Numerical modelling and formability of with and without heat-treated AA 6023-T6 alloy sheet with various necking/failure criteria

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Abstract: Sheet metal forming is a process widely used in the manufacturing industry. There are numerous sheet metal forming processes to evaluate and understand the formability. Among all formability tests, the basic formability can be formulated through tensile tests and followed with specialized tests. In the present paper, the formability of AA 6023-T6 sheet of 2mm thickness by modelling for stretching test namely limit dome height (LDH) test was performed using PAM STAMP 2G a commercial finite element software. For the simulation, input mechanical properties like yield strength ($\sigma$), material strength coefficient (K), strain hardening exponent (n), plastic strain ratio (R) etc., were considered from the existing literature. For the simulation, two different conditioned sheet such as at room temperature and annealed sheet at 400°C. For all the simulations, four strain paths 100x200mm, 125x200mm, 150x200mm, 175x200mm and 200x200 mm were taken. Results are drawn based on the three localized necking criteria namely the effective strain rate-based criterion (ESRC – R1), major strain rate-based criterion (MSRC – R2), thickness strain rate-based criterion (TSRC – R3).

Form the obtained results, forming limit diagrams are developed for the both condition of sheet metal. It is observed that, formability of AA 6023-T6 sheet in-plane condition (i.e. 100x100 mm) annealed sheet at 400°C is shown better forming whereas in bi-axial condition (i.e. 200x200 mm) got reduced compared to room temperature sheet. The same phenomenon is noted in all the necking criteria too.

1. Introduction

Sheet metal forming analysis is a revolutionary for the industrial applications. The most of sheet metal applications meant for the weight reduction of automotive bodies leads to improve the fuel efficiency. Later on, industries progressed on many other applications of sheet metals emphasis ferrous sheet metal were replaced with non-ferrous metals. Among all non-ferrous metals, aluminium alloys had the great impact in majority applications. Although aluminium alloys have different series by various alloying elements such as 1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 6xxx, 7xxx, 8xxx and 9xxx, in which 6xxx series aluminium alloy has better feature for applications. Knowing the localized necking limits for forming behaviour of any sheet metal is the most important before application. For evaluating the forming behaviour of sheet metal, there are many formability tests like deep drawing, stretching, incremental forming, bending, hydro forming etc., at different process conditions such as
cold, warm, and hot conditions and process parameters [1]. In the literature, there were many researchers worked on the necking limits strains evaluation through different failure criteria.

A failure criterion was developed with respect to thickness gradients during stretching. This criterion was compared with the existing criteria to predict the forming limit diagram (FLD) and proved successfully [2, 3]. This criterion was used to predict the forming limit stains of welded blanks. The simulations were performed using PAM-STAMP. The un-welded blank and tailor welded blanks forming limit curves (FLCs) were predicted by the thickness gradient based necking criterion compared with the experimental FLCs obtained by limit dome height (LDH) test [4]. The applicability of necking criteria namely the effective strain rate-based criterion (ESRC), major strain rate-based criterion (MSRC), thickness strain rate-based criterion (TSRC), and thickness gradient-based criterion (TGNC) were used to quantify and predict the FLC unwelded and tailor-welded blanks at different lubricant conditions. It was identified that the FLCs predicted by ESRC, MSRC, TSRC, and TGNC were comparable with experimental FLCs. The predictions were accurate in the low-friction condition, demonstrated that the necking criteria valid under altering friction conditions. Furthermore, the overall FLD had not affected with friction conditions. In the case of laser welded blanks, modified necking criteria as \( R_1 \geq 25 \), \( R_2 \geq 32 \), and \( R_3 \geq 32 \), which showed a better prediction compared with the original criteria. The original and modified limit strain criteria illustrated the better correlation with results [5]. Based on the modified four necking criteria namely effective strain rate-based, major strain rate-based, thickness strain rate-based, and thickness gradient-based failure criteria, both in original and modified forms, FLCs were predicted for unwelded blank and tailor welded blanks (TWBs) with longitudinal weld, during stretching and drawing operations. FLC predictions were consistent with the experimental result in the drawing side, but considerable difference was observed in the stretching side in FLD of unwelded sheet. Moreover, in TWBs failures were seen near to the weld region, the strain rate-based criteria were modified as \( R_1 \geq 25 \), \( R_2 \geq 32 \), \( R_3 \geq 32 \) for failure to occur. TWB FLC predicted using the modified criteria demonstrated the better precision than the original failure criteria in the stretching side of the FLD. Whereas in the drawing side, FLC predicted by original criteria was the same as that from modified criteria. From the entire work, they demonstrated that using modified failure criteria, forming limit of TWBs can be predicted with better accuracy, while the original failure criteria were sufficient for a drawing operation [6].

