Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 2363-2370
doi:10.4028/p-99k4fg

Submitted: 2021-12-08
Revised: 2022-01-25
Accepted: 2022-01-25
Online: 2022-07-22

Resistance Heating by Means of Direct Current for Resource-Saving CO_2-Neutral Hot Stamping

Bernd Arno Behrens[1,a], Sven Hübner[1,b], Lorenz Albracht[1,c]
and Ehsan Farahmand[1,d, *]

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

[a]behrens@ifum.uni-hannover.de, [b]huebner@ifum.uni-hannover.de,
[c]albracht@ifum.uni-hannover.de, [d]farahmand@ifum.uni-hannover.de

Keywords: hot stamping, DC resistance heating, CO_2 neutral heating, energy saving

Abstract. Hot stamping is a well-established and frequently used manufacturing process in automotive body construction. The number of components manufactured in this way is continuously increasing. Hot stamping is used to produce components with a completely martensitic structure, resulting in high strength and hardness. These components are mainly used in safety-relevant areas of the passenger cell, such as the A-pillar, B-pillar, tunnel and sill. For hot-stamping processes, it is necessary to austenitize the blanks. Heating the sheet metal up to 930 °C in a furnace is very energy-intensive. In large-scale industrial applications, the sheets are generally heated in gas-fired roller hearth furnaces up to 60 m long. Apart from the poor energy balance and the high CO_2 emissions of such furnaces, they are associated with high investment and maintenance costs, large space requirements and a long heating time. Rapid heating by means of the Joule effect and direct current instead of alternating current offer an energy-efficient and environmentally friendly alternative for sheet metal heating. Therefore, this technology can make a major contribution to environmental protection and resource saving. Within the scope of this work, parts were rapid-heated and subsequently hot-stamped by means of a novel heating system based on direct current with energy savings of up to 80 %. Using electricity guarantees a good CO_2 balance. In addition, resistance heating with a new type of DC-heating system and an adapted process chain is compared with conventional furnace heating. In thermographic images and microstructural examinations of the hot-stamped parts, it can be demonstrated that this direct-current technique is well suited for achieving homogeneous hardness and strength in the whole sheet metal. Thus, this new heating system can enhance the efficiency of the hot-stamping technology.

Introduction

The production of a safe passenger cell for the case of a crash is associated with a high financial and energetic investment. Steel sheets with higher strength are increasingly used in lightweight vehicle body construction [1]. An important reason for this are the improved mechanical properties in the case of a crash. Particularly for crash-relevant components, the highest possible strength is desired. One manufacturing process to fulfill these demands is hot stamping (press hardening). Here, the forming step for producing the component is combined with a heat treatment in a single operation. For this purpose, the sheets are heated to the austenitizing temperature of 930 °C and then formed and hardened in a cooled forming tool [2]. In addition to the good formability, very high component strengths greater than 1,500 MPa [3] and a hardness of about 450 HV [4] can be achieved. This process is currently established in almost all body structures of all vehicle manufacturers, with a steadily increasing trend [5]. Examples of components are door beams, bumpers, A-, and B-pillars.

However, the heating of the components is associated with increased expenses. Gas-fired roller hearth furnaces up to 60 m long are used here for large-scale production, and electrically powered industrial furnaces for small-scale production. Convection heating in the furnace goes hand in hand with high energy consumption, heat loss and heating times of 3-8 minutes from ambient temperature to austenitizing temperature [1]. Resistance heating offers an alternative to industrial furnaces. The sheet metal can be heated here with electricity instead of gas. Due to the significantly shorter and more energy-efficient heating through the direct energy conversion in the sheet, an increase in efficiency can be achieved. In addition, the use of direct current (DC) instead of alternating current (AC) further increases energy efficiency, since induction effects are significantly reduced by the DC current. This technology is based on the principle of power conversion according to Ohm's law of resistance (see Fig. 1). If an electric current flows through a conductor, the thermal power P generated by the electrical resistance R is available in this conductor. Here, the workpiece to be heated represents the consumer in the circuit. To induce current in the consumer, the electrodes are pressed onto the sheet metal.

