# Increasing the performance of hot forming parts by resistance heating in XHV-adequate atmosphere

*Bernd-Arno* Behrens, *Sven* Hübner[1], *Ulrich* Holländer[2], *André* Langohr[2], *Alexander* Schnettger[2], *Jan-Ulrich*Gellermann[1], *Jörn* Wehmeyer[1], and *Lorenz* Albracht[1]

[1]Leibniz University Hannover, Institute of Forming Technology and Machines, An der Universität 2, 30823 Garbsen, Germany
[2] Leibniz University Hannover, Institute of Materials Science, An der Universität 2, 30823 Garbsen, Germany

**Abstract.** In hot stamping, manganese-boron steel is heated above the austenitisation temperature and subsequently cooled at a rate of 27 K/s using a water-cooled process, resulting in lightweight components with ultra-high strength that enhance passenger safety, such as A- or B-pillars. Industrial heating takes place in roller hearth furnaces, where the sheet metal is heated up to 950 °C within 6 to 10 minutes and the AlSi coating bonds with the base material to protect it from scaling. Resistance heating is an alternative heating method. The direct current flow through the sheet enables heating rates of more than 100 K/s and heats the sheet in less than 10 seconds. This rapid heating also improves the mechanical properties by reducing the growth of coarse grains. However, the AlSi coating is not designed for such rapid heating, as there is not enough time for the diffusion layer to form. However, an XHV (extreme high vacuum)-adequate protective atmosphere with nitrogen and silane offers an alternative for scale-free heating without coatings. This process atmosphere binds oxygen, effectively preventing scale formation.

**Keywords:** Hot Stamping; Resistance heating; XHV-adequate atmosphere; coating.

## 1 Introduction

As part of the energy transition, fossil fuels are to be replaced by renewable energies in order to achieve the politically defined $CO_2$ limits. The reduction targets are set by the European Union in the European Climate Law and declared on a sector-specific basis. In forming technology, hot forming processes are particularly affected, as the workpieces are often heated using gas [1, 2]. One of the most important hot forming processes is hot stamping. By combining forming and hardening, components with ultra-high-strength properties can be produced in a single process step. The most commonly used material for hot forming is 22MnB5, which can achieve tensile strengths of over 1500 MPa at cooling rates of more than 27 K/s. In the transport sector this leads to lighter and safer cars, which in turn reduces fuel consumption. A reduction in weight of 100 kg leads to a decreased fuel consumption of 0.3 - 0.5 l/100 km, [3–6]. The hot stamping involves four steps - Cutting the Coil, austenitisation, transfer, forming and quenching. Firstly, the sheet metal is cut to size. This must be carried out close to the final contour, as post-processing can only be carried out using a laser, as the components have a hardness of 450 HV after hot stamping. These sheets are then heated above the austenitisation temperature $Ac_3$, typically up to 950 °C, in order to form a martensitic microstructure during the subsequent hot stamping process [7]. The overheating to 950 °C is necessary to counteract the cooling during the transfer between furnace and water-cooled hot stamping tool. After cooling with the required cooling rate below the final martensite temperature, the sheet is removed from the press, resulting in an ultra-high-strength component. Heating takes place industrially in roller hearth furnaces within 5 to 10 min, depending on the sheet thickness and coating system. The most commonly used coating is the aluminium-silicon (AlSi) coating with a maximum heating rate of 12 K/s [8]. This slow heating rate is due to the formation of an intermetallic phase between the AlSi coating and the base material to ensure sufficient formability. During the forming process, cracks can form down to the base material, which are closed in the subsequent cathodic dip coating process in the body-in-white, thus providing passive corrosion protection. Due to the slow heating process, these furnaces are up to 60 m long in order to provide sufficient heated sheet metal blanks for each press stroke [9].An alternative heating method is resistance heating. By integrating the sheet metal into the electrical circuit, several 10,000 A are conducted through the sheet metal and heated according to Joule's law. The heating can reach temperatures of up to 950 °C within a few seconds. The direct current flow and heating speeds of more than 100 K/s make this process very efficient and space-saving [10, 11]. As there is insufficient time for the AlSi coating to form an intermetallic phase, this coating system is not suitable for rapid heating processes. The accelerated rise of temperature leads to scale formation on the surface of uncoated sheets, which reduces the mechanical properties. The formation of scale depends on time and temperature and, despite rapid heating, requires reworking of resistance-heated uncoated sheet metal. Another method of suppressing scale formation is the deployment of protective gas atmospheres during heating. These ensure a reduction of oxygen content and therefore also of scale formation. A promising protective gas atmosphere consists of a nitrogen monosilane protective gas mixture. Nitrogen displaces the normal atmosphere from the process chamber and monosilane reduces the remaining oxygen in the nitrogen and in the process chamber due to its high reactivity. Fig. 1 shows that very small quantities (10 ppmv) are sufficient to reduce the oxygen content to a level adequate for XHV conditions. In this range, the oxygen content is reduced to a point where sheet metal can be heated without scale formation [12].

