Prediction of necking & thinning behaviour during hot stamping conditions of 22MnB5 steel

Amarjeet Kumar Singh, K. Narasimhan
Department of Metallurgical Engineering and Materials Science
IIT Bombay, Mumbai, Maharashtra, 400076
Email: - nara@iitb.ac.in

Abstract. Hot stamping is a high-temperature forming operation in which the blank is heated to austenitization temperature, and subsequent forming and quenching operations are done simultaneously. In the current research, forming limits were determined using a thickness gradient-based criterion. For this purpose, the tensile and plane strain mode of deformation were considered. The study was carried out in a wide range of temperatures, viz. 750 °C, 800 °C and 850 °C at a constant strain rate of 0.01/s. The experiments were carried out in the thermomechanical simulator (Gleeble-3800), and subsequent measurement of thinning evolution for all the deformed specimens were carried out. It was observed that with the increase in temperature, thickness reduction was less and the distribution of thickness was uniform in tensile specimens and at the point of necking thickness gradient ratio is below 0.92 at various temperatures.

Keywords: Hot Stamping, Thickness Gradient Criteria, Thinning Predictions, High-Temperature Tensile Test

1. Introduction
Due to various advantages associated with the hot stamping process, demand for hot stamped components has increased in the automotive industry[1]. The major challenge faced in hot stamping process is poor understanding of formability because of the involvement of high temperature and high strain rate process (typically forming temperature range is between 750 °C and 850 °C and velocity of punch is approx. 100 mm/s). Determination of formability is usually done with the help of limit dome height test at room temperature, but in case of hot stamping process deformation generally takes place at high temperature with simultaneous cooling and under such conditions specific cooling rate and maintaining the temperature is quite difficult. Ghiotti et al.[2] and Merklein et al.[3] tried to determine the formability experimentally [4-7] by using modified Nakazima setup, but the difficulty in this system was the achievement of exact temperature, cooling rate and velocity of punch[8], during the test. In this study, we use the thermomechanical simulator to overcome these problems. In this study, a series of the experiments were performed on the thermo-mechanical simulator to determine constitutive behaviour of material at a wide range of experimental conditions. Measurement of forming limit strain was done with the help of thickness gradient-based necking criterion. In addition to that, the thickness distribution of the specimen was also measured.

2. Experimental Procedure
2.1 Material Used
The material used in this study was coated 22MnB5 steel with the sheet thickness of 2.4 mm, chemistry and mechanical properties of the material are given in Table 1 & 2 respectively in as received condition.
Table 1. Chemistry of coated 22MnB5 Steel in as received condition

| Chemistry of Coated 22MnB5 Steel (Wt. %) |   Al  |   B   |   Cr  |   Cu  |   Mn  |   Ni  |   Si  |   P   |   Ti  |
|-----------------------------------------|------|------|------|------|------|------|------|------|------|
|                                         | 0.108| 0.003| 0.163| 0.063| 1.17 | 0.0055| 0.23 | 0.013| 0.018|

Table 2. Mechanical Properties of Coated 22MnB5 Steel in as received condition

| Mechanical Properties before Hot Stamping | Yield Stress | Tensile Stress | Total Elongation |
|------------------------------------------|--------------|----------------|------------------|
|                                          | 352MPa       | 530MPa         | 24.25%           |

2.2 Gleeble Test

Tensile test was performed on the thermomechanical simulator in the temperature and cooling rate-controlled mode. A thermomechanical process cycle was designed based on the work done by Sarawagi[9]. Different strain paths were generated using tensile specimen with notch and without notch. The tensile specimen with notch gives plane strain mode of deformation whereas, one without notch gives uniaxial mode of deformation. Dimensions of these specimens are shown in figure 1. The specimens were engraved with a laser mark to measure strain distribution under deformed conditions. Measurement of thickness was done with the help of Rapid-I optical measuring instrument. Experiments were performed at temperatures 750 °C, 800 °C and 850 °C while strain rate was kept constant at 0.1/s, the heating rate is 10 °C/s and cooling rate is 30 °C/s as shown by the process cycle in figure 2.