The validity of effective strain rate based necking criterion (ESRC) in both original and modified forms to predict the forming limit of friction stir welding (FSW) blanks made of AA6111, DP590 was analysed. The predicted FLCs were compared with thickness gradient based necking criteria and literature. It was found that the validation done with literature results were consistent and accurate from modified ESRC when compared to original ESRC. The failure pattern prediction was supportive with the literature results [7]. The influence of friction stir welding parameters such as tool rotation speed (1300 and 1400 r/min) and feed rate (90 and 100 mm/min) on the forming limit of friction stir welded AA 6061-T651 sheets investigated through TGNC necking criterion. The FLC was evaluated through limit dome height test. The forming limit of friction stir welded sheets is better than unwelded sheets. The thickness gradient after forming was severe in the cases of friction stir welded blanks made at higher feed rate and lower rotation speed. It was demonstrated that the change in the forming limit of friction stir welded sheets with respect to welding parameters due to the thickness distribution severity and strain hardening exponent of the weld region during forming. There was not much variation in the dome height among the friction stir welded sheets tested. When compared with unwelded sheets, dome height of friction stir welded sheets was higher in near-plane-strain condition, and lesser in stretching strain paths [8]. A theoretical method was proposed to predict the formability of magnesium alloy sheet at elevated temperatures by combining the Marciniak and Kuckzinsky model with the Logan–Hosford yield criterion. Forming limit tests on AZ31B magnesium alloy sheets were performed for the theoretical FLD verification at elevated temperatures of 200, 250, and 300°C and, simultaneously, the material sensitivity effect under a selective strain rate of 0.01 s\(^{-1}\). Based on the verified FLD prediction results, numerical simulations of warm-forming AZ31B camera casing of thickness 0.8mm as an example were then carried out. The warm forming experiments for this camera casing, under the identical conditions, were also performed for verification. It was found that the effect of strain rate on the prediction of FLDs did have a significant influence with increasing temperatures.
Furthermore, the results of numerical simulations showed a good agreement with those of the warm forming experiments at different elevated temperatures. The proposed theoretical method offered an accurate prediction in warm-forming magnesium alloy sheets and should lead to a remarkable reduction of trials, at least in the sense of both time and cost benefits, before a large batch production [9]. The simulations were designed to obtain FLDs through hemispherical die stretching of low-carbon steel blanks of various thicknesses. The multiple criteria, including the second time derivatives of major strain, thickness strain and equivalent plastic strain extracted from the strain history of simulations, were used to detect the start of necking in forming limit diagrams. It was observed that necking starts when the second derivative of the thickness strain, major strain or plastic strain reaches the maximum value. Moreover, a modified Marciniak and Kuczynski method was used to predict the forming limit diagrams. The results from the proposed methods and experimental test results were compared to demonstrate the efficiency of the proposed methods [10].

A free bulge test and ductile fracture criteria were used to obtain FLD of aluminium alloy AA6063 tubes at high temperatures. Ductile fracture criteria were calibrated using the results of uniaxial tension tests at various elevated temperatures and different strain rates through adjusting the Zener-Holloman parameter. High temperature free bulge test of tubes was simulated in finite element software Abaqus, and tube bursting was predicted using ductile fracture criteria under different loading paths. FLDs were obtained from finite element simulation were compared to experimental results to select the most accurate criterion for prediction of forming limit diagram. According to the results, all studied ductile fracture criteria predict when forming condition was close to the uniaxial tension, while Ayada criterion predicts the FLD at 473 K and 573 K very well [11]. A computational approach was introduced for prediction of the forming limit diagram of Al–Cu two-layer metallic sheets. The computational approach was based on the modified Marciniak and Kuczynski theory. The FLD of Al–Cu two-layer metallic sheets were obtained through the modified Marciniak and Kuczynski theory and experimental investigations. In the modified Marciniak and Kuczynski theory, there existed four nonlinear equations which were solved simultaneously. The Quasi-Newton Method was applied for a solution to the system of equations. To verify the theoretical predictions, the experimental works were accomplished on the Al–Cu two-layer metallic sheets and a good agreement between the proposed method and experimental works was observed [12].

