

Resistance Heating in an Atmosphere Suitable for XHV with thin Aluminium Film Coating

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Abstract. Hot stamping of manganese–boron steels is widely used in automotive manufacturing to produce ultra-high-strength components with tensile strengths exceeding 1500 MPa [1, 2]. Conventional industrial heating relies on gas-fired roller hearth furnaces, which require 5 – 10 min to reach austenitization and exhibit low energy efficiency [3, 4]. Resistance heating offers a compact and energy-efficient alternative, enabling heating rates above 100 K/s and full austenitization within seconds. However, rapid heating of uncoated steels leads to severe oxidation, and established coating systems such as AlSi are not designed for diffusion-controlled bonding within such short times [5]. This study demonstrates that resistance heating in an XHV-adequate atmosphere – consisting of nitrogen and monosilane – suppresses oxidation while simultaneously enabling adhesion of a pre-laminated aluminum foil to the steel substrate. For coating preparation, 22MnB5 sheets were roughened by corundum blasting, cleaned, and laminated with an aluminum foil using a flat-die pressing tool. The pre-coated blanks were heated in a self-developed resistance-heating chamber, in which the oxygen concentration was reduced to an XHV-adequate level. Several heating profiles were investigated to determine suitable process windows for coating formation. The results show that resistance heating achieves austenitization within a few seconds, reducing heating times by more than an order of magnitude compared to furnace heating. The XHV-adequate atmosphere reliably prevents scale formation, enabling completely oxidation-free surfaces during rapid heating. Under these conditions, the laminated aluminum foil bonds uniformly to the substrate, forming a continuous coating layer. Metallographic cross-sections and SEM analyses confirm the formation of Al–Fe intermetallic phases at the interface, demonstrating robust metallurgical bonding suitable for subsequent hot stamping operations. Overall, the combination of resistance rapid heating and an XHV-adequate atmosphere provides a highly energy-efficient process route for hot stamping while offering an opportunity to integrate aluminum-based protective coatings directly into the heating step. This approach addresses the limitations of current furnace-based heating and coating technologies and opens a promising pathway toward more flexible, sustainable, and functionally integrated hot-stamping process chains.

Introduction

Hot stamping has become one of the most important manufacturing routes for producing ultra-high-strength components in the automotive industry. By heating manganese–boron steels above the austenitization temperature and subsequently forming and quenching them in a cooled die, tensile strengths exceeding 1.500 MPa can be achieved [2]. These properties are essential for safety-relevant structures such as A- and B-pillars, bumpers, and intrusion-resistant components. Industrial heating is typically carried out in gas-fired roller hearth furnaces, which require 5 – 10 min to reach the target temperature of approximately 950 °C [3, 4]. The slow heating rate is primarily dictated by the AlSi

protective coating, which requires sufficient time to form diffusion-controlled intermetallic phases that prevent scale formation during heating [7]. As a consequence, furnace systems are large, energy-intensive, and limit the flexibility of the overall hot-stamping process chain [8]. Resistance heating represents a highly efficient alternative, as Joule heating enables heating rates above 100 K/s and full austenitization within seconds [9]. Due to the direct power input into the material, high energy savings are achievable, and the compact design of the equipment significantly reduces required installation space [10]. However, the extreme heating rates pose a substantial challenge to conventional coating systems. The diffusion time required for AlSi coatings to bond with the substrate is not available during rapid resistance heating, while uncoated steels suffer from severe oxidation, leading to surface degradation and reduced mechanical performance. A promising solution is the use of an oxygen-free process atmosphere. By employing a nitrogen–monosilane gas mixture, the oxygen concentration in the heating chamber can be reduced to levels equivalent to an extreme high vacuum (XHV), preventing the formation of scale even during rapid heating. At the same time, this environment opens the possibility of applying alternative coating systems that can bond within seconds [11]. In this study, we investigate the feasibility of combining resistance rapid heating with an XHV-adequate atmosphere to enable scale-free austenitization and simultaneous bonding of a mechanically pre-laminated aluminum foil to 22MnB5 steel. The resulting process route aims to combine high energy efficiency, compact equipment layout, and integrated surface functionalization, thereby addressing key limitations of conventional hot-stamping technology.

