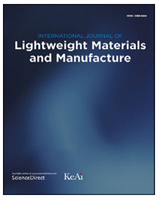
International Journal of Lightweight Materials and Manufacture 7 (2024) 327–343

Contents lists available at ScienceDirect

International Journal of Lightweight Materials and Manufacture

journal homepage: www.keaipublishing.com/ijlmm



A data-informed review of scientific and technological developments and future trends in hot stamping

Jiaqi Li, Chenpeng Tong, Ruiqiang Zhang, Zhusheng Shi*, Jianguo Lin

Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK

ARTICLE INFO

Article history:
Received 12 October 2023
Received in revised form
20 November 2023
Accepted 21 November 2023
Available online 23 November 2023

Keywords:
Sheet metal forming
Hot stamping
HFQ
Lightweighting
Boron steel

ABSTRACT

As a promising solution to the growing demand for lightweighting, hot stamping has gained considerable applications in the automotive industry. Over the past few decades, the market for hot stamping has experienced explosive growth, with ongoing advancements offering potential for further expansion of its applications. This paper provides a historical overview of hot stamping alongside an in-depth analysis of future trends. Scientific publications, patents and industrial applications of hot stamping are systematically reviewed, with major developments in materials, processes, tools, and other relevant aspects being highlighted. Through data analysis, the current state of hot stamping is comprehensively depicted, and the trends in the development of hot stamping are revealed. Additionally, the future of extending hot stamping technologies to a broader range of materials is discussed, with suggestions furnished from both academic and industrial perspectives.

1. Introduction

As the trend of global warming intensifies, international collaborations have been ramped up to reduce greenhouse gas emissions. Unprecedentedly stringent policies are being enacted to achieve net-zero emissions within the next three to four decades [1,2]. Among all sectors, transportation stands as a major contributor to greenhouse gas emissions, constituting 23 % of global CO_2 emissions according to data from the International Energy Agency (IEA) in 2021 [3]. In countries such as the US and UK, transportation's contribution to greenhouse gas emission is even more pronounced, accounting for 29 % in the US [4] and 27 % in the UK [5], the largest portion among all industrial sectors. Within this sector, road transportation, especially passenger cars, is the most primary source of emissions. As a result, automotive manufacturers face huge regulatory pressure to reduce CO_2 emissions.

Lightweighting is one of the most prevalent strategies to increase fuel efficiency and reduce carbon emissions. It is estimated that a 10 % reduction in weight vehicle can yield 6–8 % reduction in fuel consumption [6]. Several lightweight materials have been introduced to make cars lighter without compromising increasingly stringent safety standards. Advanced high-strength steels (AHSS), high-strength aluminium alloys, and carbon-fibre-reinforced polymers (CFRPs) have been developed to address the growing demand for high-specific-strength materials. Among these materials, ultra-high-strength steels (UHSS), a subset of AHSS known for their exceptionally high strength (commonly characterised by an ultimate tensile strength (UTS) above 980 MPa), are particularly suitable for safety-critical components in vehicle. However, the increased strength of these steels undermines the formability, necessitating high forming forces and resulting in severe springback. To overcome these challenges, the automotive industry has adopted the hot stamping process, which has proven highly effective in forming UHSS components for decades.

The hot stamping process consists of three stages: (1) heating and austenitising; (2) high-temperature stamping; and (3) rapid in-die quenching to a certain low temperature [7]. The elevated stamping temperature significantly reduces forming force and enhances formability. Furthermore, the rapid in-die quenching minimises springback and generates a fully martensitic microstructure, leading to ultra-high strength properties. Therefore, in comparison to other forming methods for automotive structural components, hot stamping exhibits superior capability in crafting intricately designed parts with exceptional strengths [8]. Traditionally, hot stamping was predominately associated with ultra-high-strength boron steels. However, the high operation temperatures (over

---

* Corresponding author.
E-mail address: zhusheng.shi@imperial.ac.uk (Z. Shi).

Peer review under responsibility of Editorial Board of International Journal of Lightweight Materials and Manufacture.

https://doi.org/10.1016/j.ijlmm.2023.11.003

900 °C) of boron steel hot stamping technologies present challenges such as reduced productivity caused by long heating and cooling cycle, as well as high costs, imposing limitations on the widespread adoption of this process. Addressing these issues has become the main focus of recent studies, with improvements to material design, processes and tools to tackle the issues. Additionally, non-conventional hot stamping techniques applied to lightweight materials other than boron steels also attracted attention recently. For example, medium-Mn (MMn) steel has emerged as a promising alternative to boron steels, offering lower operation temperatures and improved post-formed mechanical properties [9,10]. On the other hand, hot stamping technology has also been applied to high-strength aluminium alloys to enhance their formability and mechanical properties for broadening their application in automotives [11,12].

The recent decade has seen a surge in the developments and applications of hot stamping. As the technology matures, the focus of researchers and developers has shifted significantly from initial academic and fundamental studies to more practical and refined topics. This review aims to present the macroscopic development of the hot stamping technologies and primarily concentrates on the analysis of hot stamping of boron steels which have been extensively researched and mostly commercialised. This paper commences with a historical review of the developments and applications of the hot stamping technology. Trends in the development of hot stamping are then explored through a statistical analysis of published scientific papers and patents concerning this technology, in terms of time-series, geographical distribution and topics. Recent developments in materials, processes and tools are highlighted. Furthermore, as a future trend, the adaptation of hot stamping technologies beyond boron steels for a broader spectrum of materials, such as high-strength Al alloys and medium-Mn steels, is discussed.

2. The development and industrial applications of hot stamping

2.1. Hot stamping processes and boron steel

The hot stamping technique has reached maturity and is now globally commercialised. The most commonly used materials in hot stamping technology are boron (Mn–B) steels, with 22MnB5 boron steel being particularly popular. Basic methods of hot stamping process include direct process (Fig. 1a) and indirect process (Fig. 1b). In the direct process, the steel coil begins by being cut into blanks, which are then heated to a temperature range of 900–950 °C in a furnace. These blanks are maintained isothermally for roughly 5–10 min to allow the initial ferrite-pearlite microstructure to fully transform into austenite. Afterward, these blanks are transferred from the furnace to a press, where they are shaped at temperatures typically around 700 °C or even higher, and subsequently cooled rapidly to ambient temperature at a rate of at least 27 $^\circ C\ s^{-1}$ for 22MnB5 steels to ensure a full martensitic transformation [13]. Therefore, compared to other forming techniques adopted in car structure components, hot stamping shows an outstanding ability to produce highly complicated components with little spring-back and ultra-high-strength using single-stage forming process. Notably, 22MnB5 steel typically features a yield strength exceeding 1000 MPa, an ultimate tensile strength approximating 1500 MPa, and an elongation of 6–7% following hot stamping [14–16]. Following this, the hot-stamped piece undergoes post-processing steps, including tempering, trimming, and punching, to meet the specific needs of commercial clients [17]. The change of temperature and microstructure of the blank during this process is illustrated in Fig. 2. In contrast, in the indirect process, the parts are pre-formed at room temperature before heating. They are then austenitised and calibrated at hot stamping temperature and quenched in the die to achieve the highest strength. Indirect hot stamping is suitable for steel blanks with Zn-coatings [18]. Compared with direct hot stamping, indirect hot stamping offers the capability to manufacture parts with very complex geometries while mitigating die wear, as the blank predominantly undergoes forming prior to hardening. However, this approach requires two sets of presses and dies, resulting in higher costs for equipment and the overall process [8]. When applying hot stamping technology in other promising materials, namely MMn steels and high-strength Al alloys, as mentioned in Section 1, the process remains similar with modifications in operating parameters. More details are discussed in Section 4.

The widespread adoption of boron steels in hot stamping is attributed to the following factors: 1) In achieving equivalent or higher levels of strength and hardness, boron steels typically incur lower costs compared to other conventional steels. 2) Boron steels, thanks to the addition of boron, have high martensite finish temperatures (M_f), typically exceeding 250 °C (i.e. wider process window), which is particularly advantageous for mass production [19]. 3) The exceptional hardenability of boron steels (attributable to boron as well), as evidenced by the low critical cooling rates needed for achieving a fully martensitic microstructure, translates into uniform mechanical properties across manufactured components [7].

Owing to the merits of the hot stamping, considerable advancements have been made to further improve this technology and broaden its application scope. Specifically, a comprehensive understanding of the relationship between mechanical properties and microstructure has been grounded, in conjunction with advanced modelling techniques, to optimise critical process parameters such as heating temperature, duration and cooling rates, etc. that impact the final performance [20–22]. Innovations in process equipment, tooling techniques and material design have also been developed to make the process more energy-efficient, productive and environmentally sustainable, as well as to improve the final performance of the components. Further details are discussed upon in the subsequent sections.

2.2. The history and application of hot stamping

Hot stamping originated in Sweden in the 1970s, initially finding applications in the production of agricultural parts. The first patent (SE7315058A) was filed in 1973 by Plannja AB, later a subsidiary of Swedish Steel AB (SSAB) [23]. SSAB initially held key boron steel patents and had an exclusive supply to major OEMs like Ford and Volkswagen in the early 1990s, primarily focusing on door beams. After the original patent expired in the mid-1990s, various companies began developing their own hot stamping technologies. By the late 1990s, 8 million hot-stamped parts had been produced globally. A notable example was the 2004 VW Passat car, which applied 15 % of hot-stamped boron steel in its body structure [7]. In the 2000s, diverse hot stamping processes to produce components with tailored mechanical properties, notably tailor-welded blanks (TWB) and tailor-rolled blanks (TRB) manufacturing technologies, were introduced to meet varied requirements in different areas of automotive components like B-pillars [24]. These tailored components reduce the need for additional welding and trimming processes, enhancing efficiency and design flexibility.

In the 2010s, the drive to reduce vehicle weight boosted the use of hot stamping, and hot stamping expanded to more complex car parts. By the early 2010s, major automakers widely embraced this technology for key body parts [8]. In the recent decade, the application of hot stamping expanded from structural reinforcements to

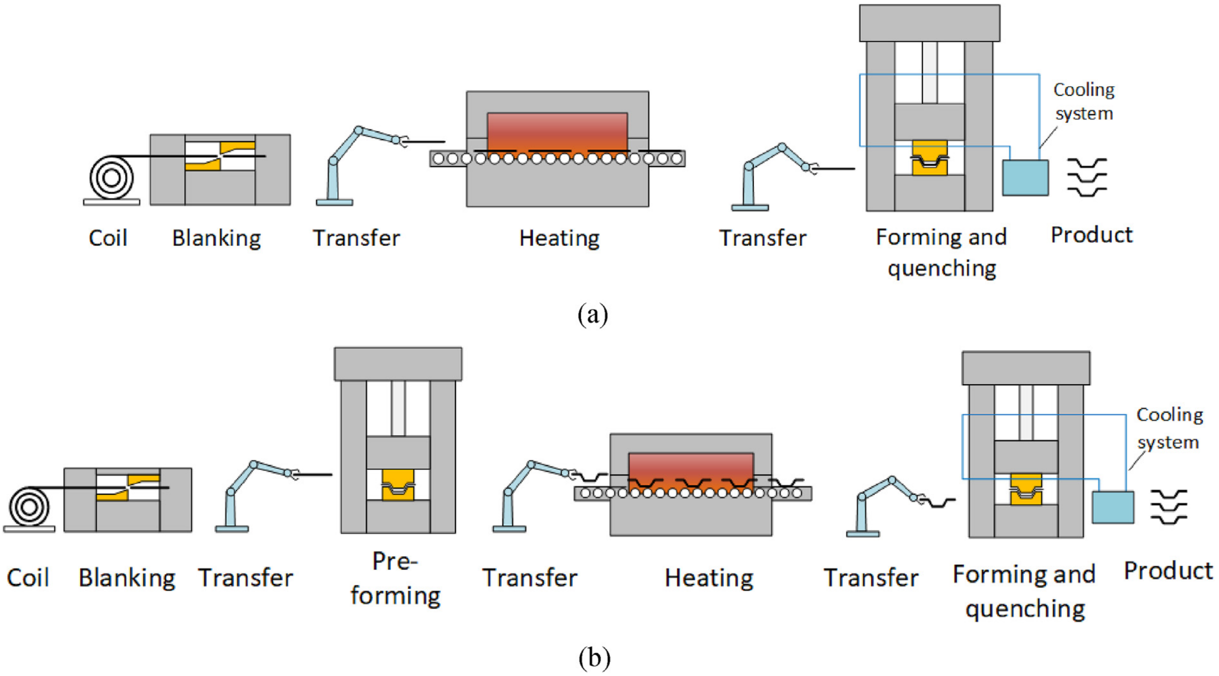


Fig. 1. Schematic of hot stamping processes. (a) Direct hot stamping process (b) Indirect hot stamping process.

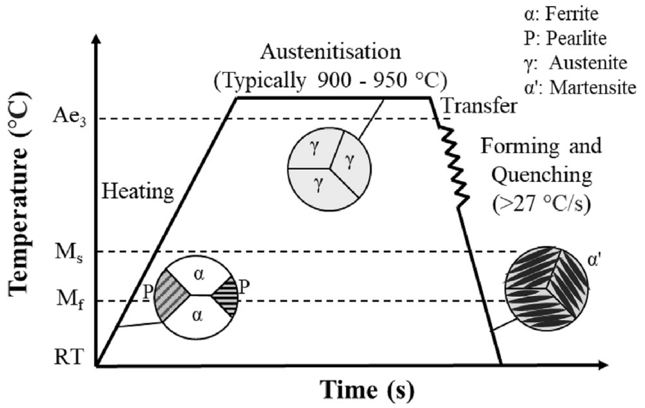


Fig. 2. Schematic of temperature profile of a direct hot stamping process and associated microstructural changes for 22MnB5 steels.