From the literature, it is observed that there are many failure criteria are existed to evaluate the formability of the sheet metal at various conditions like temperatures ranges, frictional conditions, strain path consideration etc. Eventhough, the present paper is induced to estimate the formability of AA 6023-T6 alloy of 2 mm thickness through modelling and simulation process analysis by considering the effective strain rate-based criterion (ESRC), major strain rate-based criterion (MSRC), and thickness strain rate-based criterion (TSRC). These all criteria are not new even-though they are the meticulousness to analyse the formability of any material.

2. Methodology

2.1 Base material chemical composition and mechanical properties

For this study, base material details were adopted from the existing literature [13]. The chemical composition of AA6023-T6 alloy sheet was shown in the Table 1.

| Chemical composition of AA6023-T6 alloy sheet |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Si               | Fe    | Cu    | Mn    | Mg    | Bi    | Sn    | Residuals | Al    |
| 0.57%            | 0.5%  | 0.19% | 0.24% | 0.41% | 0.3%  | 1.2%  | 0.59%     | 96%   |

Considered mechanical properties were shown in the Table 2 and Table 3. Table 2 mechanical properties were at room temperature and Table 3 were mechanical properties of heat-treated alloy at 400°C.
Table 2 Mechanical property of AA6023-T6 alloy sheet at room temperature

| Orientation of samples | UE (mm) | UTS (MPa) | σ_y's (MPa) | K (MPa) | n | R_0 | R_{45} | R_{90} |
|------------------------|---------|-----------|-------------|---------|---|-----|-------|-------|
| 0°                     | 0.38    | 200±9     | 180±3       | 313±40  | 0.132 | 0.49 | 0.68  | 0.56  |
| 45°                    | 0.54    | 208±4     | 190±18      | 338±20  | 0.134 |       |       |       |
| 90°                    | 0.52    | 212±12    | 200±12      | 358±20  | 0.133 |       |       |       |

UE-uniform elongation; UTS-ultimate tensile strength

Table 3 Mechanical property of AA6023-T6 alloy sheet after heat treatment

| Orientation of samples | UE (mm) | UTS (MPa) | σ_y's (MPa) | K (MPa) | n | R_0 | R_{45} | R_{90} |
|------------------------|---------|-----------|-------------|---------|---|-----|-------|-------|
| 0°                     | 0.19    | 206±13    | 170±17      | 326±33  | 0.149 | 0.43 | 0.58  | 0.47  |
| 45°                    | 0.21    | 197±2     | 168±5       | 323±16  | 0.162 |       |       |       |
| 90°                    | 0.25    | 193±6     | 166±7       | 315±28  | 0.155 |       |       |       |

UE-uniform elongation; UTS-ultimate tensile strength

2.2 Simulation methodology

Simulations were performed using PAM STAMP 2G a finite element code. During the simulation, limit dome height test simulations were performed at a constant punch speed of 10m/s, blank holding force of 80kN and coefficient of friction 0.2 for all stretching side strain paths (100×200mm, 125×200mm, 150×200mm, 175×200mm and 200×200 mm). The base material model comprised quadrilateral shell elements of the Belytschko–Tsay formulation, with five through-thickness integration points. A constant mesh size of 2mm was used. Hollomon’s power law was used to describe the strain-hardening behaviour of the base material, Hill’s 1948 isotropic hardening yield criterion was used as the plasticity model.

