

Review on sheet and tube forming at elevated temperature of third generation of high-strength steels[☆]

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Abstract. The paper intends to review the most recent research works carried out in the framework of forming processes carried out at elevated temperature on steel sheets and tubes. The increasing demand of high strength-to-weight ratio components in different sectors, such as the automotive and aerospace ones, has recently pushed a more and more remarkable development of forming processes that involve the heating of the sheet at such temperatures to assure not only enhanced formability characteristics, but also microstructural features that can improve the component in-service properties. The focus of the paper will be on variants of the hot stamping process carried out on high strength-to-weight steel sheets and tubes to tailor the part characteristics.

Keywords: Hot stamping / tailored tempering / partitioning / steel / sheets / tubes

1 Introduction

Since the last few decades, the transportation industry has been obliged to reduce more and more the CO₂ emissions, which has forced to decrease the weight of the vehicles, still with the need to keep, or even increase, their safety characteristics. If we focus on the automotive field, the reduction of the weight of the car body-in-white can be achieved by manufacturing parts made of high strength-to-weight metal alloys, among which high strength steels are the most used.

Sheet-like parts are usually formed through forming operations carried out at room temperature, which can be particularly challenging when using high strength steel sheets, since the latter are usually characterized by reduced formability and severe springback in cold conditions and can induce significant wear in the forming tools, forcing their premature replacement. To face such drawbacks of room temperature forming, processes at elevated temperature have been developed and implemented already at industrial scale. Hot stamping of high strength steel sheets was developed in the nineties in its variant called direct hot stamping and still used for manufacturing several parts of the car body-in-white. 22MnB5 is the most widespread

steel grade for hot stamping, commercialized with the name of Usibor 1500, which was patented by Arcelor-Mittal with a specific Al-Si coating aimed at reducing the sheet oxidation inside the heating furnace before being press-formed. During direct hot stamping, the sheet is heated above the steel austenitization temperature inside an external furnace and kept at this temperature to assure both complete austenitization and temperature homogeneity. After that, the sheet is rapidly transferred to the forming press, where the deformation stage takes place simultaneously to the part quenching thanks to the contact with the water-cooled forming dies. Thanks to this process chain, the 22MnB5 initial ferritic-pearlitic microstructure becomes fully martensitic assuring a mechanical resistance in terms of ultimate tensile strength up to 1500 MPa.

Nevertheless, direct hot stamping presents some drawbacks, which are desirable to be overcome for an even higher exploitation of the process. It is worth citing the need to reduce the high-energy content of the process in favor to less energy intensive variants and the requirement to manufacture parts characterized, at the same time, by high mechanical resistance and reasonable ductility. This has led to the development at lab and industrial scale of different variants of the conventional direct hot stamping process. In addition, the concept of sheet forming at elevated temperature has been applied to various steels, other than the conventional 22MnB5, proving the feasibility of the approach.

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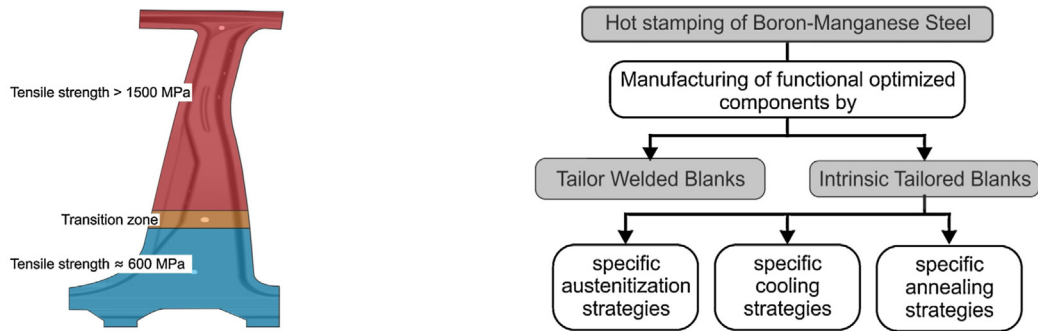


Fig. 1. Example of a B-pillar that can benefit of a tailored microstructure (on the left); possible variants of hot stamping for tailoring the part microstructure (on the right) [1].

2 Tailoring the part microstructure through hot stamping

Direct hot stamping allows manufacturing parts in a fully martensitic state, which implies outstanding mechanical resistance, but very much reduced ductility. On the contrary, for instance, some parts of the car body-in-white can benefit of an enhanced ductility, as is the case of the B-pillar shown in Figure 1 on the left, whose bottom region is desirable to show a higher energy absorption capacity than the upper region, where a martensitic microstructure is envisaged to have maximum intrusion resistance. In recent years, different variants of the direct hot stamping process have been developed with the aim of tailoring the microstructure of such parts: Figure 1 on the right reports some of these approaches [1].

Tailored welded blanks can be used for this purpose, as they already present a tailored microstructure and they do not need any modification of the existing hot stamping process; nevertheless, they are much more costly than monolithic sheets.