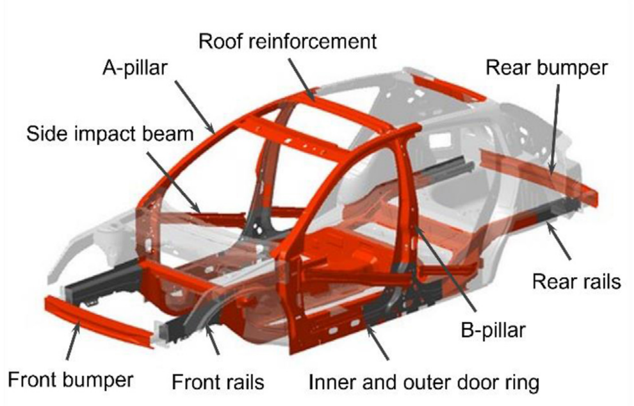


Fig. 3. Typical application of hot-stamped components in a passenger car (base image from Ref. [28]). Red labels a harder hot-stamping steel and black indicates a softer hot-stamping steel.

areas such as A-pillars and door rings [25–27], enabling further lightweighting, unique designs and enhanced visibility. Typical applications of hot stamping for a family car's body are illustrated in Fig. 3.

The percentage of hot-stamped components in the body-in-white (BiW) has been gradually increasing in recent years. A clear example of this trend is reflected in Volvo's BiW design evolution (Fig. 4): In 2002, the first generation SUV XC90 had only 7 % of its BiW made of hot-stamped steel, specifically in its B-pillars and bumper beam (highlighted in red in Fig. 4). By 2015, this percentage had risen to 38 % in the second generation XC90, featuring more parts made of UHSS [29,30]. Around 360 million parts had been made with hot-stamped steels in 2015, a notable increase from the 124 million parts recorded in 2010 [31].

Although already extensively adopted by carmakers like Volvo, the global usage of hot stamping still has substantial room for growth. Research by consulting firm Roland Berger in 2017 [33] indicates that the share of hot-stamped parts in the total BiW market, is expected to rise from 8 % in 2015 to 17 % by 2025. This growth is anticipated to elevate the market value of hot stamping from 11.6 billion euros to 17.4 billion euros (see Fig. 5a). Their projections suggest that while Europe may reach a plateau due to market saturation, China is expected to become a key driver of this growth, given its increasing focus on improving safety standards and reducing carbon emissions (see Fig. 5b).

The rise of new energy vehicles, particularly battery electric vehicles (BEVs), represent another growth factor of hot stamping market. Due to the weight of the battery itself and the increasing demand to safeguard the battery pack, the curb mass of a typical BEV is about 10 % higher than that of combustion engine cars [34]. This elevates the necessity for lightweighting, making hot stamping a more prominent choice for BEVs. According to a recent report [35], automaker Hyundai Motors uses hot-stamping steels for approximately 15 % of all steel parts in their internal combustion engine cars, while the percentage rises to 20 % for their electric

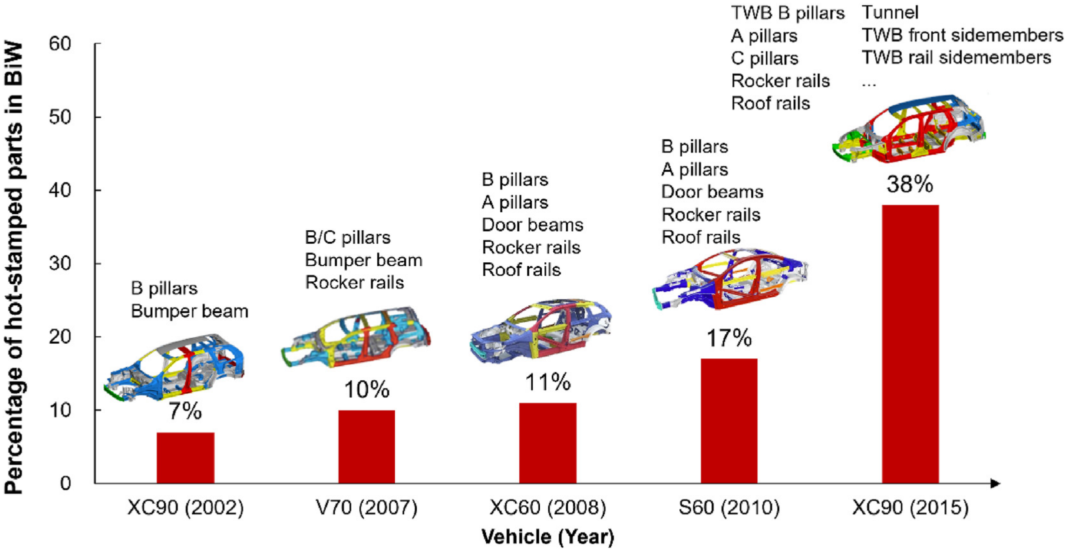
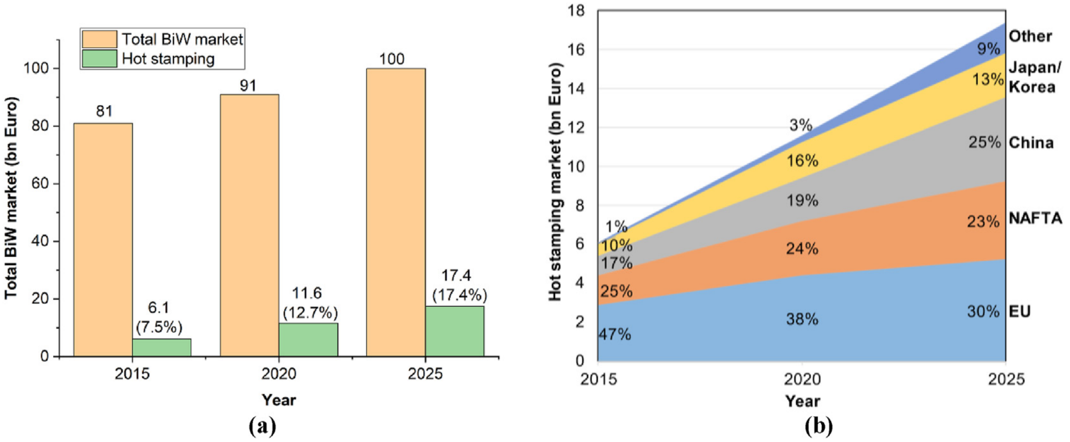


Fig. 4. Usage of hot stamped parts in Volvo vehicle models (data from Refs. [30,32]).



(a) (b)

Fig. 5. Total BiW market value, hot stamping value and of hot stamping market share by regions (data from Ref. [33]). (a) Total BiW market and share of hot stamping (b) Hot stamping market share by regions.

vehicles. Beyond conventional reinforcement components commonly found in non-electric cars, hot stamping has demonstrated potential applications in structures uniquely found in new energy vehicles. The steelmaker ArcelorMittal is at the forefront of innovation, developing a novel hot-stamped battery ring that ensures safety for both battery and occupants [36]. The company has also proposed design concepts advocating the introduction of hot-stamped components in the battery enclosures of electrical vehicles [26,37].

In summary, hot stamping technology has undergone a remarkable transformation in the nearly 50 years. It has shown substantial promise and now stands as a fundamental technique extensively embraced within the automotive industry. With continuing innovations and ongoing pursuit of sustainability and safety standards, hot stamping is poised to continue its growth, serving as a critical technology in the constantly evolving automotive landscape.

3. Scientific and technical research on hot stamping

3.1. Data analysis of scientific publications and patents

To comprehensively illustrate the development of the hot stamping technologies, a statistical analysis of scientific publications and patents related to hot stamping is conducted. The raw data of scientific papers is obtained from the Web of Science database, while the patents are sourced from the online patent service Espacenet. Using carefully chosen keywords associated with hot stamping, data are collected and manually checked to ensure their relevance. The validated entries are then categorised according to various criteria including time, topic, region and affiliation. While most of the information is extracted directly from the metadata of the entries, additional manual work is undertaken to complete missing information in the dataset. To streamline the process, Python natural language processing libraries are utilised to parse and categorise the raw data. Specifically, the natural language toolkit NLTK is employed to semantically tokenise the text, while the topic modelling library Gensim is used to categorise the publications and patents by topics based on their titles, keywords, and abstracts. These results are then manually verified to increase the accuracy.

In this research, a total of 2177 scientific papers and 4567 patents related to hot stamping is analysed. The dataset covers publications dates ranging from January 1970 to December 2022, providing a robust overview of the developments in hot stamping technologies over several decades.

3.1.1. Time-series analysis

Fig. 6 shows the numbers of scientific publications and patents related to hot stamping from 1975 to 2022; the patents are presented by the year of publication. The graph reveals that before 2000, both papers and patents on hot stamping were relatively scarce. The numbers start to rise from 2000 to 2005 and then experience a significant surge until 2017, which is accelerated by the demands of lightweight applications due to environmental issue and legal requirements. The main research aspects focus on material design and process development, leading to a comprehensive understanding of the fundamental issues and basic mechanisms of hot stamping. The near-parallel growth in the number of papers and patents from the early 2000s to around 2017 suggests that academic research was likely driving patentable innovation, with new discoveries and theories quickly being translated into practical applications. Post-2017 trends for the patents and papers show some divergences: the number of papers appears to reach a peak in 2017 and start to decline afterward, while patent numbers continue to grow. The relationship between the trends in patents and papers suggests that while the fundamental academic research in hot stamping may be maturing, there remains a dynamic and evolving landscape of industrial innovation. The industry may have accumulated enough foundational knowledge to continue innovation at a more applied level, and focuses on the improvement of existing technologies and on the customisation of hot stamping processes for specific applications. It is noteworthy that the numbers of scientific papers from 2020 to 2022 may be influenced by the economic downturns and the impact of the pandemic.

3.1.2. Geographical distributions analysis

Fig. 7 displays the regions associated with the main affiliations of the papers on hot stamping technologies. Notably, China, Germany, South Korea, Japan, North America and the UK emerge as primary contributors to research in this field. Germany, maintaining a steady output, reflects the country's longstanding commitment to engineering and technological innovation, particularly in the automotive sector, which extensively utilises hot stamping for producing high-strength components. The decline in research output from regions like North America and the EU, except for Germany, may suggest a shift in research priorities or a transition towards other emerging technologies. Alternatively, it could reflect a maturation phase in hot stamping technology within these regions, where the initial research fervour has stabilised as the technology has become more integrated into industrial practices. The intensive studies and high institutional engagement in China, underscored by the substantial portion of overall research in this field as shown in the pie chart in Fig. 7a and the fact that six out of the top ten universities in this field are Chinese, suggest that the epicentre of research gravitates towards China and China plays a pivotal role in shaping the advancements of hot stamping technology on a global scale.

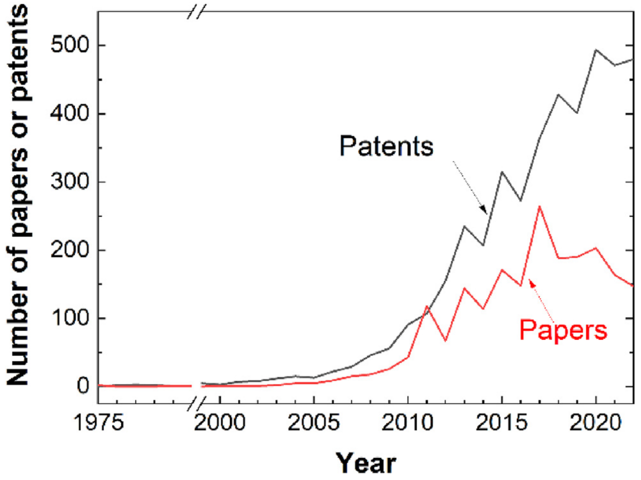
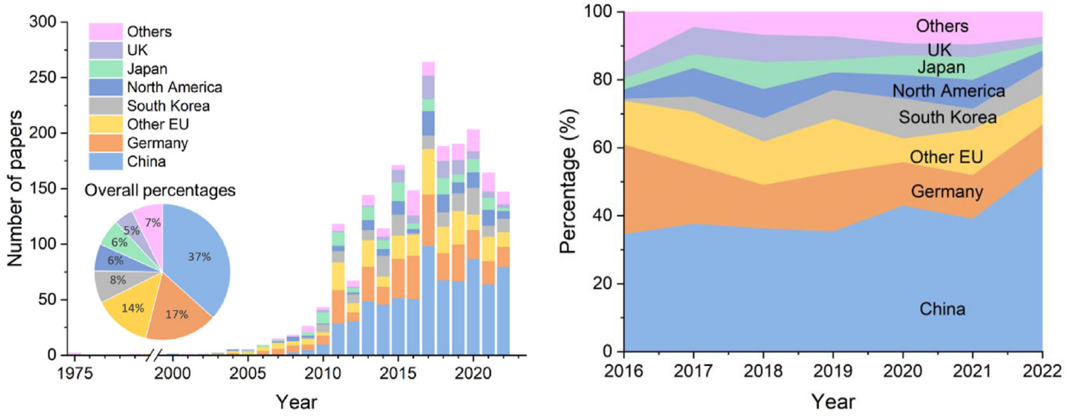


Fig. 6. Numbers of scientific papers and patents related to hot stamping over the years.

The evolution of the distribution of patents are shown in Fig. 8. The major countries involved are similar, but the percentages differ significantly. China, again, has the most patents in recent year. The number of patents from Japan and South Korea is also remarkably high, largely due to the extensive patent applications from major steelmakers like Nippon Steel, Kobe Steel, Hyundai Steel and POSCO. In fact, material suppliers account for 58 % of all applicants (see Fig. 9). Part suppliers and carmakers account for 16 % each of the total patent applications, with the research institutes contributing 8 %, and the remaining share comes from equipment and tools suppliers. It is noteworthy that this percentage by classification is not absolutely definite, given that many equipment suppliers also engage in parts manufacturing. The diverse range of applicants underscores the ongoing innovation in hot stamping technology with a collaborative effort involving all participants across the supply chain. Moreover, the establishment of a complete and mature supply chain for the hot stamping industry, initially originating in Europe and subsequently expanding into markets like South Korea and China, reflects widespread acceptance and robust support for hot stamping technology across the industry. The thriving presence of emerging manufacturers in East Asia, particularly in parts production, tools development, and ancillary equipment supply, further accentuates the technology's industry-wide embrace and sustained growth.