Figure 1. Dimensions of simple & notch tensile specimen

Figure 2. Thermo-mechanical process cycle in Gleeble system at 0.1/s
Temperature distribution in specimen depends upon grip used in Gleeble 3800 [10]. In the present study, half grip was used which provides 10 mm gauge length heating. To measure the thickness distribution in tensile geometry, homogenous temperature is desired. In general, homogeneous temperature distribution is achieved in 10 mm gauge length during the experiment; the thickness distribution is measured under the same gauge length.

3. Results and Discussion
Flow behaviour (True stress vs true strain) of 22MnB5 steel for different temperatures is shown in figure 3. It is observed that with the increase in temperature, there is a reduction in flow behaviour of the material, which is due to softening occurring at higher temperatures. Load vs displacement curve with notch and without notch tensile specimens are shown in figure 4. It can be observed that, in case of notch tensile specimen, both load and elongation reduce because of stress concentration and triaxiality induced in notch specimen [11].

![Figure 3. True stress vs true strain behaviour at different temperatures for tensile specimen without notch](image1)

![Figure 4. Load vs elongation curve at different temperature under notch (plane strain) and without notch tensile specimen at a constant strain rate](image2)

3.1 Thickness distribution
Determination of thickness was done with an interrupted tensile test at various points, namely, before the initiation of necking, at the point of necking and at fracture. Thickness distribution before the initiation of necking, at the point of necking and at fracture for notch and tensile specimens are shown in figure 5 & figure 6 respectively.

During progressive deformation, thickness of the specimen reduces, and severity of strain localization at the centre is more as shown in figures 5 and 6. At higher temperature, the thickness reduction is less as compared to lower temperature because softening is more at higher temperature. It is found that uniform thickness distribution in case of high temperature and severity of localization is less compared to lower temperature as shown in figure 10.
Figure 5. Thickness distribution before the initiation of necking, at the point of necking and fracture at 850°C in simple tensile specimen.

Figure 6. Thickness distribution before the initiation of necking, at the point of necking and fracture at 850°C in Notch tensile specimen.

Figure 7. (a) Circles on sheet metal part before deformation and after deformation (b) thickness distribution in tensile specimen

3.2 Necking criterion validation

In the previous study on different necking criteria in simulation of 22MnB5 steel under hot stamping condition, it was found that thickness-based necking criterion gave better result as compared to other necking criteria[12] and it is also simple to use.

Thickness gradient necking criterion: Consider a sheet metal part having nine circles in deformed region as shown in figure 7(a), assumed that there are three circles in a row (i-1th, ith, i+1th) having thickness \( t_0 \) before deformation, at start of necking average thickness of these circles \( t_{i-1}, t_i, t_{i+1} \) respectively as shown
in figure 7(b). When the ratio of two adjacent elements in that row reaches below a critical value, then necking is defined to have occurred. The necking criteria have been represented in mathematical form as below

\[ R_{\text{thickness gradient}} = \frac{\text{current thickness of necking element}}{\text{current thickness of adjoining element}} \leq R_{\text{cri}} \]

As mentioned earlier, interrupted tensile tests were performed at different temperatures, and measurement of thickness was performed for all the specimen as shown in figure 8. The tricky part was to measure the thickness after the test so a procedure developed by Nandedkar et al.[13,14] was used to measure the average thickness. Figure 9(a) shows the variation in the measured thickness and figure 9(b) shows the thickness gradient across the minimum thickness location. It was found that when the thickness gradient was below 0.92, necking occurred at different temperatures as shown in figure 11.

