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Low-Carbon-Emission Hot Stamping: A Review from the Perspectives of Steel Grade, Heating Process, and Part Design

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Abstract

Hot stamping steels have become a crucial strategy for achieving lightweighting and enhancing crash safety in the automotive industry over the past two decades. However, the carbon emissions of the materials and their related stamping processes have been frequently overlooked. It is essential to consider these emissions during the design stage. Emerging materials and technologies in hot stamping pose challenges to the automotive industry's future development in carbon emission reduction. This review discusses the promising materials for future application and their special features, as well as the emerging manufacturing and part design processes that have extended the limit of application for new materials. Advanced heating processes and corresponding equipment have been proven to improve heating efficiency and control temperature uniformity. The material utilization and the overall performance of the components are improved by tailored blanks and an integrated part design approach. To achieve low-carbon-emission (LCE) hot stamping, it is necessary to systematically consider the steel grade, heating process, and part design, rather than solely focusing on reducing carbon emissions during the manufacturing process stage. This review aims to present the latest progress in steel grade, heating process, and part design of hot stamping in the automotive industry, providing solutions for LCE from a holistic perspective.

Keywords Low-carbon-emission · Hot stamping · Steel grade · Heating process · Part design

Abbreviations

AHSS	Advanced high strength steels
CF	Coating free
FLB	Front longitudinal beam
HSS	Hot stamping steel
LCE	Low-carbon-emission
LME	Liquid–metal embrittlement
Ms	Martensitic start
OR	Oxidation resistance
Q&P	Quenching and partitioning
RA	Retained austenite
SPHS	Short process hot stamping
TEL	Total elongation
TRB	Tailor rolled blanks
TRL	Technical readiness level
TS	Tensile strength
TWB	Tailor welded blanks

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1 Introduction

The application of hot stamping steels (HSS) has been an important strategy to realize automotive lightweighting and enhance crash safety over the past two decades [1–6]. The hot forming process (Fig. 1) resolves the contradiction between strength and formability by forming first and hardening later, attributed to the obviously improved thermal processing performance of the material at high temperatures. In hot stamping, the HSS sheet is usually heated to about 930 °C in a furnace first, then soaked for a few minutes to reach full austenite state, and stamped and quenched simultaneously in dies to obtain a full martensite microstructure [1, 3]. The subsequent paint-baking process tends to increase the toughness of the martensite while gently decreasing its strength. The current hot stamping steel for industrial applications is mainly 22MnB5 steel, with a tensile strength of about 1500 MPa and elongation of about 5–7% after hot stamping to full martensite [7]. Recently, new materials

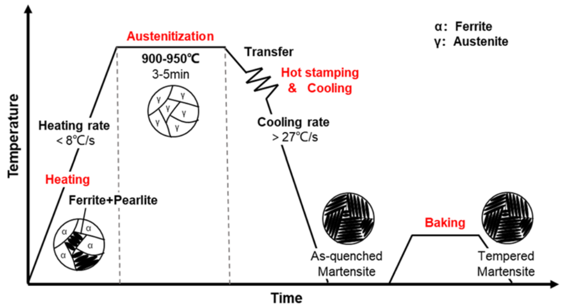

Fig. 1 Conventional hot stamping process and the related microstructure evolution during hot stamping

and technologies have emerged in the field of hot forming. However, these advancements have posed new challenges to the future development of hot forming for the automotive industry, particularly in light of the tremendous demand for reducing carbon emissions [8].

Carbon emissions of HSS involve a series of processes, such as ore mining, smelting, rolling, hot forming, assembling, and recycling. The primary purpose of lightweighting is to reduce carbon emissions during the assembly or the use stage of components. Nonetheless, the carbon emissions of the materials of HSS and their related forming processes which should be taken into consideration in the design stage are usually overlooked. The developments of new HSS are mainly in the steel substrate and the surface condition [9–20]. The evolution of substrate microstructure is mainly in developing martensite substrate with higher strength and toughness, controlling nano-precipitates, such as NbC and VC, or introducing austenite through the quenching and partitioning (Q&P) process [9, 11, 13]. In terms of surface condition, pre-coating is usually applied to the HSS surface to avoid oxidative decarburization at high temperatures, where Al-Si coating has been the most commonly used among various coatings [14]. Research on surface condition focuses on developing Al-Si coating with higher toughness and economy, or even not applying coating through surface control in hot stamping process combined with material design [16–17, 20–22]. Generally, materials are the basis for process and part design. This review separately discusses the promising materials for future application and their special features.

The emergence of new manufacturing and part design processes has expanded the range of applications for new materials. A key focus of this review is how to apply these materials to achieve carbon reduction. In addition, advancements in heating processes and corresponding equipment have improved heating efficiency and temperature uniformity control [1, 23–26], such as the innovative fast heating and partial heating process. For example, multi-stage hearth furnaces can regulate the heating temperature of HSS sheets by smoothly controlling the stage temperature, while conduction heating could heat HSS sheets up to 800 °C in 2 s [27]. Meanwhile, induction heating and infrared heating have received much attention in partial heating applications [2, 28]. Tailored blanks and an integrated design approach have improved the material utilization and overall performance of components [29–32]. It is worth mentioning that integrated design, such as single and double door rings, has become a popular issue in light weighting.

The development of green, low-carbon, and high-efficiency manufacturing of materials is expected to be at the forefront of advanced manufacturing in the future. To reduce carbon emissions, which are mainly related to materials and the heating process, various strategies can be implemented during the manufacturing process. These strategies include improving heating efficiency, reducing soaking time, and lowering heating temperatures. Meanwhile, the design process is directly related to the ability to reduce carbon emissions through component integration. The component design process aims to reduce carbon emissions by minimizing material usage. This involves utilizing low-carbon emission materials and employing advanced green manufacturing processes. Recognizing the interdependence of materials, heating processes, and design, a collaborative approach is essential for achieving significant carbon emission reductions. The steel material, the heating process, and the part design should be systematically considered when designing low-carbon-emission (LCE) hot stamping parts, instead of concentrating only on reducing emissions during the manufacturing process. In this review, the latest advancements in steel grades, heating processes, and part design for hot stamping in the automotive industry are presented. Firstly, the paper introduces the development of materials and gave suggestions for future materials. Then, several heating methods necessary to prepare parts are presented and their advantages and disadvantages are discussed. Finally, the paper explores how to integrate materials and processes on the design side in order to achieve low carbon emission goals.

2 Steel Grades

This section is a comprehensive overview of the recent developments in new materials for hot stamping, especially the research progress within the past five years, including the related LCE strategies. To assess the technological maturity of these advancements, the concept of technical readiness level (TRL) is introduced, which measures the progress of technology from its basic principles to commercialization [33]. TRL is roughly divided into 9 levels, where TRL 1–3 are defined as lab scale, TRL 4–6 as pilot scale, and TRL 7–9 as fully industrialized scale. The discussion begins by highlighting materials that are currently in industrial use or are near industrial application, such as traditional HSS

Developments in Materials		Properties (TS & TEL, OR)	TRL
Traditional HSS	22MnB5	1500MPa & 5-9%	9
Traditional HSS with higher strength	34MnB5 37MnB4 34MnB5V …	1700-2000MPa & 4-8%	9
HSS with or without coating	Al-Si coating	High grade	9
	Zn coating	High grade	8-9
	Coating free	Medium grade	4-6
Medium Mn HSS	MnSi MnSiCr+Nb/V MnSiV …	1600-2000MPa & 10-25%	3-5

Fig. 2 Recent developments in new materials and their corresponding features, including tensile strength (TS), total elongation (TEL), and oxidation resistance (OR)

with strength levels exceeding 1800 MPa, and even reaching 2000 MPa. Then, surface protection technologies are discussed, together with a newly reported coating-free (CF) HSS with superior oxidation resistance. Finally, a series of medium Mn HSS materials with uncompromised strength and toughness are presented (Fig. 2).

This section presents an overview of three novel material types, discussing their alloy composition, strength, toughness, oxidation resistance strategies, process characteristics, TRL, and LCE. The first material is a thinner Al-Si coating HSS with a strength exceeding 1500 MPa and improved toughness, which enables increased heating efficiency and reduced carbon emissions by reducing soaking time. Although commercially available, its application in short-process hot stamping (SPHS) is limited due to the formation of Al–Fe intermetallic compounds. The second material is a CF HSS that exhibits superior oxidation resistance and improved mechanical properties compared with traditional HSS. This material contains higher levels of Cr and Si, resulting in the formation of a thin oxide film that prevents additional oxidation, leading to its antioxidant property. The appropriate addition of Si and Cr enables dynamic carbon partitioning from martensite to austenite during cooling, stabilizing the retained austenite (RA) and enhancing both oxidation resistance and mechanical properties. Furthermore, the SPHS technology was also proposed to further reduce soaking duration for HSS. The third material, medium Mn HSS, has gained increasing attention for its low austenitization temperatures and superior properties, making them a promising replacement for traditional HSS. Their low cost, high productivity, and better mechanical properties have made them advantageous for producing components with LCE.

2.1 Traditional HSS with Higher Strength

In the past decade, 22MnB5 steel has always been the most prevalent type of HSS. However, with the growing demand for lightweighting in the automotive industry, there has been significant development of ultra-high strength HSS in recent years. Initially, the industry commonly relied on increasing the carbon content to enhance the strength of HSS. However, solely increasing the C content of the steel to improve the strength of hot stamping steel will inevitably lead to a significant decrease in its toughness and plasticity.

