Finite Element Analysis of Blanking Operation of Magnesium Alloy (AZ31) Sheet Using Ductile Fracture Criteria and Its Experimental Verification at Various Temperatures

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Abstract. This study focuses on modeling and analyzing sheet blanking process of Magnesium alloy sheet (AZ31) using finite element method at various temperatures. The computational analysis is then compared with the results obtained through the experimental setup. In the finite element model fracture initiation and the shape of the blanked edge are influenced by the value of critical damage criteria (C). The value of critical criteria is determined and compared using the ductile fracture criteria proposed by various researchers by varying various process parameters and temperature. The effect of temperature and process parameters on the geometry of the blanked edge including burr, fracture zone, shear surface and rollover has been investigated. Moreover, numerical predictions were compared with the experimental results.

1. Introduction

The cut surface formed through the blanking process is characterized by localized deformations followed by crack propagation and ductile failure. The resulting blanked edge is distinguished by regions known as rollover, shear zone, fracture zone and burr. Their formation depends on various blanking process parameters such as punch-die clearance [1,2,3], punch-die radius [4], punch speed [5], and temperature.

Previous researchers have been analyzing the effects of process parameters on shearing mechanism through various descriptions of fracture initiation. Fang et al. [6] examined the forming quality of the blanking process and concluded substantial effect of punch/die clearance on the shape of the blanked edge. Thereby, ductile fracture criteria’s have been applied in finite element codes to predict failure in cold blanking operations [7,8]. Myint et al. [9] applied finite element methods to determine the relationship between the value of critical criteria (C) and process parameters in punching processes.

The aim of the present work is to evaluate the relationship between the value of critical criteria (C) and temperature of the magnesium alloy sheet (AZ31). The value of critical criteria (C) is determined using the ductile fracture criteria. Microscope images of the blanked slugs are compared with results of finite element analysis to check the validity of the procedure. The effect of punch/die clearance and temperature on the shape of the blanked edge is also examined and were compared to the experimental results.

2. Blanking Experiment

2.1 Blanking Material
The blanking workpiece is Magnesium Alloy (AZ31) sheet with a thickness of 1 mm. The initial workpiece has a rectangular shape.
2.2 Experimental Setup

2.2.1 Blanking Apparatus

The blanking experiment was performed using a conventional punch-die setup and universal testing machine (UTM). For the efficient removal of the workpiece and scrap, elastic stripper arrangement of blank-holder was selected. Different punch/die clearances were analyzed by the implementation of die slide mechanism. Limitations in manufacturing precision resulted in fictitious punch/die radius. Schematic of blanking apparatus used for the experiments is shown in Figure 1.

![Blanking Apparatus Diagram](image)

**Figure 1. Schematic of Blanking Apparatus.**

| Parameters                | Dimensions          | Units |
|---------------------------|---------------------|-------|
| **Geometry**              |                     |       |
| Thickness (t)             | 1                   | mm    |
| Clearance (c)             | 0.05, 0.1, 0.15     | mm    |
| Initial Blank Size        | 60×30               | mm×mm |
| Punch/die Radius          | 0.05 (fictitious)   | mm    |
| **Control**               |                     |       |
| Test Speed (v)            | 2                   | mm/min|
| Temperature (T)           | 25, 100, 150, 200, 250 | °C    |

**Table 1. Experimental Parameters.**

2.2.2 Experimental Procedure

During the blanking experiment the punch speed coincided with that of the crosshead of the universal testing machine (UTM). The workpiece material was heated by inserting heat cartridges into the holes, pre-drilled into the die, punch and blankholder. Constant temperatures were maintained by the cartridge heater with the PID controller. Summary of the punch/die clearance, temperature and other process parameters is shown in Table 1.

