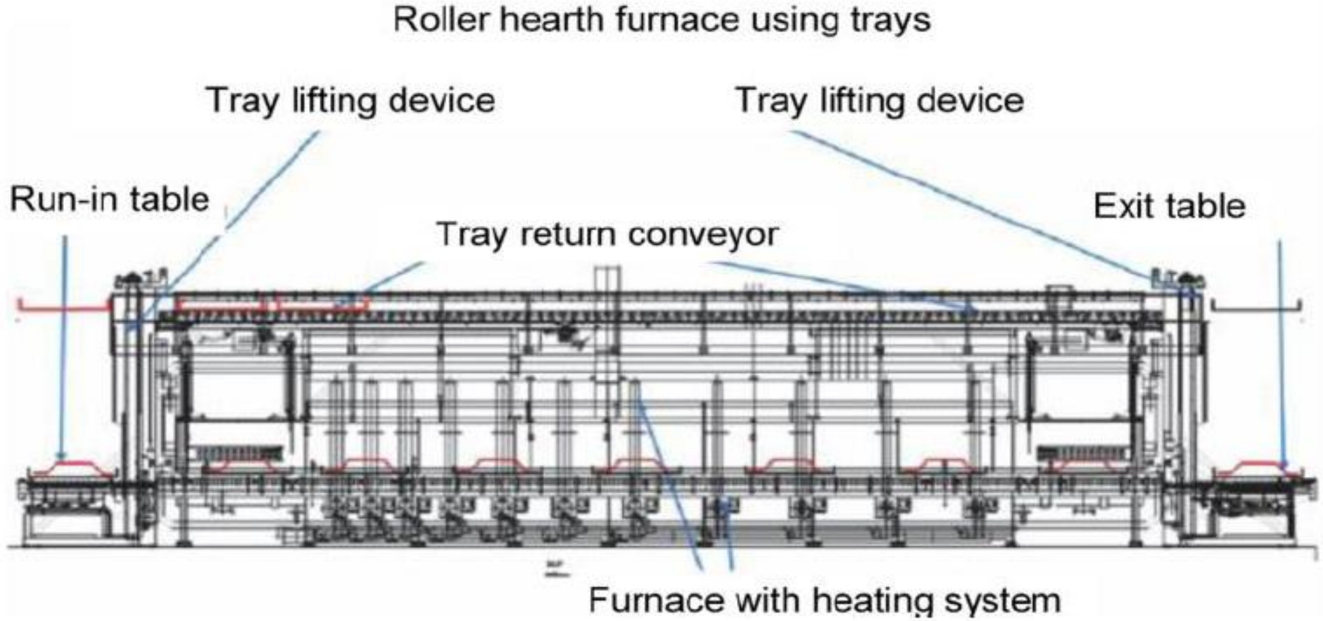


Relying on the sol-gel process, a suspension was developed for application to the conveying rollers by spray-coating. (0-sample = uncoated roller sample)

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

Roller hearth furnace ➡ Indirect process

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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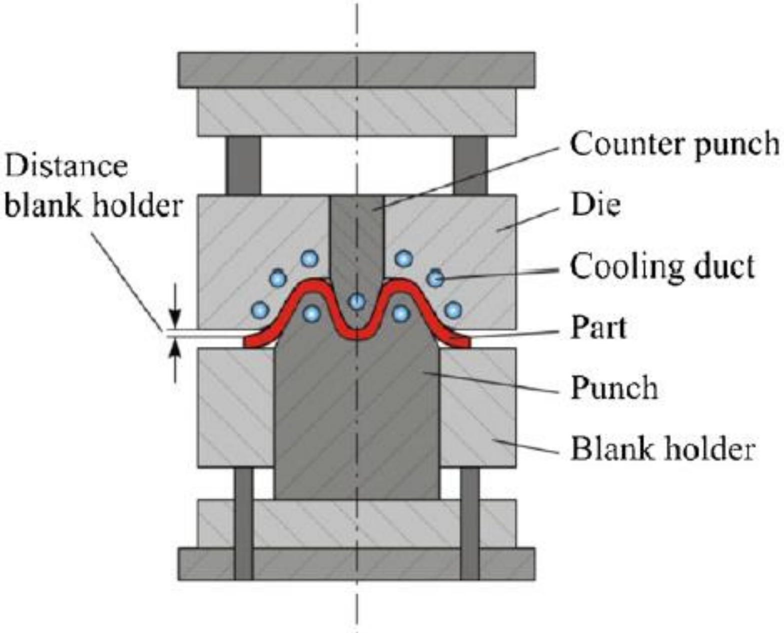
Forming



Tool design for the hot stamping process

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

Source: Karbasian and Tekkaya 2010

Die design

Optimization of locations of cooling channels in hot stamping dies

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

- defined by size location and distribution of the cooling ducts

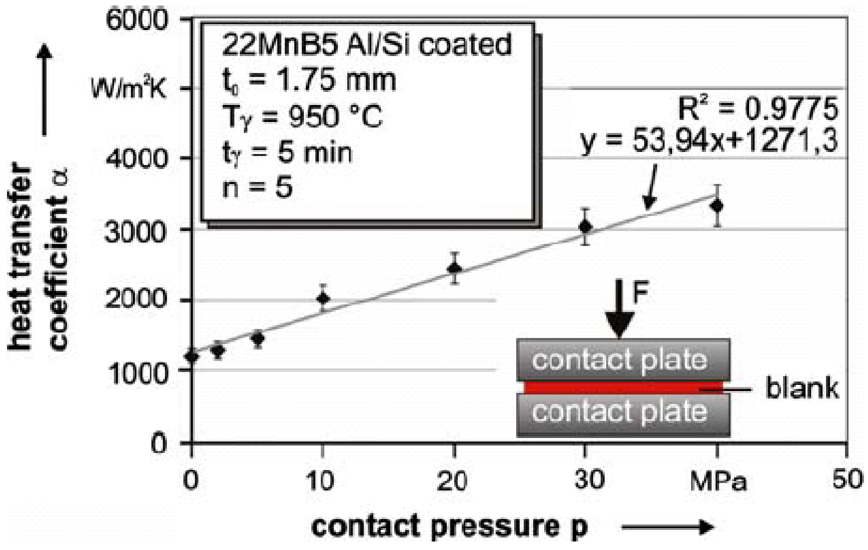
Temperature and type of coolant

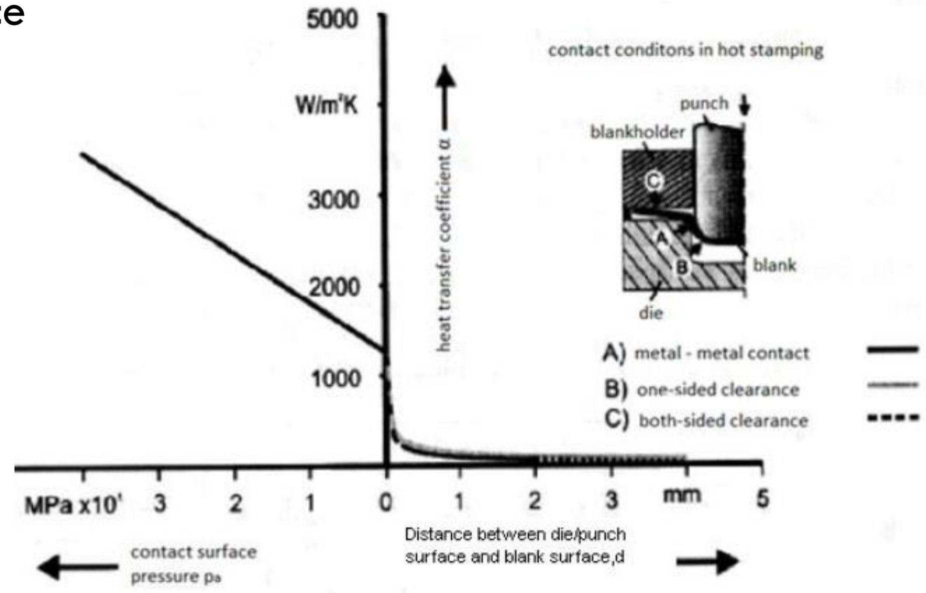
- Temperature difference between coolant and tool affects the heat transfer