$$P = I^2 \times R = \frac{U^2}{R} \tag{1}$$

When this power acts on the workpiece during a certain period of time t, the electrical energy P is converted into thermal energy W.

$$W = P \times t \tag{2}$$

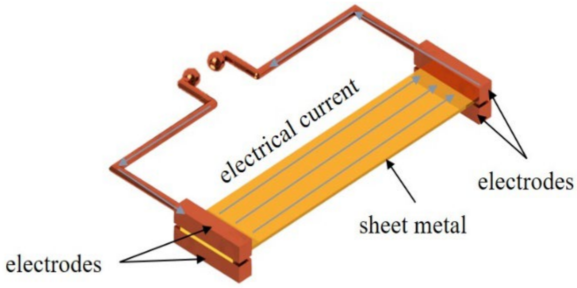


Fig. 1: Principle of resistance heating

The greatest challenge in resistance heating is the generation of homogeneous temperature distribution. The current always takes the path of least resistance. Maki et al. [6] investigated the feasibility of hot stamping and press quenching of ultrahigh-strength steel sheet using AC direct heating. An increase in tensile strength to more than 1,400 MPa and a hardness up to 500 HV were observed at a heating temperature of approximately 800 °C and above. The influence of the heating temperature on the hardness obtained was also evaluated. By means of resistance heating, a hardness of more than 450 HV could be realized in the as-received sheets. Mori et al. [7] present a 2-stage progressive-die hot-stamping process using partial resistance heating to produce small-sized ultra-high-strength steel parts without additional heat treatments. A non-coated 22MnB5 sheet with a thickness of 3.2 mm was heated up to 1,000 °C within 8 s and subsequently hot-stamped without springback. A significantly lower oxidation on the surface of the resistance-heated parts compared to the furnace-heated sheets was determined. Lee et al. [8] investigated the influence of heating time on the surface oxidation of resistance-heated 22MnB5. With increasing heating time, the surface oxidation of the zinc-coated sheets rises. Maeno et al. [9] investigated the homogeneity of the hardness distribution of resistance-heated parts and observed a deviation of 12 HV. Furthermore, it was possible to reduce the deviation to 5 HV using a holding time of 3 seconds at the austenitizing temperature. Behrens [10] and Albracht et al. [11] developed a new coating and heating system for uncoated sheets of 22MnB5. In this process, uncoated sheets could be simultaneously heated and coated with a specially developed nickel-based coating. To prevent scale formation during the heating of the sheet, they were heated in a nitrogen-silane atmosphere. In this paper, an energy-saving process chain for hot stamping by means of a self-developed resistance heating system based on direct current is introduced. Subsequently, resistance heating is compared with furnace heating and critically analyzed in terms of achievable mechanical properties and energy consumption.

Experimental Setup

For the investigation of sheet heating by means of direct current, a resistance heating system has been developed at the Institute of Forming Technology and Forming Machines. A schematic illustration of the system and the investigated process chain is shown in Fig. 2. By means of two medium-frequency inverters, which are arranged as master-slave, the AC power is first converted to a medium frequency of 1 kHz and then rectified. The inverters can deliver an output current of 1,062 A at a supply voltage of 400 V and a supply current of 336 A. The system is controlled by a Siemens PLC type 1511, which allows setting any power for heating. The maximum allowed power for each heating is limited in the Human Machine Interface (HMI) of the plant. A transformer-rectifier unit with a maximum DC power of 248 kW provides the required power for sheet metal heating. A pyrometer measures the temperature of the sheet metal. The recorded temperature is used to control the power. A PID controller readjusts the power. Thus, the target temperature is reached within the desired time and it is also not exceeded. By means of a Janitza energy measurement device, the current and voltage data as well as the consumed apparent, active and reactive power are recorded simultaneously with the heating.

The process chain of direct hot stamping was used for the investigations and is shown in Fig. 2. The used 22MnB5 sheets were uncoated and had dimensions of 1.6 × 150 × 400 mm. The specimens were austenitized at a temperature of 930 °C and then hot-stamped and quenched for 8 s at 1,000 kN in a water-cooled tool. For hot stamping, a hydraulic forming press of the company Dunkes was used. The transfer of the sheet from the resistance-heating machine to the die was performed by hand and took 8 s (transfer distance ≈ 3 m). In Fig. 3, the experimental setup is shown.

