Materials and Design 94 (2016) 424–432

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

An introduction to medium-Mn steel: Metallurgy, mechanical properties and warm stamping process

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ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form 10 January 2016
Accepted 12 January 2016
Available online 14 January 2016

Keywords:
Medium-Mn steel
Third-generation automotive steel
Hot stamping
Warm stamping
Design of experiment

ABSTRACT

The medium-Mn steel with M^3 characteristics (multi-phase, multi-scale, meta-stable) is a promising third-generation automotive steel. Its chemical composition, microstructure, thermal and mechanical properties are introduced and a warm stamping process for the medium-Mn steel is proposed. The optimal process parameters are identified through mechanical testing and microscopic analysis to achieve balanced properties of hardenability, hardness, strength, elongation and fracture behavior. The optimal forming process consists of an austenitization temperature of 790–840 °C, a soaking time of 4–7 min, an initial stamping temperature of 450–500 °C, and a cooling rate of 10–60 °C/s. A typical automotive structural part B-pillar was stamped using the proposed process and the final part exhibits ultrafine martensite-lath microstructure and desired mechanical properties for intrusion prevention and energy absorption.

1. Introduction

The application of advanced high strength steels has become a major concern in automotive industry to improve the vehicle's fuel economy, exhaust emissions and safety. The literature review by Karbasian and Tekkaya [1] showed that hot stamped automotive structural parts not only increase the vehicle's crashworthiness and dimensional quality, but also help weight reduction. Hot stamping is a complex manufacturing process for sheet metal parts, which integrates shape forming and die quenching into a single operation and achieves precise dimension, high rigidity, and complex geometry of the formed parts. The applications of hot stamping process in global automotive industry are expanding rapidly.

Unlike cold stamping of conventional high-strength steels, hot stamping of boron steel involves heating and quenching which cause phase transformation. The proper control of phase transformation is a critical aspect of the hot stamping process. The widely adopted hot stamping process for 22MnB5 steel is: heat the blank to 900–950 °C for complete austenitization and then transfer it to water-cooled dies for stamping, followed by quenching at a cooling rate no less than 30 °C/s [1].

Merklein and Lechler [2] investigated the temperature-dependent formability of 22MnB5 steel. Abbasi et al. [3] reported a tensile strength of about 1500 MPa of hot stamped 22MnB5 steel. Zhao et al. [4] showed high hardness and minimum springback of a hot stamped automotive structural part. However, it was found from all these studies that the total elongation of hot stamped 22MnB5 steel was limited to less than 7%, which was difficult to further improve.

Tailored tempering of 22MnB5 and other alloys have been used recently in hot stamping to produce automotive body-in-white components with a combination of strong and soft properties. Liu et al. [5] achieved tailored properties of 22MnB5 through the control of air cooling rate. Rasera et al. [6] carried out experiments of direct contact heating on Usibor 1500P to obtain desired properties through nonuniform austenitization during the heating stage. Marten et al. [7] presented partial hardening of a new type of press hardenable steel MBW 1400.

As a promising third-generation automotive steel, the medium-Mn steel is drawing more and more attention. Shi et al. [8] experimentally proved the enhanced work-hardening behaviors and mechanical properties of ultrafine-grain steels with large-fractioned metastable austenite. Wang et al. [9] utilized a quenching and partitioning process on low alloy steel to obtain a multi-phase microstructure that consists of initial martensite, fresh martensite and retained austenite.

Han et al. [10] reported hot stamping of a medium-Mn steel containing 5–12 wt.% of manganese at temperatures between 780 and 850 °C. The hot stamped medium-Mn steel exhibits 1800 MPa tensile strength and over 10% total elongation, but the yield strength is only 915 MPa, which is about 150 MPa lower than the yield strength of hot stamped 22MnB5 steel. Rana et al. [11] investigated a cold rolled medium-Mn steel containing 9.67 wt.% of manganese by continuously annealing the steel at 650–800 °C followed by a hot stamping process with

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http://dx.doi.org/10.1016/j.matdes.2016.01.048
0264-1275/

reheating to 650–800 °C. Excellent tensile strength of 1330–1488 MPa and total elongation of 16.7–25.3% were obtained by reheating at 700 °C in the hot stamping cycle, however the yield strength is only 490–793 MPa. Yi et al. [12] presented a medium-Mn steel containing 5–8 wt.% of manganese that was tempered at 250 °C for carbon partitioning after going through a hot stamping cycle with an austenitization temperature of 760 °C and a soaking time of 10 min. The final mechanical properties achieved by this two-step process include 1400 MPa yield strength, 1880 MPa tensile strength and 16% total elongation.

The medium-Mn steel presented in this paper has multi-phase, multi-scale, meta-stable characteristics and is suitable for both room temperature stamping and elevated temperature stamping. The as-received steel exhibits 500 Mpa yield strength, 720 MPa tensile strength and 45% total elongation in room temperature stamping. The final properties of this steel after going through a typical hot stamping cycle include 1220 MPa yield strength, 1440 MPa tensile strength and 12% total elongation. An existing hot stamping production line is ready to stamp this medium-Mn steel since neither pre-annealing nor post-tempering is needed.