Source: Naganathan and Altan 2010

Heat transfer from drawn part to tools

Heat transfer coefficient - depends on surface scaling effects and gap between part and tool surface





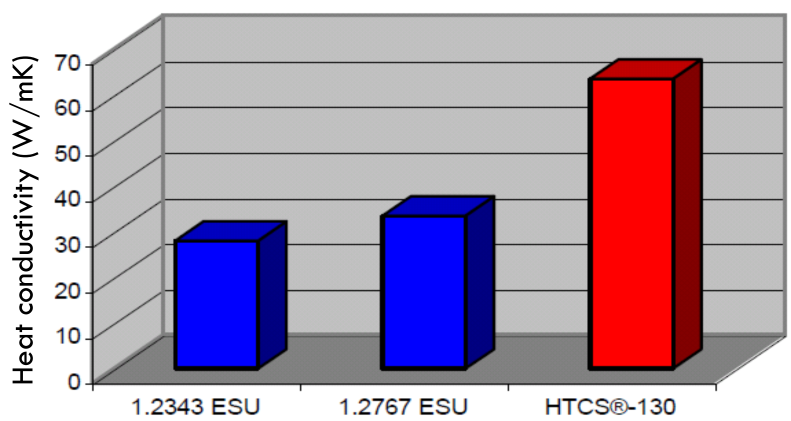
Source: Geiger et al. 2008, Lechler 2009

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.

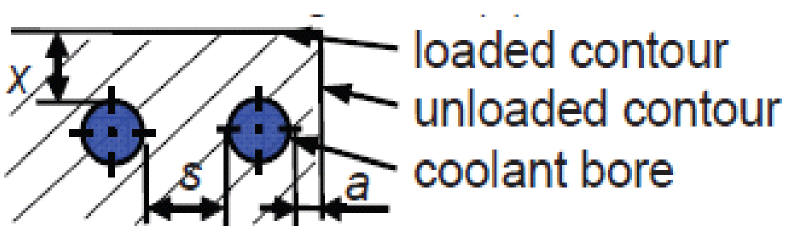
Comparison of heat conductivity by 44 HRC



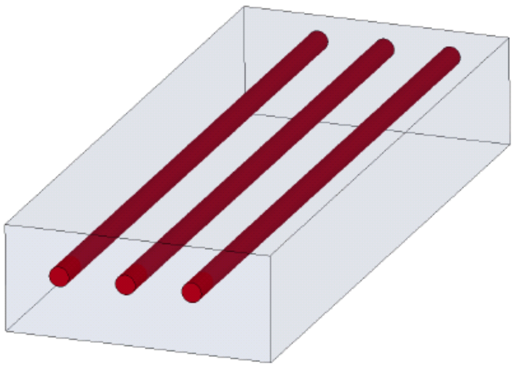
Temperature 100°C

Design of cooling ducts

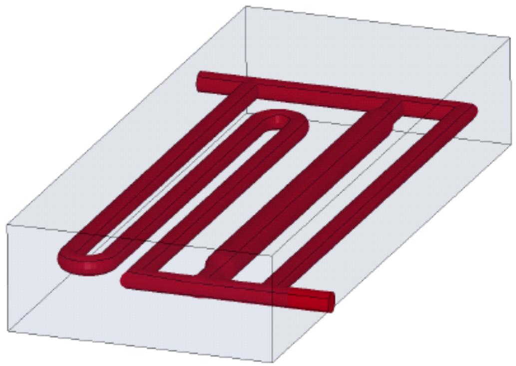
Convection coefficient - defined by size location and distribution of the cooling ducts



BULKFLOW



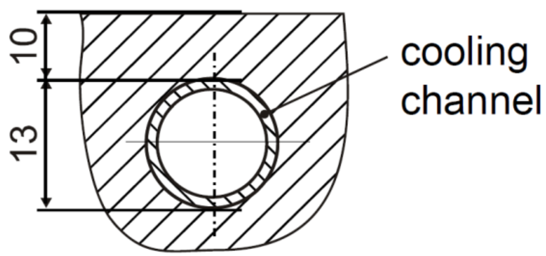
Network Analyzer



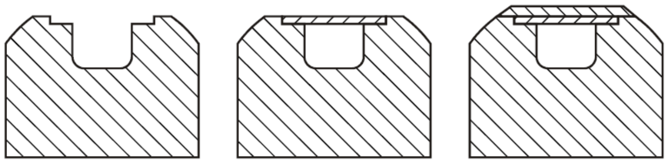
Source: Hoffmann et al. 2007, Shapiro 2009

Design of cooling ducts

Current Practice: Cast-in or drilled cooling channels

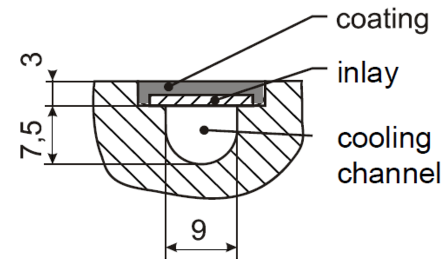


Proposed: near-surface cooling channels



(a) Milling (b) Inlay (c) Coating

- 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.



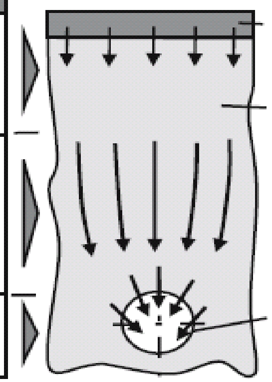
Source: Kolleck et al. 2010

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.

factors	technical potential for optimization
heat transfer pressing - tool	• preventing the formation of scale • preventing/minimizing gaps in the contact zone
heat conductivity within the tool	• heat conductivity of the tool material • cooling surface • distance between tool surface and cooling surface
heat transfer tool - cooling system	• turbulent flow of the cooling medium • temperature of the cooling medium