When using monolithic blanks, partial heating can assure zones where a full austenitization takes place thanks to heating above the steel austenitization temperature, and zones where the austenite transformation is prevented being heated below the austenitization temperature. Afterwards, conventional direct hot stamping is carried out, which leads to martensite only where austenitization has taken place. Even if the stamping process is the conventional one without the need of modifications in the forming dies, this approach requires dedicated heating set-ups, such as furnaces with separate chambers, which may significantly increase the technological efforts of the process chain. An alternative is to use a resistance heating system with bypasses [2] in order to heat only those zones that require a full austenitization: even if the heating approach is pretty simple, this procedure can be applied just to simple geometries, which basically restrains its industrial applicability.

Rather than partial heating, tailored tempering is more widespread, which implies the fulfillment of different cooling rates in different zones of the part, with the aim of inducing or not the martensitic transformation. When using blanks of 22MnB5, cooling at rates higher than 27 K/s leads to the formation of martensite, whereas at lower rates, a

mixture of different phases forms with enhanced ductility. The variation in the cooling rates can be accomplished through various strategies, basically based on the variation of the heat transfer coefficients between the heated blank and forming dies. One possibility is to heat those zones of the forming dies where the martensitic transformation must be prevented, as was done in [3], where an increase of ductility of more than 70% was reached. Ceramic inserts can be used as well to insulate these zones of the forming dies [2]. However, using dies with zones characterized by different thermal conductivities can lead to transition regions in the stamped part that must be properly evaluated and their properties quantified: in [4] it was proved that using an air gap between the different zones of the dies could reduce these transitions regions to less than 10 mm of width. The relief method is used as well for tailored tempering [5], which limits the contact between the cooled dies and those regions of the blank where other microstructures than the martensitic one are desirable. The scheme of the hot stamping process employing the relief method is shown in Figure 2: the process is divided into two stages, with the first one that leads to the forming of just those regions that need to be martensitic, while the second stage assures the forming of softer zones.

A more recent strategy for tailored tempering is based on the variation of the blank initial characteristics: in [6] tailored carburization was introduced, combining hot stamping and prior local carburization. Before hot stamping, the regions of the blank where a higher mechanical resistance is desirable are coated with a carbonic material and subjected to carburization. Afterwards, conventional hot stamping with no modifications in the forming dies is carried out assuring the manufacturing of a part with regions of enhanced strength.

3 Hot stamping based on quenching and partitioning

A recent variant of the hot stamping process can help in fulfilling the requirement of high strength, but ductile, parts, which includes, after quenching, a partitioning step for developing retained austenite capable to increase the steel ductility together with martensite for higher strength. The first application of the quenching and partitioning (Q&P) process is due to Speer in 2011 [7]. Q&P is characterized by a first step where the steel blank is

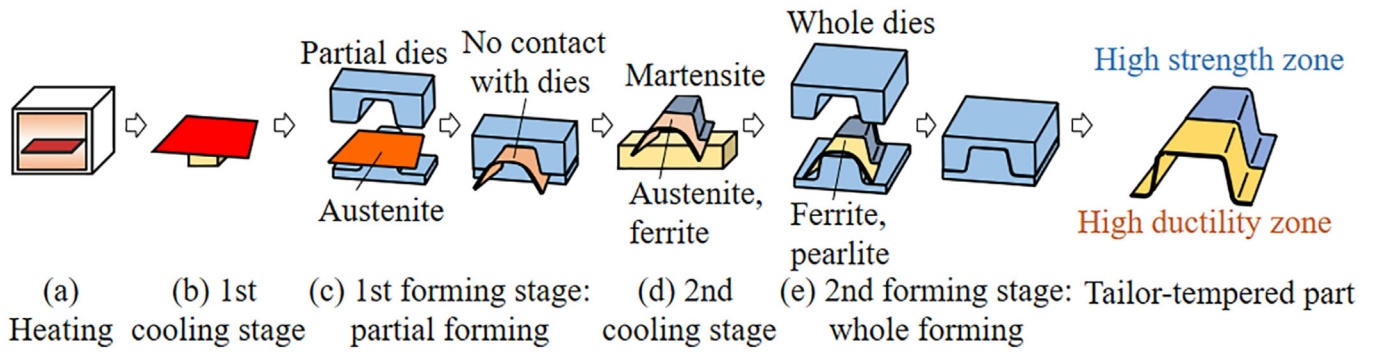


Fig. 2. Hot stamping process using the relief method for tailoring the part microstructure [5].