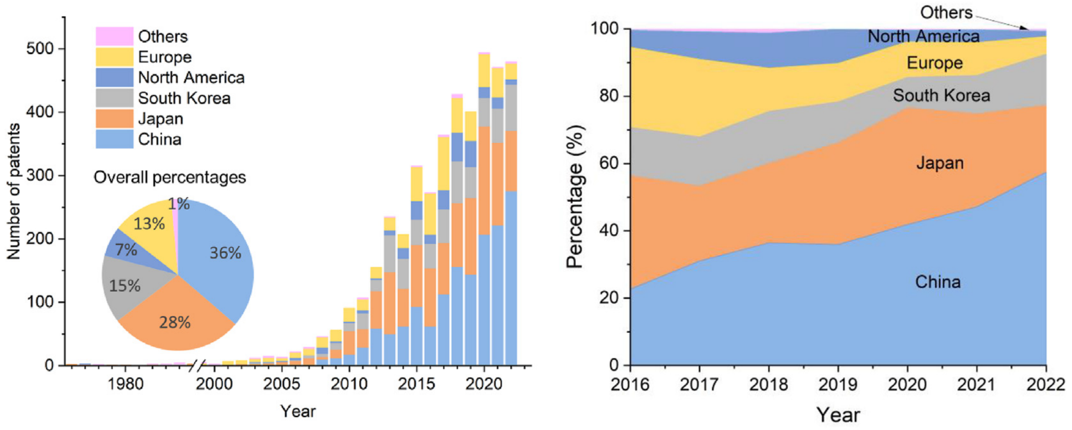
3.1.3. Topic analysis

Figs. 10 and 11 show the scientific papers and patents, respectively, categorised by topics including material, process, equipment and others. The categorisation of scientific papers and patents varies based on their respective significance in both datasets. The number of academic papers on hot stamping topics appears to either stabilise or decrease slightly in recent years. It is plausible to infer that the basic principles and methodologies of the technology are reaching a saturation point, and the fundamental scientific issues related to hot stamping have been largely understood. In contrast, the increasing number of patents signals ongoing innovation and the application of these scientific principles into new and improved technologies. The rising patent trend is indicative of a shift from basic research to application and optimisation, where the focus is on refining processes, enhancing materials, and developing more advanced equipment. When comparing different topics within the field, it can be inferred that certain areas are experiencing more rapid technological development. For example, the consistent emphasis on materials in both papers and patents points to a dynamic area of development in new material designs



a) b)

Fig. 7. Evolution of the number of scientific papers on hot stamping by region of the affiliations. The pie chart in (a) represents the overall percentages for all years. (a) Evolution of paper numbers by region (b) Trends in percentage of papers by region.



a) b)

Fig. 8. Evolution of the number of patents on hot stamping by region of the affiliations. (a) Evolution of patent numbers by region (b) Percentage of patents by region.

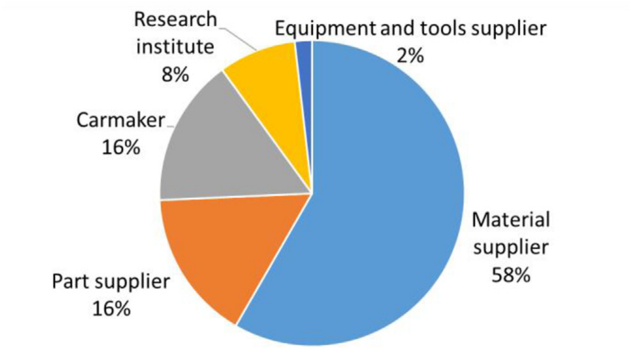
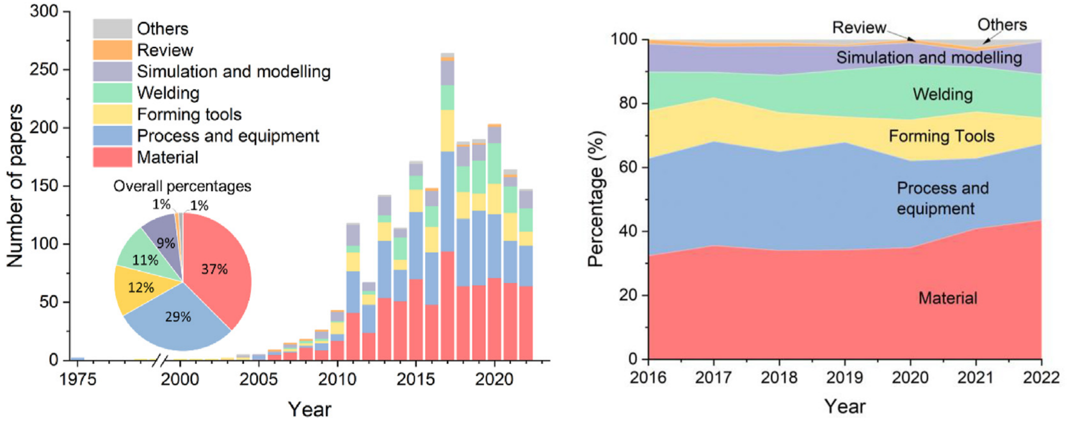


Fig. 9. Patents on hot stamping by type of applicants.

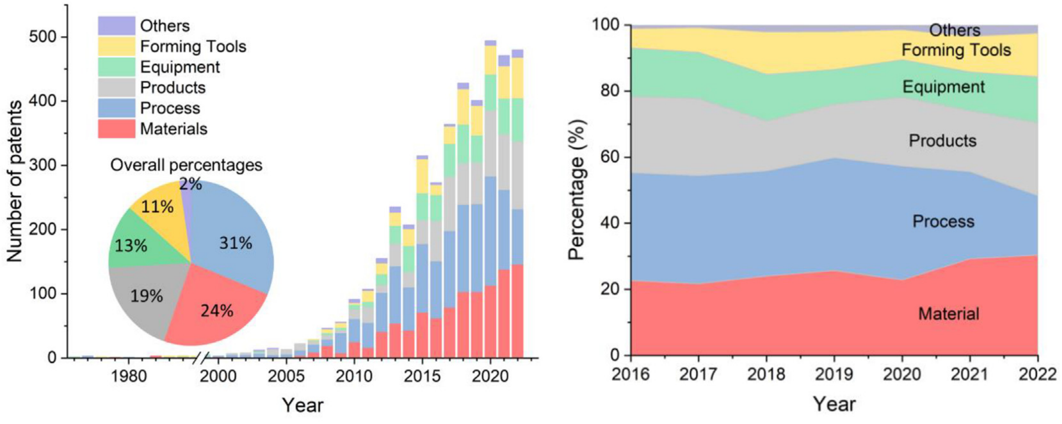
(e.g. MMn steels and high-strength Al alloys) or improvement in existing ones. This persistent research intensity underlines the critical role of material science as a driver of innovation in hot stamping technology. Process, equipment and tools also command a significant portion of patents, underscoring an industry push towards optimising the efficiency and capability of hot stamping machinery. The focus here is likely on making the process more cost-effective, precise and adaptable, which is crucial for keeping up with the evolving demands of manufacturing sectors that utilise hot stamping. Overall, the hot stamping field that is evolving from a phase of expansive research to one of focused application and commercialisation. The data suggests that while the academic interest in the fundamental aspects of hot stamping may have reached the peak, the industry is actively seeking to capitalise on these advancements, driving the technology towards wider industrial application and integration into the manufacturing landscape.

Based on the above data, it is evident that hot stamping is evolving into a mature and conventional technology. From the diverged evolution of scientific papers and patents, and the change of topics of these publications, one can see that pure academic interests is giving way to applicable studies. However, the classification of the topics in the analysis is broad, and any structural changes within these macro-topics are not captured here. By delving into the content of the publications and focusing on the main topics, recent trends in development can be better understood. These publications are reviewed and trends in various areas are summarised in the following section.



a) b)

Fig. 10. Evolution of the number of papers on hot stamping by topics. (a) Number of papers by topics (b) Percentage of papers by topics.



a) b)

Fig. 11. Evolution of the number of patents on hot stamping by topics. (a) Number of patents by topic (b) Percentage of patents by topics.

3.2. Recent trends in the development of hot stamping of boron steels

In expanding the application of hot stamping, the impact of fundamental parameters on the performance of hot stamping has been extensively investigated [38–43]. Key factors such as heating rate, austenitising temperature, soaking time, and cooling rate are critical in defining the mechanical and microstructural properties of hot-stamped steels, necessitating specific adjustments for different cases [38–40]. The thermomechanical properties (e.g. flow curves) and forming limit diagrams, affected by forming temperature and speed, have been studied to predict material flow and understand how to achieve the desired characteristics of the final hot-stamped product [41–43]. While these fundamental effects are general and not the primary focus of this paper, this section discusses the practical improvements in hot stamping derived from these fundamental effects, which is helpful as a guidance for further research.

3.2.1. Developments in steels and associated coatings

Recent studies on hot-stamping materials mainly focus on developing steels with higher strength. Beyond the conventional 22MnB5, steels like 27MnCrB5, 28MnB5, 30MnB5, 33MnCrB5, 34MnB5, 37MnB4, and 38MnB5 have also proven suitable for the hot stamping process. Due to their higher equivalent carbon contents brought by additional C, Mn and Cr, these steels typically offer greater strength than 22MnB5. In addition to increasing strength and hardness, Mn can lower the austenitisation temperature and Cr can improve corrosion resistance. Many of these higher-strength hot-stamping steels have been commercialised and are used in the automotive industry, including brands like Docol PHS 1800 by SSAB [28], BTR 2000 by Benteler [44], MBW-K 1900 by Thyssenkrupp, and Usibor 2000 by ArcelorMittal [14]. Table 1 lists the nominal chemical compositions and mechanical properties of some commercialised hot-stamping steels with higher strength. In addition, developers seek hot-stamping steels with greater ductility. For example, following simulated hot stamping, 20Mn2Cr steel achieved a UTS of 1513 MPa, a yield strength of 1190 MPa, and an elongation of 12 % [45]. Another hot-stamping steel was developed by adding Cr and Si to produce transformation-induced plasticity (TRIP) effect through a small fraction of retained austenite (RA) [46]. This RA-stabilised steel was reported to have a UTS of 1680 MPa and a total elongation of 9.2 % after die quenching; both properties are higher than that of the conventional 22MnB5.

Hot-stamping steels are susceptible to hydrogen embrittlement compared to other steels. The tetragonal structure and high dislocation density of martensite in hot-stamped steels mean that more H atoms can be trapped [51,52]. Hydrogen can be absorbed into the

Table 1
Mechanical properties of major commercialised hot-stamping steels with higher UTS than 22MnB5.

Commercial name	Nominal composition	Steelmaker	YS (MPa)	UTS (MPa)	Elongation (%)
USIBOR 2000 [14]	37MnB4	ArcelorMittal	≥1400	≥1800	5
MBW-K 1900 [15]	38MnB5	ThyssenKrupp	1200	1900	4
Docol PHS 1800 [16]	28MnB5	SSAB	1300	1800	6
Docol PHS 2000 [16]	37MnB4	SSAB	1380	2040	6
1800HPF [47]	–	POSCO	≥1100	1650	≥5
2000HPF [47]	–	POSCO	≥1200	1800	≥4
NSHS28CB [48]	28MnB5	Nippon Steel	–	~1500[a]	–
NSHS35CB [48]	35MnB5	Nippon Steel	–	~1750[a]	–
NSHS42CB [48]	42MnB5	Nippon Steel	–	~2000[a]	–
B1800HS [49]	30MnB5	Baosteel	1213	1830	5.5
AC1800 HS [50]	34MnB5	Ansteel	1232	1890	5.12

[a] Converted from hardness (HRC) after quenching.

steel during austenitising, production, painting, or in-service corrosion [53]. Hydrogen embrittlement cause catastrophic degradation of mechanical properties and may lead to hydrogen-induced delayed fracture once the intake of hydrogen exceeds a critical value which is very small for hot-stamped steels. It was found that a hydrogen concentration of 9 wppm led to more than 75 % reduction in UTS of hot-stamped 22MnB5 [53]. Besides meticulous control in the hot stamping process, microalloying is a primary method to mitigate hydrogen embrittlement. Improvements are achieved by adding elements such as Nb, Ti [54], V [55], Mo and Ta [56]. These additions increase the strength and impact energy through parent austenite grain refinement and reduce the risk of delayed fracture by trapping hydrogen [57]. Microalloyed hot-stamping steels have been commercialised; for example, PHS1500 IB, a Nb + V microalloyed hot-stamping steel developed by automobile company General Motors and Brazilian niobium provider CBMM, offers a better balance of strength and bendability compared to conventional 22MnB5, and has improved resistance to hydrogen embrittlement [58].

Coating is another important focus in the study of hot-stamping materials. Prolonged exposure to high-temperature atmospheres can lead to oxidation and decarburisation on the surface of the hot-stamped boron steel [59,60]. The scale that forms on the surface of the steel can also impair the heat transfer between the die and the blank, reducing productivity, as well as causing severer wear on the tools [61]. In addition, hot-stamping steels are also under the risk of corrosion in service like other automotive steels. Coatings are generally employed to solve these problems. Al-based coatings and Zn-based coatings are the two major categories applied although other types of coatings, such as varnish coatings, are also adopted in the hot stamping steels [8].

Al–Si coating, one of the most common coatings, has been used in BiW components for over 20 years due to barrier protection provided by the surface Al_2O_3 layer. The microstructure of the Al–Si coating consists of eutectic Al–Si along with a continuous layer of Al–Fe–Si intermetallic compounds. This alloy layer serves as a barrier to corrosion and formation of scale [62]. The formability of the Al–Si coating is inferior to that of the substrate and at lower temperatures, cracks tend to form in the Al–Si layer [63]. As a result, it is unsuitable for both cold forming and indirect hot forming.

Hot dip pure Zn coatings, or galvanised (GI) coatings, are also widely used on steel sheets. Compared to Al-based coating, Zn-based coatings offer better corrosion resistance due to the additional cathodic protection they provide. Zn-based coatings also have better formability and resistance to fracture at low temperature, and much lower abrasive tool wear [64]. However, Zn-based coatings are susceptible to liquid-metal-induced embrittlement (LMIE) at high temperatures and certain stress levels, limiting their use in hot stamping [65,66]. To avoid LMIE, an indirect hot stamping process has been developed to separate the deformation and heating processes to avoid embrittlement. Another solution is to use galvannealed (GA) coating, a type of Zn coating that undergoes additional heat treatment to form a Zn–Fe alloy layer on the surface of the substrate. Also known as Zn–Fe coating, GA coating has higher melting point than pure Zn, allowing for a broader processing window without triggering LMIE. However, GA coating has its limitations, such as the formation of ZnO during hot stamping, which can reduce weldability [67]. Table 2 presents a comparison of the major types of coatings for hot-stamping steels. It was estimated in 2017 that 76 % of the hot stamping steel in EU and Turkey were Al–Si coated, 18 % were uncoated, and only 6 % were Zn coated [68].