Materials and Methods

The experimental investigations were carried out using a resistance heating system specifically developed to enable rapid austenitization of manganese–boron steel sheets under XHV-adequate conditions. Shown in fig. 1 the core of the setup is a sealed high-temperature process chamber manufactured from stainless steel, in which the sheet is positioned such that the active heating zone lies fully inside the controlled atmosphere. Quartz-glass observation windows allow optical access as well as pyrometric temperature measurement, while an exhaust and sampling port positioned above the sheet continuously supplies gas to an external lambda probe for oxygen monitoring. Heating is achieved by direct current flow through the sheet, which is clamped between two water-cooled copper electrodes. The left electrode is fixed, whereas the right electrode is mounted on a motorised ball-screw spindle. This enables continuous compensation for thermal expansion during heating, ensures a stable and planar sheet position, and allows defined plastic stretching to be introduced during selected experiments. The electrical power is supplied through a water-cooled thyristor unit and a high-current transformer that reduces the mains voltage to approximately 30 V, enabling currents of several tens of kiloamperes. These conditions allow heating rates exceeding 100 K/s and peak temperatures of 950 – 1050 °C within only a few seconds.

To generate an XHV-adequate environment, the system is equipped with a dedicated gas management unit capable of metering nitrogen and controlled amounts of silane. The atmosphere is established through a two-step process. First, nitrogen (N₂ 5.0) is introduced at a high flow rate to displace the ambient atmosphere inside the chamber. Within 60 – 120 s, this purge reduces the oxygen concentration to below 10⁻³ vol. %. Subsequently, a nitrogen–silane mixture containing approximately 100 ppm SiH₄ is fed into the chamber. Monosilane reacts spontaneously and selectively with residual oxygen according to the reaction $\text{SiH}_4 + 2 \text{O}_2 \rightarrow \text{SiO}_2 + 2 \text{H}_2\text{O}$, thereby chemically binding the oxygen in the form of solid silica particles and water vapour. In a second, temperature-triggered reaction step, the resulting H₂O is further converted by silane into H₂, again forming inert SiO₂ [12, 13]. This reaction mechanism enables a further reduction of the initial oxygen concentration to ~10⁻¹⁵ vol. %, equivalent to the conditions of an extreme high vacuum (XHV) without the need for mechanical vacuum generation. As the reaction rate increases with temperature, the oxygen content continues to decrease during the subsequent heating stage. Once XHV-adequate conditions are reached, resistance heating is initiated. The sheet was heated to 950 °C within 12 s. Subsequently, the temperature was maintained for an additional 30 s in order to reduce temperature gradients and promote a more homogeneous temperature distribution within the sheet. The XHV-

adequate atmosphere suppresses any formation of oxide scale, even at temperatures exceeding 1000 °C, enabling metallurgical surface reactions to proceed without interference from oxidation. These conditions also allow the integration of coating processes directly into the heating step. Two coating strategies were investigated. In the first approach, nickel-based brazing powders (alloys Ni700, Ni710 and Ni720) were applied to the sheet surface. Their melting ranges between 875 °C and 950 °C make them suitable for rapid bonding during short holding times [14].

