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AN EFFECTIVE WARM FORMING PROCESS; NUMERICAL AND EXPERIMENTAL STUDY

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ABSTRACT: To investigate the effectiveness of the warm forming a coupled thermo-mechanical model is developed in LS-Dyna. The temperature dependant material properties of the material, a long-life 3000 series clad aluminum alloy brazing sheet are modelled using a user defined material subroutine accommodating the Barlat YLD2000 anisotropic plane-stress yield surface and the physically motivated Bergstrom hardening rule. The maximum thickness reduction is adopted as a simplified failure criteria to determine both the location and failure depth for the numerical models. The original progressive tooling is modified to incorporate the application of individual temperatures on the dies and the punch. The dies (die and blank holder) are heated with embedded cartridge heaters and the punch is cooled by circulation of chilled water. Select experimental cases are modelled. FEA model is validated against experimental results by comparing punch force versus displacement as well as failure location. The numerical results for either successful or failed simulations are compared with corresponding experimental samples.

KEYWORDS: Warm forming, formability, Independent temperature, Bergstrom

1 INTRODUCTION

Warm forming has been recently considered to improve the formability of aluminum alloy sheets. In comparison to the traditional stamping of aluminum alloys, warm forming has some important advantages. The most important is that the forming limit strains at elevated temperatures are increased significantly; therefore, more complex geometries can be achieved by this method and/or fewer die progressions are necessary to form a given geometry. The challenge for process design is to investigate the complex interaction between mechanical and thermal effects on formability. Li and Gosh (2003) have shown that warm forming can considerably improve the formability of aluminum alloy sheets. Naka and Yashida (1999) studied deep drawing with different die temperatures and a water cooled punch. Mckinley et al (2008) showed that a gradient of temperature between die and punch improves the drawability of aluminum alloy sheets.

Finite element analysis (FEA) has been used widely to reduce the trial-and-error process in designing part and tooling. Using finite element analysis product design can be achieved faster. The finite element models, however, must be accurate and confidence in their suitability for the specific forming process must be verified. A temperature-dependant anisotropic material model based on Barlat's YLD2000 yield function and Bergstom hardening rule is implemented in LS-DYNA.

The current research focuses on an effective warm forming process to reduce the number of forming steps of the resulting form of a heat exchanger core plate (Fig.1). The part is currently manufactured at room temperature with multiple stamping steps and a final pierce punching step. The goal is to maximize the formability of the material and reduce the number of stamping steps by application of a warm forming process.

The tensile test data is used to fit the yield surface and hardening parameters. Developed model is used in a coupled thermo-mechanical finite element analysis. Experimental results are compared to numerical predictions developed using the new temperature-dependant model.

2 EXPERIMENT SETUP

Heat exchanger core plate is formed using a hydraulic press at the University of Waterloo. Tooling consists of heated die and clamp using embedded cartridge heaters and cooled punch using circulation of chilled water. The dies and punch temperatures are controlled and monitored using thermocouples. Blanks with a dimension of 100x33mm and a thickness of 0.61mm are used. A schematic section of tooling is shown in Figure 1. Different configurations of die and punch temperatures and clamping force are used however for the sake of brevity only a few are presented here. For all

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configurations the punch temperature is kept cold at 10 °C while the die and clamp are kept at three different levels i.e. room temperature, 250 °C and 300 °C. Temperatures are measured using imbedded thermocouples into the dies and punch. Two levels of clamp force are used for the experiments which are 2.24 KN and 4.48 KN. Also two different punch speeds of 4 mm/s and 8 mm/s are used. Using the factorial method, 12 different calculations have been derived and performed to investigate the effects of the temperature, clamp force and punch velocity and their interactions on part formability. The forming process starts by placing the blank on the previously heated die. The blanks are cleaned thoroughly and a siloxane emulsion lubricant is applied. The clamp is closed and then punch advances and pushes the blank to the depth of 1 mm. This is to ensure that the surfaces are in contact and the heat is transferred between the die, punch and blank. The tooling is held at this position for 30 seconds to allow the temperature of blank and dies to equalize. Finally the punch is moved to form the part completely with or without failure.