Due to the above various issues, researchers seek to develop coating-free steels with strong oxidation resistance. For example, collaborating with General Motors, Lu et al. [69] developed a coating-free steel with Cr and Si additions, which allow for greater hardenability and a stable oxide layer in the furnace for protection against oxidation and decarburisation. Known as coating-free press-hardening steel (CF-PHS), this type of steel can achieve a UTS of 1722 MPa and an elongation of 5.1 % [70]. Besides no coating cost, one of the major advantages of coating-free steels is that they can be laser-welded without the need for laser ablation or filler metal, and thus, reducing the cost and time associated with the joining process. Along with the aforementioned 1.7 GPa steel, another 1.2 GPa CF-PHS was also developed and a lab-scale tailor-welded door ring combining these two CF-PHSs was successfully produced by hot stamping and laser welding [71]. General Motors has successfully produced the coating-free steel by conventional processes and industrial applications are expected [69].

3.2.2. *Developments in processes*

Heating, forming, and quenching are the core procedures of a typical hot stamping cycle. After a workpiece is hot stamped, it undergoes post-processing such as trimming and punching, and sometimes welding to produce a finished component. Therefore, any development in these areas will benefit the hot stamping process.

During hot stamping, it is crucial to precisely control the austenitisation temperature and soaking time to achieve the desired properties, given their impact on the extent of austenitisation. Moreover, the mechanical properties and fracture behaviours of boron steels are influenced by the prior austenite grain size (PAGS), which is again determined by austenitising temperature and soaking time [20]. Therefore, an efficient heating system is of great significance. The roller hearth furnace is the most commonly used heating device for hot stamping, offering good flexibility and stable performance. It not only provides a homogeneous temperature but

Table 2
Comparison of main types of coatings for hot-stamping steels.

Type of coatings	Advantages	Disadvantages
Uncoated	• Low cost	• Oxidation • Decarburisation • No corrosion protection
Al–Si	• Oxidation protection • Barrier corrosion protection	• Not suitable for indirect hot stamping • No cathodic protection • Hard to be laser-welded
Zn (GI)	• Both barrier and cathodic corrosion protection • Compatible to conventional galvanising line in automotive industry • Applicable to indirect hot stamping	• Susceptible to LMIE • Narrow processing window in direct hot stamping
Zn (GA)	• Both barrier and cathodic corrosion protection • Applicable to indirect hot stamping • Less susceptible to LMIE than GI	• Formation of ZnO during hot stamping

can also be designed for tailored heating [72]. One drawback of the roller hearth furnace is that it must be long enough to complete the austenitisation process while conveying the workpieces. To address this issue, double-decker or multi-layer furnaces have been developed to reduce the space required for the furnace [73].

Another concern is that it takes 2–5 min to heat the blanks (i.e. low heating rates) to the hot forming temperature using roller hearth furnaces [73]. Therefore, many researchers and developers are exploring the potential of using conduction or induction heating for hot stamping. In addition to enhanced productivity, hot-stamped boron steel using conduction heating has shown smaller martensitic grain size along with improved strength and elongation [74]. However, unless special measures such as using unequal radiation shields are taken, conduction heating usually results in inhomogeneous temperature distribution [75]. If the shape of the blank is irregular, it is even harder to precisely control the temperature uniformity [76]. Induction heating is efficient due to the high power density it generates, and the induction-heated component was reported to have good performance in terms of microstructure and mechanical properties. However, maintaining a homogenous and constant temperature during heating is also challenging. Another drawback of induction heating is that the size of the blank is constrained by the shape of the induction coil [74]. Due to these limitations, furnace heating is still the most frequently used heating method in mass production.

The forming process is the core of a hot stamping line. Conventionally, parts are hot-formed using hydraulic press machines, but mechanical servo presses have also been introduced to reduce the energy and increase flexibility [77,78]. Other innovations focus on enhancing the productivity of the line. For example, Ges-Multistep, a hot stamping method proposed by the major hot stamping developer Gestamp, is a patented multi-step hot stamping technology designed for Zn-coated steels. The steel used in this method is a modified boron steel with elevated Mn content, allowing it to be formed at a lower temperature for further improving productivity [79]. During the forming process, the parts are transferred through a series of pressing stations consecutively, undergoing gradual cooling. This successive fashion allows for precise control over the geometry of the parts, resulting in better performance [80]. By integrating the transferring process and the forming process, this technology proves efficient for mass production and has been in use for producing BiW parts since 2019. Gestamp has also developed tempering methods for the Multistep process to achieve tailored properties. Alternatively, Balint et al. [81], Ota et al. [82] and Ganapathy et al. [83] have introduced an innovative forming method in which austenitised steel blanks are rapidly pre-cooled to a temperature slightly above the martensite start temperature (M_s) prior to stamping. This approach enhances productivity by reducing the cooling cycle duration and mitigating die wear through lower die temperatures, particularly during mass production.

Novel heat treatment methods have been introduced to improve the ductility and toughness of hot-stamped steels while maintaining their high strength. Among them, quenching and partitioning (Q&P) process stands out. Liu et al. [84] integrated the Q&P process into the hot stamping process for a slightly modified 22MnB5 which has higher contents of Mn (1.58 %) to enhance austenite stability and Si (0.81 %) to prevent carbide precipitation. The temperature profile of the Q&P-integrated hot stamping process and the microstructural change in the process are demonstrated in Fig. 12. The so-called HS-Q&P process has been proven feasible for the boron steel, with elongation significantly increasing to 14.8 % compared with 6.6 % for unpartitioned samples, though the UTS slightly dropped by 30–120 MPa and the yield strength decreased by 130–200 MPa. The microstructure of this modified steel after Q&P consists of lath martensite and RA [85]. In a recent study, a further modified HS-Q&P steel with even higher contents of Mn (2.32 %) and Si (1.63 %) achieved a yield strength of 1350 MPa and elongation of 14.24 % [86]. Despite its potential, the widespread commercialisation of HS-Q&P is constrained by challenges of executing an isothermal partitioning process in an industrial environment, and further research and development are required.

Blanking and trimming are integral part of the complete hot-stamping process. They are challenging because the hot-stamped steel exhibits a fully martensitic microstructure and has high hardness. During blanking and trimming, wear or failure of tools can occur, increasing the overall cost. To solve this problem, warm cutting and hot semi-cutting [89–91] as well as laser cutting [92] have been proposed. While laser cutting eliminates mechanical wear, its cycle time is much longer and thus the overall cost is increased. In fact, in a typical hot stamping production line of Al-coated 22MnB5, the cost of laser trimming attribute to 20 % of

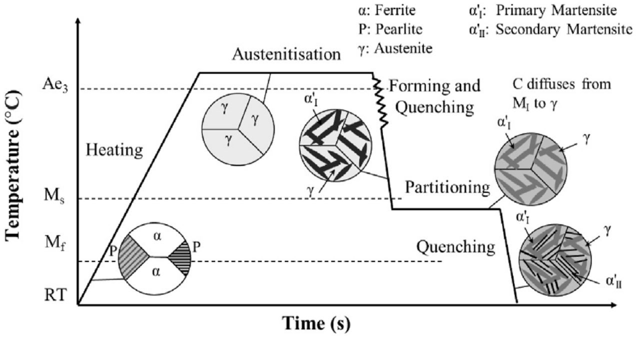


Fig. 12. Schematic of temperature profile of HS-Q&P stamping process and associated microstructural changes (based on [85,87,88]).

the total costs, which is only behind the material cost and is twice the cost of the hot stamping process itself [93]. In contrast, in the warm cutting process, the cycle time is reduced by integrating cutting and forming in one step. However, the die for warm cutting can be hard to design for the purpose of convenient removal of the scraps, and sometimes an extra laser cutting process is performed to remove the scraps. Hot semi-cutting is developed to overcome this problem [94]. Instead of completely cutting off the scraps, the hot semi-cutting only reduces the thickness at the trim lines during forming and the scraps are then removed by an extra mechanical cold cutting in which the cutting force has been largely reduced compared with a complete cold cutting. Hot semi-cutting is sensitive to tool clearance and temperature [95,96].

Assembling the hot-stamped parts with other components presents another major issue in applying hot stamping to car bodies. Welding is the most important method for joining components in the automotive industry. Among all welding methods, resistance spot welding (RSW) and laser beam welding are two primary techniques for the mass production of automobiles due to their high efficiency, flexibility and capability of automation. The RSW weldability of the hot stamped steels with different coatings is mainly affected by electrical resistance [97]. Compared with uncoated steels, Al–Si coating can improve the weldability of resistance spot welding by producing larger nugget [98]. The suitable welding current range of Al–Si coated 22MnB5 is wider than that of Zn-coated hot stamped steels.

Laser beam welding is also used to produce tailor-welded blanks (TWB). However, the existence of Al–Si coating layer reduces the mechanical properties of the welded joints due to the formation of Fe–Al intermetallic phases and the increased fraction of ferrite caused by high Al content [99,100]. To solve this problem, an approach known as laser ablation was developed by ArcelorMittal, and it has been successfully applied to produce the hot-stamped door ring in 2014 Acura MDX and 2019 RDX [101,102]. In addition to laser ablation, Lin et al. [103] found that a simple de-coating process using a snap-off blade knife before laser welding and hot stamping can also produce welded joints with higher strength and ductility by eliminating δ-ferrite formed due to high Al content. Other measures, such as inserting Ni interlayer [104], in-situ ablation by introducing a colloidal graphite coating [105], in-situ alloying by electro-spark depositing [106], and defocusing the laser beam [107], have been proposed to improve the mechanical properties of the laser welded joints. GA-coated steel has a good laser weldability, but the process window is narrow due to multiple targets of avoiding liquid-metal-induced embrittlement and oxidation [67]. Gestamp is applying Zn-coated boron steels in its Ges-Multistep procedure to produce TWB door rings and it is reported that no ablation is needed before laser welding [79,108].

3.2.3. Developments in tools

During hot stamping, steel blanks are usually formed in a die to achieve a fully martensitic microstructure. Generally, the cooling system is integrated into the tool through cooling channels. The key parameters for the cooling system are the temperature homogeneity in the blank and the required cooling rate it can provide. According to a study in 2013, the cooling time typically accounts for 30 % of the overall hot stamping process cycle time, making it the most time-consuming stage in the hot stamping cycle [109]. Therefore, many studies have been carried out on optimising the cooling channel designs to achieve higher cooling rates and save the energy. Hoffmann et al. [110] proposed a methodology using Evolutionary Algorithm coupled with thermal-mechanical analysis to optimise the design of cooling channels. In order to better describe the temperature distribution in the cooling ducts, Lin et al. [111] introduced a thermal-fluid-mechanical coupled approach based on MpCCI, a software developed by Fraunhofer Institute that is capable of coupling the results of thermal-mechanical analysis by Abaqus with thermal-fluid analysis by Fluent. Shape factor models [112], energy balance models [113] and multi-objective swarm optimisation algorithm with Monte Carlo simulation [114] have also been proposed to optimise the design of the cooling system. According to the simulated results of these models, it has been found that reducing the diameter and increasing the number of cooling ducts are beneficial for cooling performance. The relative positions of the channels to the surface of the tool are also key parameters [115].

The complexity of cooling system design poses challenges for tool manufacturing. A conformal cooling channel design can reduce cooling time by 28 % compared to traditional designs [115], and further simulation has shown the potential to cut cooling time by 55 % [116]. However, manufacturing such a system using conventional drilling or casting methods can be difficult or expensive. Among all manufacturing methods, additive manufacturing emerges as a promising solution for producing dies with conformal cooling channels [117]. Moreover, with the aid of additive manufacturing, lattice structures can be introduced to enhance the cooling performance of the tools [118].

Die wear is another major issue during the forming process. Recently, intensive studies have been conducted on the tribological behaviours of hot stamping materials, and various methods and equipment have been proposed to measure the friction coefficient at high temperatures. Yanagida and Azushima [119] studied the friction between the die and the blank using a specially designed simulation testing machine. They found that lubricant had a considerable effect in reducing die wear during hot stamping. For Al–Si coated blanks, factors like temperature, contact pressure and the morphology of the coating also influence the tribological behaviour [120–122]. Effective lubrication at high temperatures is crucial for the hot stamping process. To reduce the friction between the tool and the sheet metal, Torres et al. [123] introduced self-lubricating coatings, which are prepared by laser cladding on the surface of material. Various methods and instrument have been proposed for measuring friction and selecting proper lubricants. In a recent study, a digitally enhanced lubrication evaluation system was established [124], demonstrating the promising future of more data-centric methods in the industry.

3.3. Summary

A wide range of perspectives of hot stamping have been studied and major breakthroughs have been made in recent years. Evolving from a lab-scale technique to a mass-production method, hot stamping has gradually become a primary lightweight solution for manufacturing safety-critical components in the body-in-white. As the major challenges in the commercialisation of the technology have been addressed to a certain extent, researchers are now interested in more refined and practical topics such as saving energy, reducing costs, enhancing productivity, and improving the overall performance of the final components. This includes advanced developments in material design, process equipment and tooling techniques as reviewed above. However, a significant amount of work remains to be done in the following fields.

1) **Tailored designs:** Tailor-Welded Blanks (TWB) and Tailor-Rolled Blanks (TRB) technologies have been applied in automotive industry. However, theses tailored blank technologies increase production costs [125]. Alternative approaches such as tailored heating and tailored tool tempering have been proposed to achieve locally varying properties [125]. Although these methods have been reported to successfully produce graded

materials, their ability to optimise the performance of hot-stamped components has not been fully exploited.