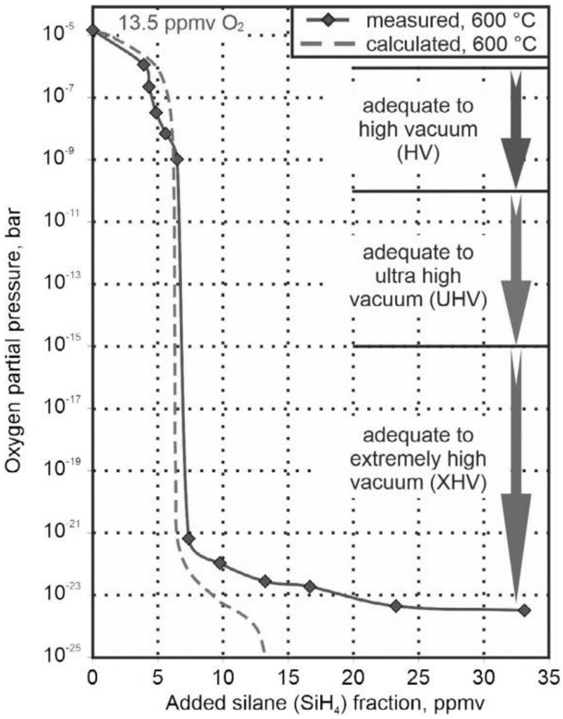


**Fig. 1.** Influence of the added silane ($SiH_4$) fraction on the oxygen partial pressure at a temperature of 600 °C. Measured values (rectangular dots) and calculated values (dashed line) show a significant decrease in oxygen partial pressure with increasing silane concentration. The resulting atmospheres correspond to areas of high vacuum (HV), ultra-high vacuum (UHV) and extreme high vacuum (XHV) [12]

As the silcone oxide and hydrogen are formed during the reduction of oxygen, their influence on the mechanical properties is important for evaluating this advanced technology. Key parameters include the tensile strength, the bending energy, which are analysed in this work and compared with standard furnace heated uncoated and AlSi coated samples.

## 2 Material and Methods

### 2.1 Resistance heating machine

In order to create an XHV-adequate process atmosphere, a resistance heating system at the institute of forming technology and machines (IFUM) was specifically modified to meet the requirements of the XHV-adequate atmosphere. The set-up is shown in Fig. 2. The process chamber is located on the left-hand side, where the electrodes for transferring the electrical power to the sheet metal plate are also located. The left-hand electrode is permanently connected, while the right-hand electrode is attached to a stretching device. This stretching device ensures that the sheet metal is held horizontally due to thermal expansion. It also enables plastic stretching of the sheet at defined temperatures in order to investigate the forming during hot forming in laboratory conditions. This allows the forming capacity of applied coatings to be defined as a function of temperature. To the right of the process chamber, the control panel enables setting the heating, the process atmosphere, the coating application and the stretching device step by step. It takes approx. 8 minutes to set up the XHV-adequate atmosphere and begins with flushing the process chamber with nitrogen 5.0 until the oxygen content is reduced to 0.01 % by volume. Silane is then added to the nitrogen at a maximum concentration of 100 ppm. This reduces the residual oxygen in the chamber and in the nitrogen, achieving an oxygen concentration at a level adequate for XHV conditions [13].