**Figure 9.** (a). Thickness distribution vs distance from minimum thickness element at 850°C  
**Figure 9.** (b). Thickness gradient vs distance from minimum thickness or necked element at 850°C
4. Conclusions
In this paper thickness-based necking criteria is validated at high temperature, under different deformation conditions and thickness distribution is measured under these conditions. The validation of thickness gradient criterion at high temperature is the significant outcome of this work. This will enable us to predict the formability under hot stamping condition for 22MnB5 steel. Furthermore, the flow stress behaviour of 22MnB5 steel under the hot deformation condition is observed to be dependent on temperature. Future scope of our work is to find how thickness distribution, thickness gradient at the onset of necking varies with strain rate for different strain paths. The above study can be summarized as follows:

i. An increase in temperature reduces the flow behaviour of the material.
ii. Value of thickness gradient at the point of necking is observed to be below 0.92 for high-temperature deformation. This validates the applicability of the thickness gradient criterion for hot stamping applications.
iii. During progressive deformation, both thickness reduction and severity of localization at the centre are more.
iv. At higher temperature, thickness reduction is less, thickness distribution is uniform, and the severity of localization is less as compared to lower temperature.

References
[1] H. Karbasian and A. E. Tekkaya, “A review on hot stamping,” J. Mater. Process. Technol., vol. 210, no. 15, pp. 2103–2118, 2010.
[2] A. Turetta, S. Bruschi, and A. Ghiotti, “Investigation of 22MnB5 formability in hot stamping operations,” J. Mater. Process. Technol., vol. 177, no. 1–3, pp. 396–400, 2006.
[3] M. Merklein and J. Lechler, “Investigation of the thermo-mechanical properties of hot stamping steels,” J. Mater. Process. Technol., vol. 177, no. 1–3, pp. 452–455, 2006.
[4] A. Turetta, A. Ghiotti, and S. Bruschi, “Optimization Of Nakazima Test At Elevated Temperatures,” AIP Conf. Proc., vol. 907, no. 2007, pp. 223–228, 2007.
[5] P. F. Bariani, S. Bruschi, A. Ghiotti, and A. Turetta, “Testing formability in the hot stamping of HSS,” CIRP Ann. - Manuf. Technol., vol. 57, no. 1, pp. 265–268, 2008.
[6] D. Pellegrini, J. Lechler, A. Ghiotti, S. Bruschi, and M. Merklein, “Interlaboratory Comparison of Forming Limit Curves for Hot Stamping of High Strength Steels,” Key Eng. Mater., vol. 410–
411, pp. 297–304, 2009.

[7] Y. Dahan, Y. Chastel, P. Duroux, P. Hein, E. Massoni, and J. Wilsius, “Formability investigations for the hot stamping process,” Iddrg 2006, p. 8, 2006.

[8] R. S. Lee, Y. K. Lin, and T. W. Chien, “Experimental and theoretical studies on formability of 22MnB5 at elevated temperatures by Gleeble simulator,” Procedia Eng., vol. 81, no. October, pp. 1682–1688, 2014.

[9] V. Sarawagi, “Forming Limits in Hot Stamping,” Master’s Thesis, Indian Institute of Technology, Bombay, 2016

[10] Gleeble 3800 user manual, dynamic system inc, 1998-2007, pp 34-48

[11] William D. Jenkins and William A. Willard, Effect of Temperature and Notch Geometry on the Tensile Behavior of a Titanium Alloy, JOURNAL OF RESEARCH of the National Bureau of Standards - Co Engineering and Instrumentation Vol. 70C, No. 1, January- March 1966

[12] Veerangana Sarawagi, Sudhanshu Narkhede, Amarjeet Kumar Singh & K Narasimhan, “Formability studies on 22MnB5 steel during hot stamping process conditions,” IOP Conference Series: Materials Science and Engineering, vol 418, 2018

[13] K. Narasimhan, “A Novel Criterion for Predicting Forming Limit Strains,” Materials Processing and Design: Modelling, Simulation and Applications, NUMIFORM 2004, pp. 850855, 2004

[14] V. M. Nandedkar, “Formability Studies on a deep drawing quality steel,” Doctoral Thesis, IIT Bombay, 2001.