2) **Cost reduction and productivity enhancement:** Despite its increasing applications, the hot stamping process is still not a default option for economy cars because of its relatively high cost and long cycle time compared to cold stamping. From blanking to post-processing, and from materials to equipment, the hot stamping process can be further optimised to meet the growing demands for lightweighting. There are still a lot of works to do with regard to aspects such as heating, cooling and cutting devices and methods.
3) **Advanced characterisation and testing methods:** Testing the microstructural evolution, mechanical properties, forming limit, tribological behaviours and corrosive properties of the material under hot stamping condition is more complex than in standard situations. Physical simulators, such as Gleeble system, are used by researchers [126,127], and specially designed methods need to be developed to facilitate the measurement process.
4) **Modelling and simulation:** Hot stamping is a dynamic process involving high temperatures, high strain rates, and complex microstructural changes. Computer-aided simulation and modelling have been extensively used to predict and analyse behaviours such as plastic flow, damage, hydrogen diffusion, and heat transfer in materials during hot stamping. Recently, more studies have adopted machine learning [128] and cloud-based finite element analysis (FEA) approaches [129] to predict these behaviours.

4. Beyond boron steel: expand hot stamping to more materials

As the material use in passenger cars continues to evolve, the application of hot stamping is likely to broaden if it can be effectively applied across a variety of materials in addition to boron steels. Due to the high cost of lightweight materials like high-strength aluminium alloys, current material usage in BiWs of passenger cars is still largely confined to steels. As the net-zero emission targets are becoming stricter, the current measures of lightweighting combined with improving technologies of internal combustion engines will not be sufficient anymore. Recent developments of BEVs have further amplified the need for enhanced lightweighting approaches [130]. Table 3 presents a comparison of current and prospective material use in key vehicle components, sourced from a 2019 study by Centre for Automotive Research (CAR) [131]. According to its projection, hot-stamping steels exhibit considerable potential for applications in roof structures, rockers, and bumper structures. However, it is important to note that hot-stamping steels are not the sole solution to all the lightweighting challenges. Along with them, third generation advanced high-strength steels (Gen-3) and high-strength Al alloys are also emerging as promising materials for future lightweighting purposes. Hence, the future potentials for extending the current hot stamping process to a wider range of materials will be discussed.

A major future trend is the diversification of lightweight materials in BiW components. The CAR study suggests that usage of mild and high-strength steels will decline, supplanted by ultra-high-strength steels and high-strength aluminium alloys [131]. The projection, demonstrated in Fig. 13a, shows that aluminium alloys would make up 26 % of future BiW components in 2040. This projection assumes that aluminium cost in 2035 would still be 80 % higher than UHSS. Yet, if cost-effective production technologies emerge, especially for high-strength aluminium, its usage could surge. One promising hot stamping technology to manufacture high-strength aluminium is Hot Form Quench (HFQ®) [132], which will be discussed in Section 4.1.

Another emerging trend is the application of different steel grades. According to CAR's projection [131], the future share of Gen-3 such as Q&P steels and MMn steels (Fig. 13b) will gradually increase at the expense of lower strength steels. The advent of MMn steels offers prospects for further processing cost reduction and enhanced ductility of components, which is a promising material to replace conventional boron steels. With appropriate modifications, hot stamping technologies hold the potential for application in MMn steels, with further details provided in Section 4.2.

4.1. High-strength aluminium alloys and HFQ

Compared to mild steels, high-strength Al alloys can meet safety standard while achieving a significant 40–60 % weight reduction [133]. Therefore, substituting steel with Al alloys is a promising strategy for reducing weight. In fact, the Al usage in the automotive industry has been growing consecutively for years. In the North America market, the Al usage per vehicle increased from 154 kg in 2010 to 208 kg in 2020, and is expected to reach 258 kg in 2030, mainly because of its increasing use in BiW, closures, chassis [134]. The growing prevalence of BEVs is likely to offer even greater opportunities for Al alloys. However, the usage of Al alloys is restricted by their high processing costs and limited capability to be processed.

The rise of BEVs has led to increased use of Al die-cast parts, notably with Tesla's introduction of the so-called Giga Press high-pressure die casting for the rear body piece in its Model Y. In 2020, Al castings account for more than 65 % of the total Al parts in the cars [134]; sheet formed parts, on the other hand, share 23.3 % of the total Al usage, but is expected to be a main driving force for the growth of Al [135]. The weight of sheet formed Al parts per vehicle is projected to increase about 24 % from 2020 to 2026. However, currently sheet formed Al are mainly used for bonnets which have simple shape to stamp at room temperature [133]. Al alloys, especially high-strength Al alloys such as 6xx and 7xx series, are rarely cold stamped and used in safety-critical parts (e.g. B-pillars) and parts with complex geometries (e.g. panels), due to

Table 3
Current and future material use for key vehicle components.

Component	Current	Future
B-pillar	DP, hot-stamping steel	Hot-stamping steel, Gen-3, CFRPs
Bumper structure	DP, hot-stamping steel	Hot-stamping steel, Gen-3, 6xxx/7xxx Al
Closures	Mild steel, BH, 6xxx Al	6xxx Al, Mg, polymer composite
Front crash structure	BH, HSLA	High-strength steels, 6xxx/7xxx Al
Rockers	HSLA	Hot-stamping steel, Gen-3
Roof header	HSLA	Hot-stamping steel, Gen-3
Roof rails	DP, hot-stamping steel	Hot-stamping steel, Gen-3, CFRPs

*Note: DP - Dual-phase steel, BH - bake-hardening steel, HSLA - high-strength low-alloy steel, Gen-3 - third generation advanced high-strength steel, CFRPs - carbon fibre reinforced polymer composite.

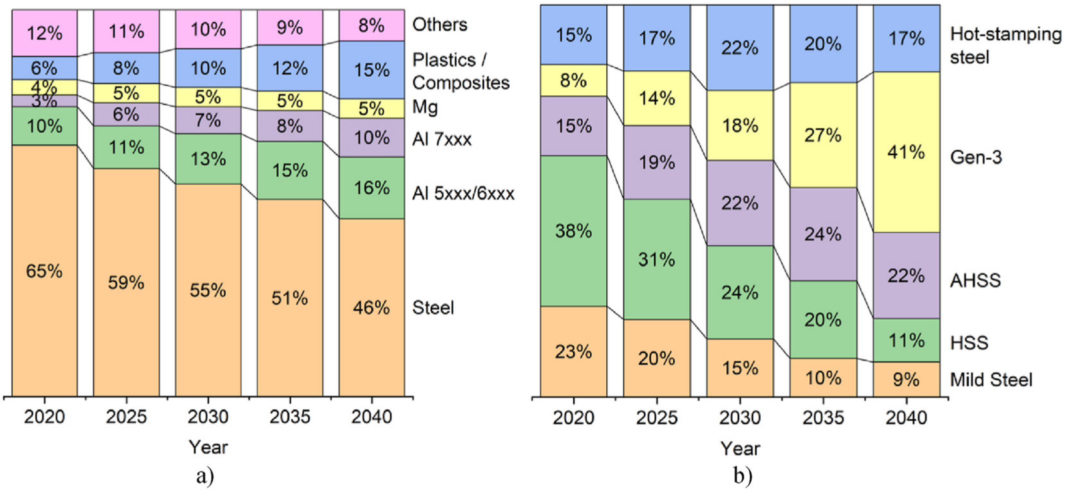


Fig. 13. Evolution of material percentage of average vehicle structure (BiW and closures) by curb weight per vehicle, AHSS for 1st and 2nd generation AHSS, Gen-3 for 3rd generation AHSS, data from Ref. [131]. (a) Usage of materials (b) Usage of steels.

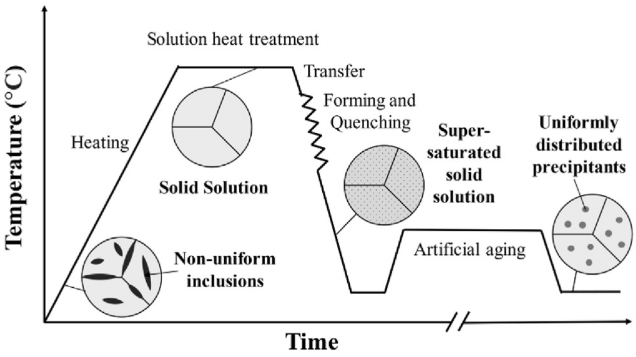


Fig. 14. Schematic of a typical HFQ® process for AA6082 (Based on [137,138]).

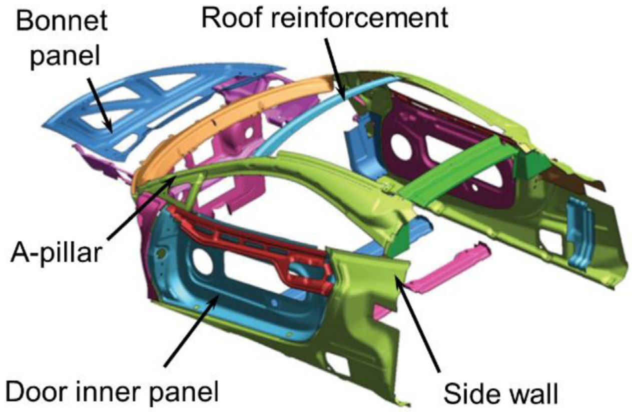


Fig. 15. Potential applications of HFQ, different colours distinguish individual parts, modified from Ref. [147].

their low formability at the room temperature and springback after forming [11].

However, the recently developed HFQ® technology appears to overcome the above drawbacks for the wider application of high-strength Al alloys. The HFQ® process is illustrated in Fig. 14 using AA6082 as an example. In the process, the Al blank is heated, solution heat treated (SHT) and then formed at an elevated temperature which significantly improves the formability of the Al sheet. Subsequently, the formed part undergoes in-die quenching to obtain super saturated solid solution (SSSS) at room temperature, which can be artificially aged to achieve an enhanced strength due to precipitation hardening. The HFQ® process takes advantage of the fact that Al alloys become dramatically softer and ductile at elevated temperatures. For example, the yield strength of a 7075-T4 Al sheet decreases from 396.8 MPa at room temperature to 78.7 MPa at 440 °C. Simultaneously, its total elongation increases from 15 % at room temperature to 26.1 % at 440 °C [136]. The enhanced ductility and decreased strength enable high-strength Al alloys to be formed to a complex shape at a high temperature with smaller force.

The HFQ® process is able to produce complex components from high-strength Al alloys with remarkably reduced springback [139]. Typically, this method can be applied to Al alloys that can be precipitation-hardened, such as 6xx and 7xx. Moreover, it can also find utility in other Al alloys such as 5xx [140], and even in Mg alloys [141]. A life-cycle analysis showed that the adoption of HFQ® could bring a net positive benefit to the environment [142]. Fig. 15 demonstrates the potential applications of HFQ® technology in the car body. Up until now, the HFQ® technology has been successfully applied in high-end cars, including parts for luxury carmaker Aston Martin, such as door inner panels, side wall panels and A-pillars [143]. HFQ® technology also finds its potential application in the battery trays for BEVs. This novel technology eliminates the need to weld multiple parts together to create a single, complex component. However, the wider applications of the HFQ® process is still hindered by its high cost, primarily stemming from the expense of raw Al material itself [144]. Apart from the high cost of the material, another bottleneck of the HFQ® process is the long cycle time required to produce high-strength components. Conventionally, the Al sheets are heated in a furnace to undergo SHT. However, the heating rate of the SHT furnace is slow, not only resulting in higher production cost, but also leading to insufficient heat treatment to achieve the desired strength. Another significant factor reducing the productivity of HFQ® is the extended duration of artificial ageing. Efforts have been made recently to enhance the productivity by optimising the SHT and ageing conditions [145] or introducing novel heating methods [146].

The study of HFQ® is still ongoing and a broad range of research topics are being explored. While the effects of primary parameters

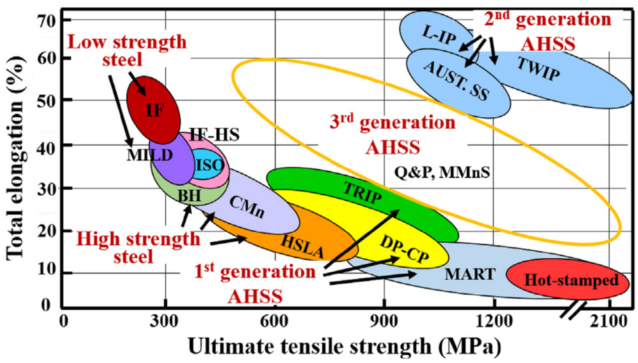


Fig. 16. Comparison between mechanical properties of various types of industrially manufactured steel grades, modified from Ref. [10]. IF: interstitial-free steels; MILD: mild steels; IF-HS: interstitial-free high-strength steels; BH: bake hardening steels; CMn: carbon-manganese steels; HSLA: high-strength low-alloy steels; TRIP: transformation induced plasticity steels; DP-CP: dual phase and complex phase steels; MART: martensitic steels; Hot-stamped: hot-stamping steels; Q&P: quenching and partitioning steels; MMnS: medium-Mn steels; AUST. SS: austenitic stainless steel; L-IP: Light steels with induced plasticity; TWIP: Twinning-induced plasticity steels.

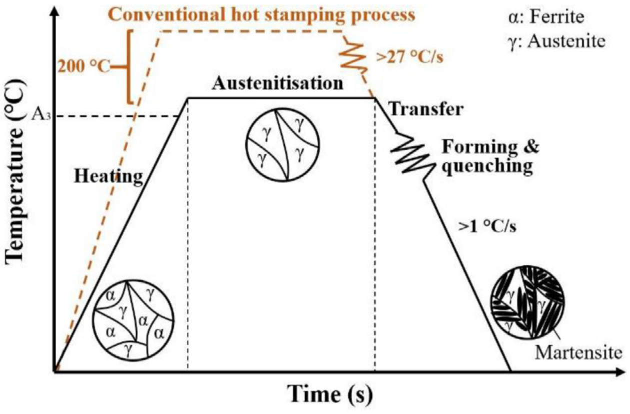


Fig. 17. Comparison of conventional hot stamping and low-temperature hot stamping technique [10].

and underlying mechanisms have been comprehensively understood, there are still many detailed technical aspects that warrant in-depth exploration. Recent efforts have been concentrated on various aspects including process optimisation [148], material characterisation [149], thermal behaviours [150], formability testing [151], coating and lubricants [152], welding [153,154], and modelling [155], among others.