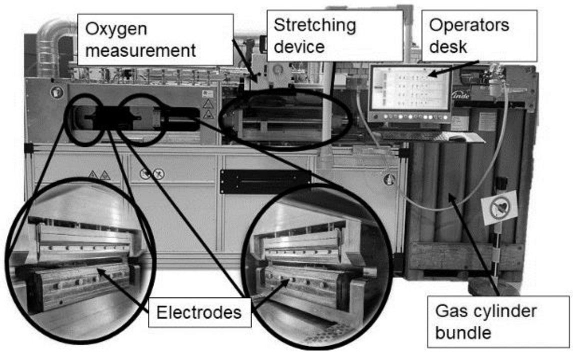


**Fig. 2.** Design of the resistance heating system for the XHV-adequate atmosphere with integrated stretching system for testing the formability of coatings and in-situ coating [13]

### 2.2 Mechanical Testing

The experiments were conducted using a resistance-heating machine and an electric furnace as shown in **Fig.** ***3***. For the resistance heating tests, the sheets were heated to 950°C within 8 seconds and held for 15 seconds to ensure a uniform temperature throughout the sheet. The furnace-heating trials were performed by placing the sheets in a preheated 950°C furnace for 6 minutes. The temperatures of the sheets were measured with thermocouple, which welded on the surface of the sheets. All sheets reached 950 °C, but the sheets in the XHV-adequate protective atmosphere overheated up to 1020 °C. This is due to the temperature control of the resistance heating system, which was implemented by a pyrometer to regulate the sheet temperature. As scale-free surfaces have a different emission coefficient, this difference resulted. Subsequently, the sheets were formed and hardened using a plate tool at a surface pressure of 30 MPa and a cycle time of 30 s. The plate tool consists of two flat water-cooled surfaces, which allows flat, hot-formed plates to be produced for mechanical tests.

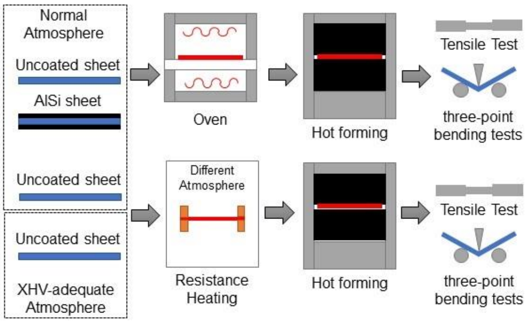


**Fig. 3.** Graphical illustration of the hot forming tests

Table 1 summarizes the experimental parameters and conditions for resistance and furnace heating trials. In order to investigate the influence of the XHV-adequate atmosphere, uncoated sheets from the same batch were heated by means of furnace and resistance heating in a nominal atmosphere. In addition, furnace heating was carried out with an AlSi coated sheet as those are widely used in industry. The specimens for the three-point bending tests and the tensile specimens were then cut out of these sheets using water jet cutting. The S100/ZD tensile testing machine from DYNA-MESS Prüfsysteme GmbH was used to determine the mechanical parameters. This enables tensile, compression and fatigue tests to be carried out with a maximum test force of 100 kN. The tensile testing machine is equipped with high-precision force and displacement measuring systems to precise recording of mechanical parameters. For the evaluation of the experiments, tensile tests according to DIN EN ISO 6892-1/2 with AS 50 (form h) flat tensile specimens and three-point bending tests according to VDA 238-100 with 60 x 60 x 1.5 mm sheets were carried out. The bending angle and the bending energy result from the tensile testing machine's load-force curve and the geometry of the three-point bending test device, which are calculated using the formulae from VDA 238-100.