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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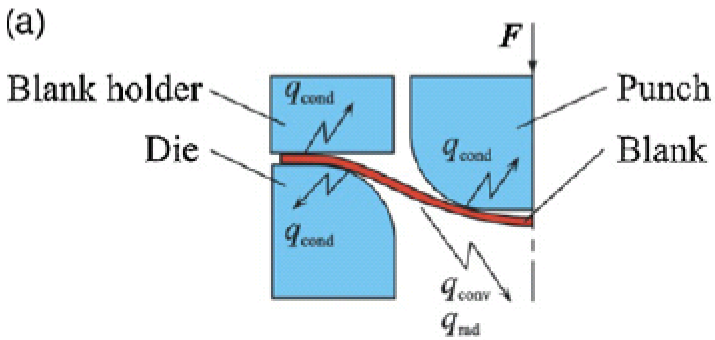
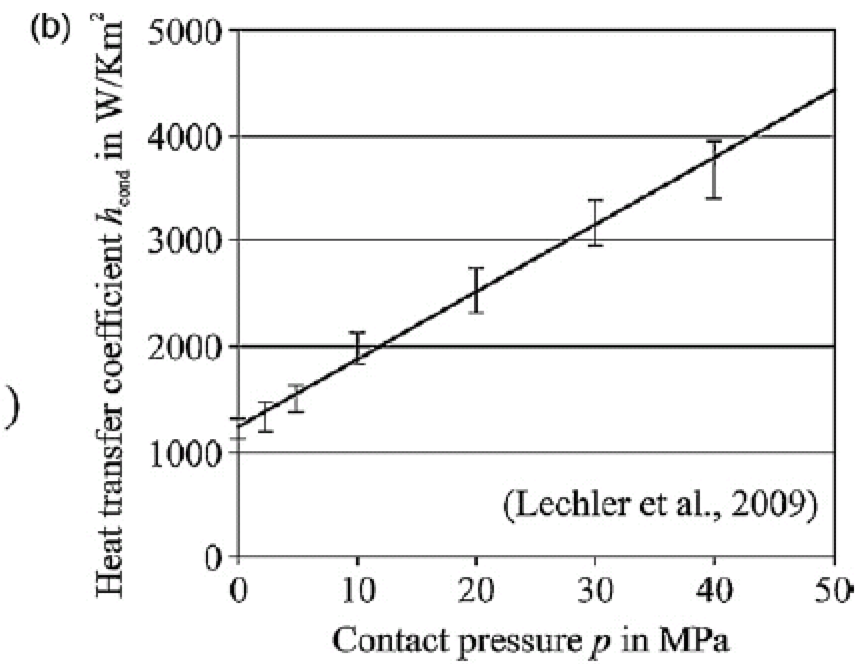
Thermal characteristics



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

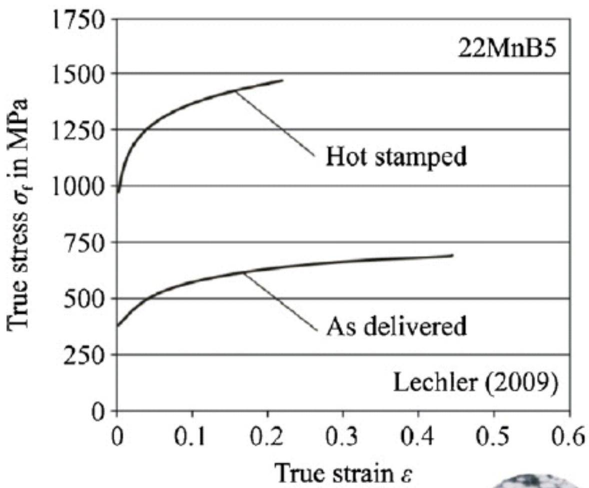
Heat transfer coefficients:

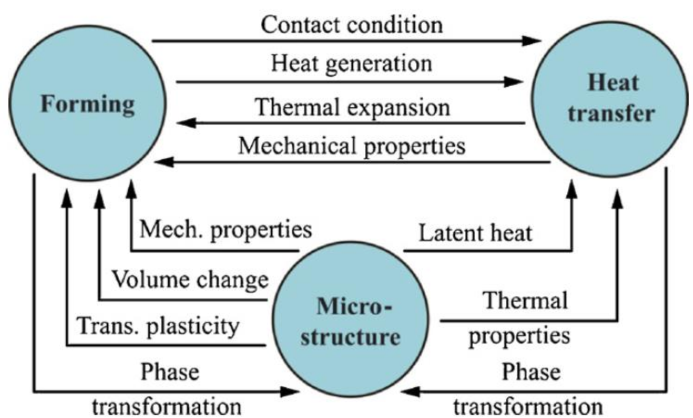
Convection	$h_{conv} = f(T)$
Conduction	$h_{cond} = f(p, T)$
Radiation	$h_{rad} = f(T)$

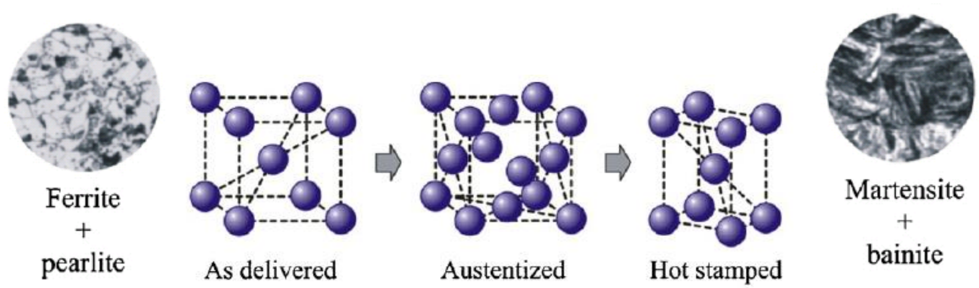


Source: Karbasian and Tekkaya 2010

Phase transformation behavior





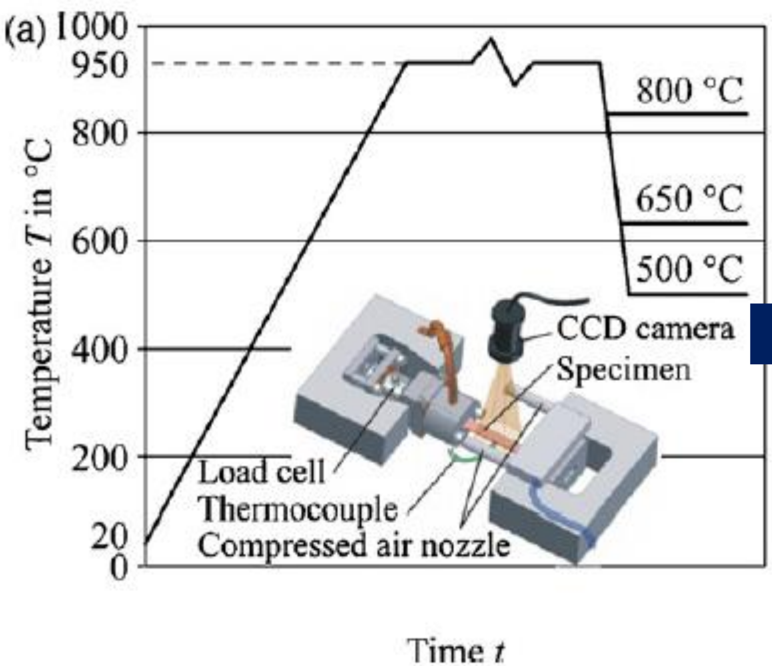


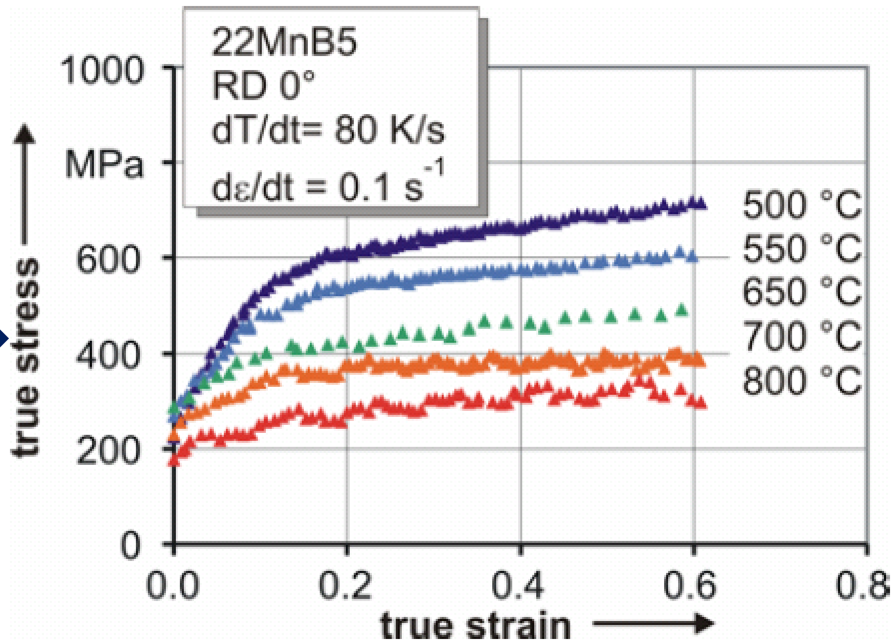
- The transformation from austenite (FCC) into martensite (BCT) causes an increase in volume, which influences the stress distribution during quenching.