4.2. Medium-Mn steels and low-temperature hot stamping

With the growing need for lightweight solutions in car manufacturing, third generation AHSS have been introduced. Fig. 16 shows different grades of steels in the space of strength and elongation. Based on Fig. 16, 3rd Gen AHSS design not only adheres to the rigorous demands of the automotive sector, such as exceptional mechanical characteristics (encompassing both strength and ductility) at a reduced gauge while upholding superior safety standards compared to first generation AHSS. Moreover, they sidestep the high expenses tied to incorporating substantial volumes of alloying components, and the related issues like the diminished weldability seen in second generation AHSS [156]. One notable type among these steels is MMn steels, characterised by compositions of roughly 3–12 wt% Mn, 0.05–0.6 wt% C, 0–3 wt% Si, and 0–6 wt% Al [157–159].

Recently, MMn steels have garnered significant attention in research circles, especially regarding their feasibility for hot stamping, as depicted in Fig. 17. A notable benefit of employing these steels, illustrated in Fig. 17, is that their Ae_1 and Ae_3 values are roughly 100–200 °C lower than those of traditional hot-stamping boron steels, attributable to the alloying constituents (namely C and Mn). The reduced heating and subsequent forming temperatures in hot stamping can be readily harnessed in MMn steels, paving the way for enhanced cost-saving, productivity and throughput, while preserving the stellar strengths derived from thorough austenitisation and martensitic transformation. Furthermore, the inherent hardenability and superior end mechanical characteristics of MMn steels underscore their appeal. The term “hot stamping” is typically associated with scenarios involving a total transformation to austenite during the heating phase, facilitating the emergence of an entirely martensitic grain structure upon adequate quick cooling post-forming. Consequently, the concept of “low-temperature hot stamping” (LTHS) has been introduced to describe the hot stamping techniques in MMn steels where the material achieves full austenitisation, albeit executed at temperatures lesser than those typical for conventional hot stamping of boron steels [9,10].

Table 4 showcases various process conditions and the resulting mechanical properties of low-temperature hot stamped MMn steels with varied chemical compositions. Chang et al. [9] delved into the application of LTHS on cold-rolled-annealed MMn (5Mn) steels. Their findings indicate that, after undergoing austenitisation at approximately 850 °C, soaking for 5 min, and quenching at a rate exceeding 10 $°C\ s^{-1}$, the material exhibited commendable mechanical properties. Specifically, the 0.2 % offset yield stress (YS) registered near 1220 MPa, the UTS was close to 1418 MPa, and a total elongation (TE) of 11.8 % was observed. Such conditions are compatible with conventional hot stamping production setups. In a separate study, Wang et al. [160] proposed that an austenitising temperature of 800 °C suffices for the thorough austenitisation of 5Mn steel, while yielding minimal oxidation and decarburisation. The steel processed at this low temperature exhibited a refined grain structure and achieved a UTS of 1500 MPa alongside a TE of 11 %. Meanwhile, Tong et al. [161] probed the influence of thermal treatments on the phase evolution of low-temperature hot-stamped MMn steel, asserting that comprehensive austenitisation necessitates heating between 740 and 800 °C and isothermal retention for 1–2 min, thereby offering economic and efficiency benefits. Nonetheless, the realm of MMn steel hot stamping remains relatively unexplored, signifying considerable gaps in foundational knowledge pertinent to this technological advancement.

Table 4
Tensile properties of some low-temperature hot stamped MMn steels.

Ref.	Chemical composition (wt%)	Initial state	Austenitisation condition	YS (MPa)	UTS (MPa)	TE (%)
[9]	0.14C, 5Mn	Cold-rolled-annealed	850 °C, 5 min	1220	1418	11.8
[160]	0.14C, 5Mn	Cold-rolled-annealed	800 °C, 5 min	1050	1520	10–11.3
[161]	0.1C, 8Mn	Cold-rolled	780 °C, 1 min	1300	1750	9.3

5. Conclusions

From the review and data analysis focusing on the developments and applications of hot stamping, an overall depiction of hot stamping technology has been presented in this paper. With regard to the current status and future trends of the development of hot stamping, several conclusions are drawn:

- The time-series analysis underscores a notable surge in hot stamping's industrial use, chiefly driven by the quest for lightweighting. While academic focus seems to have plateaued recently due to the comprehensive understanding of fundamental mechanisms, the innovation and application in industry show a continuous growth.
- The geographical and categorical analysis of contributors to hot stamping reveals a fully-fledged global industrial chain. China's dual role as both a burgeoning market and a development leader in hot stamping technology is unprecedented. This suggests a geographical shift in the epicentre of hot stamping innovation, with implications for global market strategies and research collaborations.
- A closer look at the topics covered in recent literature indicates a strategic pivot towards the downstream segment of the industry. This moving away from foundational methodological changes towards refinement in specific applications points to an industry striving for incremental innovation and process optimisation, rather than broad, sweeping technological overhauls.
- Although there have been improvements in material design, process equipment, and tooling techniques aimed at cost reduction, enhanced productivity, and customised design solutions, research in these areas remains either limited or inadequately developed for broad application across the industry. This gap suggests a crucial opportunity for further in-depth studies to bridge the division between current capabilities and their full industrial potential.
- The potential application of hot stamping in materials like high-strength aluminium alloys and medium-Mn steels, particularly in passenger vehicles, opens new avenues. The growing academic interest juxtaposed with the lag in commercialisation indicates a gap that could be a hotspot for innovation and market expansion.

Author contributions

Jiaqi Li: Writing − original draft, Visualization, Investigation. Chenpeng Tong: Writing − review & editing, Investigation. Ruiqiang Zhang: Writing − review & editing. ZHUSHENG SHI: Writing − review & editing, Supervision, Conceptualization. Jianguo Lin: Writing − review & editing, Funding acquisition, Conceptualization

Conflicts of interest

The authors declare that there is no conflicts of interest.

Acknowledgements

Financial support from Engineering and Physical Sciences Research Council (EPSRC) [Grant number: EP/R001715/1] on “Lightform: Embedding Materials Engineering in Manufacturing with Light Alloys” is gratefully acknowledged. Jiaqi Li also appreciates the financial assistance from China Scholarship Council [Grant number: 202008410205].

References

[1] Net Zero Strategy: Build Back Greener, Department for Energy Security and Net Zero, UK, 2021.
[2] Net Zero by 2050: A Roadmap for the Global Energy Sector, International Energy Agency, 2021.
[3] IEA, Global Energy-Related CO2 Emissions by Sector, IEA, Paris, 2021.
[4] EPA, Inventory of U.S, Greenhouse Gas Emissions and Sinks 1990-2019, U.S. Environmental Protection Agency, 2021.
[5] E.I.S. Department for Business, UK, UK Greenhouse Gas Emissions, Final Figures, National Statistics, Department for Business, Energy & Industrial Strategy, UK, 2019, 2021.
[6] National Research Council, Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles, The National Academies Press, Washington, DC, 2015.
[7] T. Taylor, A. Clough, Critical review of automotive hot-stamped sheet steel from an industrial perspective, Mater. Sci. Technol. 34 (7) (2018) 809−861.
[8] E. Billur, Hot Stamping of Ultra High-Strength Steels from a Technological and Business Perspective, SpringerLink (Online service), 2019.
[9] Y. Chang, C. Wang, K. Zhao, H. Dong, J. Yan, An introduction to medium-Mn steel: metallurgy, mechanical properties and warm stamping process, Mater. Des. 94 (2016) 424−432.
[10] C. Tong, Q. Rong, V.A. Yardley, X. Li, J. Luo, G. Zhu, Z. Shi, New developments and future trends in low-temperature hot stamping technologies: a review, Metals 10 (12) (2020) 1652.
[11] K. Zheng, D.J. Politis, L. Wang, J. Lin, A review on forming techniques for manufacturing lightweight complex-shaped aluminium panel components, Int. J. Lightweight Mater. Manuf. 1 (2) (2018) 55−80.
[12] M. Tisza, I. Czinege, Comparative study of the application of steels and aluminium in lightweight production of automotive parts, Int. J. Lightweight Mater. Manuf. 1 (4) (2018) 229−238.
[13] M. Naderi, W.G. Bleck, Martensitic transformation during simultaneous high temperature forming and cooling experiments, Steel Res. Int. 78 (12) (2007) 914−920.
[14] ArcelorMittal, Steels for Hot Stamping - Usibor and Ductibor. https://automotive.arcelormittal.com/products/flat/PHS/usibor_ductibor, 2020. (Accessed 20 September 2023).
[15] ThyssenKrupp Steel, MBW Product Information for Manganese-Boron Steels for Hot Forming, 2021. https://www.thyssenkrupp-steel.com/media/content_1/publikationen/produktinformationen/mbw/thyssenkrupp_mbw_product_information_steel_en.pdf. (Accessed 20 September 2023).
[16] SSAB, Docol® PHS 1500 - Hardenable boron steel for the automotive industry. https://www.ssab.com/products/brands/docol/products/docol-phs-1500. (Accessed 20 September 2023).
[17] H. Karbasian, A.E. Tekkaya, A review on hot stamping, J. Mater. Process. Technol. 210 (15) (2010) 2103−2118.
[18] T. Kurz, G. Luckeneder, T. Manzenreiter, H. Schwinghammer, A. Sommer, Zinc Coated Press-Hardening Steel-Challenges and Solutions, SAE Technical Paper, 2015.
[19] L. Kong, Y. Peng, In situ observation on microstructure evolution of 22MnB5 in hot stamping process, Metall. Res. Technol. 116 (2) (2019).
[20] L. Golem, L. Cho, J.G. Speer, K.O. Findley, Influence of austenitizing parameters on microstructure and mechanical properties of Al-Si coated press hardened steel, Mater. Des. 172 (2019) 12.
[21] M. Nikravesh, M. Naderi, G.H. Akbari, W. Bleck, Phase transformations in a simulated hot stamping process of the boron bearing steel, Mater. Des. 84 (2015) 18−24.
[22] M.C. Somani, L.P. Karjalainen, M. Eriksson, M. Oldenburg, Dimensional changes and microstructural evolution in a B-bearing steel in the simulated forming and quenching process, ISIJ Int. 41 (4) (2001) 361−367.
[23] C.-E. Ridderstrale, Procedure for Preparing a Part of Hardened Steel, Plannja Ab, Sweden, 1973.
[24] Baosteel, Tailored Blanks - History, 2017. https://www.tailored-blanks.com/en/history. (Accessed 20 September 2023).
[25] ArcelorMittal, ArcelorMittal Unveils World's First Inner and Outer Door Ring System, 2018. https://automotive.arcelormittal.com/news_and_stories/news/2018AcuraRDXinnerouterdoorring. (Accessed 20 September 2023).
[26] N. Gokhale, Multi-part Integration Concepts for Innovative BEV Body Architecture, American Iron and Steel Institute, 2023. Great Designs in Steel 2023.
[27] D. Bartolomucci, EV Structure - Lightweight Combo Made of OLPB Door Ring & Wave Rocker, Gestamp, 2023. Great Designs in Steel 2023.
[28] ArcelorMittal, Formed for Safety, 2023. https://germany.arcelormittal.com/icc/arceloren/broker.jsp?uMen=022609c4-5f00-be31-3d5b-74357d7b2f25&uCon=2e2609c4-5f00-be31-3d5b-74357d7b2f25&uTem=aaaaaaaa-aaaa-aaaa-aaaa-000000000011. (Accessed 20 September 2023).
[29] J. Bakewell, Hot Stamping Hits Heights, 2016. https://www.automotivemanufacturingsolutions.com/joining/hot-stamping-hits-heights/35144.article. (Accessed 20 September 2023).
[30] H. Linberg, Advanced High Strength Steel Technologies in the 2016 Volvo XC90, Great Designs in Steel 2016, American Iron and Steel Institute, 2016.
[31] J. Bakewell, Warming to Hot Stamping, Automotive Manufacturing Solutions, Ultima Media, 2016, pp. 52−53.

[32] P. Hu, L. Ying, B. He, Hot Stamping Advanced Manufacturing Technology of Lightweight Car Body, Springer, 2017.

[33] Roland Berger, Automotive Metal Components for Car Bodies and Chassis Global Market Study, Roland Berger, 2017.

[34] China Society of Automotive Engineers, Annual Evaluation of Technology Roadmap for Energy Saving and New Energy Vehicle 2019, China Machine Press, Beijing, 2020.

[35] Pulse News, Korea's Steel, Wire Industries Focus on EV-Related Businesses, 2023. https://pulsenews.co.kr/view.php?sc=30800028&year=2023&no=316916. (Accessed 20 September 2023).

[36] G. Tandon, Integrated Battery Occupant Protection Body-In-White Concept Using Tailored Blanks, Great Design in Steel 2021, American Iron and Steel Institute, 2021.

[37] K. Eldridge, A Catalog of Design Solutions for BEV Battery Enclosures, Great Designs in Steel 2023, American Iron and Steel Institute, 2023.

[38] Y.J. Jeon, M.J. Song, H.K. Kim, B.S. Cha, Effect of hot-stamping process conditions on the changes in material strength, Int. J. Automot. Technol. 16 (4) (2015) 619–627.

[39] B. Abdulhay, B. Bourouga, C. Dessain, Experimental and theoretical study of thermal aspects of the hot stamping process, Appl. Therm. Eng. 31 (5) (2011) 674–685.

[40] N. Li, J. Lin, D.S. Balint, T.A. Dean, Experimental characterisation of the effects of thermal conditions on austenite formation for hot stamping of boron steel, J. Mater. Process. Technol. 231 (2016) 254–264.

[41] M. Abspoel, B.M. Neelis, P. van Liempt, Constitutive behaviour under hot stamping conditions, J. Mater. Process. Technol. 228 (2016) 34–42.

[42] A. Merklein, J. Lechler, Investigation of the thermo-mechanical properties of hot stamping steels, J. Mater. Process. Technol. 177 (1–3) (2006) 452–455.

[43] A. Turetta, S. Bruschi, A. Ghiotti, Investigation of 22MnB5 formability in hot stamping operations, J. Mater. Process. Technol. 177 (1–3) (2006) 396–400.

[44] P. Delle, F. Schaefers, Next Generation Steels for Hot and Cold Stamping in BIW, Great Designs in Steel 2019, American Iron and Steel Institute, 2019.

[45] F. Huang, Q. Chen, H. Ding, Y. Wang, X. Mou, J. Chen, Automotive steel with a high product of strength and elongation used for cold and hot forming simultaneously, Materials 14 (5) (2021) 1121.