**Table 1.** Heating Conditions and Oxygen Concentrations during Experiments

| Nomination | Atmosphere | Repetition |
|---|---|---|
| oven NA uncoated | 21 Vol. % $O_2$ | 3 |
| oven NA AlSi | 21 Vol. % $O_2$ | 3 |
| Resi Na uncoated | 21 Vol. % $O_2$ | 3 |
| Resi XHV uncoated | $10^{-15}$ Vol. % $O_2$ | 3 |

## 2.3 Material

The steel 22MnB5 (material number 1.5528) is a boron-alloyed heat-treatable steel in accordance with DIN EN ISO 683-2. It belongs to the group of hot-formable steels and is primarily used in the automotive industry for components that require ultra-high-strength properties, such as the A and B pillars. It is also used in mechanical engineering and in the agricultural sector. 22MnB5 has several advantages in terms of mechanical properties. In its initial state, it has good formability and, in combination with hot stamping, tensile strengths of up to 1500 MPa can be achieved. The hardened microstructure ensures increased wear resistance, which improves the service life of components, for example in agricultural applications. Components made of 22MnB5 can be effectively joined using selected welding processes, such as spot welding. As with all micro-alloyed steels, the corrosion resistance is moderate, but can be optimised through applying suitable coatings.

# 3 Results

To highlight the importance of the XHV-adequate atmosphere, Fig. 4 shows the scale-free cross-section coated on one side [14]. The XHV-adequate atmosphere ensures complete suppression of scale formation during complete heating to 950 °C, which means that the heating energy for hot stamping can be used for coating during the hot stamping process, as shown as in Fig. 4. Even with rapid resistance heating within 10 s to 930 °C, the scale thickness is approx. 7 µm [10], which means that post-treatment is required to remove the scale from the finished components.

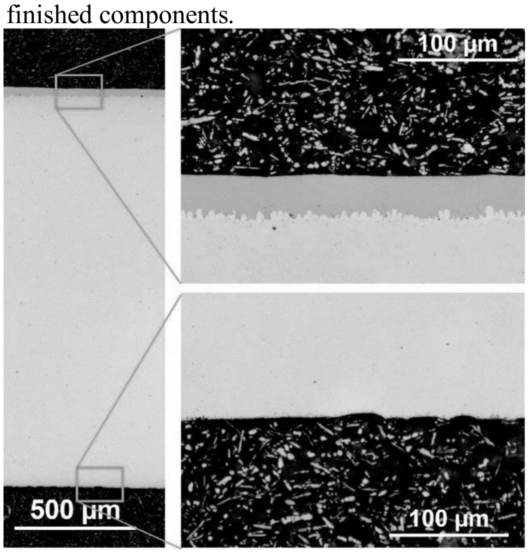


**Fig. 4.** Cross-section of a sheet coated on one side with nickel after heat treatment in an XHV-adequate atmosphere. The coated side shows a homogeneous nickel layer, while the uncoated side remains free of scale formation [14]

The results of the tensile strength tests are shown in Fig. *5*. It depicts four different tensile strengths, three of which are reference tests with different heating methods and coatings. It can be seen that the tensile strengths of the samples using furnace heating have lower values than the resistance heated samples in an XHV-adequate atmosphere. Uncoated furnace-heated sheet metal blanks have a tensile strength of about 1448 MPa, while AlSi-coated furnace-heated sheets achieve a tensile strength of 1480 MPa. The highest tensile strengths were measured for the uncoated resistance-heated sheets in a normal air atmosphere, with a value of 1535 MPa. The uncoated resistance-heated sheets in an XHV-equivalent atmosphere have a tensile strength of 1490 MPa and are therefore slightly higher than the AlSi-coated furnace-heated samples. The tensile strengths refer to the diameter without accounting for scale formation. Since the uncoated sheets oxidize significantly in a standard atmosphere, resulting in a substantial reduction in sheet thickness, this thickness loss was not considered in the measurements.

