Formability studies on 22MnB5 steel during hot stamping process conditions

Veerangana Sarawagi, Sudhanshu Narkhede, Amarjeet Kumar Singh and K. Narasimhan
Department of Metallurgical Engineering & Materials Science
IIT Bombay, Mumbai, Maharashtra – 400076

Email: nara@iitb.ac.in

Abstract. Advances in materials and manufacturing processes help in reduction of strength to weight ratio of automotive components which is a significant driver for achieving a reduction in CO₂ emissions and minimize fuel consumption. High strength materials, such as Advanced High Strength Steels have limited formability and exhibit high spring back leading to lower dimensional accuracy. Hot stamping is a thermomechanical forming process which also involves phase transformation. Due to the interaction of thermal, mechanical and metallurgical phenomena during the process, accurate simulation is extremely complex and computationally intensive. The objective of this study is to predict formability of 22MnB5 steel under hot stamping conditions. A series of experiments were carried out on a thermo-mechanical simulator to obtain the constitutive behavior of the material as a function of temperature and strain rate. The Nakazima Test was simulated to obtain Forming Limit Curves at different strain rates and temperatures. As a part of this study, different necking criteria were studied for prediction of limit strain under high-temperature deformation which demonstrated that formability increased with increasing temperature and strain rate.

1. Introduction
In the last few years, there is a rise in the number of components made using the hot stamping process in the automotive industry [1]. Formability analysis is done with the help of forming limit diagrams. Determination of formability at room temperature is well known, but at elevated temperature there is no standard process that exists. Formability depends on temperature, strain rate and microstructure of the deforming component. The objective of the current work is to predict the FLD, using the Gleeble measured tensile properties at different temperatures and strain rates. Different failure criteria were evaluated to choose the one that best predicts available experimental FLD. Using this failure criteria, the FLDs at different temperatures and strain rates are predicted.

2. Experimental Procedure

2.1 Material used
The material used in this study is 22MnB5 coated steel sheet. The chemistry and mechanical properties of the material in as the received condition is given in tables 1 & 2, respectively.
Table 1. Chemistry of 22MnB5 steel used in the present study.

| Material | C   | Si  | Mn  | P   | B   | Cr  | Mo  | S   | Al  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Mass content in wt % | 0.23 | 0.18 | 1.26 | 0.013 | 0.0035 | 0.21 | 0.14 | 0.003 | 0.03 |

Table 2. Mechanical properties of as received 22MnB5 steel.

| YS (MPa) | Tensile strength (MPa) | Elongation (%) |
|----------|------------------------|----------------|
| 442      | 574                    | 25.2           |

2.2 Gleeble Tests
To predict the FLD at different temperatures, it was required to determine the constitutive behavior of the material as a function of temperature and strain rate. A cycle was designed to perform a thermomechanical test using the thermo-mechanical simulator based on work done by Sarawagi [2]. A 22MnB5 steel sample of given dimension as shown in Figure 1 was prepared and the high-temperature tensile test was performed using a Gleeble-3800. Samples were tested at 650°C, 750°C and 850°C at strain rates of 0.01/s, 0.1/s and 1/s. The process followed for the experiments are shown in Samples were tested at 650°C, 750°C and 850°C at strain rates of 0.01/s, 0.1/s and 1/s. The process followed for the experiments are shown in Figure 2. The tabulated true stress – strain data obtained from the Gleeble is used as the constitutive behavior in the simulation for all the combinations of temperature and strain rate for the prediction of the FLD. The Gleeble tests at temperatures equal and above 750°C will have only single phase austenitic structure at all the strain rates. In the combinations of lower temperatures (650°C and 700°C) and lower strain rate (0.01 /sec and possibly at 0.1 /sec at the lowest test temperature of testing conducted), the equilibrium phase transformation to some extent will occur, as can be observed from the corresponding CCT diagram as can be observed in the CCT diagram[3]. However, in the present work, the effect of such phase transformation is assumed to be captured in the true stress strain data measured in such cases and therefore, no separate phase transformation analysis is carried out.

Figure 1. Dimensions of tensile specimen in mm.

Figure 2. Thermal process cycle used in tensile testing using Gleeble system.

3. Results and Discussion
True stress-true strain curves for the steel at different temperatures and different strain rates are shown in Figure 3. It can be seen that there is a definite trend of increase in strength with a drop in temperature (Figure 3(a)). As seen in Figure 3(b), there is also a marked effect of strain rate on flow stress of the steel at high temperature.

