Studies on the Hot Forming and Cold-Die Quenching of AA6082 Tailor Welded Blanks

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Abstract. An advanced forming process involving hot forming and cold-die quenching, also known as HFQ®, has been employed to form AA6082 tailor welded blanks (TWBs). The HFQ® process combines both forming and heat treatment in a single operation, whereby upon heating the TWB, it is stamped and held between cold tools to quench the component to room temperature. The material therefore undergoes temperature, strain rate or strain path changes during the operation. In this paper, a finite element model (FEM) was developed to investigate the formability and deformation characteristics of the TWBs under HFQ® conditions. Experimental results, i.e. strain distribution, were used to compare and validate the simulation results. A good agreement between the experiment and simulation has been achieved. The developed temperature, strain rate and strain path dependent forming limit prediction model has been implemented into FE simulation to capture the complicated failure features of the HFQ® formed TWBs. It is found from both experiment and simulation that the forming speed has important effects on the occurrence of failure position, where the failure mode for the 1.5-2 mm TWBs may change from localised circumferential necking to parallel weld necking.
HFQ® is a registered trademark of Impression Technologies Ltd.

Introduction

Aluminium alloys have been widely used as promising lightweight materials for the automotive applications. Due to its excellent mechanical properties, such as high stiffness-to-density and high strength-to-density ratios, AA6082 is suitable for structural sheet-metal fabrications [1].

Tailor welded blanks (TWBs) are single-piece semi-finished parts produced by joining sheet metals of the same or different gauges prior to deformation. The use of TWBs allows part to be formed in a more cost-effective manufacturing process. The most commonly used welding technology for manufacturing the AA6082 tailor welded blanks is laser beam welding. Laser welding has various advantages, including high productivity, high weld quality in terms of controllable heat affected zone (HAZ) and weld zone, low distortion, flexibility due to the movable heat source, reliability and precision. However, the overall formability of TWBs is significantly affected by the welding parameters [2], e.g. power source, welding speed etc., especially for heat-treatable aluminium alloys. The weld area in aluminium TWBs is typically weaker than the base material, which adds difficulty in forming such TWBs. A novel process, solution Heat treatment, Forming and in-die Quenching (HFQ®) has demonstrated its advantages in the forming of AA6082 TWBs with improved formability, as it could eliminate the welding effects and restore the mechanical properties of the welding zone [3].

In order to identify proper forming parameters for the TWBs under HFQ® conditions, the forming limit and ductile fracture characteristics have to be studied. Zadpoor *el al* [2] studied four different modelling methods for formability prediction of high strength aluminium sheets, and concluded that both ductile fracture model and Marciniak-Kaczynski (M-K) [4] models performed well. Davies developed forming limit diagrams for welded materials in AA5xxx 1-2 mm TWBs

under biaxial stretching condition based on M-K model. However, those works focused on determining the forming limit diagrams for constant temperatures and constant strain rates. As the HFQ® forming of aluminium alloys introduced the changes in temperature, strain rate or strain path, thus the tradition finite element modelling (FEM) method is no longer applicable. El Fakir *et al* developed and successfully validated a forming limit diagram prediction model for AA5754 that undergoes temperature, strain rate and strain path changes during deformation [5].

This paper is to study the complex deformation features of AA6082 TWBs under HFQ® conditions. The formability and failure characteristics have been examined experimentally. An advanced FEM technique, which incorporates temperature, strain rate, and strain path effects on the formability, has been used to achieve an accurate failure prediction.

Experimental Details

Material. Aluminium alloy AA6082-T6 has been used as the baseline material in this study. Tensile tests have been carried out at different temperatures (350-535 ℃) and strain rates (0.1-10 s^{-1}) [6] to develop the material model for FE simulation. The AA6082 blanks (initial size of 600×300 mm^2) with thicknesses of 1.5 and 2 mm were initially cut along the rolling direction, and then welded together parallel to the rolling direction into two thickness combinations, i.e. 1.5-1.5 and 1.5-2 mm TWBs. Laser welding was carried out on the blanks using a Nd:YAG source through a 0.2 mm fibre with a power of 2.1 kW. The welding speed was 25 mm/s. In this study, the investigations were focused only on butt welds with fully penetrated joints.

