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A method to evaluate the formability of high-strength steel in hot stamping

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ABSTRACT

Hot stamping is an innovative operation in metal-forming processes that almost completely prevents the cracking and wrinkling of high-strength steel (HSS) sheets. The examination of HSS defects using traditional forming limit diagrams (FLDs) is challenging. In this paper, we have used a new FLD, termed 3D FLD, which considers phase transformations (PT), to evaluate the formability of HSS in hot stamping. A numerical model of the hot stamping process was developed to predict the major and minor strain distributions in hot-stamped components. The effect of blank geometry on forming quality and other main process parameters, such as stamping velocity and forming temperature, were investigated. The measured thicknesses of typical points near the crack position agree well with those of the simulated points. These results confirm that the simulation strain was relatively accurate. Cracking and wrinkling can therefore be predicted accurately using the proposed 3D FLD. The blank was found easy to avoid rupture with optimized process parameters and die parameters. Traditional wrinkling criteria can be used to predict the wrinkling of formed parts within engineering error.

1. Introduction

Users prefer an increased sheet metal thickness and crashing strength to ensure vehicle safety. High-strength steel (HSS) components can therefore compete with mild steel components because of their high strength/weight ratio and crashworthiness. However, their manufacture is difficult because of the lower ductility and more severe springback [1,2]. Hot stamping is an innovative operation in metal forming that can be used to avoid the formation of these defects. To preclude cracking and wrinkling of HSS sheets in hot stamping, criteria for the evaluation of sheet metal formability are required.

A forming limit diagram (FLD) serves as an effective tool to describes how much the material can be deformed without cracking [3,4]. The FLD is a convenient tool for use in cold stamping, but is ineffective in hot stamping because of temperature [5]. In hot stamping, the interaction between hot blanks and cool dies results in a nonuniform temperature distribution in the formed part. Material formability is influenced significantly by temperature during deformation [6,7]. Therefore, forming limit curves (FLCs) at room temperature are insufficient to evaluate effectively the formability of a part formed by hot stamping.

One way to evaluate the formability of a hot stamped part is by thinning. In industry applications, a stamped HSS part with a thinning exceeding 15% is usually considered to be scrap. However, an evaluation of formability merely by thinning is not only inadequate but is also inaccurate where sheet material parameters are not considered. Another method to evaluate the formability of hot stamped parts is to use a FLD at elevated temperature [8]. In general, FLDs used in hot stamping consist of several FLCs obtained under isothermal conditions. The Nakazima test developed by Nakazima et al. [9] is a standard experiment that provides information on the formability of sheet material because of its simpler performance. Dahan et al. [10] developed a robust method to determine the critical strain values based on the Bragard method. The critical strain values have been confirmed and a few industrial parts for various process conditions have been compared. Holmberg et al. [11] developed a test procedure for determining the forming limit in plane, which is carried out in a tensile testing machine.

To obtain the FLCs of HSS using Nakazima tests or other experiments requires linear strain paths and is time-consuming. Therefore, empirical methods based on a calculation of FLC from

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mechanical property data have been popular for many decades [12]. Abspoel et al. [13] derived a new predictive equation from statistical relationships between measured FLC points and mechanical properties, and obtained a better result than Gerlach et al. [14]. Min et al. [15], who proposed a prediction model for hot forming limits of steel 22MnB5, observed that the result was better than that established based on M–K theory. Ghazanfari and Assempour [16] proposed an empirical law in terms of sheet thickness, from which it is possible to determine the FLD in the absence of experimental data. Kim et al. [17] reported that formability of high strength steel can be predicted using various constitutive models, which were evaluated experimentally.

Previous studies on the FLD of hot stamping were focused mostly on isothermal problems at variable temperature. Non-isothermal problems encountered during stamping have been neglected [18]. Hora et al. [19] and Shi et al. [20] established a FLD by considering the temperature effect, which only covers the strain state for 500–900 °C, whereas the FLD below the phase transformation (PT) temperature is not taken into account. Their FLD does not conclude the prediction of wrinkle phenomena. However, martensitic transformation may occur with the part under extreme conditions such as high pressure or cooler surroundings, which will increase the stress disequilibrium intensively and result in a high possibility of crack formation. Existing papers, such as [21,22], consider phase transformations (PT) during forming, whereas these studies focus on transformation-induced plasticity steel or strain induced martensitic formation, and the establishment of the FLCs below the phase transformation temperature is not well understood. Meanwhile, wrinkling is an important factor that affects the surface quality for the stamped part, and should be avoided [23]. Therefore, it is necessary to establish a new forming limit by considering the temperature effect and wrinkles in a hot forming process.