Various approaches have been proposed to address the trade-off between high strength and high toughness in HSS. One effective approach is to introduce nanoprecipitates by adding microalloying elements to the base alloy of 22MnB5 steel. It is reported that the combined addition of niobium (Nb) and vanadium (V) can improve the bending toughness of HSS [11]. The carbides formed by Nb and V can refine austenite grain boundaries and martensitic lath, thereby improving the bendability of HSS. Another strategy is to utilize the coupling of VC precipitation and hot stamping process to reduce the content of C in martensite substrate, and suppress the generation of twin martensite, thus improving the toughness of HSS [9]. Figure 3 shows the austenite grain size and carbide precipitation of the HSS with and without the addition of V.

When it comes to traditional HSS at TRL 9, the hot stamping process is mature. Currently, it has been proven that improving heating efficiency and reducing holding times during the heating and austenitization stages are the main ways to reduce carbon emissions. The realization of the above pathways relies on the upgrading and precise control of the heating process. In short, traditional HSS do not have much space to reduce carbon emissions in the hot forming stage. In particular, insufficient heating time can significantly

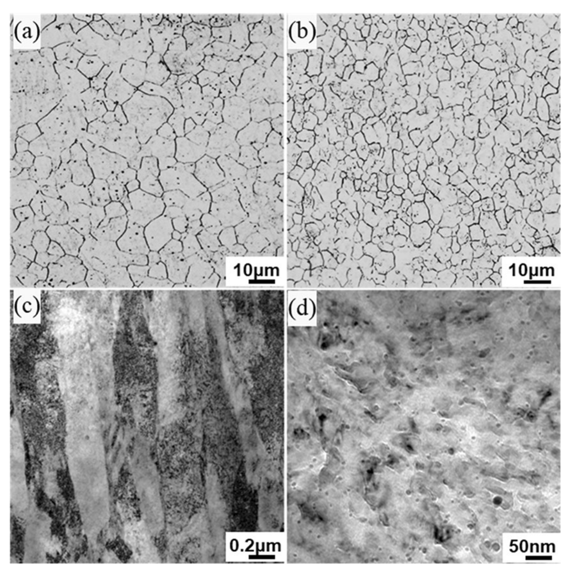

Fig. 3 Prior austenite grain boundaries of 22MnB5 **a** and 34MnB5V **b** austenitized for 4 min at 900 °C, and TEM images of quenched lath martensite **c** and VC precipitation particles **d** in 34MnB5V [9]

affect the mechanical properties of traditional HSS [2, 34]. In the following two sections, the possible means of carbon reduction are discussed in terms of surface protection technology and the promising new substrate materials for HSS.

2.2 HSS With or Without Coating

Bare HSS sheets are inevitably exposed to air during the transfer from furnace to stamping tool, which results in surface oxidation and decarburization. To meet the subsequent service requirements, the bare sheets tend to be shot peened or sandblasted to remove the oxidation layer. However, this approach results in lower dimensional accuracy and higher costs for the parts. In order to address this issue, surface protection technologies have been developed for HSS [34–39]. The first commercialized technology was Al-Si coating proposed by Arcelor Mittal [14]. Figure 4(a) and (b) show the microstructure and alloy components of Al-Si coating. After being austenitized at 920 °C for 5min, the Fe in the matrix diffuses with the pre-coated alloy layer to form an intermetallic compound of Fe and Al, which has a melting point much higher than the austenitization temperature (920 °C). Consequently, no more liquid phase appears on the surface. Meanwhile, as shown in Fig. 4(c), the intermetallic compound layer tends to facilitate the formation of micro cracks after hot stamping [39]. Another commercialized coating is Zn or Zn-alloy coating [21, 40]. Nonetheless, Zn-coated commercial HSS are often exposed to liquid–metal embrittlement (LME) induced by Zn during the hot stamping process. Therefore, the usage of Zn-coated HSS is less than 5 percent of Al-Si coating.

The conventional Al-Si coating has a thickness of around 25 µm, which increases to about 40 µm after hot stamping.

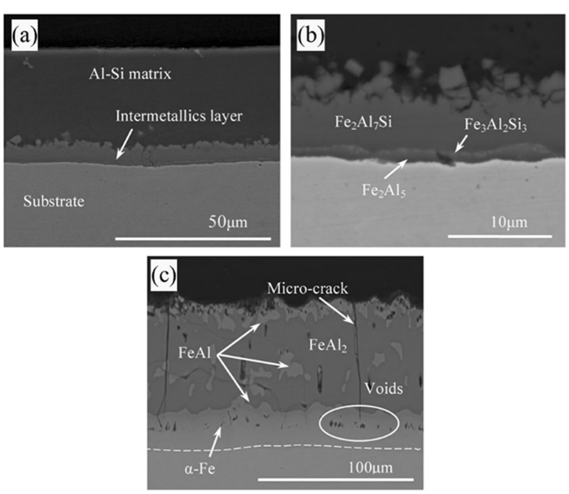

Fig. 4 Cross sectional SEM micrographs of the Al–Si coated boron steel. **a** As-coated, **b** detail of intermetallics layer and **c** austenitized at 920 °C for 5min [39]

It is reported that HSS with Al-Si coating exhibits lower bending toughness than bare HSS, which could be attributed to surface decarbonization of bare HSS. However, Northeastern University in China has developed a new technology for achieving high toughness in HSS with Al-Si coating by reducing the thickness of the coating [16]. The thickness of high-toughness Al-Si coating is typically about 25 µm, only 40% of the conventional Al-Si coating. Meanwhile, the bending toughness of hot stamped HSS sheets with high-toughness Al-Si coating is found to be 20% higher than that of conventional Al-Si coating. Yi et al. [9] deemed that reducing the thickness of Al-Si coating can lower carbon enrichment at the interface between coating and substrate, thus improving the toughness of HSS sheets. In addition, Wang et al. [20] reported the mechanics behind the improved bending toughness of Al-Si coating on HSS. In their study, Al-Si coatings with thicknesses of 35 µm and 13 µm were employed (Fig. 5). Figure 5(a) and (b) are secondary electron (SE) images. Figure 5(c) and (d) are electron back-scatter diffraction (EBSD) inverse pole figure (IPF) maps and simultaneous electron dispersive spectroscopy (EDS) maps of Al element. The black phase at the bottom of EBSD maps indicates the Fe_2Al_5. Figure 5(e) and (f) are EDS line scans. The squares in Fig. 5(a) and (b) show the regions for EBSD maps, and the arrows show the positions and directions for EDS line scans. The squares in Fig. 5(c) and (d) show the regions for EDS maps of Al element. It was found that thinner Al-Si coatings exhibit higher bending toughness due to the reduced stress intensity factor at the crack tip.

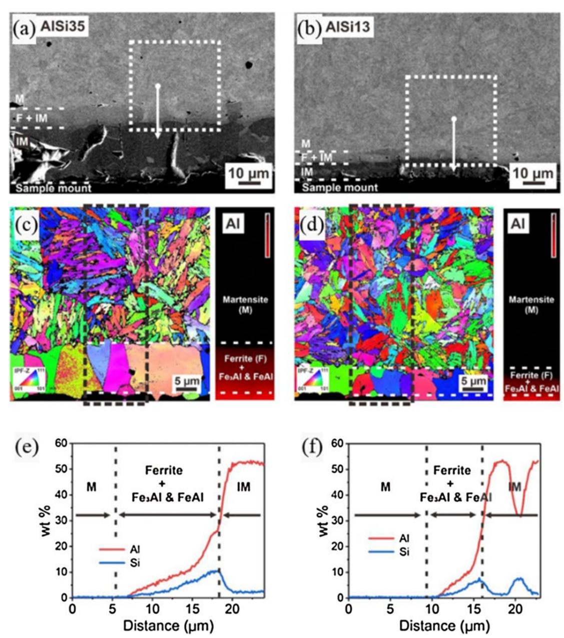

Fig. 5 Microstructure of two Al-Si coated PHS. **a**, **c**, **e** AlSi35; **b**, **d**, **f** AlSi13. *M* Martensite, *F* Ferrite, *IM* Intermetallics [20]

Thinner Al-Si coatings offer the advantage of lower material costs while maintaining comparable similar paintability and corrosion resistance. Approximately 3 million tons of the Al-Si coated HSS are used each year. The future use of thin Al-Si coating has the potential to save a large amount of Al alloy and significantly reduce carbon emissions. In addition, Al absorbs a substantial amount of heat during the alloying process when heating to the austenitization stage. As the thickness of the Al-Si coating decreases, the HSS sheet is able to heat up more quickly, thus increasing the heating efficiency. The application of thin Al-Si coating could reduce the soaking time by 10%–20%, which in turn reduces carbon emissions. It should be noted that due to the low melting point of Al, which is around 650°C, Al-Si coating cannot be heated rapidly (> 12 °C/s) until Al–Fe intermetallic compounds have been formed. Obviously, due to the characteristics of Al-Si coating and traditional HSS substrates (TRL 9), the hot stamping process may fail to meet the requirement for faster heating rate and shorter soaking time. To achieve further carbon reduction, adjusting the alloy composition and further reducing the coating dosage could be possible directions in the future.

