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RESEARCH ARTICLE

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Hot stamping of AA6082 tailor welded blanks: experiment and FE simulation

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Abstract – An advanced forming technology, solution Heat treatment, Forming and in-die Quenching (HFQ®), has been employed to form AA6082 tailor welded blanks (TWBs). In comparison with conventional stamping of TWBs, the mechanical properties and formability of AA6082 laser TWBs could be improved under the HFQ® forming condition. The TWB was divided into three physical zones, i.e. base metal, heat affected zone (HAZ) and weld zone, based on the hardness distribution. It was found that the degraded hardness of the weldment can be restored after HFQ® forming. TWBs of AA6082 with different thickness ratios of 2 (2–1 mm), 1.3 (2–1.5 mm) and 1 (1.5–1.5 mm) were used to study the TWB thickness ratio effects on the forming behaviour. Hemispherical punch dome tests on the TWBs with varying thickness ratios demonstrated different formabilities, and indicated increased displacement of the weld line with increasing thickness ratio. Finite element (FE) modelling was adopted to analyse the weld line movement and strain distributions during HFQ® forming.

Key words: Aluminium, Tailor welded blank, Hot stamping, Solution heat treatment, Artificial ageing

1. Introduction

In recent decades, aluminium alloys have attracted the attention of many researchers, engineers and designers as promising structural materials for the automotive industry applications. As a commercial alloy with high stiffness to density and high strength to density ratios, AA6082 is suitable for structural sheet-metal fabrications.

Tailor welded blanks (TWBs) consisting of multiple sheet materials joined with welds has been widely used in lightweight structures. The market for aluminium alloys is expanding into various sectors, most significantly in automotive industries where the use of tailor welded blanks in aluminium is developing rapidly. Due to the development of advanced forming technologies, it is now possible to form tailor welded blanks to produce body panels with complex structure and reduced weight [1]. 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 [2].

Many studies have concentrated on the mechanical properties of TWBs [3], the movement of weld line [4], forming process design [5], finite element simulation [6], forming limit (formability) [7] and failure prediction for TWBs [8]. Generally, the overall formability of TWBs is significantly affected by the welding parameters [9], especially for heat-treatable aluminium alloys. Miles et al. [10] have reported that the aluminium friction stir welded blanks showed similar formability as the base material in plan-strain, but had rapidly decreasing formability as biaxial strain conditions were approached. The weld area in aluminium TWBs is typically weaker than the base material, which adds difficulty in forming such TWBs with conventional methods. Additionally, the other parameters influencing the formability of TWBs may include the thickness ratio and the orientation of the weld line to the loading direction. It is well accepted that the limit dome height and strain distribution during stretch forming were greatly influenced by the thickness variation [3].

Foster et al. [11] have developed a novel process, solution Heat treatment, Forming and in-die Quenching (HFQ®[1]), which was able to overcome the major problems in forming AA6082 TWBs, such as low formability and microstructure variations. Heat treatment is required for the heat-treatable aluminium alloys to achieve desired microstructure and thus specified mechanical properties. Previous studies have shown that heating a material to its solution heat treatment temperature,

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[1] HFQ® is a registered trademark of Impression Technologies Ltd.

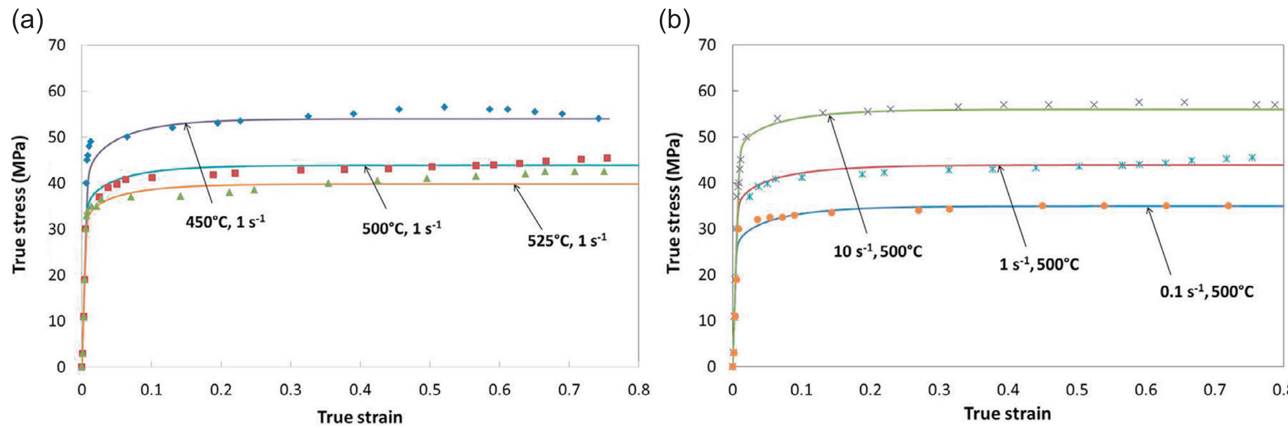

Figure 1. Uniaxial tensile test results of AA6082 at (a) different temperatures and (b) various strain rates.

e.g. 450–550 °C, significantly increases its formability, due to the complete dissolution of alloying elements and/or precipitates into the material matrix resulting in a single phase, which reduces the obstructions to dislocation motion and enhances material flow [12]. This material characteristic has been utilised for the stamping of complex-shaped high-strength aluminium panel components, and has led to applications of the HFQ® process.

