Effect of strain rate on formability of 22MnB5 steel during hot stamping process

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 and high strain rate deformation process, which is widely used in automotive industries because of the advantages associated with the process like higher formability, no spring back, higher specific strength to weight ratio etc. When strain rate increases, the formability of materials decreases but in some conditions reversal behavior was also observed, therefore in this work, the focus is to find the effect of strain rate on thickness distribution, thickness gradient evolution and formability of 22MnB5 Steel. To capture the effect of strain rate, a wide range of high-temperature tensile tests were conducted in the thermomechanical simulator (Gleeble-3800) for different strain rates (0.01, 0.1, 1/s) under uniaxial and plain strain conditions. It is found that formability of 22MnB5 steel increases with increase in strain rate in the drawing region.

1. Introduction
In hot stamping process 22MnB5 steel is used for manufacturing of automotive component. 22MnB5 steel is a low carbon boron steel that belongs to Advanced High Strength Steel (AHSS) [1]. AHSS have lower formability at room temperature therefore hot stamping process was used to form this steel into desired shape. In hot stamping process specimen or blank is formed at high temperature and at high velocity. Due to high strain rate and elevated temperature involved in the process, the determination of formability is difficult under such conditions. Percy et al. [2] used strain rate of 10^4 at room temperature and try to find the effect of strain rate on formability and suggested that during increase in strain rate formability of materials is decreases but recently Balanethiram et al. & Gerdooei et al. [3-4] reported formability of copper alloy increased with increase in strain rate at room temperature. Li et al. [5] predicted formability of 22MnB5 steel at different strain rates (0.01/s, 0.1/s, 1/s) and various elevated temperature (600 °C to 800 °C) and found that with increase in strain rate formability increase. Lee et al. [6] performed experimental and theoretical study on 22MnB5 steel using tensile test and reported that forming limit strain under uniaxial condition increases with increase in strain rates (3/s and 9/s) at temperature range of 650 °C to 850 °C, whereas in case of plain strain condition limiting strain value are decreases with increase in strain rate. However, there is no clear understanding of reason behind it therefore in this work details analysis of strain rate effect on formability is carried out in detail. To capture the effect of strain rate, a wide range of high-temperature tensile tests were conducted in the thermomechanical simulator (Gleeble-3800) for different strain rates (0.01/s, 0.1/s, 1/s) under uniaxial and plain strain conditions.
2. Experimental procedure

2.1 Material Used
Uncoated 22MnB5 steel was used in this study received from JSW Pvt. Ltd in hot rolled condition. Chemical composition (weight percentage) and mechanical properties of the 22MnB5 steel are given in Table 1 & 2 respectively. Thickness of sheet specimen used in this study was 1.8 mm.

Table 1. Chemical composition of uncoated 22MnB5 Steel in as received condition (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 uncoated 22MnB5 Steel in as received condition

| Yield Stress | Tensile Stress | Total Elongation |
|--------------|---------------|-----------------|
| 352 MPa      | 530 MPa       | 24.25%          |

2.2 High temperature characterization
Elevated temperature tensile test was performed using thermomechanical simulator (Gleeble-3800). Design of process cycle, as shown in figure 1, was used to simulate hot stamping process cycle at lab scale based on work done by Singh et al. [7-9]. To generate different strain states modification in simple tensile geometry were done as shown in figure 2. Simple tensile geometry (unnotched specimen) gives uniaxial strain condition, whereas notch specimen gives plain strain conditions. Measurement of strain distribution in these geometries were done with the help of laser engraving on surface of the specimen. Thickness distribution of deformed specimen was measured with image processing technique, for which Rapid-I and ImageJ software were used. Experiments were performed at temperatures 750°C, 800°C, 850°C and 0.01/s, 0.1/s, 1/s strain rates respectively.

![Figure 1. Thermomechanical process cycle for high temperature test](image)

![Figure 2. Dimensions (in mm) of unnotched & notch tensile specimen](image)

3. Results & Discussion
Flow behavior of 22MnB5 steel at different strain rate and different temperature is shown in figure 3. It was observed that increase in strain rate (rate of deformation) flow stress of material increases at all
temperature. Increase in temperature softening effect is dominated, therefore stress required at high temperature is low.

![Graphs showing true stress vs true strain at various strain rates (0.01/s, 0.1/s, 1/s) at (a) 750 °C (b) 800 °C (c) 850°C](image)

**Figure 3.** True stress vs true strain at various strain rates (0.01/s, 0.1/s, 1/s) at (a) 750 °C (b) 800 °C (c) 850°C

### 3.1 Thickness distribution

Thickness distribution of deformed specimen was measured using Rapid-I. Interrupted tensile test was performed at elevated temperature under three conditions before necking, at necking and at fracture. At the point of necking, it was found that with increase in strain rate the overall thinning decreased as shown in figure 4. This also indicates that at point of necking more thinning has occurred at higher strain rate.
3.2 Forming Limit strain
Quantification of forming limit strain in drawing region was done by using notch and unnotched tensile geometry as shown in figure 5. Strain was measured with the help of laser grid engraved on the specimen. The undeformed specimen consists of circular grid, after deformation shape of grid was changed according to type of loading. A special design camera CosCam was used to capture image of deformed and undeformed specimen. Change in dimension of captured image was analyzed by using image-J software. Necking strain for these conditions is also determine by using strain value provided by machine itself, but it was found that laser engraving technique give better result therefore in this paper laser engraving method was used for strain measurement.