For surface protection considerations, GM China Science Lab developed a new bare HSS named coating- free (CF) HSS [41]. This CF HSS exhibited superior oxidation resistance and better mechanical properties compared with 22MnB5 HSS. It has been globally produced in industrial sheets and successfully piloted on industrial production lines to produce hot stamping components with bright surfaces, eliminating the need for shot blasting (TRL 6). It is believed that the mass market application of CF HSS will provide strong support for LCE in the automotive industry. The CF HSS contains higher levels of Cr and Si compared with traditional HSS, enhancing its mechanical performance and oxidation resistance. Upon exposure, a thin oxide film with a thickness of 200–500 nm quickly forms on the surface of CF HSS, preventing further oxidation and imparting an antioxidant property to the material. The specific mechanism underlying this antioxidant behavior of CF HSS needs to be further investigated. The novel CF HSS has demonstrated immense strength and remarkable ductility compared with the baseline HSS grade 22MnB5. This can mainly be attributed to the formation of nano-sized retained austenite (RA) through dynamic carbon partitioning during the hot stamping process after the martensitic transformation (Fig. 6). The addition of an appropriate amount of Si and Cr to the new CF HSS enables dynamic carbon partitioning from martensite to austenite during cooling, stabilizing the RA phase while maintaining the industrial hot stamping process. Specifically, carbides rich in Cr contribute to chemical diversity, enhancing the resilience of adjacent austenite by decelerating the decomposition process, even at high temperatures used in hot stamping. Furthermore, Cr reduces the

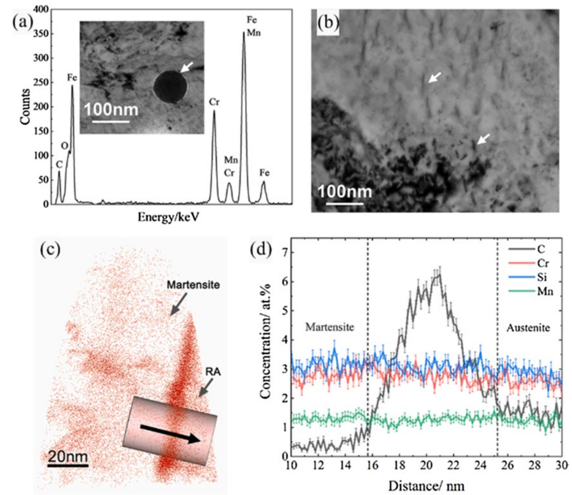

Fig. 6 Microstructure of the novel HSS. **a** Bright field image and EDX pattern of Cr carbides, **b** bright field image of rod-like carbides, **c** APT results of the novel HSS and **d** compositional profiles of elements across the martensite/austenite interface [17]

martensitic start (Ms) transformation temperature, further reinforcing the stability of austenite [17]. In summary, the introduction of Cr carbides and RA enhances both oxidation resistance and mechanical properties of CF HSS.

Rapid heating during the annealing stage is a useful method to enhance the mechanical properties of advanced high strength steels (AHSS) for cold stamping applications. Nonetheless, there is limited research on the impact of rapid heating on HSS, particularly for newly developed steel grades. Hou et al. [42] investigated the possibility and advantages of rapidly heating a CF HSS at a rate of over 100 °C/s (TRL 4). Experiments showed that a 2 mm thick CF HSS blank could be fully austenitized at 930 °C within 120 s with a heating rate of 100 °C/s. After rapid heating, soaking, water quenching, and baking, the tensile strength of the press-hardened steel (PHS) considerably increased compared with the baseline 22MnB5 under the same treatment, with an ultimate tensile strength of 1,722 MPa and a uniform elongation of 5.1%. In addition, the thickness of the oxide layer on the CF HSS, after rapid heating and 120 s of soaking in ambient atmosphere, was less than 5 µm. This thickness was considerably thinner than that observed on the 22MnB5 (36 µm). In addition, it was believed that the rapid heating procedure used for the CF HSS could be highly advantageous for the automotive industry. The above research has shown that the total heating time of CF HSS can be reduced by around 50% applied with a rapid heat strategy. This method has the potential to provide a cost-effective manufacturing alternative for press-hardened body structure components, thus further realizing LCE (Fig. 7).

Based on previous research, short-process hot stamping (SPHS) technology has been proposed to further reduce the

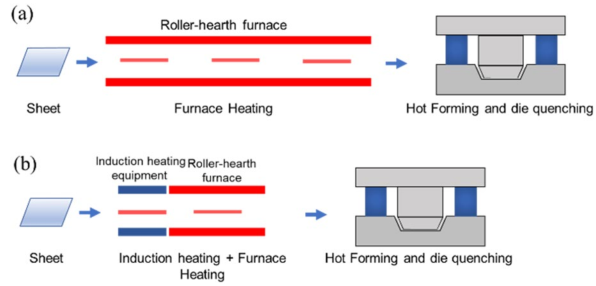

Fig. 7 Schematics showing **a** traditional hot forming process with a roller-hearth-type furnace, **b** hot forming process with rapid heating, i.e., induction heating or resistance heating [42]

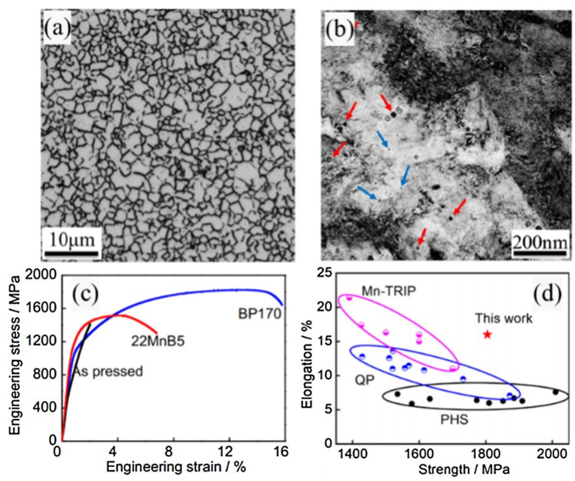

Fig. 8 Bake partitioning HSS. **a** OM by grain boundary etching exhibiting prior austenite grain size, **b** indicating the VC precipitation with size of approximate 5–20 nm, **c** tensile curves of BP170 compared to as-press alloy and typical 22MnB5 PHS, and **d** properties compared to other sheet steels in references [13]

soaking duration [43]. The efficiency of complete austenitization of HSS can be increased by changing the annealing process of the cold rolled sheet to convert the initial microstructure to martensite (Fig. 8). This strategy significantly reduces the total heating time required for hot stamping. The mechanical properties and microstructure evolution of CF HSS and a traditional 22MnB5 were studied under this process. Results showed that CF HSS, with martensite and carbide as the initial microstructure, can be completely austenitized by heating it to 930 °C at 100 °C/s, followed by a 30 s holding time. The final material has a high tensile strength of 1,578 MPa and an elongation of 7.8%, with a mixture of martensite and 3% to 5% RA. The total heating time required for hot forming can be reduced to less than 1 min, which is more than 80% less than the conventional HSS (TRL 4). This SPHS process effectively reduces the total heating time while maintaining the toughness of the parts, contributing to energy conservation and carbon reduction goals. The applicability of the SPHS process to other ultra-high- strength steels and its feasibility for industrialization will be discussed in further works.

2.3 Medium Mn HSS

Austenitization at lower temperatures is an optional strategy employed for reducing energy consumption in hot stamping process. However, austenitization temperature is directly related to the alloy composition of the HSS. In the case of traditional HSS, the Ac_3 temperature is around 860 °C. And a temperature above 920 °C is usually applied to ensure complete austenitization. Thus, it can be seen that there is currently limited potential for reducing the heating temperature in traditional HSS. New HSS with improved mechanical properties and lower Ac_3 temperature have garnered significant attention. One promising new grade is medium Mn HSS, owning 5%–10% content of Mn. Mn acts as a strong austenite stabilizer, effectively lowering the Ac_3 and Ms temperatures. Besides, the concept of split-Q&P was proposed to eliminate the immediate need for partitioning after quenching. For instance, in a 7 wt% Mn HSS, the Mf was designed to be below room temperature, allowing quenching to be performed at room temperature. Furthermore, carbon partitioning during the paint-baking process was proposed to enhance the ductility of HSS [13]. The design led to the refinement of prior austenite grains by combining Mn addition and VC precipitations, resulting in a relatively low austenitization temperature (850 °C applied in the study). This refinement resulted in the formation of ultra-fine prior austenite grains measuring 2.6 μm. Consequently, austenite films with a thickness of around 5 nm were preserved between martensite laths in the as-quenched state. During paint baking at a temperature of 170 °C for 20 min, the carbon diffusion distance in austenite was estimated to be 2.7 nm. The thickness of the austenite films, approximately 5 nm, allows enough carbon partitioning from the surrounding martensite into austenite. The final medium Mn HSS exhibited excellent mechanical properties, including an ultimate tensile strength of 1800 MPa and a total elongation of 16% (Fig. 8).

By increasing the content of Mn and C, the Ac_3 temperature of HSS can be further reduced. Meanwhile, other alloys/microalloys like Cr, Si, Mo, Nb, V, and Ti, among others, are added to ensure the desired mechanical properties of HSS [18, 44–46]. Thus, the complete austenitization temperature can be lowered to 750 °C or even below. Recently, a novel medium-Mn HSS with superior mechanical properties and minimal oxidization was proposed [18]. Similar to the development of CF HSS, Cr and Si were added. Besides, Al was also added. It is claimed that the formation of a dense Cr/Al/Si oxide band at the bottom of the oxidation layer significantly reduced oxidation during the hot stamping process.