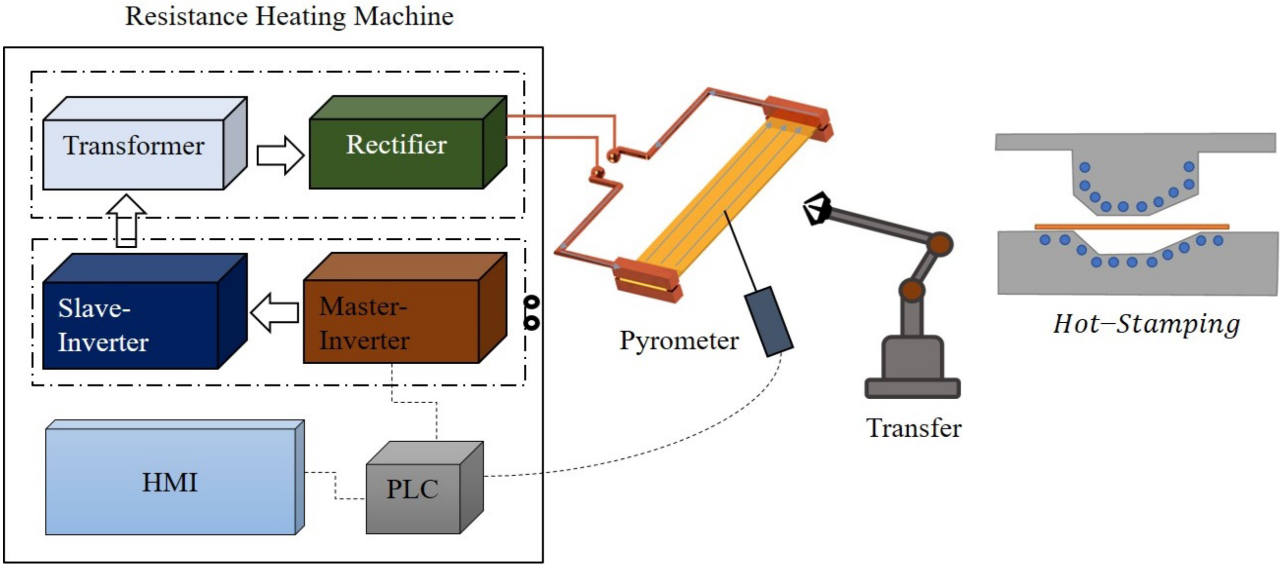


Fig. 2: Schematic illustration of the process chain of hot stamping by means of resistance heating