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

Source: Karbasian and Tekkaya 2010

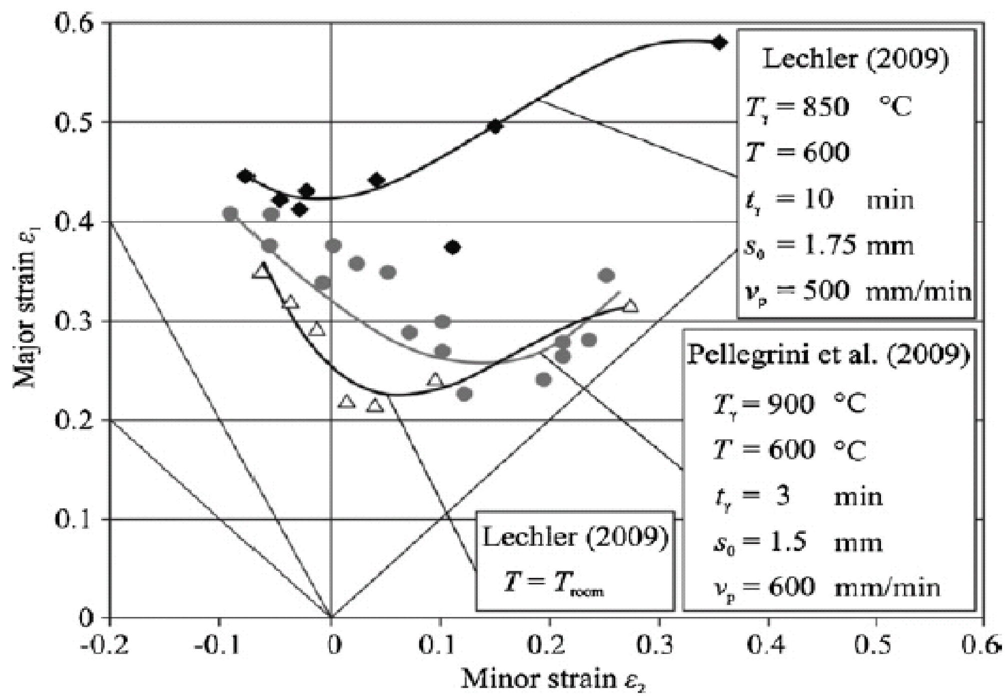
Flow behavior





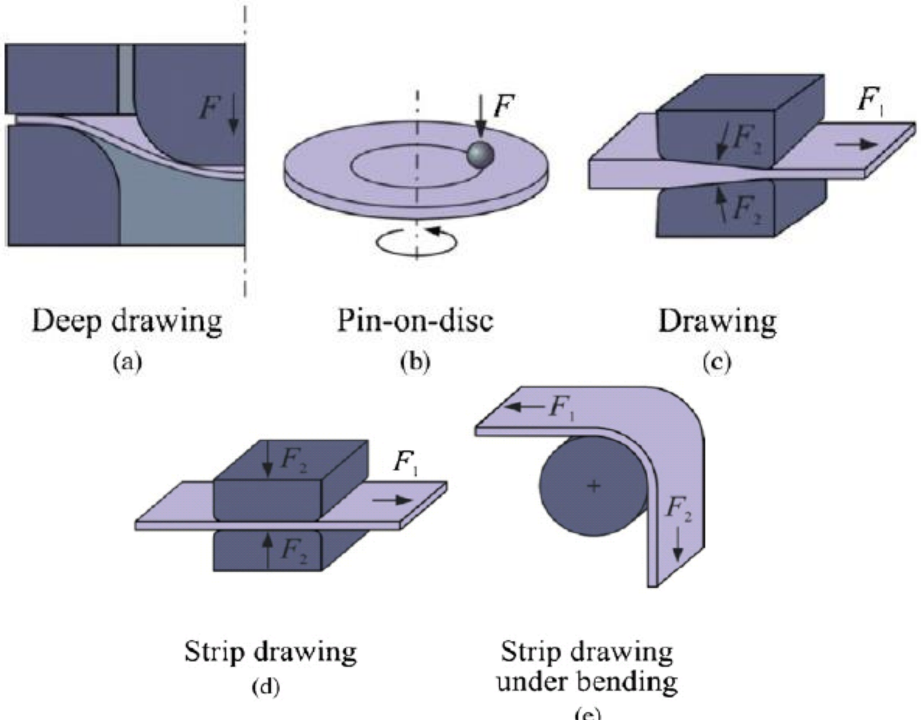
Source: Merklein and Lechler 2006

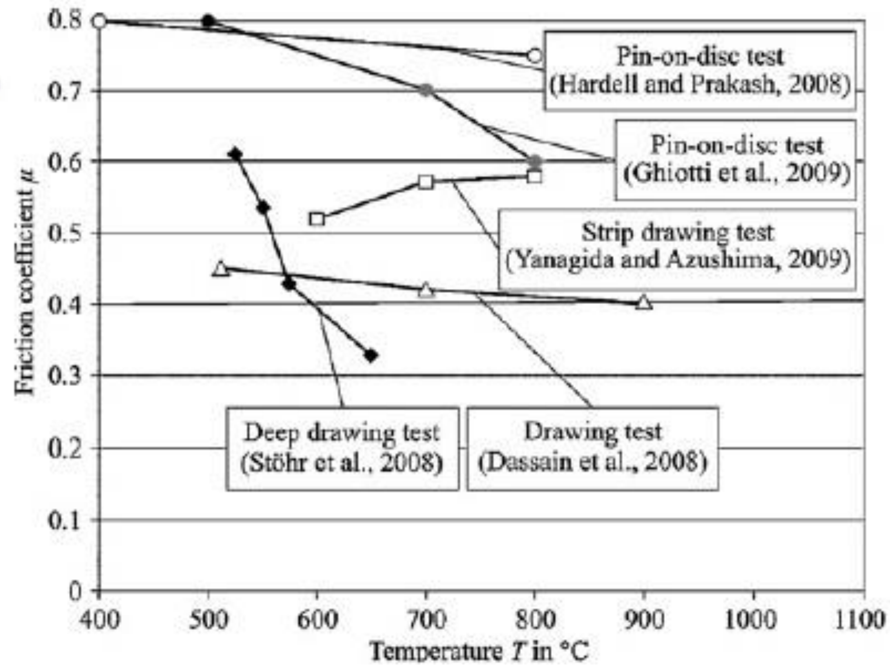
Forming limit curve



Source: Karbasian and Tekkaya 2010

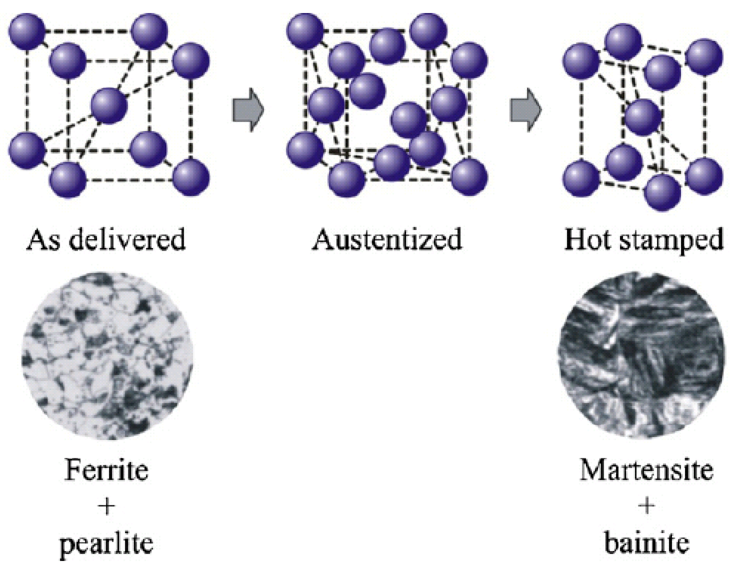
Friction coefficient

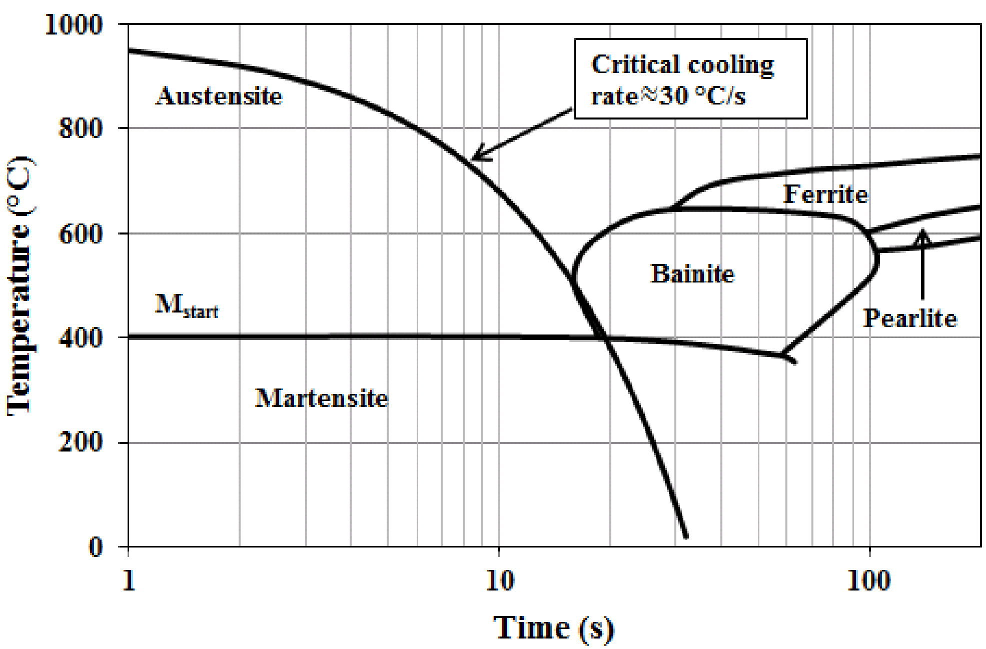




Source: Karbasian and Tekkaya 2010

Microstructure evolution



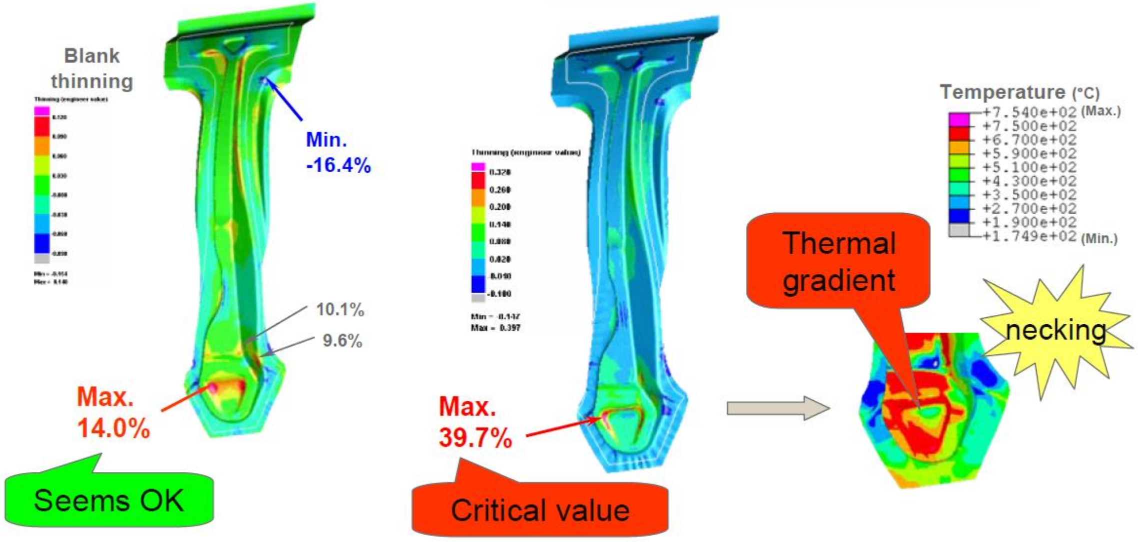


Source: Karbasian and Tekkaya 2010 and ArcelorMittal 2012

FE simulation performance

KMUTT

Isothermal	Thermo-mechanical



Thermo-mechanical calculation is necessary to validate the feasibility