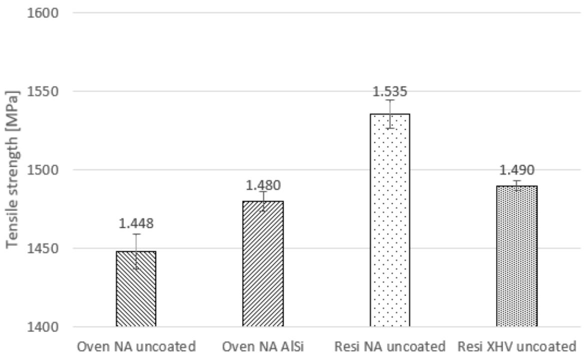


**Fig. 5.** Tensile strength of various test specimens according to VDA 238-100. Comparison of furnace heating (uncoated and AlSi-coated) and resistance heating (normal air atmosphere and XHV-adequate atmosphere)

Another important mechanical parameter for hot stamped components is the bending strength. Three-point bending tests were carried out in accordance with VDA 238-100 on the S100/ZD tensile testing machine. The characteristic values determined are shown in Fig. *6*. Equivalent to the tensile strength tests, samples were prepared using furnace heating with uncoated and AlSi-coated sheet metal blanks in a normal atmosphere and conductively heated sheet metal blanks in a normal air atmosphere and XHV-equivalent atmosphere. It can be seen that the bending angles of the samples coated in the furnace with an AlSi coating and conductively uncoated samples in a normal atmosphere have the lowest bending energies of 57.8  and 60.7 J respectively. The highest bending energies were achieved for the uncoated furnace-heated samples (80.7 J) and with the resistance-heated samples in the XHV-equivalent atmosphere (79.5 J). The associated bending angles show a clear gradation of the individual samples. The specimens treated in the furnace with an AlSi coating (59.8°) and the resistance-heated uncoated specimens in a normal atmosphere (60.7°) exhibit the smallest bending angles. The highest bending angles were achieved with the uncoated furnace-heated samples (77.7°) and the resistance-heated samples in an XHV-appropriate atmosphere (75.4°).

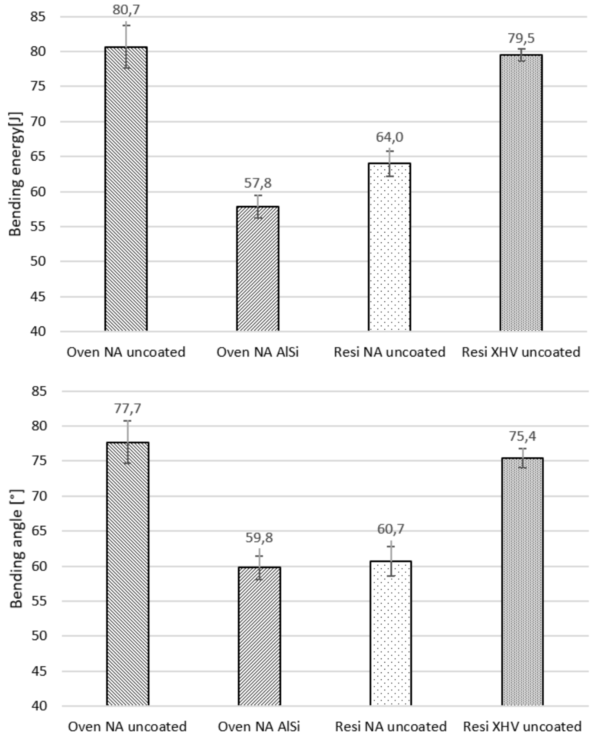


**Fig. 6.** Bending energy and bending angle of various test specimens according to VDA 238-100. Comparison of furnace heating (uncoated and AlSi-coated) and conductive heating (normal air atmosphere and XHV-adequate atmosphere)

