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Description of microstructures and mechanical properties of boron alloy steel in hot stamping process

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ABSTRACT

Hot stamping process has been increasingly applied for producing automotive parts with ultra-high strength property. Hereby, reduction of car body weight and increasing crashworthiness of new generation vehicles could be simultaneously achieved. In this work, a direct hot stamping of the boron alloy steel was investigated by experiment and FE simulation. Temperature evolutions of blank and dies were gathered during the experiments and verified with FE results. Metallographic analysis, hardness measurement and tensile test were performed for different locations of formed samples. Based on time–temperature–transformation (TTT) diagram, local emerged microstructure constituents and corresponding distributed hardness values of the stamped parts were predicted. Additionally, quenching tests under various media were carried out for the examined boron steel. Determined tensile stress–strain curves from each cooling condition were described using Voce hardening equation. Relationships between hardness and Voce model parameters were established. Then, developed constitutive equations were used in combination with the obtained FE results to evaluate local mechanical properties of hot stamped samples. It was found that calculated stress–strain responses for different areas fairly agreed with those from the experiments.

1. Introduction

Most current demands in the automotive industries are enhancement of passenger safety as well as reduction of vehicle weight regarding energy consumption, which can be effectively realized by applications of ultra-high strength steels (UHSSs) [1]. Hot stamping or so-called press hardening process was firstly developed and patented in 1977 by a Swedish company named Plannja [2]. Later, Saab Automobile AB Hardtech (today Gestamp Hardtech) was the first vehicle manufacturer that used a boron alloyed steel component in the Saab model 9000 in 1984 [3,4]. Hot stamping is an innovative process for manufacturing sheet steel parts with extraordinary high strength. Such press-hardened components in a vehicle are mostly structural elements like A-, B-pillar, bumper, roof rail, and tunnel [5,6]. The number of automotive parts produced by the hot stamping was increased from 3 million parts/year in 1987 to 124 million parts/year in 2010 and most likely go up to approximate 350 million parts/year in 2015 [7].

Mechanical properties, especially so-called tailored properties of components produced by the hot stamping significantly depend on occurred microstructure and its characteristics such as phase fraction, grain size and morphologies. Therefore, in product development process, microstructure evolutions of the boron alloy steel are of great importance for precisely describing performances of any structural parts of a vehicle. In general, phase transformations of steel play a vital role in the hot stamping, which are strongly influenced by temperature distribution of the hot blank. In turn, the temperature development can be controlled by many process parameters like forming cycles, holding time in die, layout of cooling channels and cooling medium. Recently, finite element (FE) analyses have been widely used to design optimized hot stamping process. Cui et al. [8] applied FE simulations for predicting microstructure evolution and tensile strength of hot-formed parts made of the BR1500HS steel grade. The influences of process cycles and holding times on the temperature during the process were examined. A simple relationship between hardness and tensile strength was established. A fully coupled thermo-mechanical FE model was proposed by Cui et al. [9] for a non-isothermal hot forming of boron alloy steel. Phase transformations and resulted microstructure evolutions during the hot forming were described. In addition, the convection heat transfer coefficients

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

C	Si	Mn	P	S	Cr	Ti	B	N
0.2000	0.2000	1.3000	0.0090	0.0050	0.2000	0.0300	0.0014	0.0200

were determined and verified by in air cooling experiments of a flat plate. The significant effects of cooling medium in tools on temperature development in the process were analyzed. Bardelcik et al. [10] investigated the effects of cooling rate on mechanical properties of hardened boron steel under high strain rate conditions. Quasi-static and high strain rate tensile tests using a split Hopkinson machine were performed for miniature dog-bone specimens of the steel cooled under various media. The determined true stress–true strain curves were fitted by the Hollomon equation [11]. It was found that strain hardening rate increased for the specimens quenched at higher cooling rates. The high strain rate conditions also showed a greater hardening rate prior to fracture than the quasi-static one. The contact heat transfer coefficient at different contact pressures and gap distance between part and die was determined through inverse parameter identification in [12]. A phenomenological model was presented for the prediction of flow curves of the boron steel after hot stamping. The distribution of phase constituents occurred during the process was firstly calculated under consideration of the temperature history and a continuous cooling transformation (CCT) diagram. The flow curve model was based on a Hockett–Sherby [13] approach. The model parameters were defined as a function of the phase fractions and cooling rates. Bardelcik et al. [14] determined flow stress curves at four strain rates between 0.003 s^{-1} and 1075 s^{-1} of the boron alloy steel quenched at five different cooling rates. The results were used to develop a constitutive model according to a Voce hardening model [15], which was a function of strain, strain rate, and as-quenched Vickers hardness or area phase fraction. Hereby, a forced-air quenching apparatus was used to realize the cooling rates between 14 °C/s and 50 °C/s, for which the micro hardness values between 268 and 466 HV were obtained and the ultimate tensile strength increased from 816 MPa to 1447 MPa. Eller et al. [16] proposed a constitutive model for quench-hardenable boron steel. The hardness values of the examined steel ranged from 165 HV to 477 HV for the ferritic/pearlitic and fully martensitic microstructure, respectively. The model was based on an extended Swift [17] hardening law and a stress triaxiality and lode angle dependent fracture criterion. A developed tapered tensile test specimen exhibiting a hardness transition zone was used to verify the model.