Source: ArcelorMittal: Hot Stamping with USIBOR1500P® 2010

Overview

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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.

Source: Karbasian and Tekkaya 2010, Albrecht 2011, Banik 2011, Weigert 2011, Osburg 2012

Hard cutting

- 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.

Source: Karbasian and Tekkaya 2010, Albrecht 2011, Banik 2011, Weigert 2011, Osburg 2012

Warm cutting

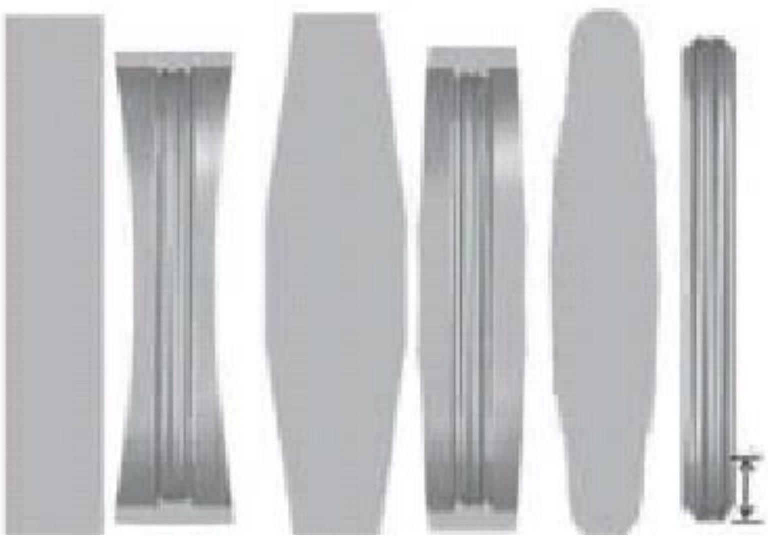
- Cutting parts during quenching at elevated temperatures

- 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.

Source: Karbasian and Tekkaya 2010, Albrecht 2011, Banik 2011, Weigert 2011, Osburg 2012

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.