![Figure 5. Modified tensile geometry for strain measurement](image)

| Table 3. Experimental forming limit value at necking at 800°C |
|-------------------------------------------------------------|
| **Experimental** | **Notch specimen** | **Unnotched specimen** |
| Strain Rate | Major Strain | Minor Strain | Major Strain | Minor Strain |
Measured strain in drawing region is given in Table 3 for uniaxial and plain strain conditions. It was found that formability of material increases with increase in strain rate and temperature as shown in figure 6. Formability depends upon strain hardening exponent (n) and strain rate sensitivity index (m). It was found that at high temperature strain rate sensitivity index (m) have dominated effect than hardening exponent (n). Higher value of sensitivity index (m) indicates higher formability because of delay in localized deformation.

| Strain Rate | Strain at UTS (0.01/s) | Strain at UTS (0.1/s) | Strain at UTS (1/s) |
|-------------|------------------------|-----------------------|---------------------|
| 0.01 /s     | 0.13                   | -0.05                 | 0.22                | -0.17                |
| 0.1 /s      | 0.17                   | -0.06                 | 0.28                | -0.18                |
| 1 /s        | 0.21                   | -0.07                 | 0.33                | -0.19                |

**Figure 6.** (a) Strain at UTS vs strain rate at different temperature (b) Strain at UTS vs temperature at different strain rate

### 3.3 Fracture morphology

Thickness distribution and limit strain clearly support that with increase in strain rate formability of 22MnB5 steel increase. For more detailed analysis morphology of fractured specimen was observed by Scanning Electron Microscope (SEM).
Figure 7. Morphology of fracture surface at different strain rates and temperatures (a) strain rate of 0.01/s at 750 °C (b) strain rate of 0.1/s at 750 °C (c) strain rate of 1/s at 750 °C (d) strain rate of 0.01/s at 850 °C (e) strain rate of 0.1/s at 850 °C (f) strain rate of 1/s at 850 °C.

Fractured morphology of tensile specimen was analyzed for different temperature and various strain rate. In this work two extreme case of temperature at 750 °C and 850 °C are shown in figure 7. Fractured morphology shows ductile fracture behavior for all conditions. It was observed that with increase in strain rate depth and size increased. However, at 850 °C at lower strain rate no visible dimple were seen. Whereas while observing at lower magnification it indicates cup and cone type fracture that indicate ductile type of failure. At higher strain rate more, stress is required for deformation therefore more stress applied for coalescence due to that size of dimple are increased at higher strain rate. At higher temperature (850 °C) post necking strain is low which indicates sudden failure of specimen, therefore in this condition morphology of fracture surface look like a line.

4. Conclusions
In this paper effect of strain rate on thickness distribution, formability, fracture morphology of 22MnB5 steel during hot stamping conditions had been studied. Addition to that true stress vs true strain behavior was analyzed and found that with increase in temperature flow stress is decreases due to softening effect, while flow stress increases with increase in strain rate because of strain rate hardening. Above study can be summarized as below:

a) At higher strain rate, thickness value was less whereas thickness distribution was uniform and severity of localization was less compared to lower strain rate.

b) Formability of 22MnB5 steel increase with increase in strain rate.

c) Fractography study shows that with increase in strain rate depth of dimple increases as well as more dimple are formed.

d) Increase in temperature the area of deformation zone for dimple decreases.

References
[1] H. Karbasian and A. E. Tekkaya, “A Review on Hot Stamping,” Journal of Materials Processing Technology, vol. 210, no. 15, pp. 2103–2118, 2010.

[2] Percy JH, “The effect of strain rate on the FLD for sheet metal”, Annals of CIRP 29:151–152, 1980.

[3] Balanethiram VS, Daehn GS, “Hyperplasticity-Increased forming limits at high workpiece velocities”, Scripta Metallurgica 31:515–520, 1994.
[4] Gerdooei M, Mollaei Dariani B, “Strain rate-dependent forming limit diagrams for sheet metals”, *Journal of Engineering Manufacture* **222**:1651–1659, 2009.

[5] Hongzhou Li, Xin Wu, and Guangyao Li, “Prediction of Forming Limit Diagrams for 22MnB5 in Hot Stamping Process”, *Journal of Materials Engineering and Performance* **22**:2131–2140, 2013.

[6] Rong Shean Lee, Yi Kai Lin, Ta Wei Chien, “Experimental and theoretical studies on formability of 22MnB5 at elevated temperatures by Gleeble simulator”, *Procedia Engineering* 1682 – 1688, 2014.

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

[8] A. K. Singh and K. Narasimhan, “Prediction of Necking & Thinning Behavior During Hot Stamping Conditions of 22MnB5 Steel,” *IOP Conference Series: Materials Science and Engineering*, pp. 3–10, 2019.

[9] A. K. Singh and K. Narasimhan, “Determination and predication of formability on 22MnB5 steel under hot stamping conditions using Gleeble,” *Adv. Mater. Process. Technol.*, vol. **00**, no. **00**, pp. **1**–**13**, 2021.