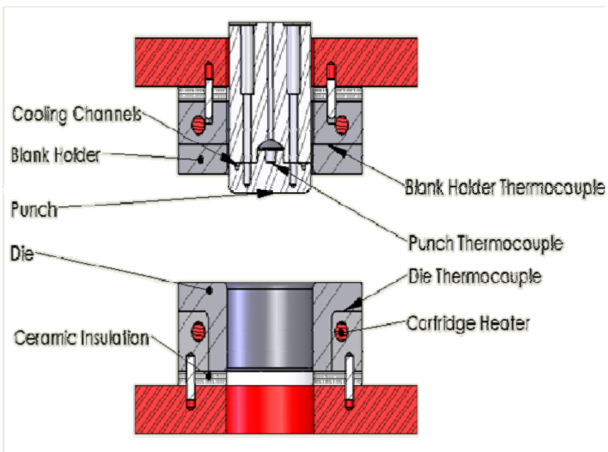

Figure 1: *tooling cross section*

3 NUMERICAL MODEL

3.1 MATERIAL MODEL

A user define material model, UMAT, is developed in LS-Dyna using Barlat YLD2000 anisotropic yield surface. The anisotropy parameters are considered to be non-temperature dependent and are shown in Table 1.
The physically motivated Bergstrom hardening rule is used to simulate the flow stress of the material. The temperature dependant hardening model is written as:

$$\sigma_f = g(T)\left(\sigma_0 + \alpha G_{ref} b\sqrt{\rho}\right) \quad (1)$$

Where

$$g(T) = 1 - C_T \exp\left(-\frac{T_1}{T}\right) \quad (2)$$

The Bergstrom model is a strain and strain rate dependant model. The effects of strain and strain rate are in term ρ [6]. The material in this study is a long-life 3000 series clad aluminium alloy brazing sheet which is fully characterized at different elevated temperatures. Figure 2 shows the stress-strain curves at several temperatures. Stress-strain curves are fitted with Bergstrom parameters. Table 2 shows the fitted Bergstrom parameters for the material in this research.

Table 1*: Parameters for Barlat's YLD2000*

α_1	0.9871632	α_5	1.00797
α_2	0.94099	α_6	0.9612199
α_3	0.9612199	α_7	0.975182
α_4	1.025119	α_8	1.0305779

Table 2*: Parameters for Bergstrom model*

σ_0	70.5 MPa	Ω_0	28
α	1	Q_v	1.0917 X $10^5 J/mol$
b	2.857 X $10^{-11}m$	ρ_0	$10^{11}m^{-2}$
C	3.34 X 10^{-5}	G_{ref}	26354 MPa
M	0.425	C_T	3300
U_0	6.093 X $10^{-8}m^{-1}$	T_1	5100 K

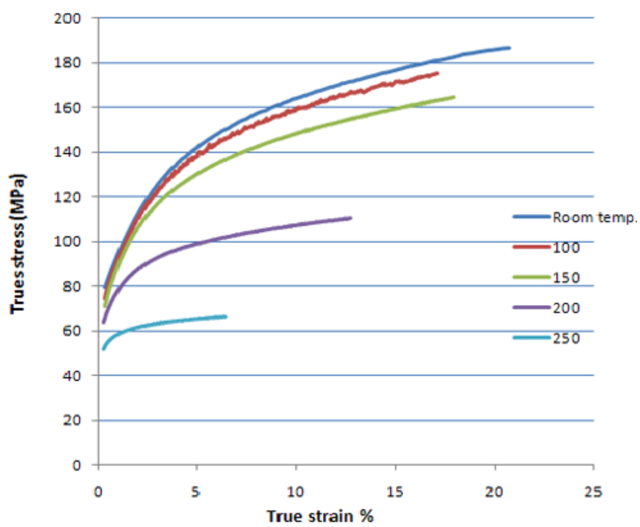

Figure 2: *Stress-strain curves at elevated temperature for a long-life 3000 series aluminium alloy sheet*

3.2 FEM MODEL

The geometry model and LS-Dyna compatible mesh are generated in Hypermesh (Figure3). Due to symmetry only one half of the part and tooling is modelled however a full mesh is shown in figure 3. Mesh is generated using 4-nodes Belytschko-Tsay shell elements. Tooling is modelled as rigid bodies with a very small thickness. All surface contacts are modelled as thermal contacts in LS-Dyna to simulate the heat transfer between hot dies, cold punch and blank. The heat transfer conductance of contact surfaces with closed gap is defined to be $50000\frac{W}{m^2}$ which is in agreement with experiments. Also a coefficient of friction has been obtained using twist compression test for the applied lubricants and considered to be 0.1 for all contact surfaces.