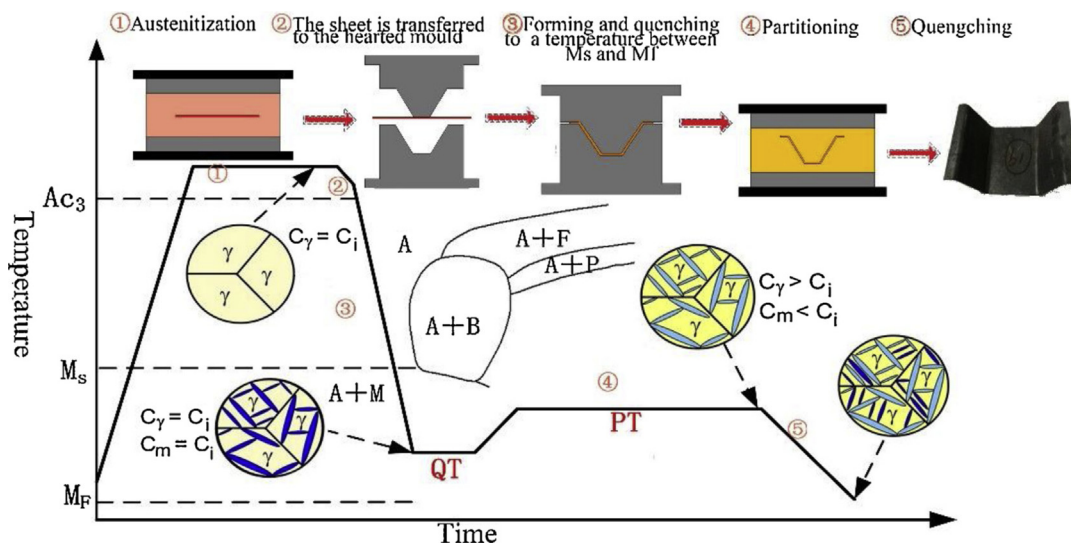


Fig. 3. Variant of the hot stamping process named quenching & partitioning [8].

austenitized and then rapidly transferred to the press where it is formed and cooled to a temperature between martensite start (M_s) and martensite finish (M_f), which implies the development of controlled fractions of martensite and austenite. The partitioning step then follows, which induces the transport of the carbon from the supersaturated martensite into the austenite, thus stabilizing the austenite at room temperature [7]. The partitioning step may take place at the quenching temperature of the first step (one step Q&P), or at higher temperature (two steps Q&P). Figure 3 shows a scheme of the Q&P process where the partitioning step is carried out at higher temperature than the quenching one. The same temperature vs. time diagram gives indication of the microstructural features obtainable during each process step [8]. The carbon partitioning step is usually carried out in external furnaces where the part is heated through radiation, nevertheless this implies a slow process and difficulty in providing temperature uniformity throughout the part. Another possibility is to use the salt bath method, which assures more homogeneous temperatures, but it is pretty much expensive. In [9], the carbon partitioning step was carried out inside a hot air device, which was proved to

assure a more homogeneous thermal field thanks to heating through convection rather than radiation. However, its applicability at industrial level is far from being established.

A non-isothermal strategy in carbon partitioning was developed in [10] where the Q&P process was implemented in a conventional hot stamping line according to the scheme reported in Figure 4 and applied to a Cr-alloyed press-hardening steel. Thanks to this procedure, an improved bending toughness was achieved together with an increase of the production efficiency.

4 Low-temperature hot stamping

The ever increasing energy costs have recently pushed the evaluation of the feasibility of forming at temperatures lower than the ones connected to the conventional hot stamping process. In addition, lower forming temperatures can be useful in reducing the blank oxidation, and increase the steel ductility, but without compromising its strength. This strategy is known as low-temperature hot stamping and refers a hot stamping process carried out at temper-

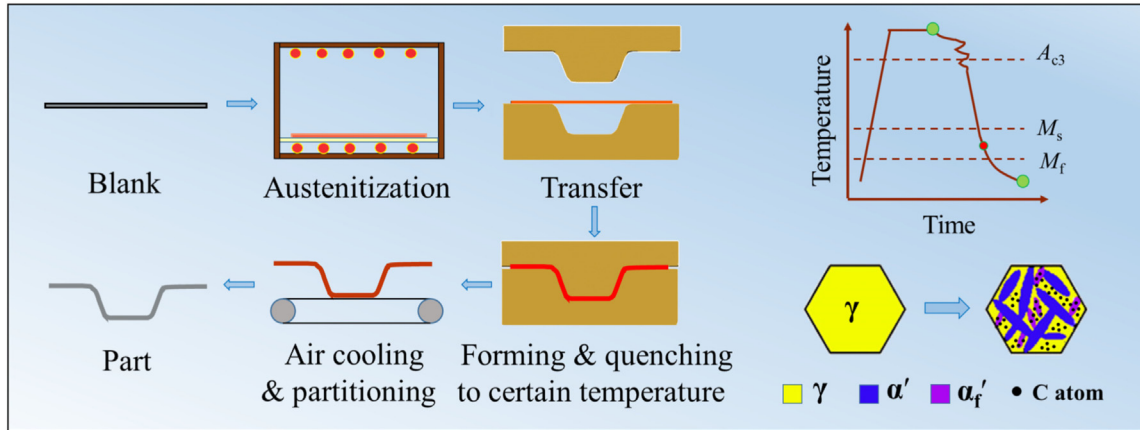


Fig. 4. Variant of the hot stamping process including in-line quenching and non-isothermal carbon partitioning [10].