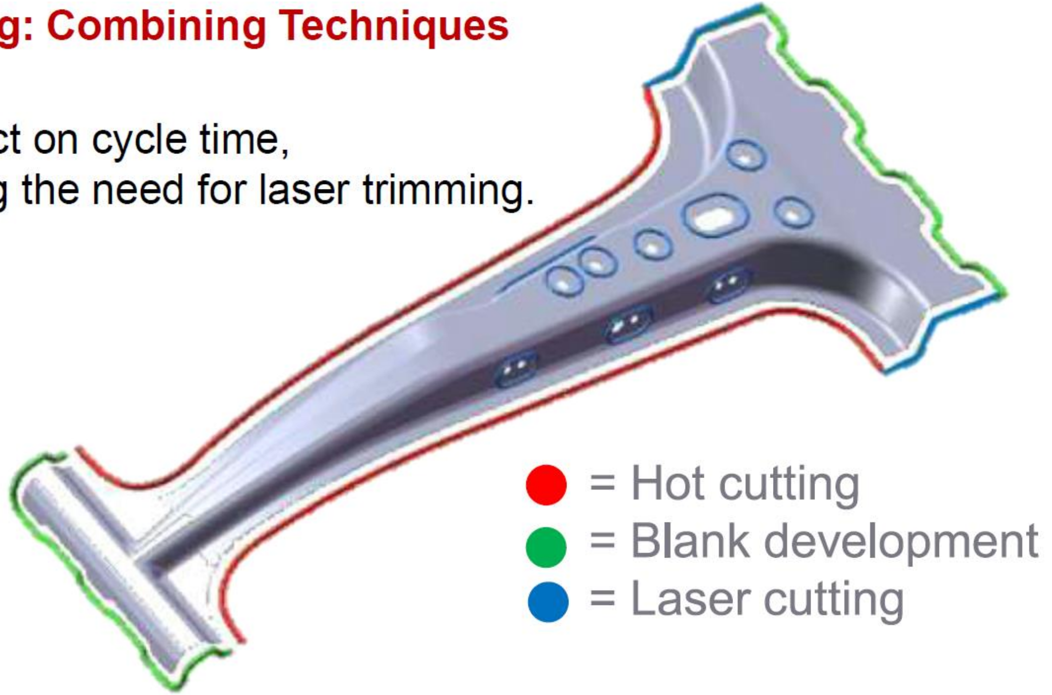
- The tolerances that can be achieved are smaller than with cutting after hot forming.

Source: Karbasian and Tekkaya 2010, Hund 2011, Baniket et al 2011

Combining techniques

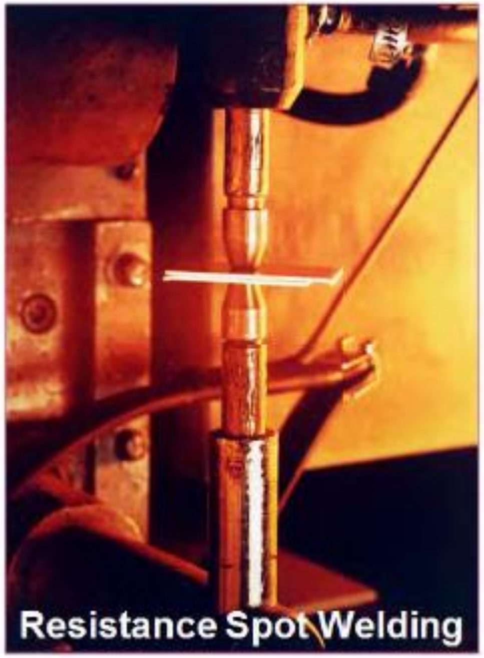
Trimming: Combining Techniques

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



Source: Karbasian and Tekkaya 2010, Josefsson 2010

Joining


Resistance Spot Welding

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 O_2 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

Joining

The coating layer and its chemical composition can cause failures during welding.

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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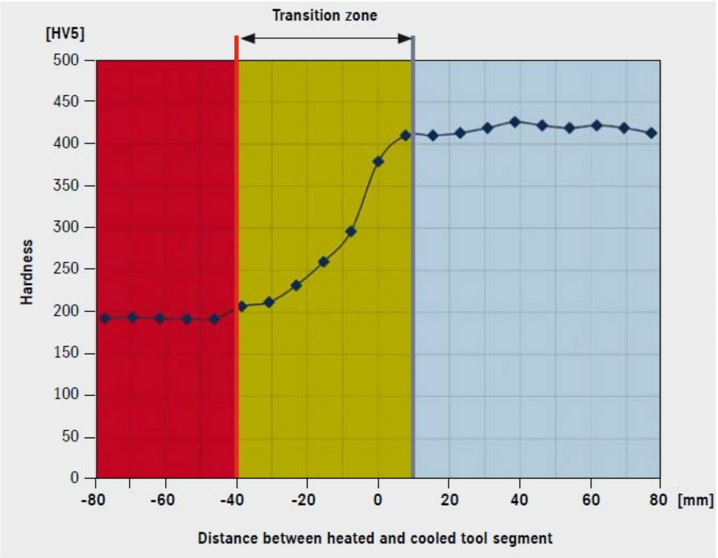
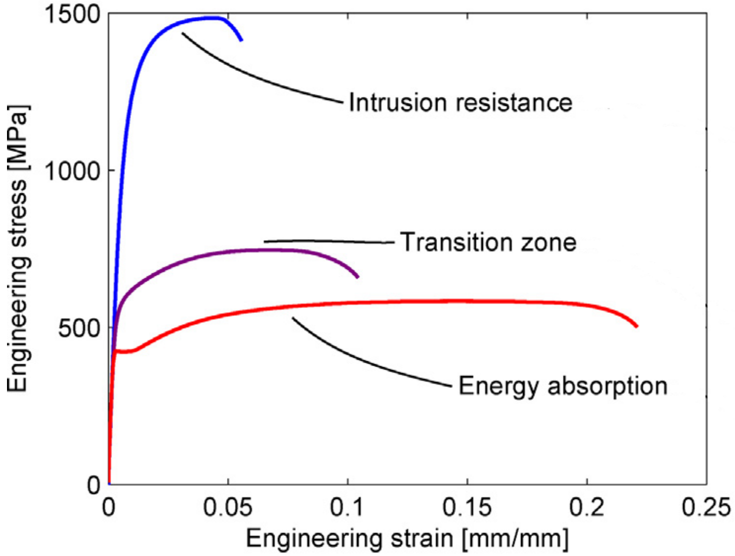
Tailored properties

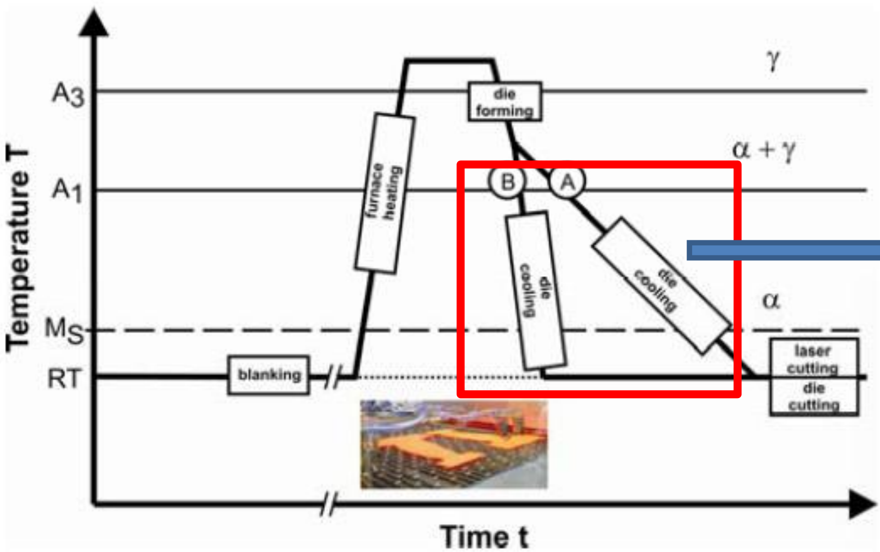
Fully martensitic transformation during hot stamping leads to a part with tensile strength of up to 1500 MPa and low elongation of about 5%. But an improved crash performance of a vehicle structural component, such as B-pillar can be achieved by introducing regions which have an increased elongation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