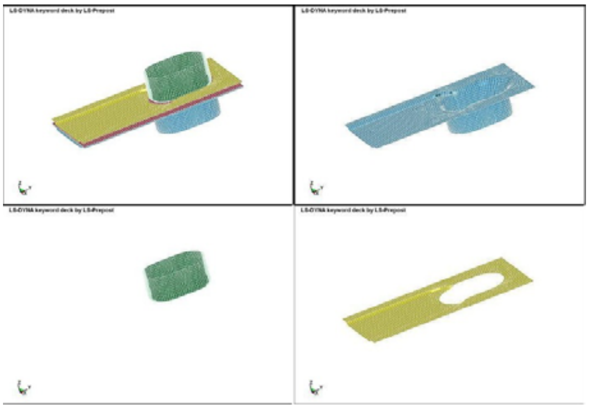

***Figure 3**: FE Model*

4 RESULTS

4.1 EXPERIMENTAL

Experiments are performed for twelve different configurations of three levels of die temperature, two levels of clamping force and two levels of punch speed. No important difference is observed between two levels of punch speed which means that the material is not very strain rate-dependant at the range of current experiment. For the sake of brevity only results regarding punch speed of 8mm/s are summarized in Table 3.

***Table 3:** Summary of experimental results for 8mm/s punch speed and total draw depth of 5 mm.*

BH Force	Room temp.	250° C	300°C
2.24 KN	**Failure** *(broken part) Fig 4 (c)*	**Failure** *(necking) Fig 4(b)*	**Draw** *Fig 4 (a)*
4.48 KN	**Failure** *(broken part)*	**Failure** *(broken part)*	**Failure** *(necking)*

The room temperature samples failed at all configurations of clamping forces and punch velocities. However for the higher punch velocity and higher clamping force the failure initiates at a lower drawing depth. The maximum possible draw at room temperature observed to be 3.2 mm with a clamping force of 2.24 KN. For the heated dies up to 250°C, the part breaks at a draw depth of 4.6mm with a clamping force of 4.48 KN. By applying a clamping force of 2.24KN the part can be drawn to the full depth however extreme necking is observed. Heating the dies up to 300°C leads to a desirable final shape with a clamping force of 2.24KN however necking is observed at the die entry radius of the part formed with a clamping force of 4.48KN.

***Figure 4:** Experimental result for warm die and cold punch. (BHF=2.24KN, Punch speed=8mm/s die temperature (a) 300℃ (b) 250° (c) room temperature)*

For all cases the temperature of the centre of blank under the punch is measured 15°C. For all cases punch force versus punch travel data is recorded

4.2 NUMERICAL

Numerical simulations corresponding to all experiments have been performed. Simulations are in good agreement with experimental results. Figure 5 shows a comparison of the punch force versus punch displacement for a clamping force of 2.24KN and die temperature of 300°C. After closing the clamp, the punch advances the blank and pushes the blank by 1 mm. This is to ensure that tooling and the blank are in contact and heat can be transferred between contact surfaces and, as a result, the gradient of temperature between the die entry radius and the blank under the punch is achievable. The sharp decline of the punch load curve is related to onset of necking. Both experimental and numerical results show that the onset of necking initiates at the punch depth of 6 mm.