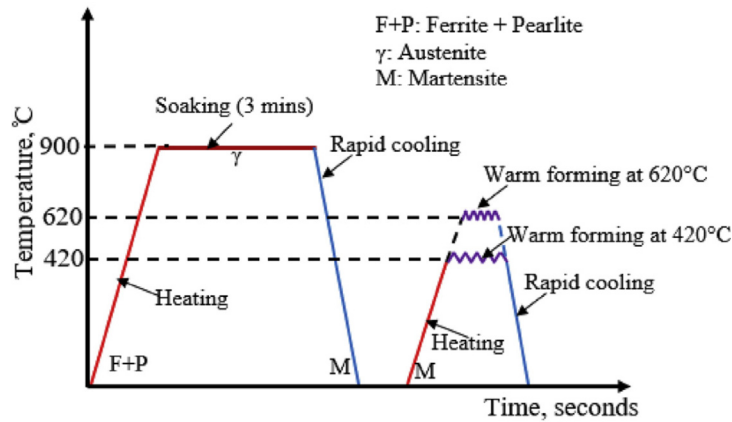


Fig. 5. Scheme of the low-temperature hot stamping process [12].

atures lower than the ones usually applied. In [11] this strategy was applied to uncoated sheets of 22MnB5 introducing a pre-cooling step between the heating and forming ones. This pre-cooling step assured to cool down the blank till 500°C, where the material is still austenitic, allowing the forming of a B-pillar part of mechanical resistance comparable to that of the same part manufactured through conventional hot stamping. Furthermore, a drastic reduction of time needed for the forming-quenching step was assured. A further variant of the low-temperature hot stamping process was proposed in [12] and its scheme applied to the 22MnB5 steel is shown in Figure 5. This approach is based on the blank austenitization, then rapid cooling to room temperature to get a fully martensitic structure; after that, the blank is heated up in a range of temperatures between 420°C and 620°C, where it is fast formed and rapidly cooled again to room temperature. Even if this strategy can assure high ductility and reduced cycle time compared to the outcomes of conventional hot stamping, the manufactured parts were characterized by a significantly lower mechanical resistance, which makes questionable its actual application at industrial level.

5 Hot stamping of medium-Mn steel sheets

The ever increasing demand in ductility, but still preserving the strength, has recently pushed the development of the so-called third generation of high-strength steels, medium-manganese (medium-Mn) steels in particular, to be used in hot stamping processes. Medium-Mn steels, containing approximately 5–12% in weight of manganese and various other alloying elements, can be subjected to the austenite reverse transformation annealing treatment. The latter is carried out between the A_{c1} and A_{c3} temperatures of the steel, and induces a dual phase structure formed by ferrite and retained austenite, the latter being 20–50% and characterized by ultra-fine grains. The retained austenite can be then stabilized at room temperature and, through the transformation induced plasticity (TRIP) effect can transform into martensite. This, in turn, significantly improves the steel mechanical properties, but still assuring a better ductility than the conventionally hot-stamped 22MnB5. Furthermore, the high Mn content in the medium-Mn steels allows a significant reduction of the austenitization temperature, compared to that of the 22MnB5 steel, which, overall,

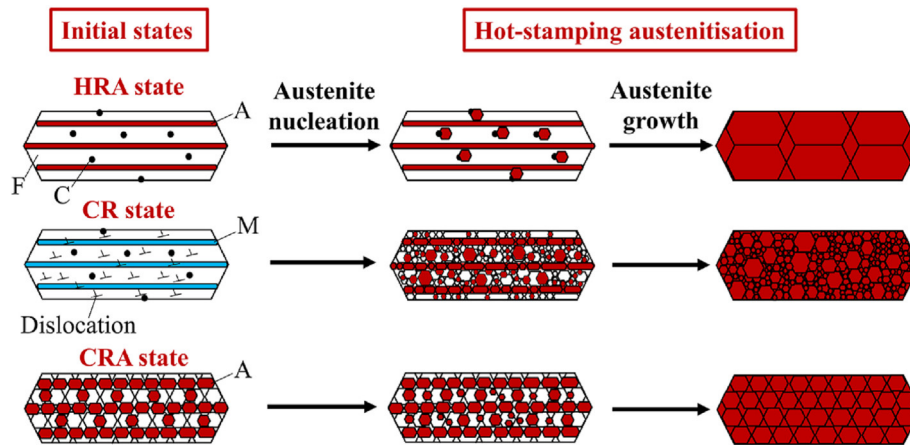


Fig. 6. Microstructural evolution of a medium-Mn steel after austenitization on the basis of different initial states (HRA = hot-rolled and annealed; CR = cold-rolled; CRA = cold-rolled and annealed) [13].

decreases the process energy consumption, but also helps in reducing the blank oxidation and decarburization at elevated temperature. In addition, the martensite start temperature is much lower, even below room temperature, which helps in enlarging the forming window, reducing the need for a tight control of the quenching stage.

Hot stamping of medium-Mn steels can be carried out on the basis of the following procedure: blank austenitization in the temperature range between 690°C and 770°C, air cooling to approximately 500°C where the simultaneous forming and quenching take place. It is worth underlining that the austenitization temperature and time, cooling rate and forming temperature all play a significant role to get the part desired properties and must be properly chosen and controlled. In addition, also the medium-Mn steel initial state can significantly affect the process outcomes, as it was proved in [13]: Figure 6 shows that, depending on the peculiar initial state, different microstructural features evolve, which, in turn, lead to different mechanical characteristics. In particular, it was proved that the best initial state was hot rolling followed by annealing.

6 Hot bending of steel tubes

Temperature-assisted processes in sheet metal stamping have introduced a disruptive innovation, creating new markets for stronger and more complex-shaped sheet components. This success has driven the development of temperature-assisted tube forming processes, aiming to produce tubular parts with customized mechanical properties and more complex shapes.