HFQ® dome test. Dome test is designed to study the formability of the AA6082 TWB under HFQ® conditions. The formed dome part has a diameter of 100 mm, and the punch stroke was set to a value where localised necking initiated. The blank holding force was set to a constant value of 20 kN, which was applied through the use of two gas springs. Graphite grease (Omega 35) was used as the lubricant to reduce friction during forming. The combinations of TWBs studied are listed in Table 1.

Table 1 AA6082 TWBs combination studied.

TWBs combination	Thickness ratio	Forming Speed		
		25 mm/s	250 mm/s	400 mm/s
1.5-1.5 mm	1		✔	
1.5-2 mm	1.3	✔	✔	✔

The experiments were conducted using a 25-tonne ESH single action press. The TWB was initially heated to 535 ℃ in the furnace for solution heat treatment (SHT) and then transferred to the cold die for deformation. The transfer was completed within 10 s, during which the blank temperature decreased to around 450 ℃ before the forming started. The experimental setup used for the HFQ® dome forming is illustrated in Fig. 1.

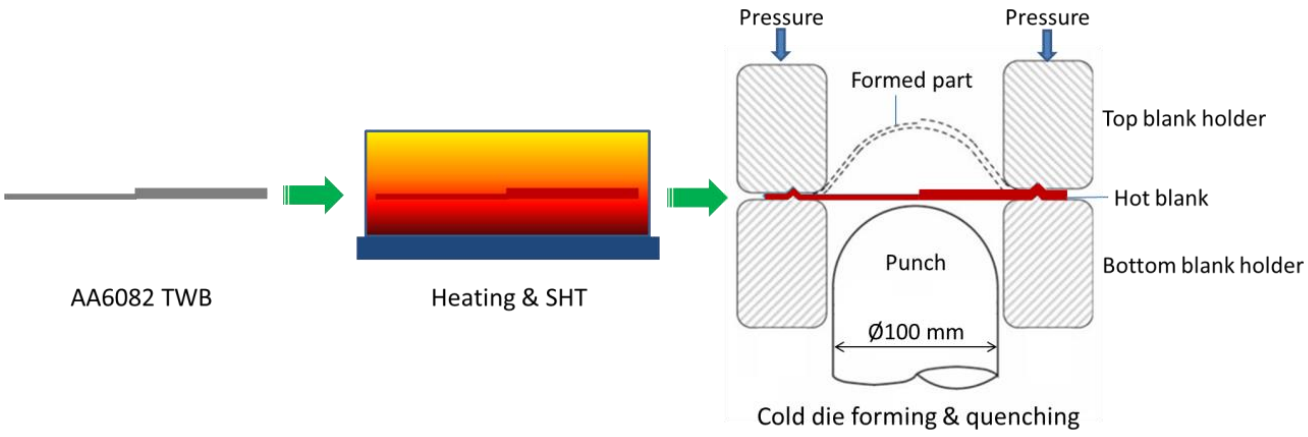


Fig. 1 Schematic diagram of the HFQ® TWB forming process.

Development of Unified Viscoplastic M-K Forming Limit Model

The Marciniak and Kuczynski, or M-K model, is a strain localisation model that assumes that sheet metals have pre-existing imperfection zones with slightly lower thicknesses than the rest of the material [4]. The model makes use of a non-homogeneity coefficient, or imperfect factor, which accounts for the initial discrepancy in the thickness. Due to the thickness inhomogeneity, as the deformation progresses, a point will be reached where deformation in the thinner region, designated *zone* B, increases at a much faster rate than the surrounding material, or *zone* A, resulting in necking and subsequent failure. As the deformation progresses, the imperfect factor f (Eq. 1) decreases, and strain becomes localised at *zone* B; failure occurs when the ratio of strains in *zones* B to A approaches a critical value, shown in Eq. (2).

$$f = \frac{t_B}{t_A} = f_0 exp(\varepsilon_{3B} - \varepsilon_{3A}) \tag{1}$$

$$\frac{d\varepsilon_{1B}}{d\varepsilon_{1A}} \geq 10, or\ \frac{d\varepsilon_{3B}}{d\varepsilon_{3A}} \geq 10 \tag{2}$$

where f_0 is the initial value of the imperfect factor, determined by calibrating against the forming limit curves (FLCs) obtained from the formability tests [7].