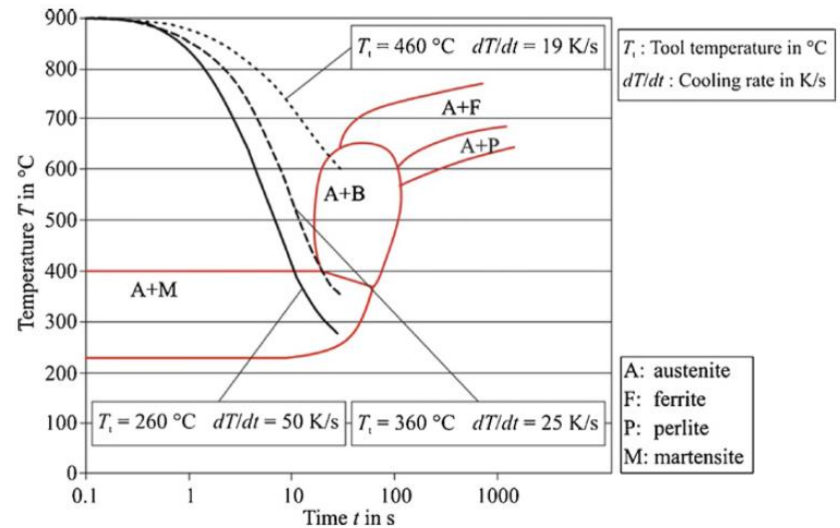




Source: ThyssenKrupp 2012, Eller et al. 2010

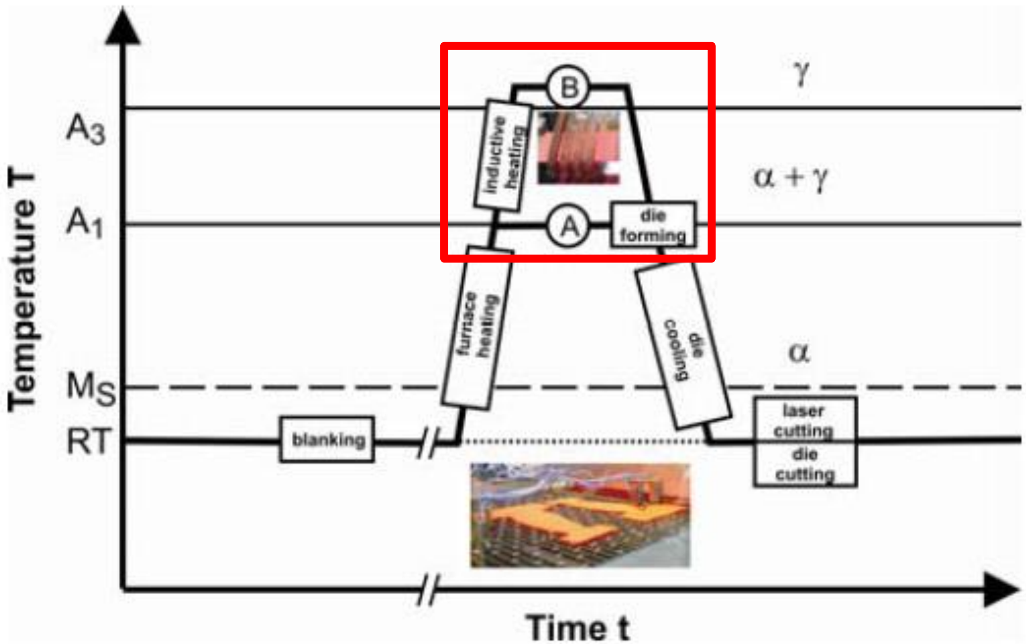
Tool tempering

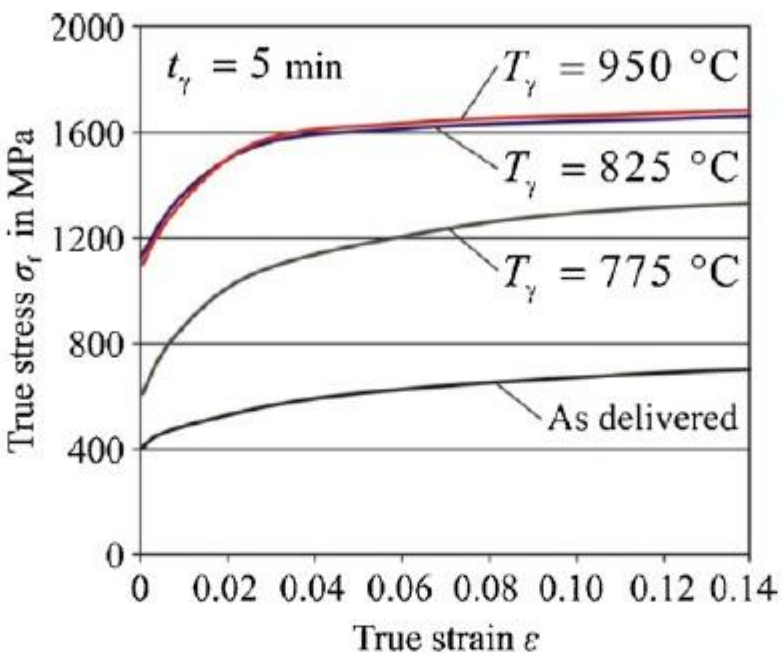




Source: Maikranz-Valentin 2007, Karbasian and Tekkaya 2010

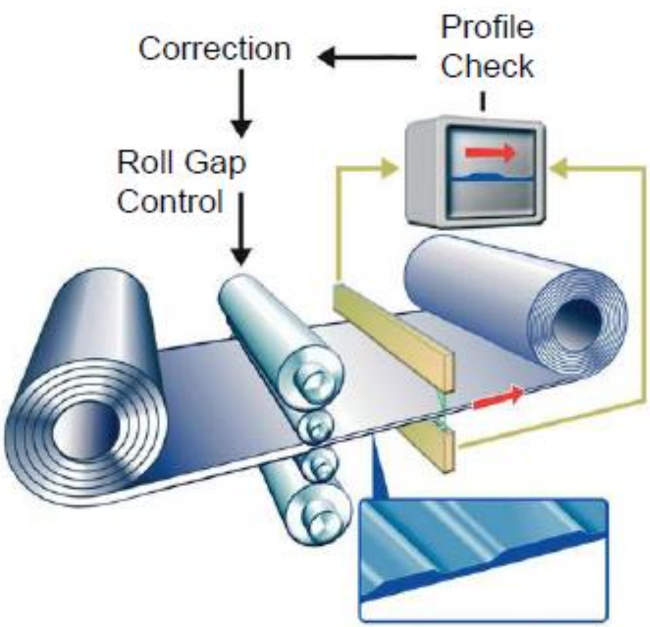
Blank tempering

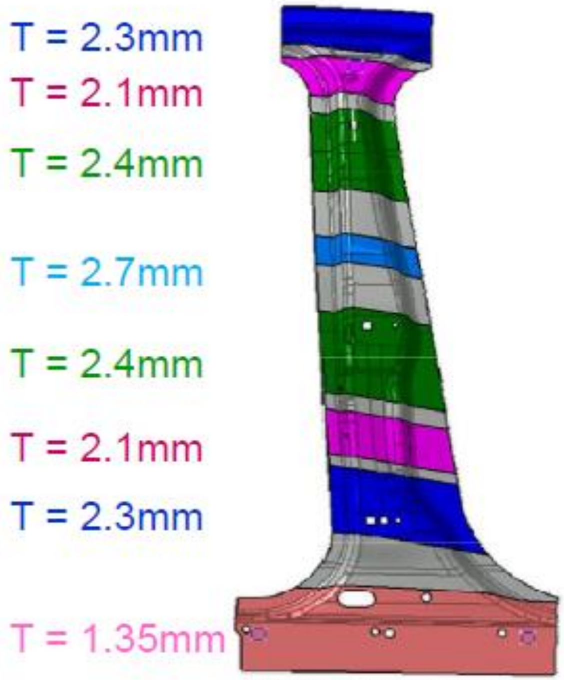




Source: Maikranz-Valentin 2007, Karbasian and Tekkaya 2010

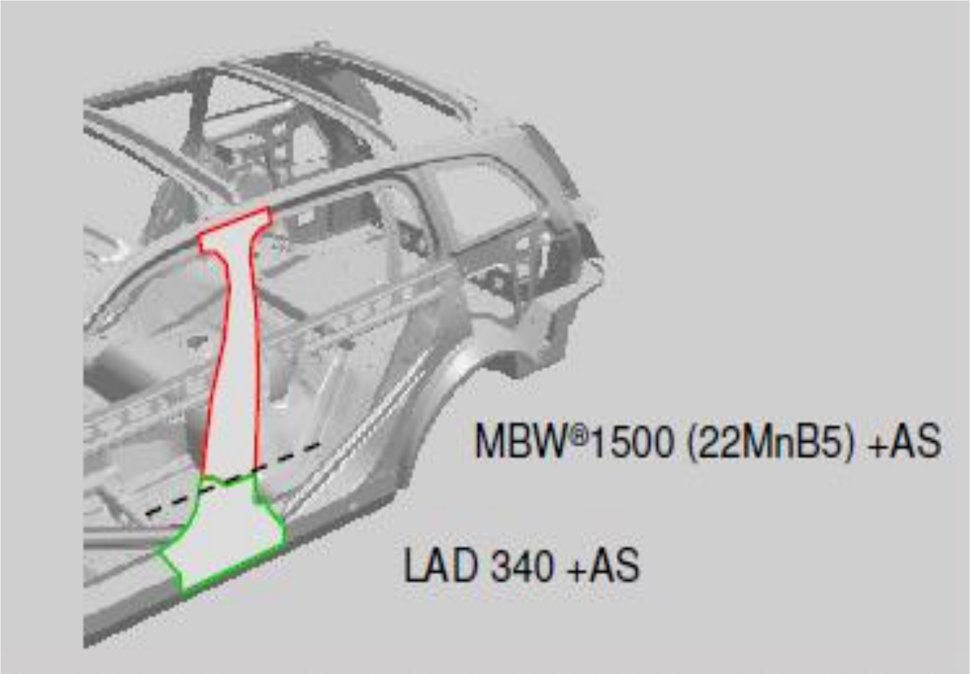
Tailor rolled blanks

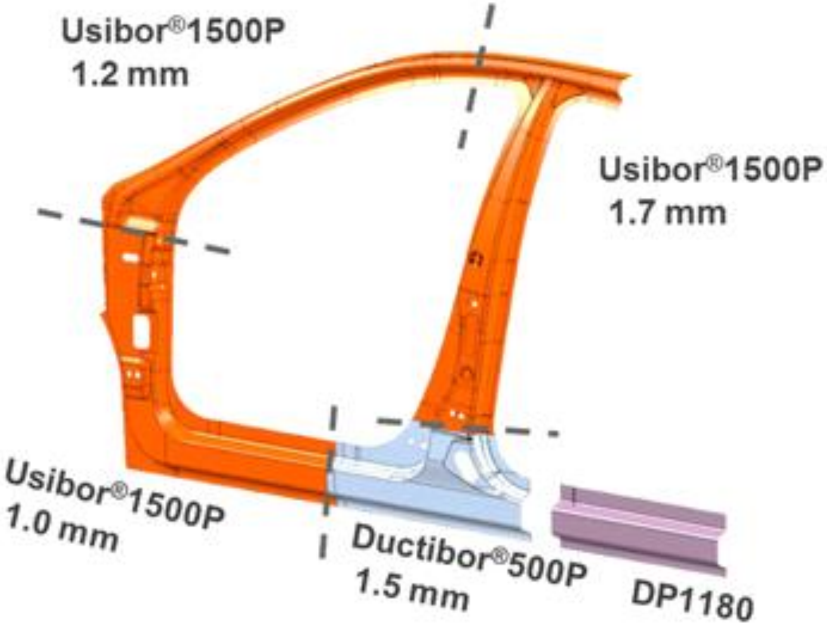