In the field of steel pipe bending, high-frequency local induction heating is commonly used for large-diameter parts in heavy industrial applications like shipbuilding or power plants [14]. However, this thermal source has some limitations, including a restricted heated zone length and reduced feasibility of application of complex thermal cycles. As a result, the primary focus of this technology

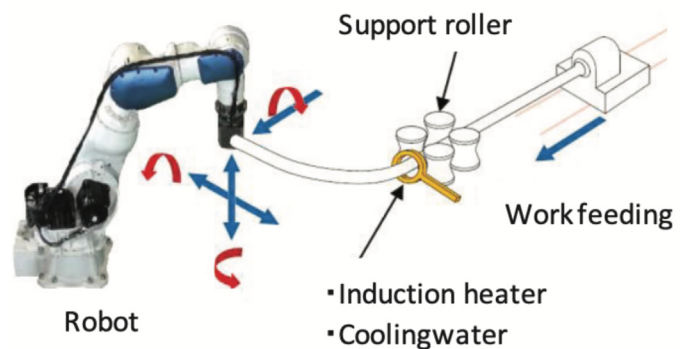


Fig. 7. 3D hot bending and direct quenching [17].

has been on reducing bending torques and springback, rather than tailoring the part microstructure or enhancing its mechanical properties.

Recent researches [15] and [16] explored the application of the induction technology on different alloy steels. In [15] the focus was on refining the P11 alloy steel microstructure, while in [16] on reducing the residual stress state in the bent zone of the Q345B steel. A three-dimensional hot bending and direct quenching (3DQ) system was proposed in [17] for bending and quenching C20 carbon steel tubes with a square section, primarily used for parts of the car body-in-white. This approach, shown in Figure 7, combines localized induction heating with a robotic arm to enhance the process flexibility. By manipulating temperatures and cooling rates along the workpiece length, the microstructure and mechanical properties of the tube can be tailored, accordingly. However, it is important to note that long soaking times required for certain workpiece materials can significantly reduce the process productivity.

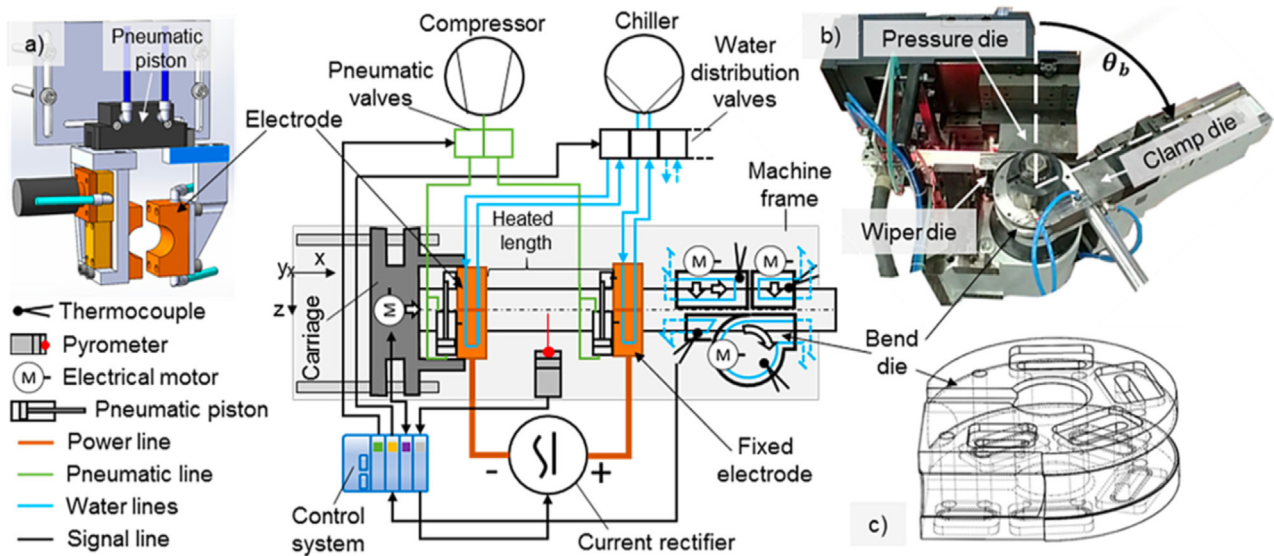


Fig. 8. Direct hot tube rotary draw bending process [18].

The direct hot tube rotary draw bending (DHTRDB) process proposed in [18] was developed to overcome the flexibility issues of induction heating systems. By utilizing two electrodes connected to a current rectifier, it employs Joule heating to apply an in-line thermal field as shown in Figure 8. The heated length can be adjusted by manipulating the electrode position, and the applied current is controlled based on the measured temperature to achieve the desired thermal cycle. Following the heating and soaking stages, the tube is subjected to rotary draw bending till the desired angle and subsequently cooled, potentially with the assistance of an inner mandrel to ensure precise bends.

The DHTRDB process was validated using 22MnB5 boron steel tubes specifically designed for automotive applications. The tubes were heated to 950°C for 3 min, then bent and cooled. The obtained results demonstrated a significant reduction in the springback angle along with an improvement in the mechanical properties of the steel across the tube section.