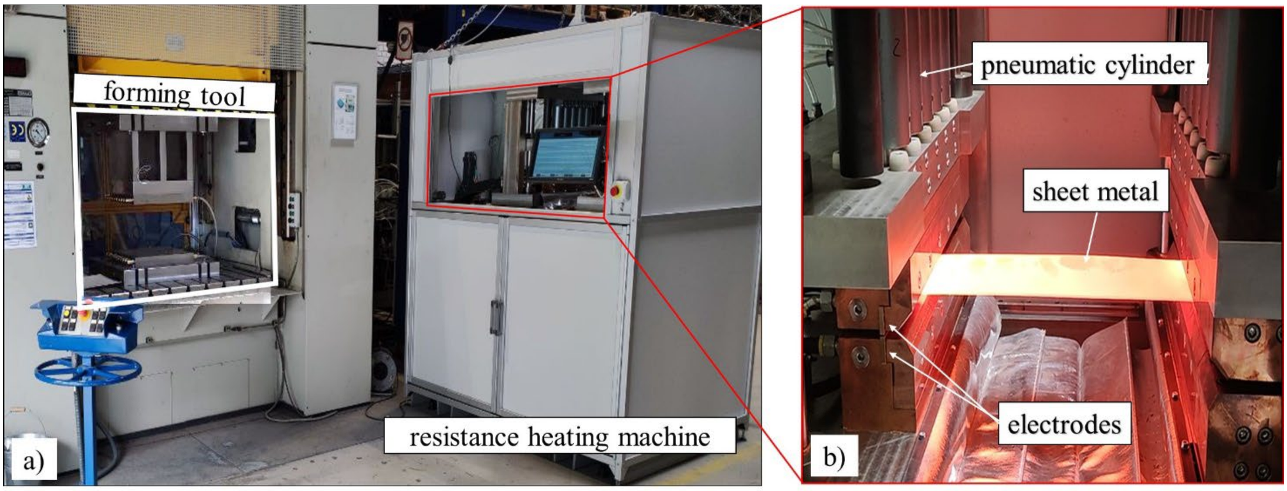


Fig. 3: a) Experimental setup for hot stamping, b) Detailed view of the DC resistance-heating system with a heated blank

In order to compare the efficiency of resistance heating with a conventional furnace heating, reference tests were carried out using an industrial furnace from Nabertherm with an output of 60 kW. The furnace was preheated to 950 °C. The material was heated to a temperature of 930 °C within 220 s. The sheet temperature during heating in the furnace was observed and measured by means of a temperature sensor positioned in the sheet (Fig. 4a). The energy measurement of the furnace is carried out with an energy measuring belt above the primary power supply. Comparison experiments using resistance heating were carried out with three different heating rates from ambient temperature to 930 °C within 4.3 s, 13 s and 44 s. In order to ensure the uniformity of heating by means of direct current, each heating was recorded by means of a thermographic camera (VarioCAM, InfraTec). To investigate the homogeneity of the mechanical properties, 15 specimens were cut out of each resistance-heated or furnace-heated sheet using a water- jet system. These were subsequently subjected to hardness tests. The measurement of the hardness was carried out using the hardness tester Qness. The specimens are 10 × 15 mm in size and were embedded and polished for the hardness measurement. The hardness was measured at three different points, each exactly in the middle of the sheet thickness over the entire length (15 mm) of the specimen.

Experimental Results

Fig. 4a shows an example of the heating process for a sheet heated in a furnace. It is noticeable that the heating time (220 s) is the longest step in the process chain. Rapid heating by means of electrical current offers great potential for shortening the process cycle time. Fig. 4b shows an example of the heating curve for resistance heating of the same sheet blank. The target temperature of 930 °C was reached in 4.3 s. This means a reduction in heating time by more than 90 %. The transfer and hot-stamping durations are identical in both processes. Hot stamping takes place at a temperature above 720 °C, which according to Nürnberger et al. [12] should result in a fully martensitic microstructure.