The different points along the FLCs representing different strain conditions were calculated by varying the ratio between the minor and major strains in *zone* A. This ratio, denoted as β, has a value of -0.5 for the uniaxial condition, and a value of 1 in the equal-biaxial condition. To determine the evolution of the strains in *zone* B, it is assumed that the strains are compatible at the interface between *zones* A and B where the minor strains are equal to each other, and there is mechanical equilibrium along the interface before the onset of necking.

$$\varepsilon_{2A} = \varepsilon_{2B}, \sigma_{1A} = f\sigma_{1B} \tag{3}$$

All the following equations had to be solved simultaneously for both *zones* A and B. The viscoplastic flow rule is shown in Eq. 4, and is a function of the flow stress and the isotropic hardening variable, *R* (Eq. 5). This in itself is a function of the normalised dislocation density (Eq. 6), which accounts for the accumulation and annihilation of dislocations during deformation; hence *R* captures the effect of hardening due to dislocation pileup and entanglement [8].

$$\dot{\bar{\varepsilon}}_{P(A,B)} = \left(\frac{\bar{\sigma}_{(A,B)} - R_{(A,B)} - k}{K}\right)^{n_1} \tag{4}$$

$$R_{(A,B)} = B\bar{\rho}_{(A,B)}^{-0.5} \tag{5}$$

$$\dot{\bar{\rho}}_{(A,B)} = A\left(1 - \bar{\rho}_{(A,B)}\right)\dot{\bar{\varepsilon}}_{p(A,B)} - C\bar{\rho}_{(A,B)}^{n2} \tag{6}$$

$$\bar{\sigma}_{(A,B)} = E(\bar{\varepsilon}_{(A,B)} - \bar{\varepsilon}_{p(A,B)}) \tag{7}$$

$$R_2\sigma_{1(A,B)}^a + R_1\sigma_{2(A,B)}^a + R_1R_2\left(\sigma_{1(A,B)} - \sigma_{1(A,B)}\right)^a = R_2(R_1 + 1)\bar{\sigma}_{(A,B)}^a \tag{8}$$

where k, K, n_1, n_2, B (Eq. 5), A (Eq. 6), and E, are temperature-dependent material constants calibrated using the results of uniaxial tension tests. The suffixes (*A*, *B)* represent the corresponding variables in *zone* A and *zone* B. R_1 and R_1 are the strain ratios (*r*-values) in the longitudinal and transverse directions, respectively. The use of a time integration procedure also enables the effect on the forming limit of time dependent phenomena and process conditions, such as the varying temperatures, strain rates and strain paths in a hot stamping process, to be captured.

HFQ® Process Simulation

FE simulation model. Finite element simulations of the hemispherical punch forming at HFQ® conditions were conducted using the commercial software PAM-STAMP and a developed temperature and strain rate dependent material model. As shown in Fig. 2, the simulation model comprises of a punch, TWB, and the blank holder sets. The tools (i.e. blank holder and punch) were

modelled using rigid elements. The initial blank temperature was set to be 450 ℃, which is identical to the experimental condition. A friction coefficient of 0.3 was chosen to account for surface interaction between the sliding sheet and the die assembly.

Shell element is used for the TWB. The element size of the blank is 2 mm for the 1.5-2 mm combination and 1.5 mm for the 1.5-1.5 mm TWB. The tailor welded blank was designed using the built-in feature provided by PAM-STAMP. Since HFQ® forming technique could eliminate the welding effects and restore the mechanical properties of the welding zone, no special consideration was taken for the weld zone and the weld line mesh was set to the same as that of base material.