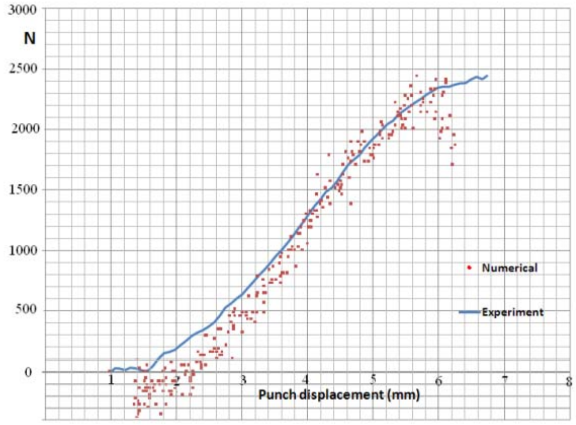

***Figure 5:** Comparison of numerical results with experimental results for clamping force of 2.24KN and die temperature of 300℃ (Data are recorded after 1 mm punch travel)*

Figure 6 shows the contour plots of thickness reduction for clamping force of 2.24 KN and punch speed of 8mm/s. The contours show that part formed at lower temperature experience higher thickness reduction at the die entry radius. The maximum thickness reduction for room temperature is predicted 46% of initial thickness and it is 26.5% and 16.7% for 250°C and 300°C respectively. The effect of the gradient of temperature on formability of part is obviously positive which is in agreement with the experimental results.

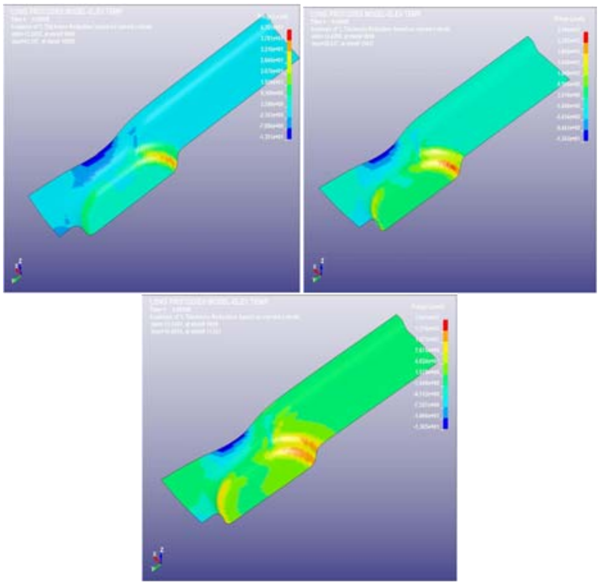

Figure 6: *Contour p[lots of thickness reduction for clamping force of 2.24KN and punch velocity of 8mm/s. Top left: room temperature, top right: 250℃ and bottom:*

Figure 7 shows the punch load versus punch travel for three different die temperature configurations. The experimental results are shown using the dots and the numerical results are shown using solid lines. The punch travel is set to 7 mm. The sharp drop of punch load is the initiation of failure in parts. Both numerical and experimental results are in very good agreement.

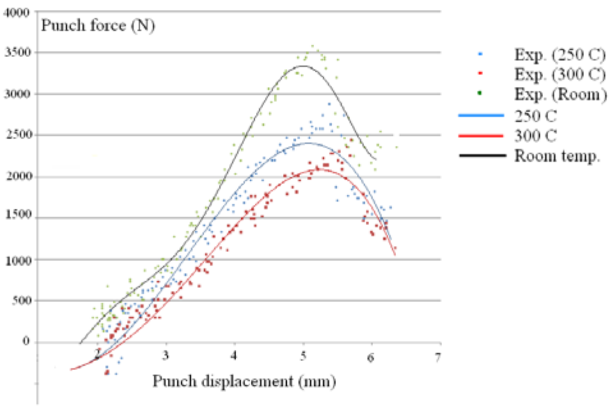

Figure 7: *Comparison of punch load vs. punch displacement for different die temperatures. Experimental results are shown with dots and numerical results are in solid lines.*

5 CONCLUSION

Experiments have shown that warm forming increases the formability of long-life 3000 series aluminum alloy sheets. It has been shown that application of different die and punch temperature, which was reported to improve the formability of simple cup deep drawing, can significantly improve the formability of parts with complicated geometry. Increasing the gradient of temperature between the punch and the die improves the formability. Warm forming also reduces required punch force and therefore equipment tonnage. Numerical model accommodating the Barlat's YLD2000 yield function and Bergstrom hardening rule is capable of capturing both punch force and failure location by considering the thickness reduction as a simplified failure criteria.

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