In [19], it was noted that the DHTRDB process experiences varying contact conditions between the tools and the workpiece due to kinematics, which impacts the cooling thermal paths. Without additional cooling, a thermal gradient arises between the bent intrados and extrados, leading to uneven microstructure and mechanical property distribution as shown in Figure 9. Along the bent inner radius, a fully martensitic microstructure with an average hardness of 503 μHV was obtained, while the bent outer radius exhibited a mixed bainitic-ferritic microstructure with a minimum average hardness of 290 μHV .

7 Hot stamping and gas forming of steel tubes

While tube bending processes focus on altering the 3D axial development of the workpiece, tube hot stamping and gas forming aim at changing the tube cross-section shape. In [20] an offline oven-based heating method was proposed for tube hot stamping, while an in-line joule heating system was used in [21], see Figure 10. In the latter case, the tube is stamped along the vertical direction to modify its cross-section shape. This technique is commonly employed for forming and quenching 22MnB5 boron steel torsion beam axles.

During the tube radial compression, buckling and other instabilities can affect the final workpiece accuracy. Whit regards to this issue, the effectiveness of using an expendable ice mandrel placed inside the entire tube length to support the deformation of the inner wall was demonstrated in [22], which helped in enhancing the cooling rate, and reducing the thermal gradients. Similarly, tools with embedded cooling channels and heating cartridges were used in [23] to modify the thermal path. This approach enabled controlling the microstructural and mechanical properties in different zones of the same tubular part.

On the other hand, gas forming utilizes high-pressure gases to expand a heated tube. However, the applied internal pressure, which can be up to 70 MPa, can develop circumferential tensile stresses potentially leading to the workpiece failure. Controlling the axial material flow is crucial to reduce defects while adjusting the gas flow and temperature enhances the cooling rates allowing the

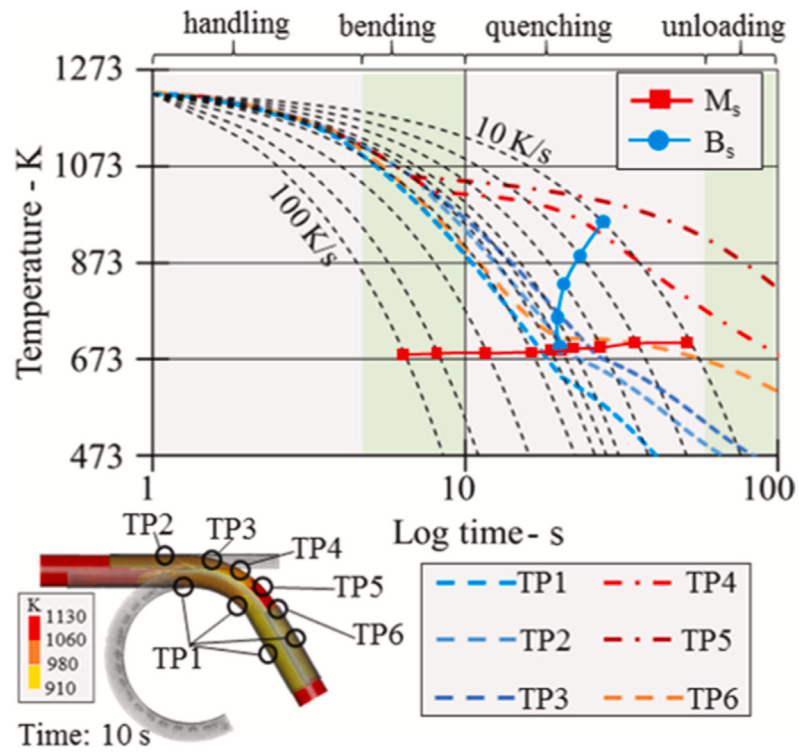


Fig. 9. Cooling paths along a 22MnB5 tube bent at 950°C [19].