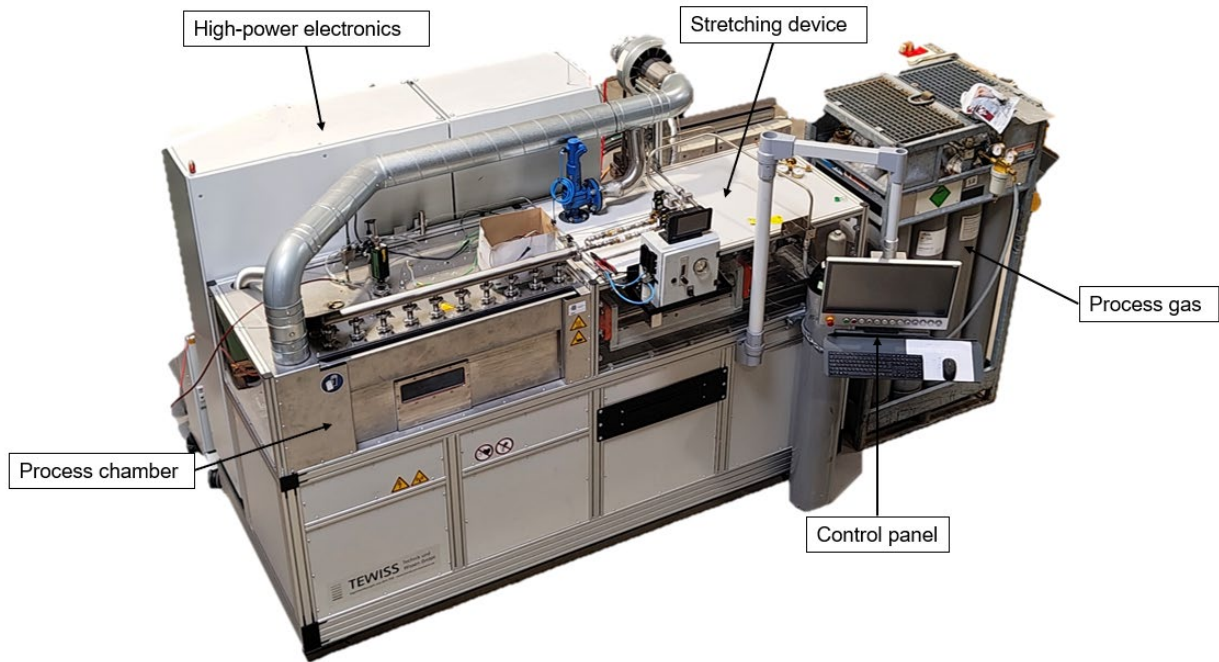


Fig. 1. Resistance heating device with XHV-adequate atmosphere

The investigations were carried out using an uncoated manganese–boron steel of grade 22MnB5, which was provided by Salzgitter Mannesmann Forschung with a nominal thickness of 1.5 mm. The chemical composition of the steel corresponds to the typical specification of 22MnB5 and is summarized in tab. 1. It is characterized by a carbon content of 0.19–0.25 wt.% and a manganese content of 1.10–1.40 wt.%, ensuring sufficient hardenability for press-hardening applications. The boron content in the range of 0.0008–0.0050 wt.% enhances the hardenability, while minor alloying elements such as silicon, chromium, aluminum and titanium are present within standard limits to stabilize the microstructure and maintain the effectiveness of boron through nitrogen fixation. The contents of phosphorus and sulfur are restricted to low levels to preserve good formability and mechanical performance. The selected material grade and sheet thickness represent an industry-relevant reference for hot stamping applications and allow direct comparison with established hot stamping processes

Table 1. Chemical composition of the investigated 22MnB5 steel (wt.%)

Element	Carbon	Manganese	Boron	Silicon	Phosphorus	Sulfur	Chromium	Aluminum	Titanium
Content [wt. %]	0.19 – 0.25	1.10 – 1.40	0.0008 – 0.0050	≤ 0.40	0.025	0.015	0.15 – 0.35	0.020 – 0.060	0.020 – 0.050