[46] X. Wei, Z. Chai, Q. Lu, J. Hu, Z. Liu, Q. Lai, J. Wang, W. Xu, Cr-alloyed novel press-hardening steel with superior combination of strength and ductility, Mater. Sci. Eng., A 819 (2021).

[47] POSCO, POSCO Products - Automotive Steel, 2023. https://product.posco.com:4451/homepage/product/eng/jsp/support/s91c5000200b.jsp. (Accessed 20 September 2023).

[48] Nippon Steel, Special Steel Sheets and Coils, 2020. https://www.nipponsteel.com/product/catalog_download/pdf/U006en.pdf. (Accessed 20 September 2023).

[49] Baosteel, Baosteel Hot Stamping Steel, 2018. http://esales.baosteel.com/portal/download/manual/PHS.pdf. (Accessed 20 September 2023).

[50] W. Liang, B. Feng, G. Zhu, Y. Kang, L. Lin, R. Liu, Laser welding properties of 1800 MPa press hardening steel and low-alloy high-strength steel CR340LA, Chin. J. Eng. 42 (6) (2020) 755.

[51] M. Okayasu, L. Yang, Influence of microstructure on the mechanical properties and hydrogen embrittlement characteristics of 1800MPa grade hot-stamped 22MnB5 steel, J. Mater. Sci. 54 (6) (2019) 5061–5073.

[52] Z. Wang, Q. Lu, Z.H. Cao, H. Chen, M.X. Huang, J.F. Wang, Review on hydrogen embrittlement of press-hardened steels for automotive applications, Acta Metall. Sin.-Engl. Lett. 36 (7) (2022) 1123–1143.

[53] G. Lovicu, M. Bottazzi, F. D'Aiuto, M. De Sanctis, A. Dimatteo, C. Santus, R. Valentini, Hydrogen embrittlement of automotive advanced high-strength steels, Metall. Mater. Trans. A 43a (11) (2012) 4075–4087.

[54] S. Zhang, S. Liu, J. Wan, W. Liu, Effect of Nb-Ti multi-microalloying on the hydrogen trapping efficiency and hydrogen embrittlement susceptibility of hot-stamped boron steel, Mater. Sci. Eng., A 772 (2020) 11.

[55] W. Chen, P. Gao, S. Wang, H. Lu, Z. Zhao, Effect of vanadium on hydrogen embrittlement susceptibility of high-strength hot-stamped steel, J. Iron Steel Res. Int. 28 (2) (2020) 211–222.

[56] S. Zhang, J. Li, Z. Peng, S. Liu, F. Huang, J. Liu, Synergistic effects of Ta and Mo on the hydrogen embrittlement resistance in ultra-high strength hot stamping steel, Mater. Sci. Eng., A 872 (2023).

[57] H. Mohrbacher, Property optimization in as-quenched martensitic steel by molybdenum and niobium alloying, Metals 8 (4) (2018) 234.

[58] C. Horvath, J. Wang, M. Enloe, Microstructural Optimization of AHSS and Press Hardened Steel, Great Designs in Steel 2019, American Iron and Steel Institute, 2019.

[59] M. Schrenk, C. Peuker, F. Franek, G. Rohm, Oxidation of Uncoated 22mnb5 Steel Grades for Hot Stamping Applications, 4th International Conference on Hot Sheet Metal Forming of High-Performance Steel (CHS2 2013), Verlag Wissenschaftliche Scripten, Lulea, SWEDEN, 2013, pp. 161–166.

[60] B. Li, Y. Chen, X. Zhao, J. Li, C. Wang, M. Wang, Effect of austenitization process on oxidative decarbonization behavior and mechanical properties of 22MnB5 steel, J. Mater. Eng. Perform. (2023) 1–14.

[61] D.W. Fan, B.C. De Cooman, State-of-the-knowledge on coating systems for hot stamped parts, Steel Res. Int. 83 (5) (2012) 412–433.

[62] C. Allely, L. Dosdat, O. Clauzeau, K. Ogle, P. Volovitch, Anticorrosion mechanisms of aluminized steel for hot stamping, Surf. Coat. Technol. 238 (2014) 188–196.

[63] J. Zhang, S.-m. Jiang, Q.-f. Zhang, C.-s. Liu, Effect of temperature on microstructure and formability of Al-10 mass% Si coatings, J. Iron Steel Res. Int. 23 (3) (2016) 270–275.

[64] J. Venema, G. Botman, T. Phan, T. Kop, Formability of AlSi and Zn coating during hot stamping, Iop Conf Ser-Mat Sci 651 (2019) 012042.

[65] C.W. Lee, D.W. Fan, I.R. Sohn, S.J. Lee, B.C. De Cooman, Liquid-metal-induced embrittlement of Zn-coated hot stamping steel, Metall. Mater. Trans. A 43a (13) (2012) 5122–5127.

[66] C.P. Couto, R.I. Revilla, R. Politano, I. Costa, Z. Panossian, I. De Graeve, J.L. Rossi, H. Terryn, Influence of austenitisation temperatures during hot stamping on the local electrochemical behaviour of 22MnB5 steel coated with hot-dip Al-Si, Corrosion Sci. 190 (2021) 12.

[67] M.H. Razmpoosh, A. Macwan, E. Biro, Y. Zhou, Effect of galvanneal-coating evolution during press-hardening on laser welding of 22MnB5 steel, Sci. Technol. Weld. Join. 25 (2) (2019) 112–118.

[68] L. Dormegny, Efficient Lightweighting with New Press Hardenable Steels, 2017. https://www.automotivemanufacturingsolutions.com/arcelormittal-webinar-efficient-lightweighting-with-new-press-hardnable-steels-/6368.article. (Accessed 20 September 2023).

[69] Q. Lu, S. Tedesco, M. Shi, J. Coryell, J. Wang, New Generation Oxidation Resistance (Coating Free) Press Hardening Steel, Great Design in Steel 2021, American Iron and Steel Institute, 2021.

[70] Z. Hou, J. Min, J. Wang, Q. Lu, Z. He, Z. Chai, W. Xu, Effect of rapid heating on microstructure and tensile properties of a novel coating-free oxidation-resistant press-hardening steel, JOM 73 (11) (2021) 3195–3203.

[71] Z. Chai, Q. Lu, S. Tedesco, M. Shi, J. Coryell, L. Reini, Q. Lai, J. Wang, L. Wang, W. Xu, Investigation on mechanical properties and oxidation behavior of 1.2 and 1.7 GPa grades coating-free press-hardened steels, Metals 13 (3) (2023).

[72] E. Ota, Y. Yogo, In-furnace Tailored Hot Stamping with Selective Austenitization by Radiant Heating Design, 6th International Conference on Hot Sheet Metal Forming of High-Performance Steel CHS2, Lulea University of Technology, Atlanta, GA, 2017, pp. 543–550.

[73] K. Mori, P.F. Bariani, B.A. Behrens, A. Brosius, S. Bruschi, T. Maeno, M. Merklein, J. Yanagimoto, Hot stamping of ultra-high strength steel parts, CIRP Ann.-Manuf. Technol. 66 (2) (2017) 755–777.

[74] W. Liang, Y. Liu, B. Zhu, M. Zhou, Y. Zhang, Conduction heating of boron alloyed steel in application for hot stamping, Int. J. Precis. Eng. Manuf. 16 (9) (2015) 1983–1992.

[75] W. Liang, Q. Wang, P. Dai, B. Zhu, Y. Zhang, Investigation on Temperature Uniformity of Blanks by Conduction Heating, International Conference on the Technology of Plasticity (ICTP), Elsevier Science Bv, Cambridge, ENGLAND, 2017, pp. 753–758.

[76] W. Liang, L. Wang, Y. Liu, Y. Wang, Y. Zhang, Blank shape sensitivity on temperature distribution of hot stamping boron steel through conduction heating, Adv. Mater. Res. 1063 (2014) 211–214.

[77] A. Ormaetxea, Servo-mechanical Presses Rise to the Challenges of Hot Stamping, 2018. https://www.metalformingmagazine.com/article/?/stamping-presses/servomechanical/servo-mechanical-presses-rise-to-the-challenges-of-hot-stamping. (Accessed 20 September 2023).

[78] X. Fang, Z. Ke, L. Dou, X. An, L. Wang, Application of Mechanical Servo Press in Hot Stamping Production Line, Advanced High Strength Steel and Press Hardening: Proceedings of the 4th International Conference on Advanced High Strength Steel and Press Hardening (ICHSU2018), World Scientific, 2019, pp. 491–497.

[79] P. Belanger, Steel Innovations in Hot Stamping, Great Designs in Steel 2016, American Iron and Steel Institute, 2016.

[80] S.A. Gestamp Automoción, Sustainability Report 2019, Gestamp Automoción S.A., 2020.

[81] D. Balint, T.A. Dean, J. Lin, Method of Forming Parts from Sheet Steel (US20140352388A1), 2014. U.S.

[82] E. Ota, Y. Yogo, T. Iwata, N. Iwata, K. Ishida, K. Takeda, Formability improvement technique for heated sheet metal forming by partial cooling, Key Eng. Mater. 622 (2014) 279–283.

[83] M. Ganapathy, N. Li, J. Lin, D. Bhattacharjee, A feasibility study on warm forming of an as-quenched 22MnB5 boron steel, Int. J. Lightweight Mater. Manuf. 3 (3) (2020) 277–283.

[84] H. Liu, X. Lu, X. Jin, H. Dong, J. Shi, Enhanced mechanical properties of a hot stamped advanced high-strength steel treated by quenching and partitioning process, Scripta Mater. 64 (8) (2011) 749–752.

[85] H. Liu, X. Jin, H. Dong, J. Shi, Martensitic microstructural transformations from the hot stamping, quenching and partitioning process, Mater. Char. 62 (2) (2011) 223–227.

[86] C. Jing, D. Ye, J. Zhao, T. Lin, C. Wu, Q. Lei, Effect of hot stamping and quenching & partitioning process on microstructure and mechanical properties of ultra-high strength steel, Mater. Res. Express 8 (3) (2021) 9.

[87] Z. Wang, K. Wang, Y. Liu, B. Zhu, Y. Zhang, S. Li, Multi-scale simulation for hot stamping quenching & partitioning process of high-strength steel, J. Mater. Process. Technol. 269 (2019) 150–162.

[88] X. Jin, Y. Gong, X. Han, H. Du, W. Ding, B. Zhu, Y. Zhang, Y. Feng, M. Ma, B. Liang, Y. Zhao, Y. Li, J. Zheng, Z. Shi, A review of current state and prospect of the manufacturing and application of advanced hot stamping automobile steels, Acta Metall. Sin. 56 (4) (2020) 411–428.

[89] H. Liu, C. Lei, Local heating-aided hot blanking of quenched ultra-high-strength steel BR1500HS, Int. J. Adv. Manuf. Technol. 77 (1–4) (2015) 629–641.

[90] H. Hou, H. Li, L. He, Effect of technological parameters on microstructure and accuracy of B1500HS steel parts in the hot blanking, Int. J. Adv. Manuf. Technol. 95 (9−12) (2018) 3275−3287.

[91] H. So, D. Fassmann, H. Hoffmann, R. Golle, M. Schaper, An investigation of the blanking process of the quenchable boron alloyed steel 22MnB5 before and after hot stamping process, J. Mater. Process. Technol. 212 (2) (2012) 437−449.

[92] P.R. Spena, CO2 laser cutting of hot stamping boron steel sheets, Metals 7 (11) (2017) 18.

[93] J. Aspacher, D. Haller, P. Thom, From First Draft to Serial Production: Hot Stamping Part Design and Feasibility Study with Respect to Functionality and Optimization of Production Costs, 5th International Conference on Hot Sheet Metal Forming of High-Performance Steel (CHS2 2015), Verlag Wissenschaftliche Scripten, Toronto, CANADA, 2015, pp. 197−207.

[94] K. Mori, T. Maeno, T. Suganami, Hot semi-punching and cold scrap removing processes for hot stamping of ultra-high strength steel parts, Manuf. Rev. 2 (2015) 8.

[95] Y. Li, Y. Zhang, S. Li, Viscoplastic constitutive modeling of boron steel under large strain conditions and its application in hot semi-cutting, J. Manuf. Process. 66 (2021) 532−548.

[96] J.H. Shin, K.H. Lee, B.M. Kim, D.C. Ko, Probability Assessment of Mechanical Trimming Using Hot Half-Trimming in Hot Stamping Process, 4th International Conference on New Forming Technology (ICNFT), E D P Sciences, Glasgow, ENGLAND, 2015.

[97] O.L. Ighodaro, E. Biro, Y.N. Zhou, Comparative effects of Al-Si and galvannealed coatings on the properties of resistance spot welded hot stamping steel joints, J. Mater. Process. Technol. 236 (2016) 64−72.

[98] A. Afzal, M. Hamedi, C.V. Nielsen, Numerical and experimental study of AlSi coating effect on nugget size growth in resistance spot welding of hot-stamped boron steels, J. Manuf. Mater. Process. 5 (1) (2021).

[99] C. Kim, M.J. Kang, Y.D. Park, Laser welding of Al-Si coated hot stamping steel, Procedia Eng. 10 (2011) 2226−2231.

[100] D.C. Saha, E. Biro, A.P. Gerlich, Y.N. Zhou, Fiber laser welding of AlSi coated press hardened steel, Weld. J. 95 (2016) 147−156.

[101] R. Vierstraete, W. Ethling, F. Pinard, L. Cretteur, A. Pic, Q. Yin, Laser ablation for hardening laser welded steel blanks, Ind. Laser Solut. Manuf. 25 (2010) 6−11.

[102] P. Seredynski, Acura and ArcelorMittal Debut World-First Hot-Stamped Door Ring System on 2019 RDX, 2018. https://www.sae.org/news/2018/04/acura-and-arcelormittal-debut-world-first-hot-stamped-door-ring-system-on-2019-rdx. (Accessed 20 September 2023).

[103] W. Lin, F. Li, D. Wu, X. Chen, X. Hua, H. Pan, Effect of Al-Si coating on weld microstructure and properties of 22MnB5 steel joints for hot stamping, J. Mater. Eng. Perform. 27 (4) (2018) 1825−1836.