3. Ductile Fracture Criteria

Due to large localized deformations during the blanking process, plastic deformation may reach a threshold value (C) leading to fracture initiation and ductile failure. The physical behavior of the material can be modelled by the mathematical function that incorporates the deformation history. In the present study, Cockcroft and Latham [10] in equation (1) and Brozzo [11] ductile fracture criteria in equation (2) have been selected to evaluate the relationship between the critical value of the damage (C) and temperature in sheet blanking processes. Both ductile fracture criteria incorporate the stress-strain history and are based on damage accumulation.
\[ \int_0^{\bar{\varepsilon}_f} \frac{\sigma_{\text{max}}}{\sigma_{\text{eq}}} d\bar{\varepsilon} = C_1 \] (Cockcroft and Latham) \hspace{1cm} (1)

\[ \int_0^{\bar{\varepsilon}_f} \frac{2}{3} \left( \frac{\sigma_{\text{max}} - \sigma_H}{\sigma_{\text{max}}} \right) d\bar{\varepsilon} = C_2 \] (Brozzo) \hspace{1cm} (2)

where \( \bar{\varepsilon}_f \) represents strain at fracture, \( \bar{\varepsilon} \) is the effective plastic strain, \( \sigma_{\text{eq}} \) is the von Mises stress, \( \sigma_H \) is the hydrostatic stress and \( \sigma_{\text{max}} \) is the maximum tensile stress.

The critical value of damage (C) in equation (1) and equation (2) for the above ductile fracture criteria are calibrated through the blanking experiment. For various clearances and temperature, the punch penetration displacements at fracture initiation were measured experimentally using microscope images. Thereafter, under similar FEM arrangements, the modelled punch is set up to travel up to the experimental punch displacement. The critical value of damage (C) is then determined to be the maximum value of the integral function, stored as state variable over the entire computational domain and hence ductile fracture is set to initiate.

4. FEA of Blanking Process

4.1 Finite Element Modeling

4.1.1 Model Geometry

The commercial software Abaqus/Explicit 2017 have been used to create the finite element model for the blanking process. The tool i.e. punch/die, blankholder and counter punch were modelled as rigid bodies while the blanking workpiece was assumed to be deformable elastic-plastic material of 1mm thickness (t). For different instances the punch/die corner radius \( r_p \) and \( r_d \) were taken identical as 1%, 5% and 10% of thickness. Similarly, the punch/die clearance to thickness ratio (c/t) were set to 1%, 5%, 10%, 15% and 20% for each case. The contact between the tool and blanking workpiece was assumed to be frictionless. Schematic of the FEA model used for the simulations is shown in Figure 2.

4.1.2 Model Material

The material data for the Magnesium Alloy AZ31 at temperatures of 25°C, 100°C, 150°C, 200°C and 250°C were obtained from the NUMISHEET 2011 benchmark study (BM 2) [12]. The flow stress curves for Magnesium alloy AZ31 at above-mentioned temperatures and hardening curve using Swift law takes the form,

\[ \sigma = k(\varepsilon_p + \varepsilon_0)^n \] \hspace{1cm} (3)

![Figure 2. Schematic of the Finite Element Model.](image1)

![Figure 3. Flow stress and plastic strain curve based on Swift’s Hardening Law.](image2)
Furthermore, the blanking workpiece was assumed be isotropic and that obeys von Mises yield criterion. Material properties of the Magnesium alloy AZ31 blank workpiece with respect to temperature is shown in the Figure 3.

4.2. Finite Element Analysis

Finite element analyzer ABAQUS/Explicit have been employed for the numerical simulation of the finite element model. User material subroutine VUMAT in ABAQUS/Explicit is used for implementation of the material and ductile fracture criteria. The blanking workpiece was meshed with four-node plane strain quadrilateral elements, reduced integration, denoted as CPE4R. The mesh density of the shear plane, particularly in the punch/die clearance region has been extra refined to capture realistic computational results. To control element distortion during the present analysis Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing technique in ABAQUS/Explicit was used. To emulate fracture propagation in the blank model, element deletion technique was implemented.