A further process route is illustrated in fig. 2 and aims to investigate the feasibility of rapid heating of coatings that form intermetallic phases. For this purpose, aluminum thin foils (thickness 8 – 14 μm) were applied prior to heating. The process begins with a targeted surface roughening of the steel sheet. To this end, the sheet surface was manually treated with corundum in order to increase the surface roughness and to prepare improved mechanical interlocking between the steel substrate and the aluminum foil. This step increases the effective contact area and establishes the prerequisite for a form- and force-fitting bond in the subsequent joining step. Subsequently, both the roughened steel

sheet and the aluminum thin foil were cleaned. Cleaning was carried out manually using acetone and served to remove contaminants such as abrasion debris, residual corundum particles, grease, or oil in order to ensure clean interfaces for the pressing operation. In the next process step, the prepared steel sheet and the aluminum thin foil were pressed together. The pressing operation was performed on a servo-hydraulic press of type Dunkes HDZ 400 using a flat die tool. An applied pressing force in the range of 2.000 to 3.000 kN was used. The objective of this step is to establish a uniform and reproducible contact between the aluminum foil and the steel substrate without inducing any intentional forming. The suitability of the pressing process was assessed based on visual criteria, with particular emphasis on whether the roughness structure of the previously roughened steel sheet was locally discernible through the aluminum foil after pressing. This imprinting of the surface structure was interpreted as an indicator of sufficiently high local contact pressure and effective mechanical interlocking.

The prepared specimens were subsequently heated by resistance heating. Heating was carried out in an XHV-adequate atmosphere, resulting in an extremely low oxygen activity and enabling oxidation- and scale-free heating of the specimens. In particular, undesired oxidation at the interface between the steel sheet and the aluminum foil during the rapid heating phase could thus be prevented. After completion of resistance heating, the specimens were transferred under ambient air conditions. The subsequent pressing operation was again performed using a flat plate tool, without any geometric forming of the specimens. This final process step serves exclusively to ensure contact and controlled cooling of the specimens without any forming component and concludes the process chain depicted in fig. 2.

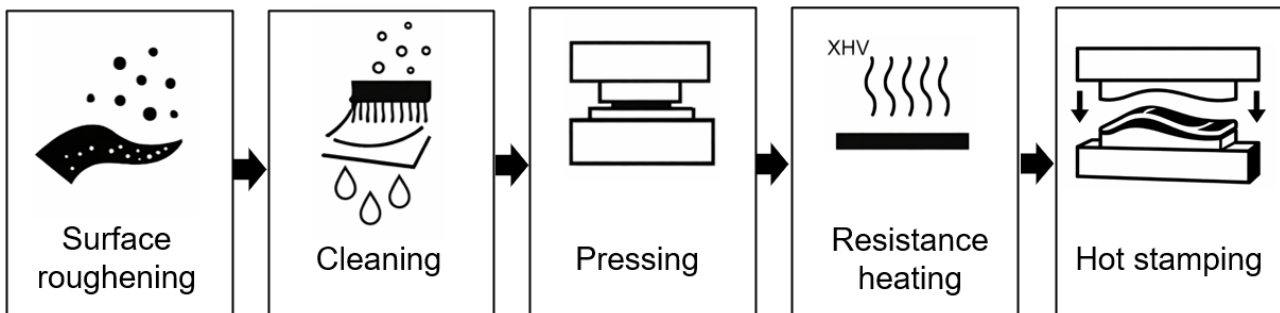


Fig 2. Process chain hot stamping with applied aluminum foil

The experimental matrix, shown in tab. 2, comprises a total of four pressing trials in which both the applied pressing force and the effective pressing area were systematically varied. In experiments 1 to 3, the pressing area was kept constant at 420 mm × 140 mm, while the applied force was increased stepwise from 2.000 kN to 2.500 kN and finally to 3.000 kN. This resulted in surface pressures of 34.0 MPa, 42.5 MPa, and 51.0 MPa, respectively. This series of experiments served to investigate the influence of increasing surface pressure at a constant contact area on the mechanical interlocking between the aluminum foil and the steel substrate. In experiment 4, the maximum applied force of 3.000 kN was maintained while the pressing area was reduced to 140 × 140 mm. As a result, the corresponding surface pressure increased significantly to 153.1 MPa. This experiment was deliberately conducted to analyze the effect of a strongly increased local surface pressure on the quality and homogeneity of the mechanical interlocking and to enable a direct comparison with the results obtained for larger pressing areas.