3.1 Simulation
The material behavior obtained at different temperatures were used to simulate the Nakazima test [3] using variety of necking criteria to predict the Forming Limit Curve. Experimental FLCs were obtained from the
literature [4, 5]. Mesh size will have an effect on the predicted results. Our previous work has shown [6] that a mesh size of the order of the sheet sample thickness size (1 mm to 2 mm) matches well the experimental results measured on using a similar experimental grid. Therefore, in the present work, a mesh size of 2 mm is used. All the simulations in the present work are carried out using the commercial FEM software, PAMSTAMP-2G. Elastic viscoplastic material model coupled with shell element are used in the present work, enabling interpolation of stress-strain data in simulation as a function of the respective temperature and strain rate of the simulation. Hill 48 Yielding criteria with isotropic hardening behavior was used for simulation.

3.1.1 Necking Criteria. Strain Path-Based Criterion (CRIT 1): This criterion defines the point of onset of necking as the state at which there is a significant change in rate of increase in major strain with time. To determine this point, a linear fit is carried out on the two sections of major strain vs. time plotted as in Figure 4, which shows a significant difference in the slopes. The point where both linear extrapolations intersect is taken as the time for onset of necking. The major and minor strains developed in the necked element at this time are considered to be limiting strain [5].

![Figure 3(a)](image1) True stress-strain behavior at different temperatures

![Figure 3(b)](image2) True stress-strain behavior a different strain rates

Thickness Gradient Criterion (CRIT2): This criterion defines the point of onset of necking as the point at which thickness ratio of an element and its neighbor element drops below a critical value. The critical value for the onset of necking was experimentally determined to be 0.92, thus the earliest state where the thickness gradient between adjacent elements reaches 0.92 is considered to be necking state as shown in Figure 5. The major and minor strains developed in the necked element at this state are considered to be limiting strains as per this criterion [8][9].

Bifurcation Point Criterion (CRIT 3): As the occurrence of plastic instabilities is determined by localized necking with size on the order of the sheet thickness, thickness strain will be used as a local criterion to evaluate the occurrence of necking. If necking occurs, a sharp change of thickness strain can be observed. From the point of necking, there is a sharp change in thickness strain. The onset of necking is considered to be the bifurcation point where two branches of the curve meet as shown in Fig. 6. In case such a point is not clearly observable, third-degree polynomials are fitted in both branches, and their intersection is considered to be the bifurcation point. Strains at the corresponding time in the necked element are considered to be limiting strains [10].

Strain Acceleration Criterion (CRIT 4): This criterion defines the point of onset of necking as one where the rate of increase of major strain is maximum [11]. Deformation evolution is hence defined by first and second order temporal derivatives of major strain. The maximum of strain acceleration i.e. second order temporal derivative of major strain is thus considered to be the point at which onset of
necking takes place. The major and minor strains developed in the necked element at this state are considered to be limiting strains, as shown in Figure 7. The second derivative has been obtained numerically using the central difference method using following formula:

\[
\varepsilon''_{11}(t) = \frac{\varepsilon_{11}(t + \Delta t) - 2\varepsilon_{11}(t) + \varepsilon_{11}(t - \Delta t)}{t^2}
\]

**Figure 4** Strain path based necking criteria

**Figure 5** Thickness ratio vs time variation

**Figure 6** Thickness strain vs time

Section Method Based Criterion (CRIT 5): As a part of this study, an attempt was made to use the experimental necking determination method in numerical simulations. The section method based on Bragard’s modified first derivative method was chosen, as it is most widely used for experimental determination of limiting strains and found to be suitable for determination of limiting strain at high temperature. In the final state, the cross-section of specimen was taken such that it is perpendicular to point of maximum localization. The major Strain was plotted against curvilinear distance on the specimen surface. The first derivative of Major strain against distance was taken. The data points between maxima and minima of first derivative are then deleted and then interpolated by using a sixth-degree polynomial. The maxima of the fitted function are taken to be the limiting major strain and
corresponding minor strain at that location is taken to be limiting minor strain as shown in Figure 8 & 9 [12]. Predictions using these different necking criteria were compared with experimentally determined isothermal FLCs obtained from the literature [4] (Figure 10). The accuracy and prediction were quantified in terms of the square of deviation residual from the experimental curve and the standard deviation of residual squared, as given in Table 3. A lower magnitude of the squared residual would imply a better fit of the simulated curve with the experimental curve while a lower standard deviation would indicate the dependability of the method throughout the region. It is seen from the analysis that CRIT 1 and CRIT 2 fit the experimental curve the best in the range of analysis. However, the standard deviation of CRIT 2 was found to be lower than that of CRIT 1, and hence it was chosen for further analysis in this work. Furthermore, it has advantage of ease of applicability as compared to other criteria.