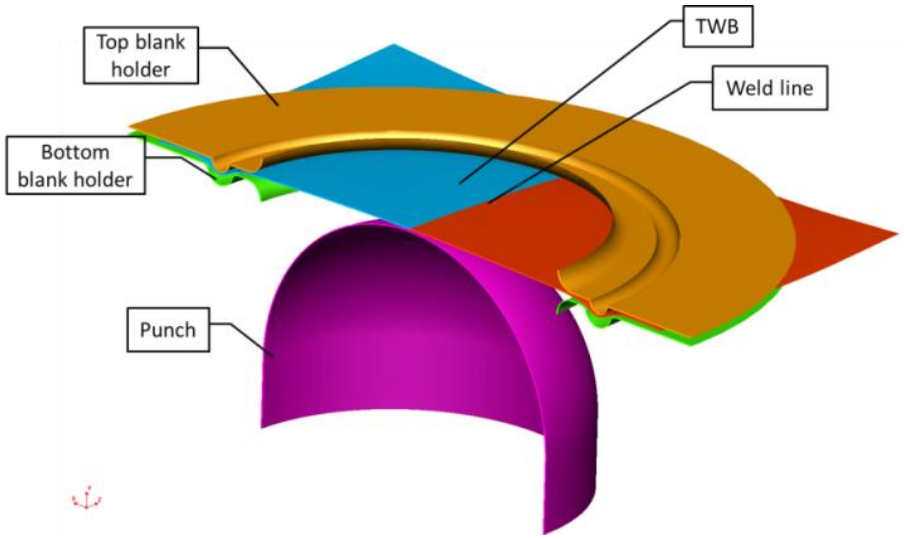


Fig. 2 Pam-Stamp simulation model (cross-sectional view).

Strain distributions. Fig. 3 shows the strain comparison of the 1.5-1.5 mm TWB between experiment and simulation at the onset of localised necking. There is circumferential necking occurring approximately halfway between the base and apex of the formed part. Since two parts of the TWB have equal thickness, the weld line stayed in the centre after forming and the strain distribution on either side of the weld line is symmetrical. The peaks represent the area of largest strains, i.e. greatest thickness reduction, which corresponds to the circumference around half way through the dome height. The failure type is classified as circumferential necking.

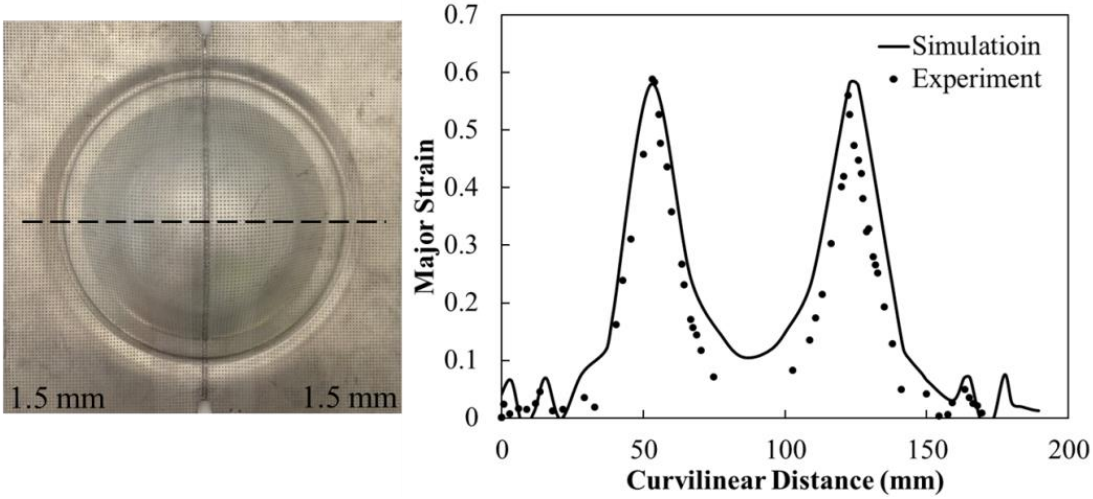


Fig. 3 Comparison of strain distributions in the 1.5-1.5 mm TWB between experiment and simulation (forming speed: 250 mm/s).