Table 2. Experimental matrix of the pressing trials

Test	Applied force F (kN)	Contact area (mm × mm)	Contact pressure p (MPa = N/mm ²)
1	2.000	420 × 140	34.0
2	2.500	420 × 140	42.5
3	3.000	420 × 140	51.0
4	3.000	140 × 140	153.1

From the well-adhering coated sheets, cross-sections were prepared by metallographic sectioning, mounting, grinding, and polishing. The cross-sectional specimens were subsequently examined using a Zeiss SUPRA 55VP field emission scanning electron microscope (FE-SEM) equipped with an energy-dispersive X-ray spectroscopy (EDX) system. Backscattered electron (BSE) imaging was employed to resolve phase contrasts across the coating–substrate interface, and elemental line scans were recorded along defined measurement paths at constant accelerating voltage to characterize compositional gradients. Depending on the accelerating voltage and material properties, the lateral spatial resolution of the EDX measurements was approximately 1 μm , with a quantitative accuracy within a few atomic percent.

Results

Fig.3 shows the results of the pressing trials with varying pressing force and pressing area. In experiments 1 to 3, it can be observed that the mechanical interlocking between the aluminum foil and the steel substrate is predominantly limited to the edge regions. The central areas exhibit large non-bonded zones, which are marked in green in the figure. These regions can lead to poor bonding, as no mechanical interlocking between the coating foil and the steel blank occurred there, preventing the formation of a metallurgical bond. With increasing pressing force from experiment 1 to experiment 3, the extent of these non-interlocked areas visibly decreases. This indicates that an increase in surface pressure generally leads to improved mechanical bonding; however, for the selected large pressing area, it is not sufficient to achieve continuous interlocking over the entire surface. The preferential bonding in the edge regions suggests locally increased surface pressures caused by edge and stiffness effects of the flat plate tool. In experiment 4, in which the pressing area was significantly reduced while the maximum pressing force was applied, a markedly different behavior is observed. The previously large non-interlocked zones are largely eliminated. Instead, only locally confined, millimeter-scale areas without interlocking remain, which are sporadically distributed within the coated region. Overall, the mechanical interlocking in experiment 4 is substantially more homogeneous than in the trials conducted with a larger pressing area. The results clearly demonstrate that local surface pressure is a dominant influencing factor for the quality of interlocking and that a reduction of the pressing area at a constant high pressing force significantly improves the areal bonding. Overall, the results show that only from test 4 (153.1 MPa), where a significantly increased surface pressure was applied due to the reduced pressing area, the aluminum foil was largely bonded to the steel substrate. Lower surface pressures applied in the preceding tests were insufficient to establish continuous contact, highlighting that adequate surface pressure is a key requirement for effective foil–steel bonding.