The resulting oxidation layer in this steel was less than 3 μm after hot stamping at 750 °C, which is much thinner compared with the 100 μm oxidation layer observed in 22MnB5. After hot stamping and baking, the studied steel exhibited impressive mechanical properties, including an ultimate tensile strength (UTS) of 1850 MPa and a total elongation (TEL) of 14%, surpassing conventional 22MnB5 HSS. The improved mechanical properties can be attributed to several factors, such as the presence of undissolved dispersed carbides, refined RA, and the pinning of segregated C atoms on high-density dislocations. Together, these mechanisms contribute to the enhanced mechanical performance of the steel grade. However, further research is needed to explore low-temperature hot stamping of medium Mn HSS, facilitating its industrial application and potential replacement of traditional HSS. A comprehensive understanding of processing conditions, microstructure, and mechanical behavior is crucial for controlling process and component quality. Overall, this study provides a comprehensive overview of novel materials with potential applications in various industrial settings (Fig. 9).

3 Heating Processes

The LCE hot stamping not only promotes the emergence of new design and materials, but also raises the demand for new manufacturing processes. Conventional hot stamping processes are generally composed of sequential blanking, heating, transferring, stamping, and quenching [1], among which heating processes usually take the longest time. In addition, heating processes have a significant influence on the microstructure and mechanical properties of final products, as well as the productivity and efficiency of hot stamping. Therefore, achieving sufficient austenitization within a shorter heating time is a promising trend in LCE hot stamping.

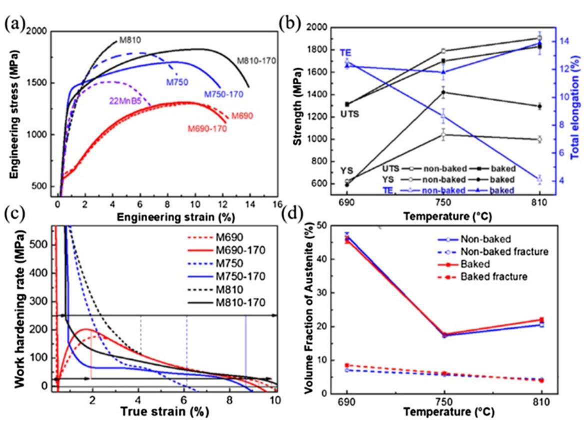

Fig. 9 Dependence of tensile properties on the hot forming and the baking processes. **a** The engineering stress–strain curves of studied specimens, compared with 22MnB5 steel; **b** Dependence of ultimate tensile strength (UTS), yield strength (YS) and total elongation (TEL) on the soaking temperature and the baking process; **c** Work hardening rates during deformation; **d** RA fractions in the baked/non-baked specimens before and after deformation to fracture [18]

3.1 Conventional Heating

In conventional hot stamping, roller-hearth furnaces are commonly employed with indirect gas firing, electrical heating, or hybrid heating methods to heat the metal sheet to the austenitization temperature. Subsequently, the sheets are held at a constant temperature to obtain homogeneous austenitization. Oxidation of non-coated metal sheets can be prevented with the help of protective gas. However, despite these measures, the average efficiency of the heating process remains inadequate from the perspective of LCE requirements, with heat loss through the furnace walls, entrance, and exit accounting for approximately 30% [23]. Taking into account the operating rate, the overall efficiency is only 53.6%. This falls significantly short of meeting LCE demands. In addition, to ensure productivity, large roller-hearth furnaces, for example, with a length of 30–40 m [47], are always necessary. However, these furnaces occupy substantial space and require additional investment costs, which are undesirable for industrial applications. Alternatively, multi-chamber furnaces can be used for mass production, whereas their compactness comes at the expense of transport efficiency. In addition to the efficiency, conventional heating processes relying on radiant heating generally take longer to reach the austenitization temperature. Although coating the sheets with high-emissivity material would be a potential method to reduce heating time to some extent for sheets with low absorptivity [48], the additional procedure would still increase the whole process duration.

3.2 Conduction Heating

Conduction heating, also termed as electrical resistance heating, is based on the Joule's Law of heating. It has garnered much attention due to its rapid heating rate, enabling temperatures to rise to 800 °C in 2 s [49]. Conduction heating is also a promising way to achieve partial heating and tailored properties in hot stamping. It is worth noting that there are basically two approaches to realize partial heating, according to Ref. [50]: separated current and bypass resistance heating, as shown in Fig. 10. The notable advantages of conduction heating have led to many investigations into its application, extending even to non-metal materials such as carbon fiber reinforced thermoplastic plates [51]. One foremost issue for the application of conduction heating is its implant into the hot stamping process. Maeno et al. [52] presented the process chain (see Fig. 11) for conduction

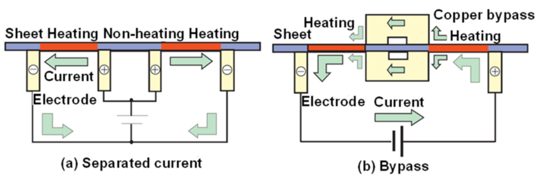

Fig. 10 Partial heating through **a** separated current and **b** bypass conduction heating [50]

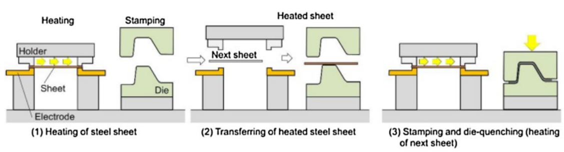

Fig. 11 Hot stamping with simultaneous conduction heating [52]

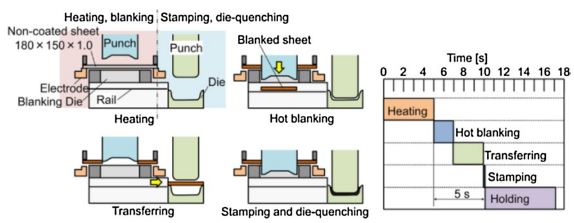

Fig. 12 Sequence of hot stamping using blanking immediately after conduction heating [53]

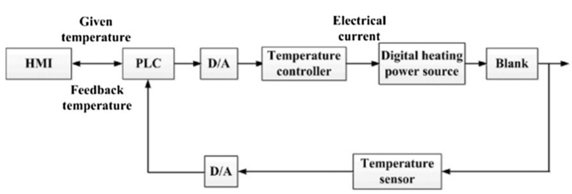

Fig. 13 Temperature closed-loop control for conduction heating [54]

heating and hot stamping, achieving heating times of as short as 4 s to ensure full hardening and a production cycle of ~ 10 s by hot stamping with simultaneous conduction heating. However, conduction heating presents an issue of temperature uniformity when heating non-rectangular sheets due to variations in electrical resistance at various positions, potentially leading to inadequate heating and even fractures. Maeno et al. [53] proposed a method of heating and blanking to solve this problem, as illustrated in Fig. 12, in which the rectangular sheets were first heated and then immediately transferred to the blanking die, followed by hot stamping and die-quenching. Also, temperature variation along the length of the sheet is sometimes troublesome for heating blanks with long geometry. Liang et al. [54] adopted temperature closed-loop control (see Fig. 13) in conduction heating to

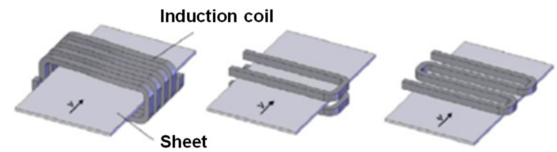

Fig. 14 Three kinds of induction coils [59]

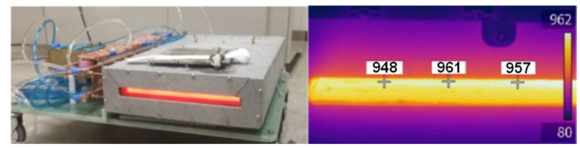

Fig. 15 Induction heating system with heating block: experimental setup and temperature distribution [60]

realize the unequal radiation heat transfer conditions on the blanks, thereby achieving uniform temperature distribution. Moreover, closed-loop control of force was also applied to eliminate deformation caused by thermal expansion. And the material utilization rate increased from 60.7% to 91.8% with the combined feedback control on temperature and force. Another challenge for conduction heating is the oxidation of non-coated sheets and coating exfoliation in the case of coated sheets [55]. Although Fang et al. [56] declared that parts heated by conduction heating exhibited better surface quality than that heated by furnace, oxidation can be more effectively addressed in furnace heating by applying protective gas. Kocar and Livatyalı [57] successfully avoided the damage of Al-Si coating by applying a 4-min heat treatment prior to conduction heating, demonstrating improved bonding between the coating layer and the base metal.

3.3 Induction Heating

Induction heating uses a rapidly alternating magnetic field to generate electric currents inside the sheets. The temperature uniformity achieved through induction heating is highly dependent on the appropriate design of the induction coils [58]. There are generally three kinds of induction coils, i.e. longitudinal field, cross field, and face inductors, as illustrated in Fig. 14 [59]. Kim et al. found that the temperature distribution was quite uneven using the face induction system and came up with an idea to heat the blank with induction heating together with a heating block, as shown in Fig. 15 [60]. It would be a wise decision to utilize the feature of induction heating. Since the electromagnetic coil can be designed and manufactured based on the metal sheets, induction heating would be a preferable method to realize partial heating and thus tailored mechanical properties in hot stamping. For example, Bao et al. [26, 61] proposed a novel design involving magnetizer rings and U-shaped

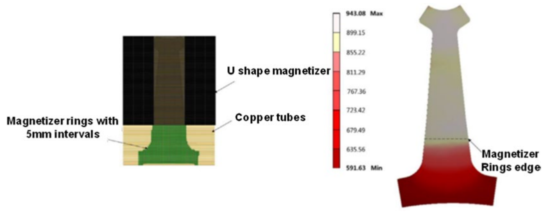

Fig. 16 The model and temperature field of the B-pillar [61]

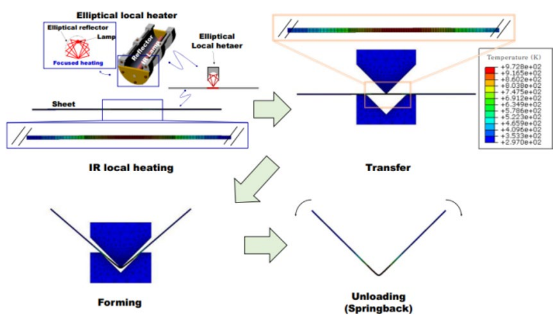

Fig. 17 Sequence of bending processes with local infrared heating [63]

magnetizers (see Fig. 16) to eliminate the obvious higher temperature and transition regions caused by the magnetizer piece, and the B-pillar with an obvious temperature gradient was finally achieved for property-tailored hot stamping.