Fig. 4 shows the strain distribution for the TWB where two blanks are of different thickness, 1.5 and 2.0 mm, respectively. Due to different deformation forces of the blanks, the weld line shifted toward the 2 mm side. The shift in weld line toward the thicker material was observed in all tests

where blanks have dissimilar thickness. The strain at area around the weld line cannot be compared because strain measurements on the welding seam are not possible.

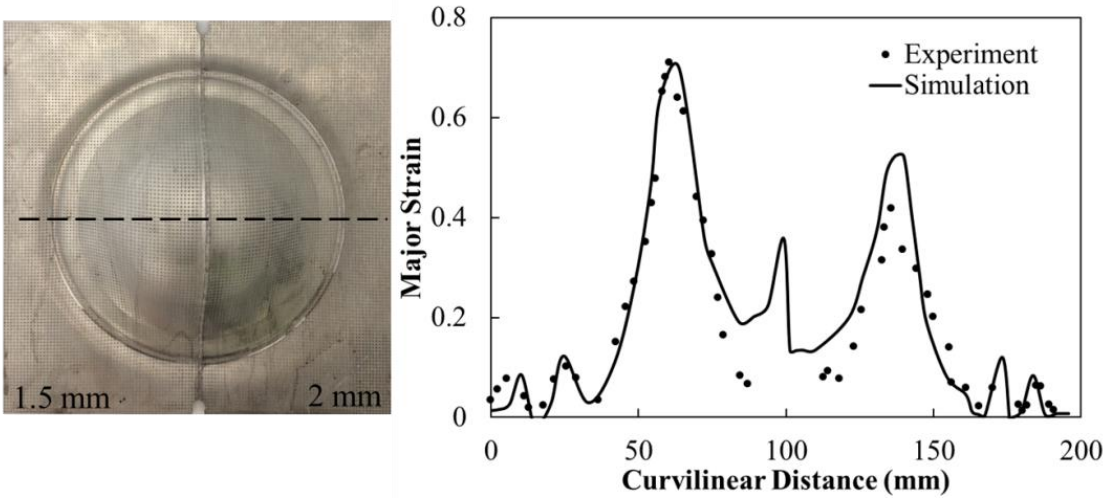


Fig. 4 Comparison of strain distributions in the 1.5-2 mm TWB between experiment and simulation (forming speed: 250 mm/s).

Forming Limit Prediction

Since the FE simulation models have been validated by the experimental results, the unified viscoplastic M-K forming limit model was further implemented into the simulations. Fig. 5 shows the forming limit prediction results where the dome is safe (no localised necking) and failed with localised necking over a certain limit dome height (LDH). For the 1.5-2 mm TWBs, the effect of forming speed on limit dome height is studied. In general, the LDH increases as speed increases. The increase in limit dome height is more dramatic from 25 to 250 mm/s than from 250 to 400 mm/s, where the limit dome height almost stays the same level.

The failure mode is found to be dependent on forming speed for the 1.5-2 mm TWBs. At a lower speed, failure occurred at the circumference, however, when the speed reached 400 mm/s, the failure occurred in the thin blank within the heat affected zone and parallel to weld line. In the case of 400 mm/s, the failure is found at a small distance away from the weld line, which is referred to as parallel failure in the study.