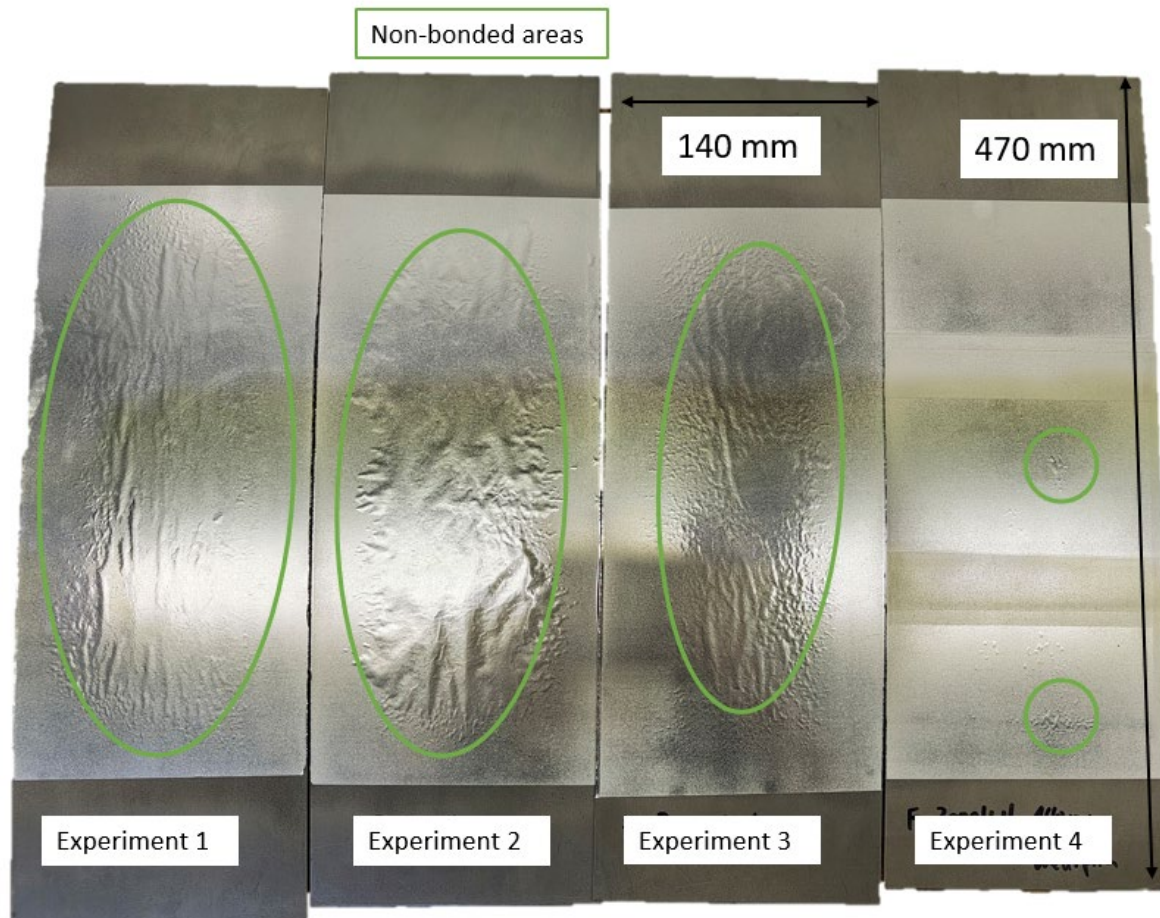


Fig. 3. Results of the pressing trials of aluminum thin foil with a 1.5 mm thick 22MnB5 sheet

The resistance-heated specimen processed in an XHV-adequate atmosphere of experiment 4 is shown in fig. 4. This figure exemplarily illustrates the results of the thin-foil coating and its analysis after resistance heating under an XHV-adequate atmosphere. In (a), a photographic image of the heated steel sheet is presented. On both lateral edge regions, zones can be identified that were not heated. These areas correspond to the contact regions where the electrodes were pressed onto the sheet during resistance heating. Between these edge zones lies the actual heated region, which is characterized by a dark blue coloration. This region represents the coated area in which the aluminum thin foil reacted during heating and formed a coating layer. The area marked in green indicates the measurement region selected for subsequent microstructural investigations. In (b), an SEM cross-section taken from this coated region is shown. It can be observed that a metallurgical bond has formed between the 22MnB5 substrate and the aluminum foil. However, the resulting layer exhibits pronounced porosity and appears locally not fully bonded. The intermetallic phase is not homogeneously formed over the entire area but occurs in a partially discontinuous manner, indicating an as-yet insufficient consolidation of the layer. The results of the EDS line scan shown in (c) confirm the reaction mechanism observed in the microstructure. The line profile reveals a pronounced mutual diffusion of aluminum and iron across the layer thickness. With increasing penetration depth, the aluminum content decreases while the iron content correspondingly increases, indicating the formation of an intermetallic phase in the interfacial region between the aluminum foil and the steel substrate. The layer formation was not affected by the XHV-adequate atmosphere, which is evidenced by the absence of a detectable oxygen signal in the line-scan analysis. This clearly demonstrates that, under an XHV-adequate atmosphere, an intermetallic phase forms during resistance heating. This metallurgical bonding occurs entirely within the heating interval of approximately 40 s that is already required for hot stamping and is therefore significantly faster than the established AlSi bonding process, which typically requires 6 – 10 min to form a load-bearing intermetallic layer. This highlights