3.4 Infrared Heating

Infrared heating, as a non-contact heating method, is also a good alternative for hot stamping. It utilizes heat radiation as its heating mechanism, resulting in a lower heating rate compared with conduction heating and induction heating. There are generally two kinds of infrared heating processes: near-infrared heating and far-infrared heating, based on the wave length of infrared. The conversion efficiency of near-infrared heating and far-infrared is 90% and 60%–70%, respectively [2]. Infrared heating is more suitable for partial heating since precise temperature control is difficult. According to the study of Lee et al. [62, 63], the springback of V-bending tests decreased drastically by applying infrared heating at the bending corner (see Fig. 17). At present, the lower heating rate and difficulty on temperature control pose major limitations for the further application of infrared heating in hot stamping.

3.5 Contact Heating

Contact heating, which heats the sheets through direct contact with high-temperature plates, is a favorable approach to achieve rapid and uniform heating, as shown in Fig. 18. The

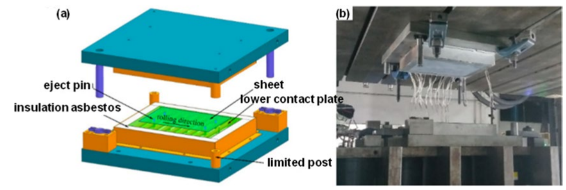

Fig. 18 The schematic of **a** device and **b** contact heating [64]

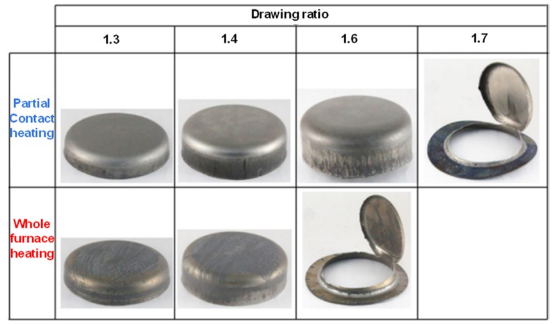

Fig. 19 Cylindrical deep drawing by partial contact heating and whole furnace heating [65]

result showed that the heating rate reached 28.7 °C/s and the heating time to a solution treatment temperature of aluminum alloy could be reduced from around 8 min to 15–20 s in comparison with furnace heating [64]. Contact heating is also one good solution for partial heating by controlling the contact surface. Maeno et al. [65] adopted partial contact heating using hot ring iron and proved that the partial contact heating method realized better-limiting drawing ratio of titanium alloy than whole furnace heating, as shown in Fig. 19.

Table 1 shows the features of those heating processes from the aspect of LCE hot stamping. The demand for property-tailored hot stamping, which enables the exploitation of material potential and the attainment of desired mechanical properties at specific positions [66], has encouraged the emergence of diverse heating processes. The innovations in fast and partial heating processes generally align with the trend of LCE hot stamping in terms of increasing energy efficiency and saving investment costs. Whereas the proposed approaches are mostly limited to laboratory scale, and the conventional roller-hearth furnace heating process still dominates in industrial applications. Hence, there is still a long way to go before the extensive application of LCE hot stamping can be achieved.

There is no doubt that the development of new heating processes remains a crucial necessity. Laser heating presents a promising approach for achieving fast heating (within 200 ms from room temperature to 1000 °C) and synchronous property control in sheet metal forming [67–69]. However, precise control over the peak temperature, heating, and

Table 1 Features of heating processes for hot stamping

Heating	Furnace	Conduction	Induction	Infrared	Contact
Heating rate	Low	High	High	Medium	High
Temperature	Uniform	Non-uniform	Non-uniform	Uniform	Uniform
Energy efficiency	Low	High	Medium	Low	Low
Space occupation	Large	Small	Small	Large	Small

cooling rates could be one of the significant challenges for its application. While previous research has mainly focused on the mechanical properties of the final product, variations in heating or cooling rates also impact phase transformation [70–72]. In addition to technological issues, the effect of rapid heating on the microstructure evolution mechanism also urgently requires regulating the process parameters, as well as the microstructure and mechanical properties of final products. Besides, a comprehensive evaluation of space, efficiency, cost, and other factors is necessary to better understand the advantages and shortcomings of various heating processes, as well as the feasibility of replacing conventional heating methods with emerging ones.

4 Part Designs

Carbon emissions can be reduced during the design process of hot stamping parts by using an integrated design approach from three perspectives: reducing raw material use, reducing energy consumption in the manufacturing process, and reducing body weight. The integrated design approach can improve material utilization by selectively using high-strength, thick materials in specific parts, reducing material engineering scrap rate through reasonably combining various steel plates, and realizing a raw material reduction in the hot stamping process. As a result, the integrated design approach significantly contributes to carbon emissions reduction due to less raw material consumption [3, 73]. Furthermore, integrated part design can realize the integral stamping and one-time forming of parts, minimizing the number of hot stamping parts, stamping equipment, workflow, and tools, and reducing energy consumption in manufacturing. Additionally, integral stamping eliminates the need for redundant reinforcements and joining elements, contributing to a reduction in overall body weight. Laser tailor welding and tailor rolling are widely used in automobile body design. The application of tailor blanks in combination with the hot stamping process can produce body structural parts with a desired geometry, shape, and mechanical properties, which is critical for achieving automotive lightweighting and LCE. The following sections introduce the development of thickness-gradient part design and integrated part design, with a focus on the contributions of both technologies to LCE hot stamping.

4.1 Thickness-Gradient Part Design

Tailor welded blank (TWB) and tailor rolled blank (TRB) are widely used in automobile body design, for achieving different thickness and performance gradients on one part. TWB is made up of individual steel sheets with varying thicknesses, strengths, and coatings that are joined together using laser welding. This process enables hot stamping operations to be performed, resulting in the desired sheet metal parts [73]. It should be noted that TWBs have the potential to significantly improve vehicle safety and reduce weight (Fig. 20), which results in lower overall manufacturing costs by using fewer forming dies, and less weight by welding sheet materials of varying thicknesses and strengths. This has improved dimensional accuracy by eliminating the inaccurate spot-welding process [74].

TRB consists of a single base material, which is typically 22MnB5. Sheets of varying thicknesses are manufactured in tailor-rolled blanks using a flexible rolling process, resulting in a smooth transition between two different blank thicknesses [75]. Therefore, no stress peaks are generated by abrupt thickness transitions, resulting in good formability. Besides, given the absence of weld seam, tailor-rolled blanks have a higher surface quality. Tailor-rolled blanks have shown a favorable potential in reducing weight and improving the crashworthiness of automobile components such as the center pillar and cross beam. Since 2001, tailor-rolled blanks have been used as semi-finished products for parts in the automotive industry. Tailor-rolled blanks include two rolling processes, longitudinal thickness variation and latitudinal thickness variation [76, 77]. Varying thicknesses in the longitudinal direction can be achieved via a flexible rolling process. The roll gap is varied during sheet rolling to achieve the desired thickness distribution (Fig. 21). The

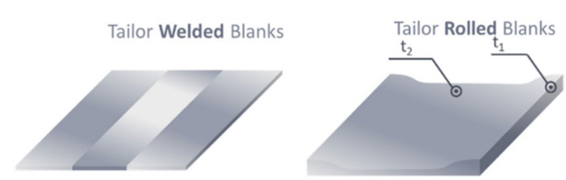

Fig. 20 Tailor welded blank (TWB) and tailor rolled blank (TRB) [77]

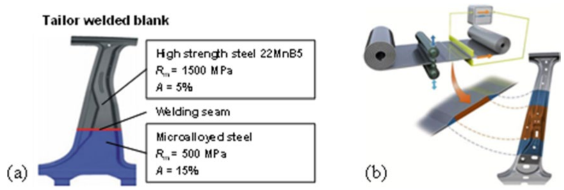

Fig. 21 B-pillar parts designed by: **a** TWB [78] and **b** TRB[79]

roll gap has been adjusted online by measuring the sheet thickness after the rolling process.

Muhr et al. produced flexible rolled blanks with an accuracy of ± 0.05 mm, the maximum sheet width for this process is 750 mm. To achieve sheets with a thickness variation in latitudinal direction, Kopp et al. developed the strip profile rolling process [76]. In this process, a special roll system that causes a material flow in a latitudinal direction was used.