| Table 3. Fitting of experimental FLC with calculated FLCs. |
|-----------------|----------------|----------------|----------------|----------------|----------------|
| Criterion       | CRIT 1         | CRIT 2         | CRIT 3         | CRIT 4         | CRIT 5         |
| Mean of square error residual from experimental curve squared | 0.005          | 0.007          | 0.016          | 0.063          | 0.011          |
| Standard deviation of distance from experimental curve squared | 0.073          | 0.067          | 0.007          | 0.035          | 0.009          |

3.2 Prediction of Forming Limit

3.2.1 Variation of Forming Limit Curves with temperature. All FLCs show similar behavior where the FLC shifts up with an increase in temperature. To better analyze the FLC’s, quantification of FLC’s based on a methodology of Omar et al.[13] has been done. It quantifies the FLC in terms of three parameters, FLC₀, FLCₐ, and FLCₐ. FLC₀ describes the plane strain condition and is equal to the major strain when the minor strain is zero. FLCₐ is calculated as the slope of line joining the extrema of FLC in drawing region and FLC₀. It indicates the drawability of the material. Higher the FLCₐ, higher is the formability in drawing region. Similarly, FLCₐ is calculated as slope of line joining the extrema of FLC in stretching region and FLC₀. It indicates the stretchability of the material. Higher the FLCₐ, higher is the formability in stretching region. The FLCₐ increases considerably with an increase in temperature. The increase in FLCₐ seems to be lower in case of strain rate of 1/s. However, it may be due to the fact that the increase in FLC₀ is found to be highest in this case and since it is used as a reference point in calculation of FLCₐ, obtained value may underestimate the actual increase in formability with temperature as shown in Figure 11 and table 4. Transient FLD which is constructed by stacking a large number of isothermal FLCs in a single graph and arranging them according to the temperature on the third axis. In this way, a 3D surface was achieved that is representing limiting strain values at a particular temperature (see Figure 12).
3.2.2 Variation of Forming Limit Curves with strain rate. In order to capture the effect of strain rate on formability, isothermal FLCs were constructed at all three strain rates at temperatures of 650°C, 750°C and 850°C. A trend of an upward shift in FLCs is observed with increase in strain rate as shown in Figure 13 and table 4. It is seen that percentage change in all cases in FLC_R is much higher than that in FLC_L indicating higher dependence of strain rate on formability limits in stretching region than in drawing region.

| Table 4. Analysis of variation of FLC. |
|--------------------------------------|
| | 650°C | 750°C | 850°C | Change% |
| 0.01/s | FLC₀ | 0.4356 | 0.4656 | 0.4807 | 9.382151 |
| | FLC_L | -0.98414 | -1.04 | -1.08785 | 9.533163 |
| | FLC_R | 0.117105 | 0.360606 | 0.447338 | 73.82177 |
| 0.1/s | FLC₀ | 0.4579 | 0.4781 | 0.4962 | 7.718662 |
| | FLC_L | -1.04089 | -1.07725 | -1.09796 | 5.197688 |
| | FLC_R | 0.105567 | 0.416202 | 0.529174 | 80.05067 |
| 1/s | FLC₀ | 0.4858 | 0.5341 | 0.5554 | 12.53151 |
Figure 11. Variation in FLD with temperatures.

Figure 12. Transient FLD.

Figure 13. Variation in FLD with strain rate.

4. Conclusions

• The thickness gradient criterion is able to predict FLC’s at high temperature with better accuracy than other criterion considered in the present work.

• A definite trend of upward shift of forming limit curves is seen with increase in temperature and strain rate.

• At all temperatures and strain rates, \( FLC_L \) increases with increase in strain rate and temperature. \( FLC_L \) does not get significantly affected by strain rate and temperature whereas in case of \( FLC_R \) there is no clear trend being observed and further analysis is needed to understand such discrepancy.
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