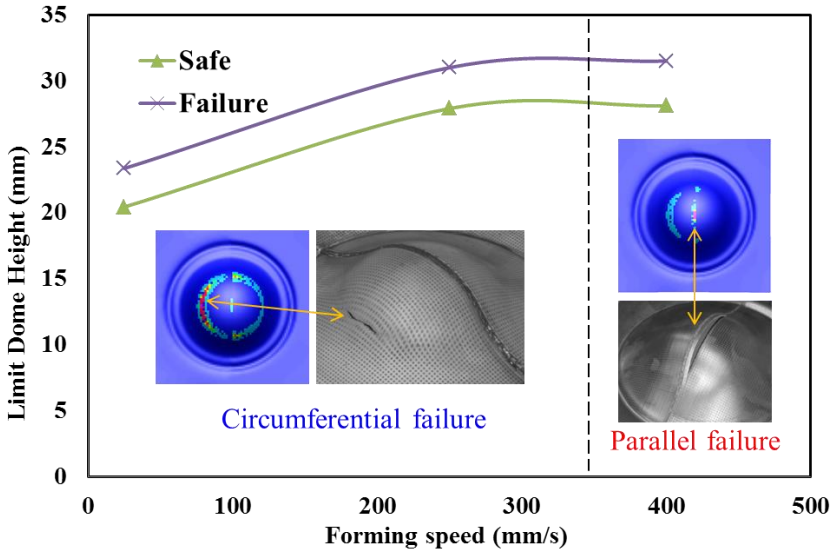


Fig. 5 Effect of forming speed on the forming limit and failure modes for 1.5-2 mm TWB.

The strain path of the weld area element (where parallel failure occurs) and side element (where circumferential failure occurs) are plotted for different forming speeds, as shown in Fig. 6. As forming speed increases, the strain difference between weld area element and side element reduces. The increase in speed also leads to decrease in major strain and increase in minor strain, i.e. β is increasing, indicating that the deformation of selected elements (strain path) is shifting from plane strain condition toward biaxial stretching condition.

The temperature evolutions at different forming speeds are inserted in Fig. 6. It is found that the temperature of the weld area element drops much quicker than that of the circumferential (side) element. This is because the moving punch was firstly in contact with the elements in the weld zone. As forming progressed, it gradually contacted with the circumferential elements. In addition, the failure strains where the localised necking initiates are varied at different forming speeds. The changes in strain path and temperature in such conditions may account for the strain variations.