the considerable potential of combining the coating and heating processes and substantially reducing process time. At the same time, a limitation of the current process state becomes evident. The produced layers exhibit locally incomplete bonding and appear highly porous overall. These inhomogeneities can primarily be attributed to the current surface pre-treatment of the sheets. Surface roughening is performed manually by corundum blasting, which does not ensure a reproducible and uniformly distributed surface roughness. A non-homogeneous surface topography leads to locally reduced contact areas and, consequently, to incomplete diffusion zones. Another significant influencing factor lies in the current method used to apply the aluminum foil. The foil application was carried out by sequential flat pressing rather than by a continuous pressing process. As a result, the contact between foil and substrate is established locally in discrete steps, which has a significant influence on the uniformity of the bonding conditions. The individual pressing steps remain clearly discernible on the sheet surface. This pressing operation results in inhomogeneous contact conditions, as the contact pressure varies across the surface and, in particular, local micro-scale air gaps are not reliably closed. In these regions, diffusion during heating is impeded, preventing the formation of a continuous metallurgical bond. Overall, the results demonstrate that the XHV-adequate atmosphere fundamentally enables rapid and effective intermetallic phase formation suitable for rapid resistance heating. At the same time, it becomes clear that the quality and homogeneity of the coating are strongly governed by the mechanical surface pre-treatment and the application method of the aluminum foil. With a more process-stable and reproducible surface preparation as well as a defined and uniform lamination process, a significantly more homogeneous and full-area bonding of the coating can be expected.