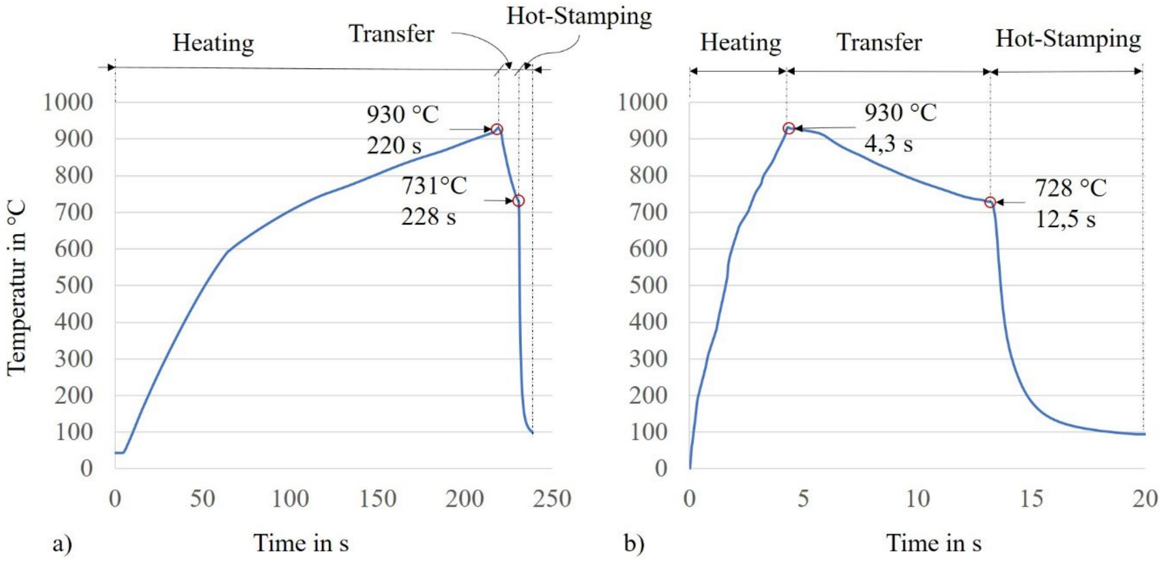


Fig. 4: Temperature-time courses of a) furnace heating with 220 s heating time and b) resistance heating with 4.3 s heating time

Table 1 shows the heating duration for the different heating processes and the measured energy consumption. Resistance heating was carried out with three different heating rates. For samples heated in the furnace, the heating time of the furnace itself was not taken into account. All tests were repeated 3 times. It is noticeable that with the increasing duration of resistance heating, the energy consumption also increases slightly. The efficiency factor of electrical energy into thermal energy for resistance-heated sheets is between 4% and 7%, which is significantly higher than for furnace heating (about 0.6%). It can be concluded that up to 92 % of the energy can be saved by resistance heating on a direct-current basis.

Table 1: Energy consumption and scale formation of resistance and furnace-heated sheets

heating method	heating rate [K/s]	duration [s]	power consumption [kWh]	scale formation	energy savings [%]
furnace	4.2	220	4.85	high	reference
resistance	216.3	4.3	0.39	negligible	92
resistance	71.5	13	0.45	negligible	91
resistance	21.1	44	0.63	negligible	87

Furthermore, the scale formation was investigated for furnace heating as well as for resistance heating. For the uncoated sheet used, only a slight reaction with the oxygen in the ambient air was detected after the resistance-heating process. Otherwise, the furnace-heating process results in a high amount of scale formation (Fig. 5a). This occurs due to the long heating time of 220 s. During this time, the uncoated sheet strongly reacts with the oxygen in the ambient air and highly oxidizes, as shown in the figure. Table 1 and Fig. 5b to d show that with increasing heating time of resistance-heated sheets, the scale formation and the energy consumption rise as well. However, the increasing energy consumption can be explained by the heat loss through thermal radiation and convection to the environment due to a longer lasting process and lower surrounding air temperature of about 25 °C compared to the furnace. Generally, there is no to very little scale in the temperature-transition zone and no scale in the electrode-contact zone. These areas remain colder compared to the rest of the sheet and potentially cannot react with ambient oxygen, as shown in Fig. 5e.