According to Chatti et al., tailor-rolled profiles improved structural behavior, resulting in 15.6% less intrusion at a 13.5% weight reduction [80]. Ryabkov et al. developed a 3D-strip profile rolling process that generated blanks with thickness transitions in both the longitudinal and lateral directions [81]. Duan et al. applied TRBs to the front longitudinal beam (FLB). FLB is a deformable part under vehicle frontal impact and its deformation pattern can greatly influence vehicle safety. The lightweight design method has been proposed to minimize the weight of the FLB-inner [79]. Han et al. [82] developed tailor-rolled blanks for an automobile door with thickness distribution in both longitudinal and latitudinal directions. The thickness distribution of a car part can be optimized to increase energy absorption during impact. Yu et al. [83] optimized the frontal crash design of automotive front-end components by making use of TRB technology. The results indicated that TRB front-end components were superior to the uniform thickness front-end components in overall crashworthiness. The optimal TRB design solutions are verified by simulation results. Results show that the weight of front-end components is reduced by 12.8%, the total energy absorption is increased by 8.73%.

TRBs have been widely used in the automotive industry due to their lightweight potential and easy adaptation to existing manufacturing processes such as hot-stamping [84]. In spite of TRB's excellent forming performance, its flexible rolling technology still needs to be improved and optimized, especially when it comes to high precision requirements. Currently, TRB is strictly delimited by the same raw materials. Further research is still needed to determine the performance of the smooth transition zone and its impact on the overall performance of the TRB. Furthermore, for a greater breakthrough in blank properties, how to make the whole tailor-rolled blanks show continuous changes is an important research topic.

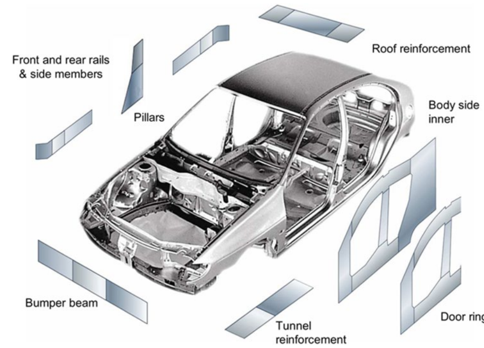

Fig. 22 Applications for tailor welded blanks in white body [86]

4.2 Integrated Part Design

TWBs (Fig. 22) have been widely used in roof reinforcement, body side inner, door ring, tunnel reinforcement, B-pillar, and bumper beam. Weight reduction is the key approach to reduce fuel consumption and carbon emissions which is achievable by TWBs [85]. Múnera et al. [86] investigated the weight reduction potential of safety-relevant parts produced by hot stamping of tailored welded blanks. The steel grade USIBOR 1500P is laser welded with Ductibor 500P. It tends to have high ductility after quenching. Using this material combination for safety-relevant car body parts could result in weight savings ranging from 4.1 to 5.4 kg. Another advantage of TWBs is the ability to tailor the mechanical strength of automotive parts by reinforcing only the regions that require strength or stiffness for crash resistance with more resistant materials and using lower-thickness materials in the rest of the components where less strength is required. Lechler et al. [87] identified the use of tailor-welded blanks for hot stamping processes. The combination of tailor-welded blanks technology and a hot stamping process in a way realized controlled energy absorption and the avoidance of overstressing in the hot-stamped part.

The B-pillar is a typical example of a hot stamping part. Its upper section necessitates high strength to provide support and ensure sufficient space for passengers to withstand external forces during collisions, thus safeguarding both vehicle integrity and passenger safety. Conversely, the lower section of the B-pillar requires lower strength but high plasticity to effectively absorb the car's impact energy, thereby maximizing passenger safety [88]. Huang et al. [89] investigated the mechanical property and structural performance of the hot-stamped TWB B-pillars. According to the CAE results, the TWB design can reduce the intrusion distance at the passenger's chest height. In the process of hot stamping, the weld line has a low crack sensitivity. The transition zone between the hard zone and soft zone is less than 1 mm. Song et al. [90] used the adaptive response surface method to optimize the design of a variable-strength B-pillar reinforcement panel. The results showed that the car body using the optimized B-pillar can meet the side impact performance requirements in a better way and reduce the weight of the part by 12.1% simultaneously. The traditional four parts are replaced by the integrated door rings with one door ring part, which is laser welded into a whole piece of material and then stamped in one piece to ensure the overall rigidity of the body while enhancing the overall lightweight effect. TWB hot forming door ring is one of the most effective methods to improve vehicle crashworthiness. Recently, GONVVAMA introduced a new technology, an integrated hot forming laser welded double door ring. The combination of the rear door ring (Fig. 23) based on the previous door ring, and the strengthened structure of the entire passenger compartment is hot formed as a whole to form a double ring structure, which is referred to as a double-door ring. The integrated double-door ring replaces the original 12 parts with a single part. Plus, when compared to the traditional multi-part spot-welded construction, the integrated double-door ring can achieve a 32% weight reduction.

In summary, integrated part design can be applied to effectively reduce raw material consumption, weight, and the number of stamping processes, resulting in LCE hot stamping. Although tailor-welded blanks have numerous advantages, an increase in processing time and overall process costs due to the additional laser welding operation should be considered. Furthermore, hot stamping blanks are typically pre-coated with a protective layer before hot stamping to prevent surface oxidation and decarburization [92]. Al-Si coating is most commonly used [93]. In spite of this, many studies show that Al-Si coatings harm the mechanical properties of welded joints. As a consequence, weld lines reduce formability, as well as create stress concentrations at the weld line when joining blanks of different thicknesses. The above issues are further important aspects to be considered in the application of integrated part design.

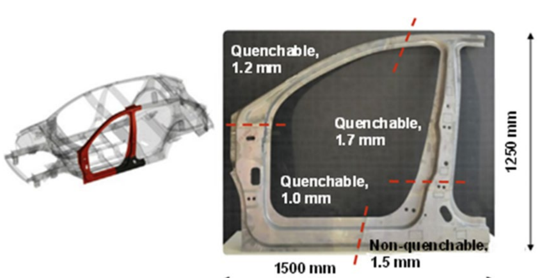

Fig. 23 Integrated door ring [91]

5 Conclusions

This study provides a comprehensive summary of the recent developments in steel grades, heating processes, and part design in the hot stamping field. Based on the findings, recommendations for achieving a low-carbon economy (LCE) in the hot stamping process are proposed. The conclusions and perspectives drawn from this study are as follows:

Firstly, a review of the characteristics of traditional HSS, coating-free (CF) HSS, and medium Mn HSS is presented. CF HSS, with its enhanced mechanical properties and oxidation resistance, has the potential to support the mass-market application of LCE in the automotive industry. Its unique antioxidant property is attributed to the quick formation of a thin layer of oxide film on the surface. The remarkable ductility observed in CF HSS is a result of the formation of nano-sized retained austenite through dynamic carbon partitioning during the hot stamping process. Meanwhile, medium Mn HSS, with its lower austenitization temperatures and improved mechanical properties, is gaining attention as a replacement for traditional HSS as it has the potential for energy consumption reduction in hot stamping. However, to fully realize its benefits and facilitate its industrial application, further research is needed to gain a comprehensive understanding of the processing conditions, microstructure evolution, and mechanical behavior associated with medium Mn HSS.

Secondly, conventional heating processes, primarily relying on radiant heating, suffer from inefficiency, leading to prolonged heating times. However, conduction heating emerges as a promising alternative due to its rapid heating rates and the ability to achieve partial heating. Nonetheless, it faces challenges in achieving temperature uniformity and preventing oxidation. In contrast, induction heating offers a potential solution for temperature uniformity, while the appropriate design of induction coils is vital. Overall, the development of efficient and effective heating processes is essential for the advancement of LCE hot stamping.

Thirdly, a part design approach can reduce carbon emissions during the design stage of hot stamping parts. This approach involves using high-strength, thick materials selectively, combining various steel plates, and realizing a raw material reduction in the hot stamping process. By adopting integral stamping and one-time forming of parts, the number of hot stamping parts can be minimized, leading to a reduction in stamping equipment, working procedures, and tools, thereby lowering energy consumption in manufacturing. Laser tailor welding and tailor rolling can produce body structural parts with the desired geometry, shape, and mechanical properties, achieving automotive lightweighting and LCE.

In summary, it is crucial to recognize the interdependence among heating processes, part designs, and the capabilities of the materials used. In other words, the boundaries of the material's capabilities must be fully understood. By pushing the boundaries of material capabilities, advanced heating processes can expand the application potential of the materials, enabling a broader scope for innovative designs. All in all, carbon reduction in manufacturing can only be achieved through a holistic approach to steel-process design.

