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Hot stamping of ultra-high strength steel parts

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ABSTRACT

The demand for new processes to produce high strength parts, under appropriate cost and productivity, has grown with weight reduction and crash safety improvements in automobile design. The hot stamping processes of quenchable steel sheets potentially offer not only small forming load and high formability, but also high strength and no springback by die quenching. This paper aims to provide an overview of the state-of-the-art in such hot stamping processes, including quenchability, formability, heating and cooling approaches and lubrication. The paper also includes a description of the mechanism of formability and quenching, tailoring, analysis of hot stamping processes and applicability.

1. Introduction

1.1. Motivation

Carbon dioxide (CO_2) emission reduction should be intensified to prevent global warming. Transportation produces the second largest CO_2 emission following electricity. Approximately 90% of transportation emission comes from automobiles, such as cars, trucks, and buses. The European committee has set a high target to reduce CO_2 emission by 20% from the 1990 level until 2020. In the case of the CO_2 emission of automobiles, the 2020 standards are 95 g/km, whereas the 2012 standards were 120 g/km [204]. Various techniques for improving the fuel consumption of automobiles were developed (e.g., [118]). Electric, hybrid, and fuel cell vehicles, among others, are attractive for fuel consumption reduction. Moreover, engines, aerodynamics, powertrain, and tires are optimised.

The reduction in the weight of automobiles is useful for improving the fuel consumption. The running distance for a 100 kg reduction increases by approximately 1 km/l. Aluminium, magnesium, and carbon fibre-reinforced polymer (CFRP) are lightweight materials, with material costs that are higher than those of steel. High strength steel sheets are low-cost, and the specific strength is high. The application of high strength steel sheets to automobile parts, especially body-in-white, remarkably increases because of weight reduction. As the strength of steel sheets increases, the formed parts obtain high functions. On the contrary, cold-stamping of the steel sheets is difficult because of large springback, high stamping load, low formability, short tool life and severe wear such as galling and seizure, as shown in Fig. 1 [2,123,127]. Although ultra-high strength steel sheets having a tensile strength of approximately 1.5 GPa were developed [58], cold stamping of steel sheets above 1.2 GPa in tensile strength is unpractical. Large springback and low tool life still remain as crucial problems even if the 1.5 GPa sheets can be cold-stamped. Hence, developing processes for producing high strength steel parts above 1.2 GPa are desirable for improvement in automobile collision safety.

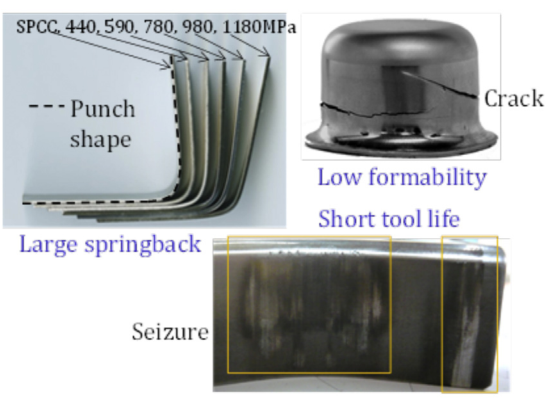

Fig. 1. Problems in cold stamping of high strength steel sheets [2,123,127].

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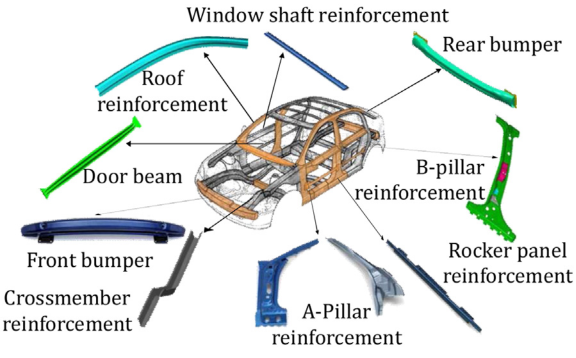

Fig. 2. Automobile parts produced by hot stamping in Benteler Automotive (courtesy of Benteler Automotive) [99].

Ultra-high strength steel parts are being increasingly produced by hot stamping of quenchable steel sheets. In hot stamping, the quenchable steel sheets are heated to approximately 900 °C to transform the sheets into austenite. The sheets are then quenched by holding at the bottom dead centre with dies in a process called die quenching. The hot-stamped parts have approximately a tensile strength of 1.5 GPa. In hot stamping, the forming load is small, the ductility is large, and the springback is considerably small. The hot-stamped parts are used for body-in-white parts, as shown in Fig. 2 [99]. High strength parts are required to improve automobile crash safety. Therefore, the hot-stamped parts are mainly used as reinforcement members. Most of the parts are bent, and drawing is partially included in the edges of parts, such as B-pillars. The crash safety is evaluated by the New Car Assessment Program (NCAP), and the automobiles are designed to increase points in NCAP. Hot stamping aims to improve crash safety under reduction or without increase in car weight.