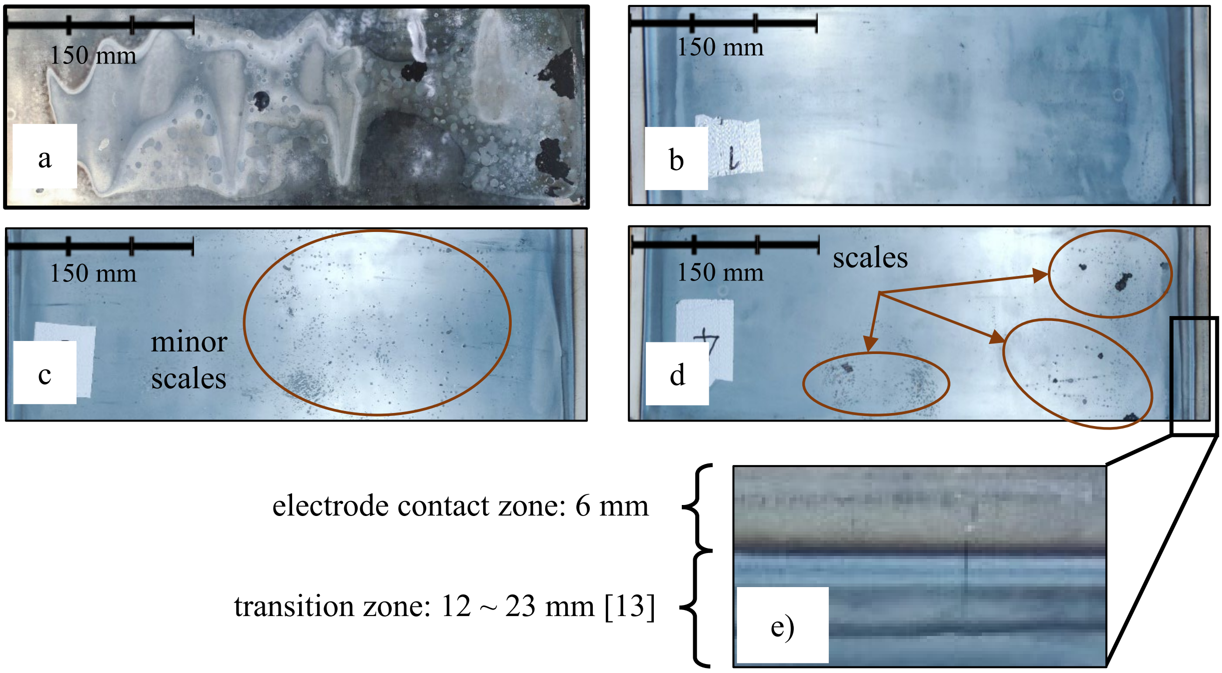


Fig. 5: Scale formation observed for a) furnace heating (4.2 °C/s), b) resistance heating (heating rate 216.3 °C/s), c) resistance heating (heating rate 71.5 °C/s), d) resistance heating (heating rate 21.1 °C/s), e) detailed view of the electrode-contact zone as well as the heat-transfer zone.

The homogeneity of the individual resistance-heating processes was evaluated by a thermographic camera. The thermographic images are shown in Fig. 6 and present the top view of the sheet at the end of each heating process. For all heating rates, a very homogeneous temperature distribution was determined. It is worth noting, that in each test there are slightly overheated areas, which can be seen in violet color. However, no clear tendency between the heating duration and the rate and size of the overheated areas could be found. Detailed examination of the thermograms showed a constantly changing temperature of ±30 °C in some cases. The different temperatures can be explained by the continuous correction of the current path. On the one hand, the current always takes the shortest path or the path of least resistance, and on the other hand, the electrical resistance increases with increasing temperature. The interaction between these effects leads to small temporal temperature differences during heating. However, these differences were balanced at least during the transfer to the forming tool due to internal heat conduction in the sheet.

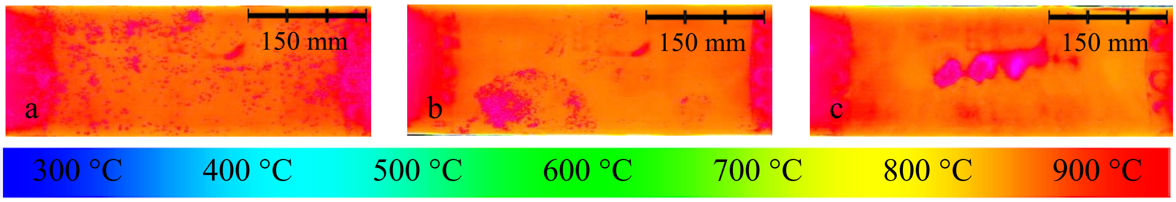


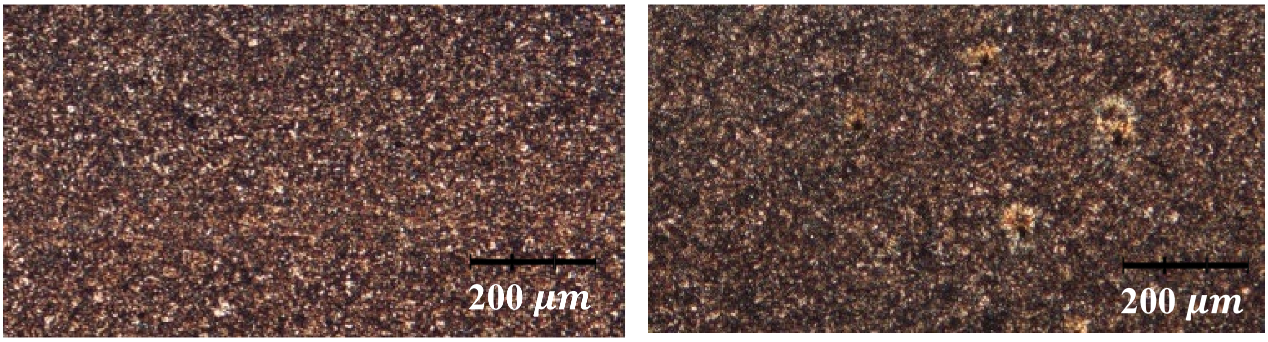
Fig. 6: Thermograms of the resistance-heated sheets a) 216.3 °C/s, b) 71.5 °C/s and c) 21.1 °C/s