[104] Q. Sun, H. Di, X. Wang, X. Chen, Suppression of delta-ferrite formation on Al-Si coated press-hardened steel during laser welding, Mater. Lett. 245 (2019) 106−109.

[105] M.S. Khan, M.H. Razmpoosh, A. Macwan, E. Biro, Y. Zhou, Optimizing weld morphology and mechanical properties of laser welded Al-Si coated 22MnB5 by surface application of colloidal graphite, J. Mater. Process. Technol. 293 (2021) 9.

[106] M.S. Khan, P. Enrique, A. Ghatei-Kalashami, J.G. Lopes, N. Schell, J.P. Oliveira, E. Biro, Y.N. Zhou, The influence of in-situ alloying of electro-spark deposited coatings on the multiscale morphological and mechanical properties of laser welded Al-Si coated 22MnB5, Mater. Sci. Eng., A 839 (2022) 142830.

[107] M.S. Khan, S.I. Shahabad, M. Yavuz, W.W. Duley, E. Biro, Y. Zhou, Numerical modelling and experimental validation of the effect of laser beam defocusing on process optimization during fiber laser welding of automotive press-hardened steels, J. Manuf. Process. 67 (2021) 535−544.

[108] D. Reed, P. Belanger, Hot Stamped Steel One-Piece Door Ring in the All-New 2019 Ram 1500, Great Designs in Steel 2018, American Iron and Steel Institute, 2018.

[109] B. Mueller, R. Hund, R. Malek, M. Gebauer, S. Polster, M. Kotzian, R. Neugebauer, A. Volkswagen, Added Value in Tooling for Sheet Metal Forming through Additive Manufacturing, International Conference on Competitive Manufacturing, Citeseer, 2013, pp. 1−7.

[110] H. Hoffmann, H. So, H. Steinbeiss, Design of hot stamping tools with cooling system, CIRP Ann.-Manuf. Technol. 56 (1) (2007) 269−272.

[111] T. Lin, H. Song, S. Zhang, M. Cheng, W. Liu, Cooling systems design in hot stamping tools by a thermal-fluid-mechanical coupled approach, Adv. Mech. Eng. (2014) 12.

[112] Y. Xu, Z. Shan, Design parameter investigation of cooling systems for UHSS hot stamping dies, Int. J. Adv. Manuf. Technol. 70 (1−4) (2014) 257−262.

[113] R. Muvunzia, D. Dimitrova, S. Matopea, T. Harms, Evaluation of Models for Cooling System Design in Hot Stamping Tools, 1st International Conference on Sustainable Materials Processing and Manufacturing (SMPM), Elsevier Science Bv, Skukuza, SOUTH AFRICA, 2017, pp. 701−707.

[114] H. Xie, W. Cheng, H. Wang, S. Fu, W. Li, W. Xiong, Multi-objective reliability-based optimization for cooling channel of a UHSS hot-stamping die, Int. J. Adv. Manuf. Technol. 97 (9−12) (2018) 3237−3249.

[115] R. Muvunzi, D. Hagedorn-Hansen, S. Matope, X. Madyibi, C.B. Swart, M. Nagel, Industry case study: process chain for manufacturing of a large hybrid hot stamping tool with conformal cooling channels, Int. J. Adv. Manuf. Technol. 110 (7−8) (2020) 1723−1730.

[116] R. Muvunzi, D.M. Dimitrov, S. Matope, T. Harms, A case study on the design of a hot stamping tool with conformal cooling channels, Int. J. Adv. Manuf. Technol. 114 (5−6) (2021) 1833−1846.

[117] D. Chantzis, X. Liu, D.J. Politis, O. El Fakir, T.Y. Chua, Z. Shi, L. Wang, Review on additive manufacturing of tooling for hot stamping, Int. J. Adv. Manuf. Technol. 109 (1−2) (2020) 87−107.

[118] D. Chantzis, X. Liu, D.J. Politis, Z. Shi, L. Wang, Design for additive manufacturing (DfAM) of hot stamping dies with improved cooling performance under cyclic loading conditions, Addit. Manuf. 37 (2021) 9.

[119] A. Yanagida, A. Azushima, Evaluation of coefficients of friction in hot stamping by hot flat drawing test, CIRP Ann.-Manuf. Technol. 58 (1) (2009) 247−250.

[120] C. Boher, S. Le Roux, L. Penazzi, C. Dessain, Experimental investigation of the tribological behavior and wear mechanisms of tool steel grades in hot stamping of a high-strength boron steel, Wear 294 (2012) 286−295.

[121] J. Venema, J. Hazrati, D.T.A. Matthews, R.A. Stegeman, A.H. van den Boogaard, The effects of temperature on friction and wear mechanisms during direct press hardening of Al-Si coated ultra-high strength steel, Wear 406 (2018) 149−155.

[122] H. Torres, M.R. Ripoll, B. Prakash, Self-lubricating laser claddings for friction control during press hardening of Al-Si-coated boron steel, J. Mater. Process. Technol. 269 (2019) 79−90.

[123] A. Ghiotti, S. Bruschi, F. Medea, Comparison of tribological and wear performances of AlSi and Zn coatings in hot stamping of boron steel sheets, Wear 332 (2015) 810−821.

[124] X. Yang, H. Liu, S. Dhawan, D.J. Politis, J. Zhang, D. Dini, L. Hu, M.M. Gharbi, L. Wang, Digitally-enhanced lubricant evaluation scheme for hot stamping applications, Nat. Commun. 13 (1) (2022) 5748.

[125] M.E. Palmieri, F.R. Galetta, L. Tricarico, Study of tailored hot stamping process on advanced high-strength steels, J. Manuf. Mater. Process. 6 (1) (2022) 11.

[126] A.K. Singh, K. Narasimhan, Design and development of a micro-LDH apparatus to determine formability of sheet metal under hot stamping conditions using Gleeble, Int. J. Adv. Manuf. Technol. 123 (11−12) (2022) 3831−3844.

[127] R. Zhang, Z. Shi, V.A. Yardley, J. Lin, Experimental studies of necking and fracture limits of boron steel sheet under hot stamping conditions, J. Mater. Process. Technol. 302 (2022) 117481.

[128] A. Abio, F. Bonada, J. Pujante, M. Grane, N. Nievas, D. Lange, O. Pujol, Machine learning-based surrogate model for press hardening process of 22MnB5 sheet steel simulation in industry 4.0, Materials 15 (10) (2022).

[129] M. Zhu, Y.C. Lim, Z. Cai, X. Liu, S. Dhawan, J. Liu, D.J. Politis, Cloud FEA of hot stamping processes using a software agnostic platform, Int. J. Adv. Manuf. Technol. 112 (11−12) (2021) 3445−3458.

[130] R. Heuss, N. Müller, W.v. Sintern, A. Starke, A. Tschiesner, Lightweight, Heavy Impact, Advanced Industries, McKinsey & Company, 2012.

[131] S. Modi, A. Vadhavkar, Technology Roadmap: Materials and Manufacturing, Center for Automotive Research, Ann Arbor, MI, 2019.

[132] Q. Liu, S. Chen, R.Y. Gu, W.R. Wang, X.C. Wei, Effect of heat treatment conditions on mechanical properties and precipitates in sheet metal hot stamping of 7075 aluminum alloy, J. Mater. Eng. Perform. 27 (9) (2018) 4423−4436.

[133] A. Taub, E. De Moor, A. Luo, D.K. Matlock, J.G. Speer, U. Vaidya, Materials for automotive lightweighting, Annu. Rev. Mater. Res. 49 (1) (2019) 327−359.

[134] The Aluminum Association, Roadmap for Automotive Aluminum, 2022.

[135] A. Svendsen, Aluminum Continues Unprecedented Growth in Automotive Applications, 2020. https://www.lightmetalage.com/news/industry-news/automotive/aluminum-continues-unprecedented-growth-in-automotive-applications/. (Accessed 20 September 2023).

[136] R. Gu, Q. Liu, S. Chen, W. Wang, X. Wei, Study on high-temperature mechanical properties and forming limit diagram of 7075 aluminum alloy sheet in hot stamping, J. Mater. Eng. Perform. 28 (12) (2019) 7259−7272.

[137] R. Zhang, W. Wang, J. Lin, T.A. Dean, An indirect hot form and quench (HFQ) for manufacturing components of aluminum alloy sheets and comparison with direct HFQ, Int. J. Mach. Tool Manufact. 192 (2023) 104073.

[138] P. Hidalgo-Manrique, S. Cao, H.R. Shercliff, R.D. Hunt, J.D. Robson, Microstructure and properties of aluminium alloy 6082 formed by the Hot Form Quench process, Mater. Sci. Eng., A 804 (2021) 10.

[139] A. Wang, K. Zhong, O. El Fakir, J. Liu, C. Sun, L.L. Wang, J. Lin, T.A. Dean, Springback analysis of AA5754 after hot stamping: experiments and FE modelling, Int. J. Adv. Manuf. Technol. 89 (5−8) (2017) 1339−1352.

[140] O. El Fakir, L. Wang, D. Balint, J.P. Dear, J. Lin, T.A. Dean, Numerical study of the solution heat treatment, forming, and in-die quenching (HFQ) process on AA5754, Int. J. Mach. Tool Manufact. 87 (2014) 39−48.

[141] J. Alias, X. Zhou, S. Das, O. El-Fakir, G.E. Thompson, Microstructure Evolution and Texture Development of Hot Form-Quench (HFQ) Az31 Twin Roll Cast (TRC) Magnesium Alloy, 3rd Advanced Materials Conference (AMC), Amer Inst Physics, Langkawi, MALAYSIA, 2016.

[142] M. Raugei, O. El Fakir, L. Wang, J. Lin, D. Morrey, Life cycle assessment of the potential environmental benefits of a novel hot forming process in automotive manufacturing, J. Clean. Prod. 83 (2014) 80−86.

[143] Impression Technologies, HFQ® Applications Collection, 2023. https://impression-technologies.com/hfq-applications-collection/. (Accessed 20 September 2023).

[144] R.W. Hall, A. Foster, A.H. Praturlon, Hot Forming and Quenching Pilot Process Development for Low Cost and Low Environmental Impact Manufacturing, 36th IDDRG Conference on Materials Modelling and Testing for Sheet Metal Forming, Tech Univ Munich, Chair Met Forming & Casting, Munich, GERMANY, 2017.

[145] N. Li, J. Zheng, C. Zhang, K. Zheng, J. Lin, T.A. Dean, Investigation on fast and energy-efficient heat treatments of AA6082 in HFQ processes for automotive applications, Matec Web Conf 21 (2015) 05015.

[146] Z. Shao, J. Jiang, J. Lin, Feasibility study on direct flame impingement heating applied for the solution heat treatment, forming and cold die quenching technique, J. Manuf. Process. 36 (2018) 398–404.

[147] A. Foster, D. Szegda, J. Sellors, Design Considerations for HFQ® Hot Stamped Aluminium Structural Panels, 4th International Conference on New Forming Technology (ICNFT), E D P Sciences, Glasgow, ENGLAND, 2015.

[148] H.R. Attar, N. Li, A. Foster, A new design guideline development strategy for aluminium alloy corners formed through cold and hot stamping processes, Mater. Des. 207 (2021) 25.

[149] K. Zheng, Y. Dong, J. Zheng, A. Foster, J. Lin, H. Dong, T.A. Dean, The effect of hot form quench (HFQ®) conditions on precipitation and mechanical properties of aluminium alloys, Mater. Sci. Eng., A 761 (2019) 138017.

[150] Y.F. Jiang, H. Ding, Investigations of interfacial heat transfer efficiency in HFQ process of high strength aluminuvm alloy, Mater. Res. Express 8 (1) (2021) 11.

[151] R.Q. Zhang, Z.T. Shao, Z.S. Shi, T.A. Dean, J.G. Lin, Effect of cruciform specimen design on strain paths and fracture location in equi-biaxial tension, J. Mater. Process. Technol. 289 (2021) 116932.

[152] N. Rigas, M. Merklein, Characterization of the tribological behavior of different tool coatings and dry lubricant for high-strength aluminum alloys at elevated temperatures, Adv. Eng. Mater. (2023) 12.

[153] F. Sun, M. Kenyon, C. Pargeter, J. Wang, C. Williams, C.I. Pruncu, B.R.K. Blackman, A. Tautscher, Performance of Ti/Zr and silane coating pretreatments on adhesive bonding of an automotive aluminium alloy produced using the Hot Form Quench (HFQ®) process, Appl. Surf. Sci. 575 (2022) 151686.

[154] D.S. Jo, J.H. Kim, B.M. Kim, Feasibility study on application of hot forming quenching to patchwork blanks using two-stage refilled friction stir spot welding, J. Manuf. Process. 41 (2019) 66–73.

[155] G. Wang, J. Zhang, W. Yan, H. Xu, Constitutive modelling of plastic deformation behaviour for AA7075-H18 alloy based on hot forming and in-die quenching (HFQ ®) process, Int. J. Material Form. 15 (5) (2022) 62.

[156] W. Cao, J. Shi, C. Wang, C. Wang, L. Xu, M. Wang, Y. Weng, H. Dong, The 3rd Generation Automobile Sheet Steels Presenting with Ultrahigh Strength and High Ductility, Advanced Steels, The Recent Scenario in Steel Science and Technology, 2011, pp. 209–227.

[157] B. Hu, H. Luo, F. Yang, H. Dong, Recent progress in medium-Mn steels made with new designing strategies, a review, J. Mater. Sci. Technol. 33 (12) (2017) 1457–1464.

[158] Y.K. Lee, J. Han, Current opinion in medium manganese steel, Mater. Sci. Technol. 31 (7) (2015) 843–856.

[159] S. Li, H. Luo, Medium-Mn steels for hot forming application in the automotive industry, Int. J. Miner. Metall. Mater. 28 (5) (2021) 741–753.

[160] C. Wang, X. Li, S. Han, L. Zhang, Y. Chang, W. Cao, H. Dong, Warm stamping technology of the medium manganese steel, Steel Res. Int. 89 (9) (2018) 6.

[161] C. Tong, G. Zhu, Q. Rong, V.A. Yardley, Z. Shi, X. Li, J. Luo, J. Lin, Investigation of austenitising behaviour of medium-Mn steel in the hot-stamping heating process, J. Mater. Process. Technol. 297 (2021) 12.