We have proposed a novel FLD that includes temperature and martensitic transformation effects. The FLD establishment methodology was divided into four steps. In the first step, serials of FLCs of steel 22MnB5 at elevated temperature are obtained based on the Nakazima test and a predicted model. A three-dimensional (3D) limit surface is established using these FLCs. Second, Pam-Stamp-2G software is used to obtain major and minor strains for variable process parameters. Third, these strains are substituted into the 3D FLD, to judge partial cracking or safety by considering the strain above or below the limit surface. Wrinkling can also be predicted using the 3D FLD. Finally, to verify the new FLD, experiments are carried out on a B-pillar part under various process conditions. The proposed method for establishing 3D FLD can also be used for other steels with the Nakazima experiment and tensile tests under various temperatures.

2. Materials and method

2.1. Materials

Commercial 22MnB5 boron alloy sheets were used (1.5 mm thick, Arcelor Corporation). Chemical compositions of the steels studied are given in Table 1. Initially, the received material exhibits a ferritic–pearlitic microstructure with a yield and tensile strength of 457 and 608 MPa, respectively. The yield and tensile strength of the blank have been enhanced significantly with firstly heated to 950 °C for 5 min and then cooled with a cooling rate of 25 °C/s as shown in Table 2.

In order to obtain the constitutive relation of the material, thermal tensile tests are performed using Gleeble 3800. In general, different gripping systems are available, e.g. wedge grips, parallel grips, shoulder grips, etc. At higher temperatures ($T > 250$ °C) wedge grips and parallel grips may be problematic. Therefore, the test pieces were gripped with a bolt at the shoulders as illustrated in Fig. 1.

Table 1
Chemical compositions of 22MnB5 (wt.%).

C	Si	Mn	N	Ni	Cr	Ti	B	Al
0.23	0.22	1.18	0.005	0.12	0.16	0.04	0.002	0.03

Table 2
Mechanical properties of 22MnB5.

Martensite start/finish temperature (°C)	Yield strength (MPa)		Tensile strength (MPa)	
	As received	Hot stamped	As received	Hot stamped
410/220	457	1010	608	1478

The Gleeble-3800 can heat test specimen by resistance which is fitted on the grips. Two compressed-air nozzles are integrated, and can supply the cooling rate of 80 °C/s. In the experiment, the specimens were first austenitized at 950 °C for 180 s, subjected to a cooling rate of 80 °C/s to the given temperature, and then tested. The temperature–time history for the specimens is shown in Fig. 2.

During the isothermal tensile test, the load–stroke curves were converted into engineering stress–strain curves and the true stress–true strain curves were obtained experimentally. The true stress–strain curves shown in Fig. 3 indicate that temperature has a significant influence on the forming behavior of the test material. Increasing the temperature leads to a reduction in stress level and a decreasing work hardening exponent. Because of the high temperature during heating, the metal experiences deformation and recovery, and the reverse processes of work hardening and softening occur. The stress variation tends to be steady with increasing strain on the stress–strain curve. Thus, it can be concluded that this is a dynamic recovery process as confirmed by literature. At 20–300 °C, the true stress increases rapidly as the true strain increases because of martensitic transformation.

The flow curves at 500 °C, 650 °C, and 800 °C for three different strain rates are shown in Fig. 4. The strain rate has a strong influence on material forming behavior. In general, an increase in strain rate leads to a significant increase in stress level with progressive strains.

2.2. FLC setup

To obtain the forming limit curves of 22MnB5 at different temperature, we break it up into two phases, one is above the phase transformation point, and another is below oppositely. The former one can be obtained through Nakazima test, and the other one can be calculated by tension test and empirical formula.

FLCs above 400 °C were obtained by the Nakazima setup as illustrated in Fig. 5. The axisymmetrical setup consisted of a hemispherical punch, a die, a blank-holder, and a draw-bead, which prevents sliding motion. Several parameters were recorded, such as the punch load and local temperature history. In the experimental work, all specimens were prepared in the rolling direction with wire-electrode cutting. The width of the specimens varies from 20 mm to 180 mm with an increment of 20 mm, and with the length of 180 mm. 2 mm circle grids were etched on the blank and allows for the determination of strain distribution using pattern recognition systems.

Before the test, specimens together with the molds were heated using resistance heating, to make sure that the temperature of the