Relative to a typical hot stamping temperature of 700 °C or higher, this medium-Mn steel is best stamped at a temperature of 500 °C or lower. The process herein is referred to as warm stamping to highlight the reduced stamping temperature. The effects of the process parameters such as austenitization temperature, soaking time, initial stamping temperature and cooling rate on the strength, ductility and hardness of the medium-Mn steel were evaluated. The optimal process parameters were validated through the stamping of an automotive B-pillar. The formability, microstructure and mechanical properties of the warm stamped B-pillar were analyzed.

2. Material and experimental setup

2.1. Material

The medium-Mn steel used in this study was developed by the Central Iron and Research Institute of China. For comparison, the conventional 22MnB5 steel was also investigated. Their chemical composition (wt.%) is shown in Table 1.

The basic process of producing the medium-Mn steel is to quench the prototype steel to obtain a martensite microstructure first and then anneal the quenched steel in the bipolar region (Ac1–Ac3) for austenite reversion transformation to obtain a multi-phase microstructure that consists of austenite, ultrafine ferrite and precipitated phase. A critical aspect of the process is the rigorous temperature control required by the ART (austenite reversion transformation) annealing. The annealing time varies from 2 to 6 h depending the content of C and Mn, and the desired mechanical properties such as yield strength, tensile strength and elongation.

Microstructures of cold rolled 0.1C5Mn steel specimens were evaluated with scanning electron microscopy (SEM, S-4300), transmission electron microscopy (TEM, H-800) and electron back scattered diffractions (EBSD) in field-gun SEM (Quanta650 EBSD/FG-SEM). The scanning step is 0.01 μm. For the microstructure observation in SEM, samples were ground and polished mechanically, and then etched by 2% nital for 30 s. For the microstructure examination in TEM and EBSD, samples were firstly ground mechanically to a thickness of about 0.04 mm, and then electro-polished in a twin-jet machine in a solution of 5% perchloric acid and 95% alcohol at about −20 °C.

2.2. Experimental procedure

The uniaxial tensile tests were conducted on a Gleeble 1500-D machine under a vacuum condition of 1.0×10^{-4} Pa for the two tested steels (medium-Mn steel and 22MnB5 steel) at elevated temperatures. The dimensions of the dog-bone type specimen is shown in Fig. 4. The thickness of the medium-Mn steel specimens is 1.8 mm, while the thickness of the 22MnB5 steel specimens is 2.0 mm. The specimen was designed according to the International Standard ISO 6892-2: Metallic materials — Tensile testing — Part 2: Method of test at elevated temperature [13]. The space constraint of the testing equipment and the gripping mechanism were taken into consideration as well. The specimens were prepared by EDM (electrical discharging machining).

The non-isothermal forming experimental procedure is as follows. The dog-bone shape specimens were heated to their corresponding austenitizing temperatures at a heating rate of 10 °C/s, specifically 850 °C for the medium-Mn steel and 950 °C for the 22MnB5 steel, to get a fine and homogenous austenite microstructure. The heated specimens were held for 5 min and then stretched at a strain rate of 0.05/s at different elevated temperatures: 350–700 °C at intervals of 50 °C for the Medium-Mn steel and 550–900 °C at intervals of 50 °C for the 22MnB5 steel, respectively. The stretched specimens were finally quenched to room temperature. Three samples were tested and recorded for each scenario after a stable testing process was established. All specimens were stretched to fracture and the fracture surface was observed using a SEM S-4300 at magnifications of 500, 1000 and 500, respectively. The cross-sectional area reduction at the fracture location was measured using an electronic caliper.

2.3. Design of experiments

The method of the design of experiments (DOE) can explore the entire process parameters through a small number of experiments. Fu and Mo [14] used the DOE method to predict the springback of high-strength sheet steel under air bending forming. Ying et al. [15] used the DOE orthogonal analysis to evaluate the strength and toughness of hot-stamped high strength steels. The DOE method can also based on numerical simulations. Cui et al. [16] used finite element simulations to predict the microstructure distribution and mechanical properties of boron steels during hot forming.

Chang et al. [17] conducted an orthogonal experimental design on the key process parameters of warm stamping medium-Mn steels. The chosen factors are austenitization temperature, soaking time, forming temperature, and cooling rate. The austenitization temperature affects the grain size of austenite. The soaking time affects the uniform distribution of austenite grains and further affects the mechanical properties. The forming temperature affects the strain-hardening capability, total elongation and martensite microstructure. The cooling rate governs the phase transformation and eventually affects the hardness and strength. The preliminary optimization results were further investigated in this study, including fine tuning of the process parameters and physical explanations of how the process parameters influence the desired mechanical properties of medium-Mn steel parts.

Table 1
Chemical compositions of the experimental steels (wt.%).

Type of steel	C	Mn	P	S	Al	Si	Ti	B	Fe
Medium-Mn	0.08–0.2	4.0–7.0	0.013	0.03	0.03	–	–	–	Balance
22MnB5	0.22	1.58	0.064	0.014	–	0.81	0.022	0.0024	Balance