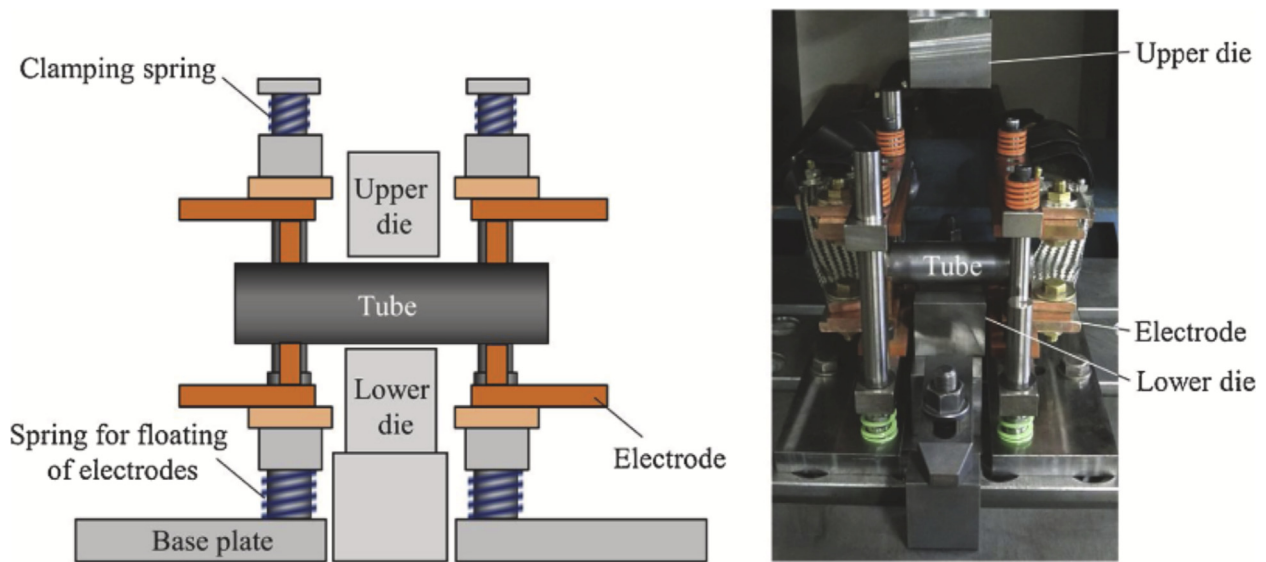


Fig. 10. Hot stamping of tubes using ice mandrel and Joule heating [22].

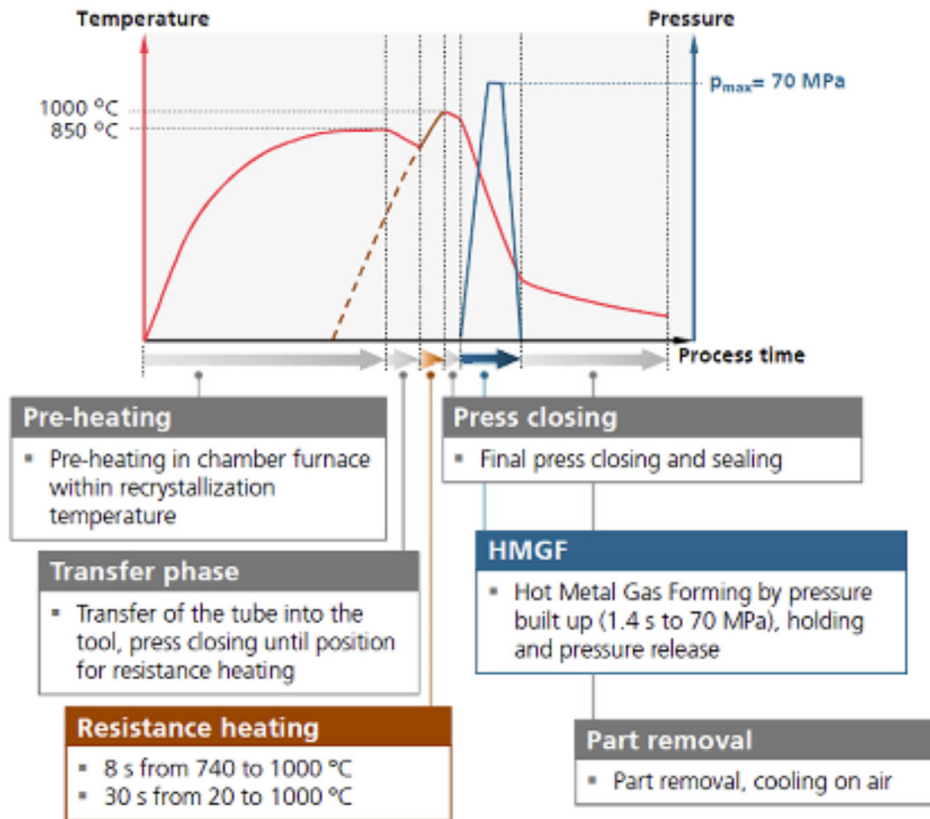


Fig. 11. Hot medium pressure forming [24].

microstructure control. Gas forming and stamping processes can be combined to support the tube's inner wall and minimize the defects. The temperature-pressure cycle shown in Figure 11 demonstrates gas forming for ferrite steel tubes used in exhaust components. The effectiveness of utilizing internal pressure to reduce defects during radial stamping was shown in [24].

8 Conclusions

The paper has provided a short review of the most recent advances of the hot stamping technology applied to different categories of high strength steel sheets and tubes. The scientific literature shows significant progresses compared to the conventional direct hot stamping process carried out on 22MnB5 boron steel sheets. The following conclusions and perspectives can be drawn:

- The development of tailored tempering processes has been driven by the need to have parts with zones at higher ductility and zones at higher mechanical resistance.
- Quenching and partitioning processes have been introduced to fulfill the requirement of parts characterized by high resistance, but with still reasonable ductility.
- The third generation of high-strength steels, in particular medium-Mn steels, has been introduced with the aim of reducing the cycle time and energy consumption in hot stamping processes.

- New tube hot bending and stamping processes have been developed to manufacture hollow parts with narrow bending radii and high mechanical resistance.