To investigate the influence of the described temperature fluctuation during the heating process, both the furnace-heated and the resistance-heated sheets are subsequently hot-stamped, and hardness tests were carried out. The results of the hardness tests are listed in Table 2. The values obtained show that both furnace-heated and resistance-heated specimens are completely hardened and have a hardness above 450 HV. DC resistance heating provides a more uniformly distributed hardness than the conventional furnace heating. The standard deviation of the resistance-heated sheets was 7.2 to 8.34 HV and is thus lower than the standard deviation of furnace heating with a value of 9.54 HV. Furthermore, due to the use of DC-heating instead of AC-heating, the induction part of the energy loss is always smaller. This induction usually causes a comparatively inhomogeneous temperature profile in the AC systems. By means of DC-heating, hot spots caused by induction and inductive energy losses are both reduced.

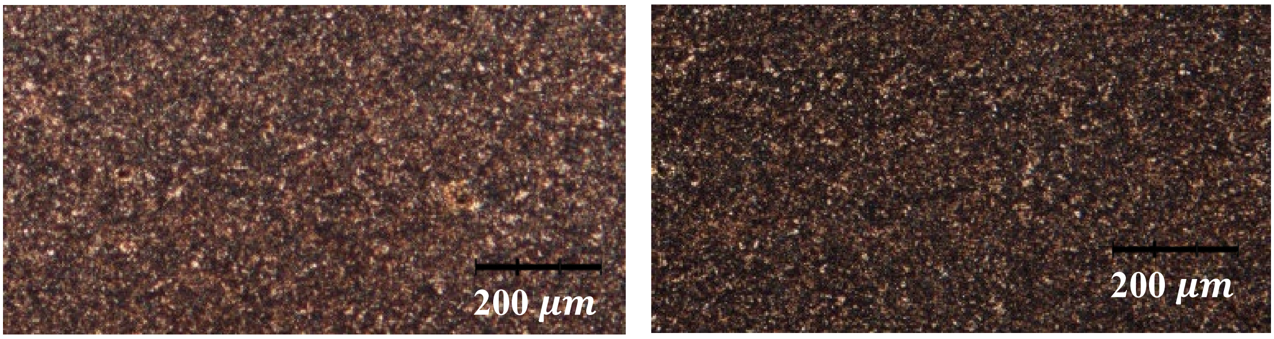
Table 2: Hardness analysis of furnace- and resistance- heated specimens

heating method	heating rate [K/s]	average hardness HV10	variance	standard deviation
furnace	4.2	478	91.05	9.54
resistance	216.3	483	54.40	7.38
resistance	71.5	472	51.80	7.20
resistance	21.1	475	69.54	8.34

Fig. 7 shows the results of the microstructural analysis. A fully martensitic and fine-grained microstructure was obtained for all processes. There is no clear difference between specimens from furnace heating and resistance heating. In conclusion, it can be stated that the heating rate has no significant influence on either the microstructure obtained or the hardness of the specimens. It only has an influence on energy consumption and scale formation.



a) furnace heating; heating rate 4.2 °C/s b) resistance heating; heating rate 216.3 °C/s



c) resistance heating; heating rate 71.5 °C/s d) resistance heating; heating rate 21.1 °C/s