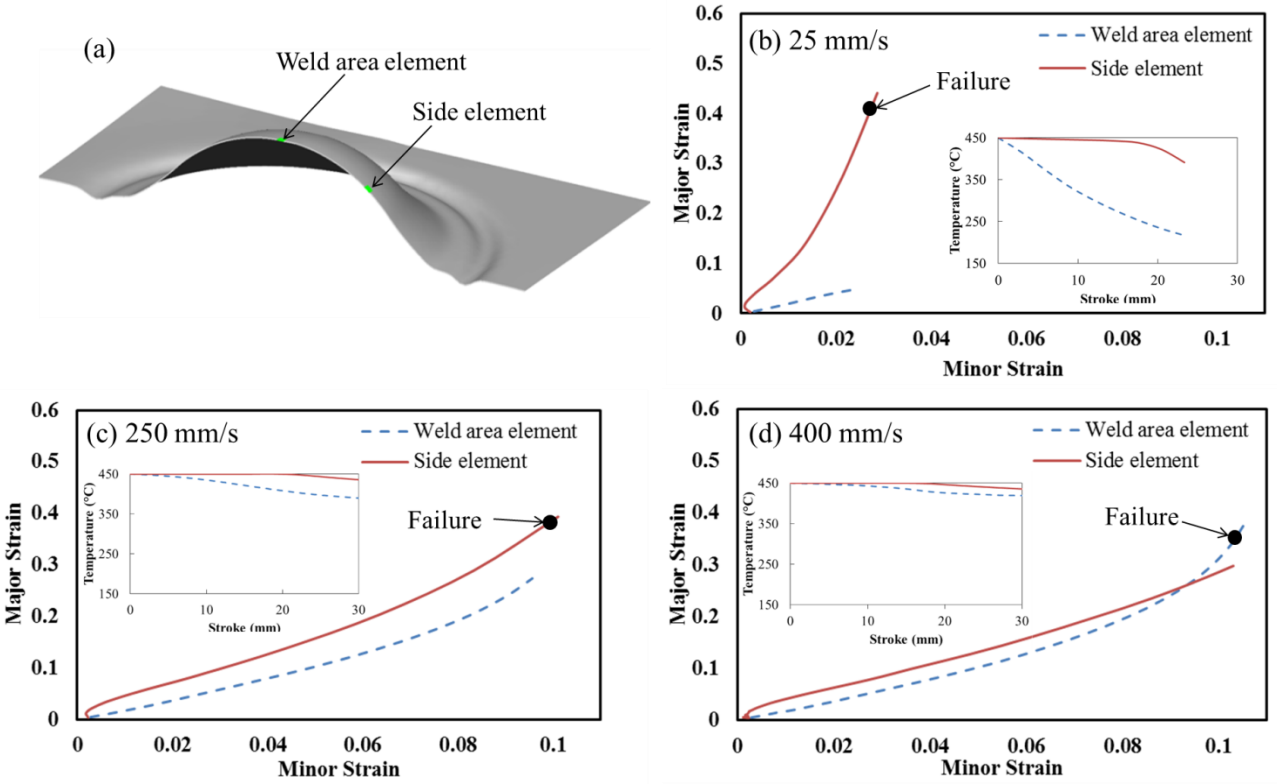


Fig. 6 Strain paths of the weld area element and side (circumferential) element for the 1.5-2 mm TWB formed at different forming speeds.

Conclusions

The dome test FE simulation for AA6082 TWBs has been successfully built and verified against experimental results. The simulation was then extended to forming limit prediction where the dome failure modes were successfully predicted. Two different failure modes, which are circumferential failure and parallel failure, were identified for the 1.5-2 mm TWBs depending on the forming parameters. The failure mode shifted from circumference failure to parallel failure as forming speed increased. The formability of the TWB is enhanced at higher forming speed. The limit dome height increases as speed increases. The optimal forming speed is 250 mm/s, and further increase of forming speed has exhibited very limited improvement in the formability.

Acknowledgements

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References

[1] J. Liu, L. Wang, J. Lee, R. Chen, O. El-Fakir, L. Chen, J. Lin, T.A. Dean, Size-dependent mechanical properties in AA6082 tailor welded specimens, J. Mater. Process. Tech. 224 (2015) 169-180.

[2] A.A. Zadpoor, J. Sinke, R. Benedictus, Mechanics of Tailor Welded Blanks: An Overview, Key Eng. Mater. 344 (2007) 373-382.

[3] J. Liu, H. Gao, O.E. Fakir, L. Wang, J. Lin, HFQ forming of AA6082 tailor welded blanks, MATEC Web of Conferences 21 (2015) 05006.

[4] Z. Marciniak, K. Kuczyński, Limit strains in the processes of stretch-forming sheet metal, Int. J. Mech. Sci. 9 (1967) 609-620.

[5] O. El Fakir, L. Wang, D. Balint, J.P. Dear, J. Lin, Predicting Effect of Temperature, Strain Rate and Strain Path Changes on Forming Limit of Lightweight Sheet Metal Alloys, Procedia Eng. 81 (2014) 736-741.

[6] M.S. Mohamed, A.D. Foster, J. Lin, D.S. Balint, T.A. Dean, Investigation of deformation and failure features in hot stamping of AA6082: Experimentation and modelling, Int. J. Mach. Tool. Manu. 53 (2012) 27-38.

[7] X. Luan, O.E. Fakir, H. Gao, J. Liu, L. Wang, Formability of AA6082-T6 at warm and hot stamping conditions, 16th International Conference Metal Forming, Kraków, Poland, 2016.

[8] J. Lin, T.A. Dean, Modelling of microstructure evolution in hot forming using unified constitutive equations, J. Mater. Process. Tech. 167 (2005) 354-362.