Source: mubea.com, Hover 2011

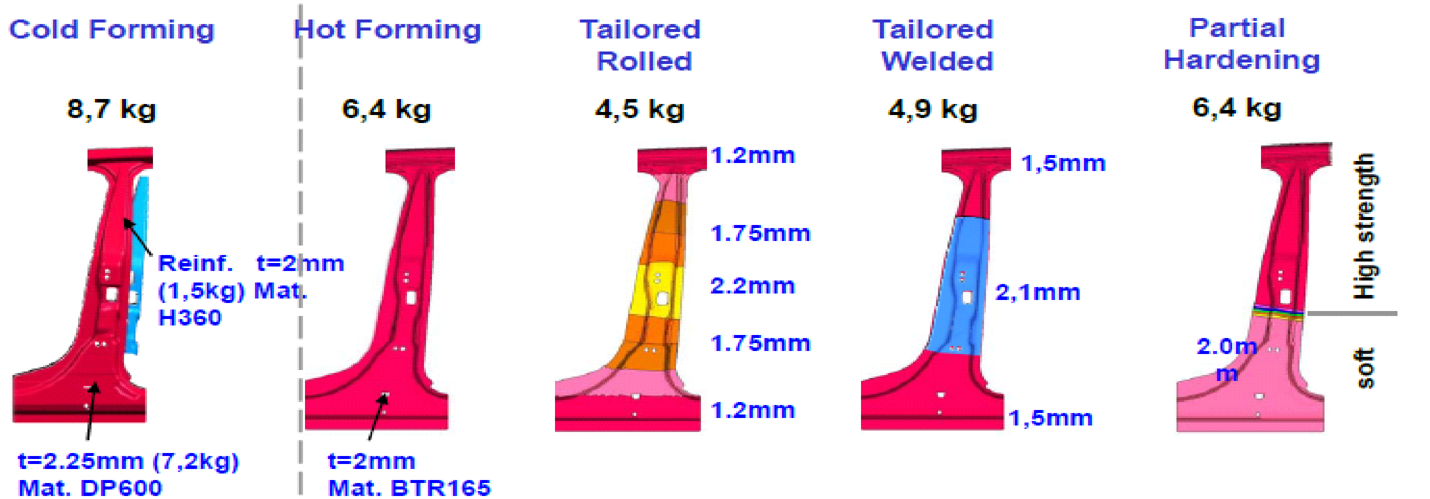
Tailored welded blanks





Source: ThyssenKrupp and ArcelorMittal

Hot stamped part with tailored properties



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 $s = 1.85$ mm

Bumper beam $s = 2.30$ mm

Windscreen upright $s = 1.20$ mm

Door reinforcement $s = 1.00$ mm

Tunnel $s = 1.0$ 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

Key Points

- 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