Fig. 7: Microstructural images of the furnace- and resistance-heated samples

Summary

Resistance heating based on direct current is an alternative to energy-intensive industrial furnaces. The use of DC leads to a reduction in energy costs, energy savings of up to 92 % and can thus make a major contribution to CO_2 savings in the car-body manufacturing sector. The austenitizing temperature can be reached within a few seconds with a homogeneity comparable to industrial furnaces. The rapid heating leads to greatly reduced scale formation on the surface of uncoated sheets. It was shown that despite the shortest heating time, the homogeneity of the mechanical properties is reflected in the hardness values measured. Considering the homogeneous mechanical properties, a good comparability with the specimens heated in an industrial furnace was obtained. Resistance heating of coated as well as non-rectangular sheets is a more complex issue. New coating methods specifically for this process and also heating approaches for real non-rectangular parts are to be developed in this context.

References

[1] T. Taylor & A. Clough, Critical review of automotive hot-stamped sheet steel from an industrial perspective, Materials Science and Technology (2018) 809-861

[2] Z. Hou, J. Min, J. Wang, Q. Lu, Z. He, Z. Chai and W. Xu, Effect of Rapid Heating on Microstructure and Tensile Properties of a Novel Coating-Free Oxidation-Resistant Press-Hardening Steel, The Minerals, Metals & Materials Society Vol. 73, No. 11 (2021) 3195-3203

[3] M. Diekamp, S. Hübner, F. Nürnberger, M. Schaper, B.-A. Behrens und Fr.-W. Bach, Optimised press-hardening process using spray cooling – process integrated heat treatment of 22MnB5 sheet metal, HTM Journal of Heat Treatment and Materials vol. 66, no. 6 (2011) 316-322

[4] J.-H. Kim, D.-C. Ko, S.-B. Lee and B.-M. Kim, Hardness Prediction in Hot Stamping Process by Local Blank Heating Based on Quench Factor Analysis, Metals 9, 29 (2019)

[5] L. M. Arias, G. Artola and I. Porto, Hot Stamping Research Scenarios from the Last Decade, Mater. Proc. (2021).

[6] S. Maki, A. Hamamoto, Sh. Saito and K. Mori, Hot Stamping and Press Quenching of Ultrahigh Strength Steel Sheet Using Resistance Heating, Key Engineering Materials (2007) 309-316.

[7] K. Mori, T. Maenob, M. Sakagamia, M. Ukaic, Y. Agatsuma, 2-stage progressive-die hot stamping of ultra-high strength steel parts using resistance heating, International Conference on the Technology of Plasticity, ICTP (2017), 17-22.

[8] C. W. Lee, W. S. Choi, Y. R. Cho and B. C. Cooman, Surface Oxide Formation during Rapid Heating of Zn-coated Press Hardening Steel, ISIJ International 54 (2014) 2364–2368.

[9] T. Maeno, K. Mori, M. Sakagami, Y. Nakao and Ali Talebi-Anaraki, Minimisation of Heating Time for Full Hardening in Hot Stamping Using Direct Resistance Heating, J. Manuf. Mater. Process. (2020).

[10] B.-A. Behrens, S. Hübner, U. Holländer, A. Langohr, C. Pfeffer and L. Albracht, Increasing the energy absorption of monolithic manganese boron steels in oxygen-free environment, IOP Conf. Ser.: Mater. Sci. Eng., 40th International Deep-Drawing Research Group Conference (IDDRG 2021) (2021) 1157

[11] L. Albracht, S. Hübner, U. Holländer, B.-A. Behrens, Coating Materials Under Oxygen-Free Silane Atmosphere for Hot Stamping, Congress of the German Academic Association for Production Technology, WGP: Production at the Leading Edge of Technology (2021) 3-10

[12] F. Nürnberger, M. Diekamp, J. Moritz, L. Wolf1, S. Hübner, B.-A. Behrens, Spray Cooling of Early Extracted Hot Stamped Parts, Springer International Publishing: 143rd Annual Meeting & Exhibition (2014) 983-990

[13] B.-A. Behrens, S. Hübner, Local Hot Stamping – Innovative and Energy-Efficient by means of Conductive Heating. Conference Strategies in Car Body Engineering (2016)