2.3 Necking Criteria for limit stain predictions

Many failure criteria are existed to predict the local necking during sheet metal forming. In the present work, three failure criteria were used for predicting the FLC. The failure criteria were Major strain rate criterion (MSRC- R_1), Effective strain rate criterion (ESRC -R_2) and Thickness strain rate criterion (TSRC-R_3) [2,3].

The strain rate in the notch to that in the bulk, R, the ratio of major principal strain rate in the notch to that in the bulk, R_1

The criterion based on major principal strain rate, was defined as follows:

\[ R_1 = \frac{\text{Major strain rate in notch}}{\text{Major strain rate in bulk}} \geq 10 \]

The next criterion is based on the scalar effective strain rates. The ratio of the effective strain rate in the notch to that in the bulk R2 exhibits a growth in slope at the onset of localized deformation. This criterion was mentioned as:

\[ R_2 = \frac{\text{Effective strain rate in notch}}{\text{Effective strain rate in bulk}} \geq 4 \]

The next criterion is based on thickness strain rates. The ratio of the thickness strain rate in notch to that in the bulk, R_3, this criterion was described as:

\[ R_3 = \frac{\text{Thickness strain rate in notch}}{\text{Thickness strain rate in bulk}} \geq 10 \]
3. Results and Discussion

3.1 Limit Dome height test

The limiting dome height (LDH) test is used to assess the formability of AA 6023-T6 alloy sheet of 2 mm thickness. Limiting dome height test setup has been used to carry out simulations by using PAM-STAMP (Fig. 1.). The LDH test can be used to obtain various strain conditions by changing the specimen geometry. Hemispherical punch is used to form the specimens. The sheet metal being formed is held in its position by means of a draw bead. Total of 4 strain paths are taken from 100×200 mm to 200×200mm i.e. in-plane condition to bi-axial condition. All the simulations are taken place with same conditions. Simulation phenomenon can be seen form the Fig. 2 (a to d). from the deformed strain paths, the data related to the effective stain, major stain, thickness stain are drawn after failure identification. The corresponding strain ratios from the notch to bulk are taken to evaluate the limit stains.

![Figure 1. Limit dome height setup in PAM STAMP](image1)

![Figure 2. Stain path of 100×200mm at different stages (a) solid blank (b) meshed blank (c) Deformed blank (d) deformed with failure location blank](image2)

3.2 Limit stain Evaluations

Based on section 2.2, failure criteria the following discussion has taken place to identify the limit strains and validations of criteria through data and figures of different strain paths. Current work indicates the first criterion as MSRC i.e. ratio of major strain rate in the notch to major stain strain rate in the bulk must greater than or equal to 10 as shown below.
10

\[ R_1 = \frac{\text{Major strain rate in notch}}{\text{Major strain rate in bulk}} \geq 10 \]

From the simulation, strain path 100×200mm is observed for MRSC at ambient condition. It can be seen from Fig. 3 that when the ratio reaches at 6.51, the data jumped to more than 10 and becomes vertical increment. From this criterion, major strains and minor strain are taken for all 100×200mm, 125×200mm, 150×200mm, 175×200mm and 200×200 mm strain paths for tested sheet at room temperature and annealed at 400°C. The corresponding data graph has been developed as shown in Fig. 4. In it clear that, sheet tested at room temperature has less formability at in-plane strain path and improved at bi-axial strain path whereas the reverse phenomenon has been observed for the sheet annealed at 400°C. Similar phenomenon is seen in the Fig. 5 and Fig. 6 for the criteria ESRC and TSNC.

**Figure 3. Major strain-corresponding R1**
4. Conclusions
The present work aimed to investigate the formability of AA 6026-T6 alloys sheet of 2 mm thickness at two different temperature conditions. The formability has been predicted through various necking criteria such as MSRC, ESRC and TSRC using simulation software. Finally, conclusion is these necking criteria have the stability to evaluate the formability of any kind of sheet metal with any kind the conditions. In this work formability of AA 6029-T6 is showed better formability with the annealed sheet at in-plane stretching and reverse in the bi-axial condition. This can be extended to verify the modified criteria of MSRC, ESRC and TSRC as $R_1>25$, $R_2>32$, and $R_3>32$ along with the TGNC also can be included for the further work.

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