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Declarations

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

References

1. Karbasian, H., Tekkaya, A.E.: A review on hot stamping. J. Mater. Process. Technol. **210**(15), 2103–2118 (2010)
2. Mori, K., Bariani, P.F., Behrens, B.A., et al.: Hot stamping of ultra-high strength steel parts. CIRP Ann. **66**(2), 755–777 (2017)
3. Cao, J., Banu, M.: Opportunities and challenges in metal forming for lightweighting: review and future work. J. Manuf. Sci. Eng. **142**(11), 110813 (2020)
4. Wang, Z., Lu, Q., Cao, Z.H., et al.: Review on hydrogen embrittlement of press-hardened steels for automotive applications. Acta. Metall. Sin. Engl. **1**, 1–21 (2022)
5. Maeno, T., Mori, K.I., Nagai, T.: Improvement in formability by control of temperature in hot stamping of ultra-high strength steel parts. CIRP Ann. **63**(1), 301–304 (2014)
6. Rosenthal, S., Maaß, F., Kamaliev, M., et al.: Lightweight in automotive components by forming technology. Automot. Innov. **3**(3), 195–209 (2020)
7. Min, J.Y., Lin, J.P., Li, J.Y., et al.: Investigation on hot forming limits of high strength steel 22MnB5. Comput. Mater. Sci. **49**(2), 326–332 (2010)
8. China automotive news: China electric vehicle council of 100 forum. 2023-04-01, http://www.cnautonews.com/yaowen/2023/04/01/detail_20230401356018.html
9. Yi, H., Chang, Z., Cai, H., et al.: Strength, ductility and fracture strain of press-hardening steels. Acta. Metall. Sin. **56**(4), 429–443 (2020)
10. Jin, X., Gong, Y., Han, X., et al.: A review of current state and prospect of the manufacturing and application of advanced hot stamping automobile steels. Acta. Metall. Sin. **56**(4), 411–428 (2020)
11. Liu, A.M., Feng, Y., Zhao, Y., et al.: Effect of niobium and vanadium micro-alloying on microstructure and property of 22MnB5 hot press forming steel. Mater. Mech. Eng. **43**(5), 34–37 (2019)
12. Liu, H., Lu, X., Jin, X., et al.: Enhanced mechanical properties of a hot stamped advanced high-strength steel treated by quenching and partitioning process. Scr. Mater. **64**(8), 749–752 (2011)
13. Hou, Z.R., Opitz, T., Xiong, X.C., et al.: Bake-partitioning in a press-hardening steel. Scr. Mater. **162**, 492–496 (2019)
14. Drillet, P., Spehner, D., Kefferstein, R.: Coated steel strips, methods of making the same, methods of using the same, stamping blanks prepared from the same, stamped products prepared from the same, and articles of manufacture which contain such a stamped product. US Patent **8**(307), 680 (2012)
15. Seo, E.J., Cho, L., Estrin, Y., et al.: Microstructure-mechanical properties relationships for quenching and partitioning (Q&P) processed steel. Acta Mater. **113**, 124–139 (2016)
16. Yi, H., Chang, Z., Liu, Z., et al.: Hot stamped component, precoated steel sheet used for hot stamping and hot stamping process. US Patent **11**, 248–276 (2022)
17. Wei, X., Chai, Z., Lu, Q., et al.: Cr-alloyed novel press-hardening steel with superior combination of strength and ductility. Mater. Sci. Eng. A **819**, 141461 (2021)
18. Li, S., Wen, P., Li, S., et al.: A novel medium-Mn steel with superior mechanical properties and marginal oxidization after press hardening. Acta Mater. **205**, 116567 (2021)
19. Hou, Z.R., Zhao, X.M., Zhang, W., et al.: A medium manganese steel designed for water quenching and partitioning. Mater. Sci. Technol. **34**(10), 1168–1175 (2018)
20. Wang, Z., Cao, Z.H., Wang, J.F., et al.: Improving the bending toughness of Al-Si coated press-hardened steel by tailoring coating thickness. Scr. Mater. **192**, 19–25 (2021)
21. Yoo, J., Kim, S., Jo, M.C., et al.: Effects of Al-Si coating structures on bendability and resistance to hydrogen embrittlement in 1.5-GPa-grade hot-press-forming steel. Acta Mater. **225**, 117561 (2022)
22. Lu, Q., Lai, Q., Chai, Z., et al.: Revolutionizing car body manufacturing using a unified steel metallurgy concept. Sci. Adv. **7**(49), eabk0176 (2021)
23. Oh, J., Han, U., Park, J., et al.: Numerical investigation on energy performance of hot stamping furnace. Appl. Therm. Eng. **147**, 694–706 (2019)
24. Mori, K.I., Maeno, T., Mongkolkaji, K.: Tailored die quenching of steel parts having strength distribution using bypass resistance heating in hot stamping. J. Mater. Process. Technol. **213**(3), 508–514 (2013)
25. Kocar, O., Livatyal, H.: Investigation on the mechanical properties of press-hardened boron steel sheets using the conductive heating technique. Proc. Inst. Mech. Eng. L. **234**(8), 1084–1098 (2020)
26. Bao, L., Liu, W.J., Wang, B., et al.: Experimental investigation on partition controllable induction heating-hot stamping process of high-strength boron alloyed steel plates with designable temperature patterns. J. Mater. Res. Technol. **9**(6), 13963–13976 (2020)
27. Mori, K., Maki, S., Tanaka, Y.: Warm and hot stamping of ultra high strength steel sheets using resistance heating. CIRP Ann. **54**(1), 209–212 (2005)

28. Bao, L., Wang, B., You, X., et al.: Numerical and experimental research on localized induction heating process for hot stamping steel sheets. Int. J. Heat Mass Transf. **151**, 119422 (2020)
29. Merklein, M., Johannes, M., Lechner, M., et al.: A review on tailored blanks—production, applications and evaluation. J. Mater. Process. Technol. **214**(2), 151–164 (2014)
30. Kumar, A., Gautam, V.: Formability of tailor welded blanks of high strength steel: a review. Mater. Today Proc. **46**(1), 6547–6551 (2021)
31. Kang, M., Kim, C.: Laser welding for hot-stamped tailor-welded blanks with high-strength steel/high-energy absorption steel. J. Laser Appl. **26**(3), 032007 (2014)
32. Samadian, P., O'Keeffe, C., Butcher, C., et al.: Fracture response in hot-stamped tailor-welded blanks of ductibor 500-as and usibor 1500-as: experiments and modelling. Eng. Fract. Mech. **253**(1080), 107864 (2021)
33. Rybicka, J., Tiwari, A., Leeke, G.A.: Technology readiness level assessment of composites recycling technologies. J. Clean. Prod. **112**, 1001–1012 (2016)
34. Cho, L., Golem, L., Seo, E.J., et al.: Microstructural characteristics and mechanical properties of the Al–Si coating on press hardened 22MnB5 steel. J. Alloys Compd. **846**, 156349 (2020)
35. Klassen, C.M., Daun, K.J.: Investigating coating liquefaction and solidification of furnace-heated Al-Si coated 22MnB5 steel using laser reflectance. Surf. Coat. Technol. **393**, 125795 (2020)
36. Chen, N., Wan, Z., Wang, H.P., et al.: Effect of Al Si coating on laser spot welding of press hardened steel and process improvement with annular stirring. Mater. Des. **195**, 108986 (2020)
37. Golem, L., Cho, L., Speer, J.G., et al.: Influence of austenitizing parameters on microstructure and mechanical properties of Al-Si coated press hardened steel. Mater. Des. **172**, 107707 (2019)
38. Grauer, S.J., Caron, E.J.F.R., Chester, N.L., et al.: Investigation of melting in the Al–Si coating of a boron steel sheet by differential scanning calorimetry. J. Mater. Process. Technol. **216**, 89–94 (2015)
39. Gui, Z.X., Wang, K., Zhang, Y.S., et al.: Cracking and interfacial debonding of the Al–Si coating in hot stamping of pre-coated boron steel. Appl. Surf. Sci. **316**, 595–603 (2014)
40. Jo, K.R., Cho, L., Sulistiyo, D.H., et al.: Effects of Al-Si coating and Zn coating on the hydrogen uptake and embrittlement of ultra-high strength press-hardened steel. Surf. Coat. Technol. **374**, 1108–1119 (2019)
41. Lu, Q., Jiachen, P.A., Wang, J.: Steel for hot stamping with enhanced oxidation resistance. US Patent **16**(958), 362 (2021)
42. Hou, Z., Min, J., Wang, J., et al.: Effect of rapid heating on microstructure and tensile properties of a novel coating-free oxidation-resistant press-hardening. Steel. JOM. **73**(11), 3195–3203 (2021)
43. Hou, Z.R., Wang, J.F., Lu, Q., et al.: Short process hot forming technology and microstructure evolution of ultra-high strength steels. J. Mech. Eng. **58**(16), 43–50 (2022)
44. Chang, Y., Wang, C.Y., Zhao, K.M., et al.: An introduction to medium-Mn steel: metallurgy, mechanical properties and warm stamping process. Mater. Des. **94**, 424–432 (2016)
45. Pan, H.J., Cai, M.H., Ding, H., et al.: Microstructure evolution and enhanced performance of a novel Nb–Mo microalloyed medium Mn alloy fabricated by low-temperature rolling and warm stamping. Mater. Des. **134**, 352–360 (2017)
46. Lu, Q., Eizadjou, M., Wang, J., et al.: Medium-Mn martensitic steel ductilized by baking. Metall Mater Trans A. **50**(9), 4067–4074 (2019)
47. Verma, M., Yan, H., Culham, J.R., et al.: Development and validation of a thermometallurgical model for furnace-based austenitization during hot stamping. J. Heat Transf. **141**(6), 62101 (2019)
48. Liu, Y., Zhu, B., Wang, Y., et al.: Fast solution heat treatment of high strength aluminum alloy sheets in radiant heating furnace during hot stamping. Int. J. Lightweight Mater. Manuf. **3**(1), 20–25 (2020)
49. Mori, K., Maki, S., Tanaka, Y.: Warm and hot stamping of ultra high tensile strength steel sheets using resistance heating. CIRP Ann. **54**(1), 209–212 (2005)
50. Mori, K., Maeno, T., Mongkolkaji, K.: Tailored die quenching of steel parts having strength distribution using bypass resistance heating in hot stamping. J. Mater. Process. Technol. **213**(3), 508–514 (2013)
51. Okayasu, M., Sato, M.: Hot-stamping technology for carbon fiber reinforced thermoplastic plates based on electrical resistance heating. J. Compos. Mater. **54**(10), 1353–1361 (2019)
52. Maeno, T., Mori, K.I., Sakagami, M., et al.: Minimisation of heating time for full hardening in hot stamping using direct resistance heating. J. Manuf. Mater. Process. **4**(3), 80 (2020)
53. Maeno, T., Mori, K.I., Ogihara, T., et al.: Blanking immediately after heating and ultrasonic cleaning for compact hot-stamping systems using rapid resistance heating. Int. J. Adv. Manuf. Technol. **97**(9–12), 3827–3837 (2018)
54. Liang, W., Wang, H., Wang, Q., et al.: Application of conduction heating on hot stamping of front bumper. Int. J. Adv. Manuf. Technol. **112**(11–12), 3177–3188 (2021)
55. Mori, K.I., Abe, Y., Miyazawa, S.: Warm stamping of ultra-high strength steel sheets at comparatively low temperatures using rapid resistance heating. Int. J. Adv. Manuf. Technol. **108**(11–12), 3885–3891 (2020)
56. Fang, H., Wang, G., Liu, S., et al.: Research on resistance heating behavior of high-strength steel and its hot-stamping forming. J. Mater. Eng. Perform. **27**(9), 4829–4837 (2018)
57. Kocar, O., Livatyalı, H.: Investigation on the mechanical properties of press-hardened boron steel sheets using the conductive heating technique. Proc. Inst. Mech. Eng., Part L: J. Mater. Des. Appl. **234**(8), 1084–98 (2020)
58. Friedrich, S., Tian, Y., Wang, L., et al.: Heating schemes and process parameters of induction heating of aluminium sheets for hot stamping. Manuf. Rev. **6**, 17 (2019)
59. Kolleck, R., Veit, R., Merklein, M., et al.: Investigation on induction heating for hot stamping of boron alloyed steels. CIRP Ann. **58**(1), 275–278 (2009)
60. Kim, D.K., Woo, Y.Y., Park, K.S., et al.: Advanced induction heating system for hot stamping. Int. J. Adv. Manuf. Technol. **99**(1–4), 583–593 (2018)
61. Bao, L., Wang, B., You, X., et al.: Numerical and experimental research on localized induction heating process for hot stamping steel sheets. Int. J. Heat Mass Transf. **151**, 119422 (2020)
62. Lee, E.H., Hwang, J.S., Lee, C.W., et al.: A local heating method by near-infrared rays for forming of non-quenchable advanced high-strength steels. J. Mater. Process. Technol. **214**(4), 784–793 (2014)
63. Lee, E.H., Yoon, J.W., Yang, D.Y.: Study on springback from thermal-mechanical boundary condition imposed to V-bending and L-bending processes coupled with infrared rays local heating. Int. J. Mater. Form. **11**(3), 417–433 (2017)
64. Geng, H., Wang, Y., Wang, Z., et al.: Investigation on contact heating of aluminum alloy sheets in hot stamping process. Metals. **9**(12), 1341 (2019)
65. Maeno, T., Tomobe, M., Mori, K., et al.: Hot stamping of titanium alloy sheets using partial contact heating. Procedia Manuf. **15**, 1149–1155 (2018)
66. Li, F., Lin, J., Fu, M.: Study on the constitutive model of boron steel 22MnB5 with different phase fractions. Int. J. Precis. Eng. Manuf. **17**(10), 1323–1331 (2016)
67. Liu, Y., Min, J., Zhang, J., et al.: Laser-assisted robotic roller forming of an ultrahigh strength martensitic steel. J. Manuf. Processes. **82**, 192–202 (2022)