For a more accurate design of press-hardened components with tailored properties, relationships between through-process parameters and resulted product performance must be clearly provided. In this work, approach for predicting local mechanical properties of a hot stamped sample under consideration of temperature, cooling rate and correspondingly occurred phase transformations was introduced. A combination of FE simulations and empirical model was applied. Initially, direct hot stamping tests of a hat shape sample were performed for the conventional boron alloy steel grade 22MnB5. Metallography analyses, hardness measurements and tensile tests were carried out for different areas of the hot-formed samples. Additionally, thermo-mechanical FE simulations of the hot stamping test were conducted. Hereby, phase transformations during hot forming and cooling of the boron steel were described using a corresponding TTT diagram. Afterwards, local temperature distribution, microstructure evolution and resulted hardness of the formed parts were calculated and verified with the experimental results. In parallel, quenching tests by different media and subsequent tensile tests were carried out for the examined steel. The relationships between cooling rates, hardness and strain hardening parameters were established according to the Voce model. Plastic stress–strain responses of different locations of the formed samples were described on the basis of phase transformation and hardness resulted by the FE simulations. Finally, local yield stresses and tensile strengths of the hot stamped part could be predicted with regard to any occurred or applied cooling processes according to product design. This presented approach will be useful for manufacturing process optimization of vehicle part maker.

2. Material characteristics

The main factor that affected mechanical properties of hot stamped parts was the final emerged microstructure. Here, the commercial boron alloy steel sheet grade 22MnB5 with an initial thickness of 1.4 mm was investigated. The chemical composition of the examined steel was given in Table 1. The as-received steel showed homogenously distributed ferritic–pearlitic microstructure, as depicted in Fig. 1(a), in which ferrite appeared in bright gray and pearlite in dark gray. Furthermore, on the surface of the boron steel sheets an aluminum–silicon layer was observed, as demonstrated by the cross section image in Fig. 1(b). This layer protected material from oxidation and decarburization during forming at high temperature [18]. Basically, the aluminum–silicon coating layer of the examined boron steel contained two separate deposits. From SEM/EDS analyses, it was found that the first outer

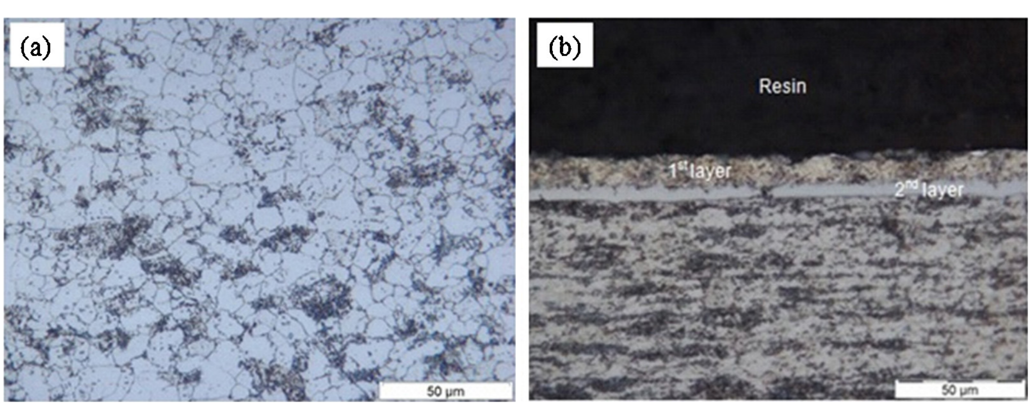

Fig. 1. (a) Microstructure and (b) cross section of the investigated boron steel.