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References

- [1] M. Merklein, M. Wieland, M. Lechner, S. Bruschi, A. Ghiotti, Hot stamping of boron steel sheets with tailored properties: a review, *J. Mater. Process. Technol.* **228**, 11–24 (2016)
- [2] K. Mori, Y. Okuda Y, Tailor die quenching in hot stamping for producing ultra-high strength steel formed parts having strength distribution, *CIRP Ann. Manuf. Technol.* **59**, 291–294 (2010)
- [3] R. George, A. Bardelcik, MJ Worswick Hot forming of boron steels using heated and cooled tooling for tailored properties, *J. Mater. Process. Technol.* **212**, 2386–2399 (2012)
- [4] B. Tang, S. Bruschi, A. Ghiotti, P.F. Bariani, Numerical modelling of the tailored tempering process applied to 22MnB5 sheets, *Finite Elem. Anal. Des.* **81**, 69–81 (2014)

- [5] Y. Nakagawa, K. Mori, Y. Suzuki, Y. Shimizu, Tailored tempering without die heating in hot stamping of ultra-high strength steel parts, *Mater. Des.* **192**, 108704 (2020)
- [6] A. Horn, M. Merklein, Functional optimization of hot-stamped components by local carburization, *International J. Lightweight Mater. Manuf.* **3**, 43–54 (2020)
- [7] J.G. Speer, E. De Moor, K.O. Findley, D.K. Matlock, B.C. De Cooman, D.V. Edmonds, Analysis of microstructure evolution in quenching and partitioning automotive sheet steel, *Metall. Mater. Trans. A* **42**, 3591 (2011)
- [8] 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**, 150–162 (2019).
- [9] B. Zhu, J. Zhu, Y. Wang, B. Rolfe, Z. Wang, Y. Zhang, Combined hot stamping and Q&P processing with a hot air partitioning device, *J. Mater. Process. Technol.* **262**, 392–402 (2018)
- [10] W. Ding, Y. Gong, A. Lu, J. Wang, Z. Wang, W. Li, X. Jin, Improve bendability of a Cr-alloyed press-hardening steel through an in-line quenching and non-isothermal partitioning process, *J. Manuf. Processes* **84**, 481–493 (2022)
- [11] M. Ganapathy, N. Li, J. Lin, M. Abspoel, D. Bhattacharjee, Experimental investigation of a new low-temperature hot stamping process for boron steels, *Int. J. Adv. Manuf. Technol.* **105**, 669–682 (2019)
- [12] 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**, 277–283 (2020)
- [13] C. Tong, V.A. Hardley, Z. Shi, Q. Rong, X. Li, B. Zhang, D. Xu, J. Lin, Investigation of the effect of initial states of medium-Mn steel on deformation behaviour under hot stamping conditions, *Mater. Sci. Eng. A* **855**, 143914 (2022)
- [14] C. Schlaseman, J. Cunningham, L. Elwell, W. Dykema, H. Deegala, S. Harp, T. King, L. Lichtenauer, R. Parthasaranthi, E. ten Siethoff, Application of Advanced Construction Technologies to New Nuclear Power Plants, U.S. Department of Energy, 2004
- [15] X. Guo, K. Jin, H. Wang, W. Pei, F. Ma, J. Tao, N. Kim, N. Numerical simulations and experiments on fabricating bend pipes by push bending with local induction-heating process, *Int. J. Adv. Manuf. Technol.* **84**, 2689–2695 (2016)
- [16] Q. Han, Z. Han, Y. Lu, Experimental and numerical investigations on residual stresses in hot-bent circular steel tube, *J. Construct. Steel Res.* **161**, 31–46 (2019)
- [17] N. Shimada, A. Tomizawa, H. Kubota, H. Mori, M. Hara, M., Kuwayama, S. Development of three-dimensional hot bending and direct quench technology. *Procedia Eng.* **81**, 2267–2272 (2014)
- [18] E. Simonetto, A. Ghiotti, S. Bruschi, High accuracy direct hot bending of hollow profiles. *Manuf. Lett.* **27**, 63–66 (2021)
- [19] E. Simonetto, A. Ghiotti, S. Bruschi, Numerical modelling of direct hot tube rotary draw bending of 22MnB5 high strength steel, *CIRP J. Manuf. Sci. Technol.* **37**, 547–558 (2022)
- [20] A.R. Park, J.H. Nam, M. Kim, I.S. Jang, Y.K. Lee, Evaluations of tensile properties as a function of austenitizing temperature and springback by V-bending testing in medium-Mn steels, *Mater. Sci. Eng. A* **787**, 139534 (2020)
- [21] M. Loh-Mousavi, M. AhmadiRad, T. Maeno, D.J. Politis, L. Wang, Coupled thermal-electrical finite element analysis of electrical resistance heating in hot stamping of ultra-high strength steel tubes, *Procedia Manuf.* **15**, 1047–1054 (2018)
- [22] A. Talebi-Anaraki, T. Maeno, R. Ikeda, K. Morishita, I.K. Mori, Quenchability improvement and control simplification by ice mandrel in hot stamping of ultra-high strength steel hollow parts, *J. Manuf. Processes* **64**, 916–926 (2021)
- [23] A. Paul, M. Strano, The influence of process variables on the gas forming and press hardening of steel tubes, *J. Mater. Process. Technol.* **228**, 160–169 (2016)
- [24] K. Zheng, J.H. Zheng, Z. He, G. Liu, D.J. Politis, L. Wang, Fundamentals, processes and equipment for hot medium pressure forming of light material tubular components, *Int. J. Lightweight Mater. Manuf.* **3**, 1–19 (2020)

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