68. Min, J., Wang, J., Lian, J., et al.: Laser-assisted robotic roller forming of ultrahigh-strength steel QP1180 with high precision. Materials **16**(3), 1026 (2023)
69. Liu, Y., Wang, J., Cai, W., et al.: A thermo-metallurgical-mechanical model for microstructure evolution in laser-assisted robotic roller forming of ultrahigh strength martensitic steel. J. Mater. Res. Technol. **25**, 451–464 (2023)
70. Liu, G., Dai, Z., Yang, Z., et al.: Kinetic transitions and Mn partitioning during austenite growth from a mixture of partitioned cementite and ferrite: role of heating rate. J. Mater. Sci. Technol. **49**, 70–80 (2020)
71. Wan, X., Liu, G., Yang, Z., et al.: Flash annealing yields a strong and ductile medium Mn steel with heterogeneous microstructure. Scr. Mater. **198**, 113819 (2021)
72. Banis, A., Bouzouni, M., Gavalas, E., et al.: The formation of a mixed martensitic/bainitic microstructure and the retainment of austenite in a medium-carbon steel during ultra-fast heating. Mater. Today Commun. **26**, 101994 (2021)
73. Shi, C.W.P., Rugrungruang, F., Yeo, Z., et al.: Identifying carbon footprint reduction opportunities through energy measurements in sheet metal part manufacturing. Paper presented at the 18th CIRP international conference on life cycle engineering, Technische Universität Braunschweig, Braunschweig, 2–4 May 2011. Berlin, Heidelberg: Springer Berlin Heidelberg, 389–394 (2011)
74. Kumar, A., Gautam, V.: Formability of tailor welded blanks of high strength steel: a review. Mater. Today: Proc. **46**, 6547–6551 (2021)
75. Brecht, J., Pohl, S., Schlender, A., et al.: Hotformed tailor rolled products, tailored lightweight design solutions for the vehicle structure. Paper presented at the 5th international conference on hot sheet metal forming of high-performance Steel-CHS^2, Association for Iron and steel technology, Toronto, May 31st–June 3rd 2015
76. Kopp, R., Wiedner, C., Meyer, A.: Flexibly rolled sheet metal and its use in sheet metal forming. Adv. Mat. Res. **6**, 81–92 (2005)
77. Hirt, G., Dávalos-Julca, D.H.: Tailored profiles made of tailor rolled strips by roll forming–part 1 of 2. Steel Res. Int. **83**(1), 100–105 (2012)
78. Erhardt, R., Böke, J.: Industrial application of hot forming press simulation. Paper presented at the 1st international conference on hot sheet metal forming of high-performance steel, Kassel, 22–24 Oct 2008
79. Duan, L., Sun, G., Cui, J., et al.: Crashworthiness design of vehicle structure with tailor rolled blank. Struct. Multidiscip. Optim. **53**(2), 321–338 (2015)
80. Chatti, S., Heller, B., Kleiner, M., et al.: Forming and further processing of tailor rolled blanks for lightweight structures. Adv. Technol. Plast. **2**, 1387–1392 (2002)
81. Ryabkov, N., Jackel, F., Van Putten, K., et al.: Production of blanks with thickness transitions in longitudinal and lateral direction through 3D-strip profile rolling. Int. J. Mater. Form. **1**, 391–394 (2008)
82. Han, S., Hwang, T., Oh, I., et al.: Manufacturing of tailor-rolled blanks with thickness variations in both the longitudinal and latitudinal directions. J. Mater. Process. Technol. **256**, 172–182 (2018)
83. Yu, L., Gu, X., Qian, L., et al.: Application of tailor rolled blanks in optimum design of pure electric vehicle crashworthiness and lightweight. Thin-Walled Struct. **161**, 107410 (2021)
84. Klinke, N., Kobelev, V., Schumacher, A.: Rule and optimization-based selection of car body parts for the application of tailor rolled blank technology. Struct. Multidiscip. Optim. **65**(2), 60 (2022)
85. Aminzadeh, A., Parvizi, A., Safdarian, R., Rahmatabadi, D.: Comparison between laser beam and gas tungsten arc tailored welded blanks via deep drawing. Proc. Inst. Mech. Eng., Part B: J. Eng. Manuf. **235**(4), 673–88 (2021)
86. Múnera, D.D., Pic, A., Abou-Khalil, D., et al.: Innovative press hardened steel based laser welded blanks solutions for weight savings and crash safety improvements. SAE Int. J. Mater. Manuf. **1**(1), 472–479 (2009)
87. Lechler, J., Stöhr, T., Kuppert, A., et al.: Basic investigations on hot stamping of tailor welded blanks regarding the manufacturing of lightweight components with functionally optimized mechanical properties. Trans. North Am. Manuf. Res. Inst. SME **38**, 593–600 (2010)
88. Bao, L., Nie, Q., Wang, B., You, X.: Development of hot stamping technology for high strength steel parts with tailored properties. IOP Conf. Ser.: Mater. Sci. Eng. **538**(1), 012016 (2019)
89. ChiuHuang, C.K., Chiang, M.F., Lee, P.K.: Numerical and experimental investigation on hot stamping of TWB B-pillar. IOP Conf. Ser.: Mater. Sci. Eng. **967**(1), 012083 (2020)
90. Song, Y.L., Han, Y., Hua, L., et al.: Optimal design and hot stamping of b-pillar reinforcement panel with variable strength based on side impact. The 2nd international conference in advanced high strength steel and press hardening: proceedings, 320–326 (2016)
91. Mu, Y., Wang, B., Zhou, J., et al.: Hot stamping of boron steel using partition heating for tailored properties: experimental trials and numerical analysis. Metall. Mater. Trans. A. **48**, 5467–5479 (2017)
92. Chen, R., Zhang, C., Lou, M., et al.: Effect of Al-Si coating on weldability of press-hardened steels. J. Mater. Eng. Perform. **29**, 626–636 (2020)
93. Khan, M.S., Razmpoosh, M.H., Biro, E., et al.: A review on the laser welding of coated 22MnB5 press-hardened steel and its impact on the production of tailor-welded blanks. Sci. Technol. Weld. Join. **25**(6), 447–467 (2020)

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