The different tensile strength, bending angles and bending energies can be explained by examining the cross-sections of the edge regions, which are shown in Fig. 7. There it can be seen that the scale formation is significantly greater with uncoated furnace heating (Fig. 7, a) compared to resistance heating (Fig. 7, c). The micrograph of the XHV-equivalent sample (Fig. 7, d) also shows scale, but this can be explained by the transfer and pressing of the sheets, as this takes place in a normal atmosphere. The grain sizes of the furnace heatings (Fig. 7, a and b) are significantly larger than in the case of resistance heating in a normal atmosphere (Fig. 7, c). The grain size of the sample with the resistance heating in XHV-adequate atmosphere is similar to that of the furnace heating, which can be explained by the higher heating temperature. The heating of the uncoated samples in a normal atmosphere has a clear change in texture towards the edge area, which is not seen with the resistance heating in an XHV-equivalent atmosphere. The AlSi-coated reference sample shows the typical structure of the edge area, a developed intermetallic phase and cracks in the coating that extend to the diffusion layer. From this it can be concluded that the XHV-adequate atmosphere suppresses scale formation, but has no further influence on the sheets. The mechanical limit values could be further increased by more precise temperature control to minimize grain size formation.

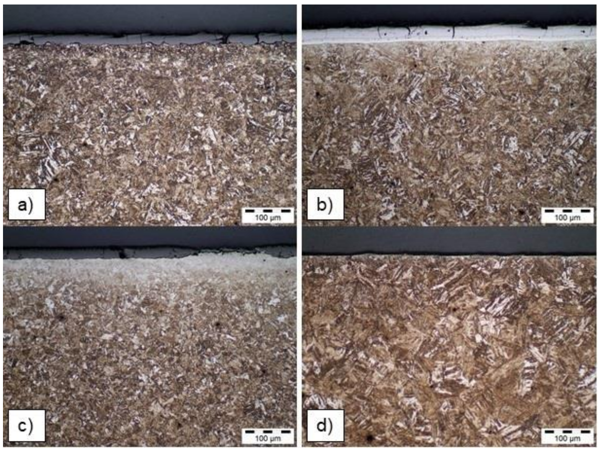


**Fig. 7.** Etched cross-sections of the four different heating methods a) uncoated, oven-heated in a normal atmosphere b) AlSi coated, oven-heated in a normal atmosphere c) uncoated, resistance-heated in a normal atmosphere d) uncoated, resistance-heated in an XHV-adequate protective atmosphere

## 4 Conclusions

The results highlight the potential of resistance heating in an XHV-adequate atmosphere for hot forming. The mechanical characteristics show that the XHV-adequate process atmosphere reduces the tensile strength of resistance-heated, hot-stamped sheet metal blanks, but these are still higher than the furnace-heated AlSi coated and uncoated sheet metal blanks commonly used in industry. The greatest advantage can be found in the bending energy, where the XHV-adequate process atmosphere enables a bending energy at the level of the uncoated furnace-heated blanks without a reduced tensile strength to the same extent. Given that the edge region of the specimens during bending tests makes a significant impact on the bending energy, it is obvious that the XHV-adapted atmosphere causes the edge region to be more ductile than heating in a normal atmosphere. In order to further characterize this effect, the edge area will be analysed metallographically using SEM. As a result, components used in crash-relevant structures could achieve the same tensile strength while simultaneously absorbing more energy, offering a significant benefit compared to existing components. The approach being pursued for further research is to use the XHV-adequate atmosphere in combination with the heating for hot stamping to coat the sheets in order to suppress scaling during transfer and hot stamping in the press and to improve the corrosion properties of the finished components.

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