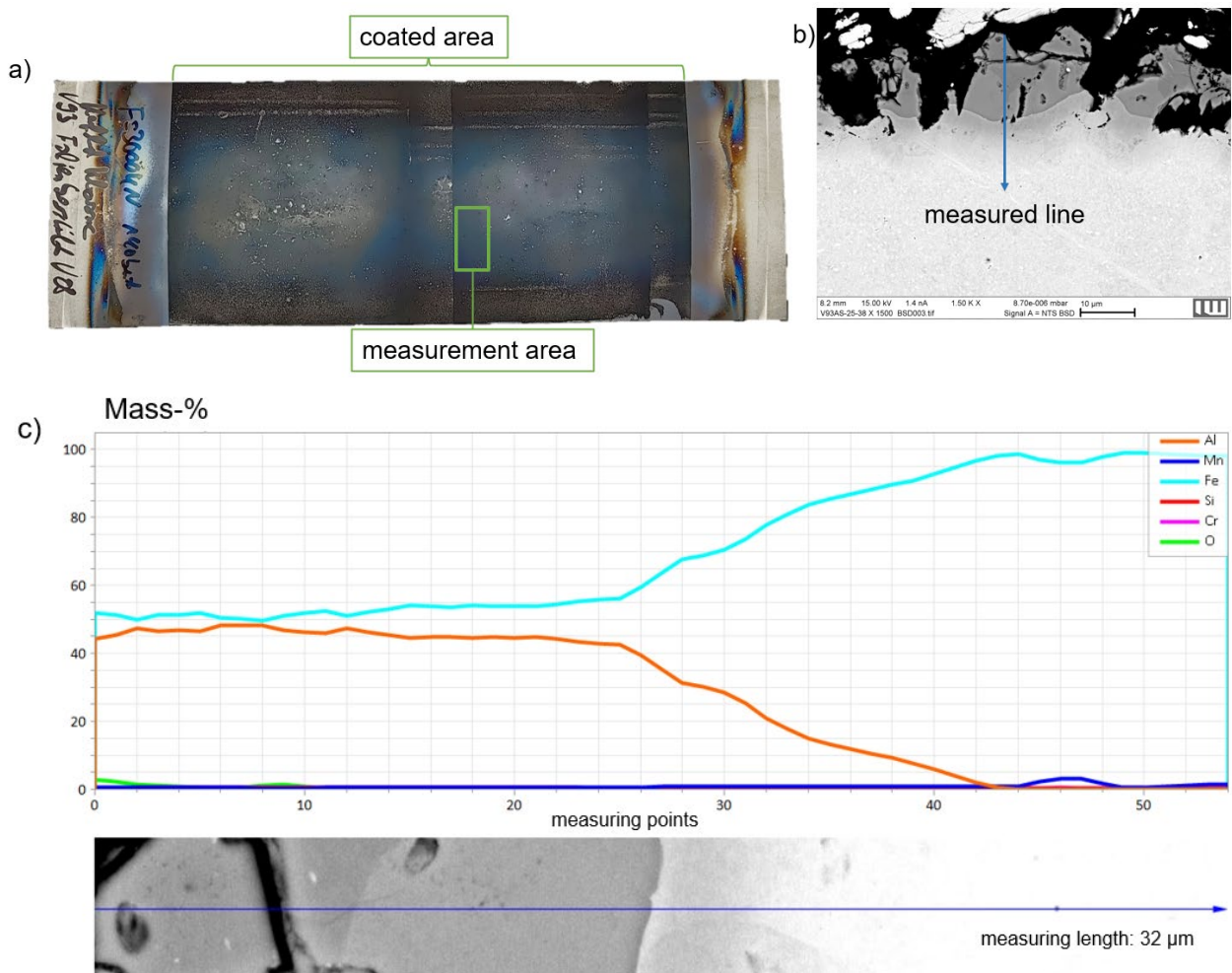


Fig. 4. Results of hot stamping of 22MnB5 sheets with aluminum thin-foil coating

Conclusions & Outlook

Within the scope of the investigations conducted, it was demonstrated for the first time that aluminum thin coatings can be successfully heated by rapid resistance heating under an XHV-adequate atmosphere and subsequently hot stamped. The results show that, during resistance heating, an intermetallic phase forms between the aluminum foil and the 22MnB5 substrate within the heating interval that is already required for hot stamping. This proves that the formation of a metallurgically effective coating is not limited to long-duration furnace processes, but can also be realized under the extremely short process times of rapid resistance heating. Compared to established coating systems such as AlSi furnace coatings, which typically require heating times of several minutes to form a load-bearing intermetallic layer, the approach presented here represents a significant reduction in process time.

In addition, the combination of thin aluminium foil coating and heating offers substantial potential for energy savings and reducing long heating times. Particularly in the context of the ongoing electrification of industrial processes and the increasing transition from fossil energy carriers to electrically driven systems, resistance heating represents an energy-efficient and future-oriented alternative for hot stamping.

At the same time, the investigations reveal that the current process route still exhibits limitations with regard to the homogeneity and continuity of the coating. In particular, the occurrence of locally non-interlocked areas demonstrates that the quality of the aluminum thin coating is strongly governed by the application and joining process. These regions can be interpreted as failure cases of the current process chain, since they represent local outliers from the otherwise continuous intermetallic bonding and may lead to reduced coating adhesion and locally impaired corrosion protection. Sheets with clearly missing mechanical interlocking between the aluminum foil and the steel blank correspondingly showed no metallurgical bonding. The currently employed flat pressing process results in inhomogeneous contact conditions and locally varying surface pressures, which prevents a uniform mechanical interlocking over the entire area from being achieved reliably. For future research and development, the application process of the aluminum foil should therefore be further optimized in a targeted manner. In particular, the use of a roller-based lamination process offers significant potential to apply the aluminum foil under a constant and well-defined contact pressure. Such a process can reduce local pressure fluctuations, close micro-scale air gaps, and minimize the occurrence of bonding outliers, thereby achieving a substantially more homogeneous mechanical interlocking between the foil and the substrate. In combination with XHV-adequate rapid heating, this is expected to enable a continuous, reproducible, and industrially scalable coating, paving the way for new energy-efficient process chains in hot stamping.

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