4.2.1 Prediction of the value of Critical Criteria (C)

Experimental investigations of the blanking process for Magnesium Alloy AZ31 provided with the microscope images of the actual blanked edge. The punch penetration at fracture initiation obtained from the experiments were used as reference displacement at which fracture was expected to initiate in the finite element analysis. For both ductile fracture criteria, the value of equation (1) and (2) was stored as state variable and the value of critical criteria (C) was determined to be the maximum value of the integrant function at the reference punch displacement.

Figure 4. Microscope Images of the blanked edge for 0.1mm clearance at (a) 25°C and (b) 200°C.

Figure 5. Shear band against temperature (experimental results).

5. Results and Discussion

5.1 Influence of Temperature on the Blanked edge

Punch penetration distance at the limits of shear band on the blanked samples were obtained using an electron microscope. The rollover along with shear zone was measured at various positions over the domain of the blanked edge. The results were averaged for three experiments performed with an individual clearance at a certain temperature. The minimum and maximum shear band at temperatures of 25°C and 200°C are shown in the Figure 4a and 4b. It is observed that the length of the shear surface increases and fracture zone decreases with increase in temperature. The length of shear band and fracture zone against temperature plots are shown in the Figure 5. Numerical analysis of the blanking process
under parallel setup confirmed the corresponding dependence of the shear band on temperature. The blanked edge shape obtained through FEA is shown in the Figure 6a and 6b.

![Figure 6. FEA of the blanking Process for 0.1 mm clearance at (a) 25°C and (b) 150°C.](image)

5.2 Variation in the value of Critical Criteria (C) with Temperature

The value of critical criteria $C_{cr1}$ (Cockcroft and Latham) and $C_{cr2}$ (Brozzo) was determined to be the maximum value of integrant in equation (1) and (2) at respective shear band displacements of the rigid punch. The computational results for the value of critical criteria as a function of temperature is shown in the Figure 7a and 7b. With the similar punch penetration distance, the damage value tended to decrease with increasing temperature while increases monotonically when allowed to travel till fracture initiation.

![Figure 7. (a) Damage Values $C_1$ (Cockcroft and Latham) and $C_2$ (Brozzo) against Temperature (b) Critical Damage Values $C_{cr1}$ (Cockcroft and Latham) and $C_{cr2}$ (Brozzo) against Temperature (at 0.1 mm clearance).](image)

5.3 Influence on Blanked Edge Quality

The numerical results along with the experimental observations provided conclusive insights regarding the quality of the blanked edge. From a manufacturing perspective the fracture zone and burr are the utmost significant quality factors and both variables displayed a downturn trend with increase in temperature. On the contrary, rollover and shear surface increases thus providing more precise blanks. Variations in the blanked edge dimensions along with temperature is shown in the Figure 8a. In addition, our study also reaffirmed the dependence of the blanked edge on the punch/die radius and clearance as shown in Figure 8b.
6. Conclusion
The study aimed to evaluate the relationship between the value of critical damage criteria (C) and temperature. Computational and experimental observations provided predictions for the onset of failure during the blanking of Magnesium AZ31 sheet using several pre-existing ductile fracture models. During warm blanking process elongation in shear surface and simultaneous reduction in fracture zone is observed. The value of critical criteria for Cockcroft Latham and Brozzo monotonically increases with temperature. Regardless of the clearance value fracture zone becomes comparably more consistent at high temperatures. Ductile fracture criteria are successfully implemented into the FEM code to predict the critical damage value. Warm forming conditions resulted an increase in the dimensions of the shear band thus providing more precise blanks with improved blanked edge quality.

Acknowledgments
This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. NRF-2017R1C1B5017648).
The authors wish to thank Mr. Sungmin Cho for his technical assistance.

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Figure 8. (a) Rollover depth and Burr versus Temperature (b) Shear surface and Fracture zone versus Clearance at 25°C (simulation results).