Saab Automobile AB was the first automaker who applied hot-stamped parts in commercial vehicles. German automobile makers have begun full production of hot stamping from the latter half of the 1990s. Hot stamping has expanded worldwide from the latter half of the 2000s. Accordingly, 7% of the body-in-white for Volvo XC90 was launched in 2003 and 17% in 2006, 17% for Volkswagen Passat launched in 2006, 12% for BMW5 launched in 2009, and 12% for Volkswagen Golf VII launched in 2012 were produced by hot stamping. The percentage for Volvo XC90 launched in 2014 was raised to 40%. The number of hot-stamped parts considerably increased and reached 250 million parts in 2014 [56].

Neugebauer et al. [149] reviewed sheet metal forming processes at elevated temperatures, including hot stamping of ultra-high strength steel parts. Karbasian and Tekkaya [72] comprehensively reviewed hot stamping processes. Meanwhile, Naganathan and Penter [147] and Bruschi and Ghiotti [29] explained hot stamping processes in a part of books, respectively. Mori [131] and Merklein et al. [115] reviewed smart hot stamping and tailoring processes, respectively.

1.2. Advantages and drawbacks of present hot stamping

The main advantage of hot stamping processes is to produce springback-free ultra-high strength steel parts having 1.5 GPa tensile strength. Both high strength and dimensional accuracy are attained by die quenching in hot stamping. This leads to a solution to the problems in cold stamping of high strength steel sheets. In addition, the stamping load is small, and the ductility is increased. Hot stamping processes are ideal, because the sheets are soft during stamping and the produced parts are hard.

The present hot stamping processes still have some drawbacks shown in Fig. 3. The investment cost is very high because of the furnace, press, and laser cutting machine costs, among others. The equipment space is large, and the energy efficiency of the furnaces is low [94]. The productivity is low because of holding at the bottom dead centre of a press for die quenching, two or three shots per minute [156]. The mechanical properties of hot-stamped parts

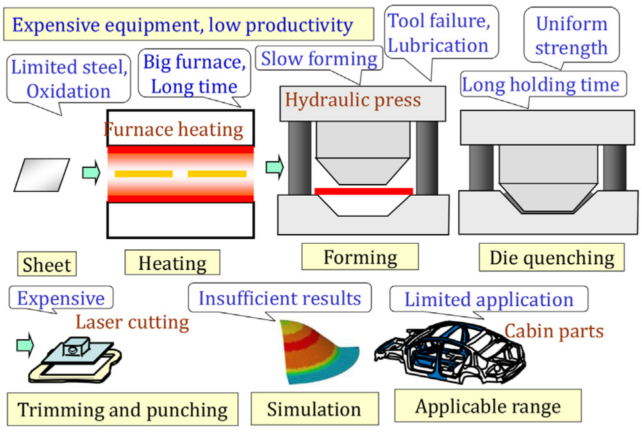

Fig. 3. Drawbacks of present hot stamping operations.

are fixed because of one sort of steel, and coatings for protecting the oxidation of heated sheets are costly. Tool failure and lubrication at elevated temperature are problematic. The applicable range of hot stamping is limited to the production of cabin parts of body-in-white for protecting passengers against automobile collisions because of insufficient energy absorption.

Challenging approaches for improving these drawbacks have been developed. These approaches for steels, heating and cooling, forming, tooling, tailoring, cutting, and simulation, among others, are reviewed in the present paper.

2. Materials

2.1. Motivation and common steel grade

In hot stamping, ultra-high strength steel parts having a tensile strength of 1.5 GPa are produced by a quenching operation included in the stamping operations. Quenchable steel sheets are austenitised by heating to approximately 900 °C and transformed into martensite by holding at the bottom dead centre of a press for die quenching. The formed parts are hardened to a tensile strength of 1.5 GPa. Quenchability and toughness are required for the steel sheets and formed parts, respectively. In addition, treatments for preventing or removing oxidation of the heated steel sheets to 900 °C are essential for subsequent welding and painting operations.

The 22MnB5 boron steel, which is often named as BTR165 or Usibor1500, is most commonly used. This steel is a micro alloyed carbon-manganese steel with chromium, molybdenum, niobium, titanium, vanadium, and boron. The addition of very little boron (i.e. approximately 0.05 wt.%) improves quenchability. The as-delivered microstructure of this steel consists of 73–77 wt.% ferrite and 23–27 wt.% pearlite. The microstructural transformation from austenite to martensite occurs above a cooling rate of 30 °C/s. Bainite or, even, ferrite resulting in lower strength and hardness levels is formed below 30 °C/s. Geiger et al. [44], Merklein et al. [109], and Feuser et al. [40] performed further investigations on 22MnB5. A longer austenitisation time combined with a lower austenitisation temperature leads to a finer microstructure after hot stamping [145].

2.2. Oxidation prevention

Pre-coated steel blanks are preferred for hot stamping because of the omission of removable treatments of oxide scale for non-coated ones, such as shot blasting. Fig. 4 shows an overview of the coating systems, which are actually available for the hot stamping application [4]. Hot-dip Al–Si-coated boron steel is one of the most suitable material systems for direct hot stamping applications in terms of the process stability and the available process window. The Al–Si-coated sheets are usually annealed at temperatures