The aim of this work is to apply the novel HFQ® process into the forming of laser welded AA6082 TWBs. The degraded hardness of the TWB can be restored after HFQ® forming and artificial ageing. AA6082 TWBs with different thickness combinations of 2–1, 2–1.5 and 1.5–1.5 mm were used to study the TWB thickness ratio effects on the forming behaviour. Finite element simulations were performed for evaluating the strain distributions and weld line movement during deformation.

2. Experimental details

2.1. Material

The base material used in this study is aluminium alloy AA6082-T6. Uniaxial tensile tests were performed on AA6082 using a Gleeble 3800 thermo-mechanical testing system. Figure 1 shows the stress-strain curves of AA6082 at various temperatures and strain rates. The symbols are the results from experimental determinations. The experimental results were used to calibrate a set of dislocation-based hardening constitutive equations [13] interpreting the unified viscoplastic behaviour at warm/hot forming conditions. Good agreements between the experiment (symbols) and modelling (solid curves) have been obtained. The calibrated material model was applied in PAM-STAMP simulations to predict the HFQ® forming process.

The blanks (initial size of 600×300 mm^2) with thicknesses of 1, 1.5 and 2 mm were initially cut along the length (rolling) direction, and then welded together parallel to the rolling direction into three different thickness combinations, i.e. 2–1, 2–1.5 and 1.5–1.5 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.

2.2 HFQ® dome test

The HFQ® process mainly consists of four phases, i.e. solution heat treatment (SHT), transfer, cold die forming and quenching, and post-forming heat treatment (artificial ageing). All the TWBs were initially heated to 525 °C (SHT temperature) and maintained at the temperature for 1 min to ensure complete dissolution of second phases during solution heat treatment. The hot TWB was then rapidly transferred to the cold die which was immediately closed to form the dome shaped component. The transfer was completed within 10 s, during which the blank temperature decreased to around 450 °C before the forming started. The HFQ® process may comprise a post-forming heat treatment stage for heat-treatable aluminium alloy components which includes heating the formed component to an artificial ageing temperature and holding it at that temperature to allow the precipitation hardening to occur. Typical temperature for AA6082 is 190 °C, and the time is 9 h in this study so as to achieve a complete T6 temper condition after artificial ageing.

Hemispherical dome tests were conducted to investigate the formability of AA6082 TWBs at speeds of 75, 250 and 400 mm/s under HFQ® conditions. The tool used for the HFQ® forming test is shown in Figure 2. It comprises of the top punch pole, 40 mm diameter hemispherical punch, top/bottom blank holders, and the TWB. During testing, the punch was fixed, while the top blank holder was moved down at the desired rate to first clamp the TWB between the top and bottom blank holders, and then to deform the blank over the punch to the limit dome height of the TWB. Graphite grease (Omega 35) was used as the lubricant and was evenly applied to the punch surface to reduce the friction during forming. Two gas springs were utilised to maintain the blank holding force at a constant value of 20 kN. The top blank holder was specially manufactured so as to accommodate the TWBs with different thickness combinations.

For a sheet metal forming process, localised necking may appear at a specific forming stage just before fracture happens,

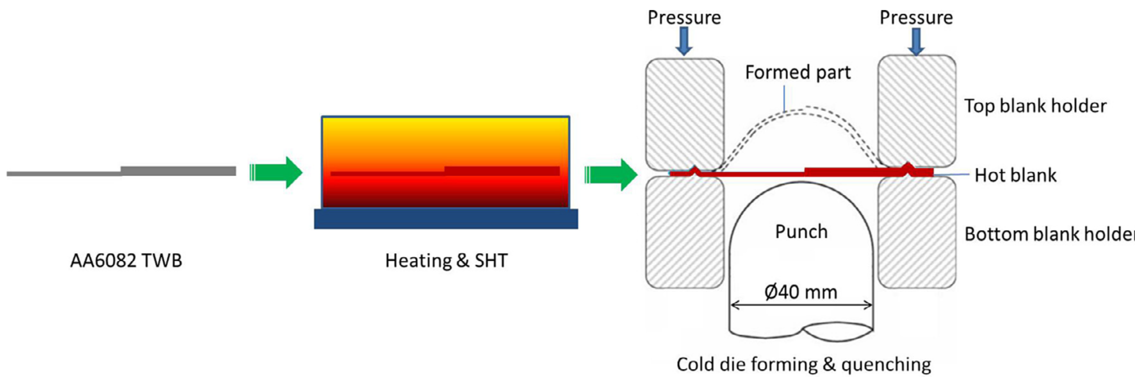

Figure 2. Schematic diagram of the HFQ® forming process.

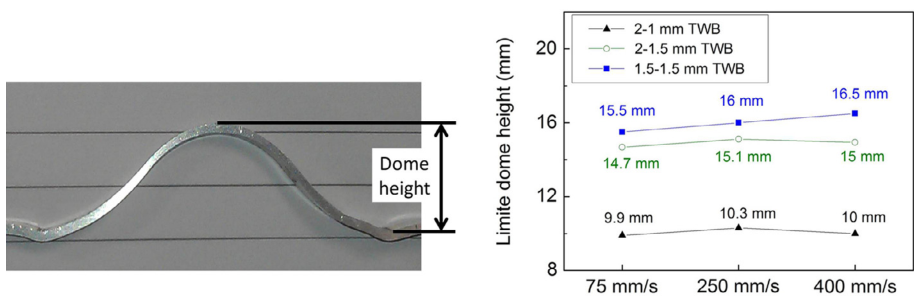

Figure 3. Limit dome height of HFQ® formed tailor welded blanks.

which is an indication of localised plastic deformation [14]. As a stroke controlled test, the stroke of the punch was always set to a value at which localised necking was estimated to initiate, and then refined through multiple trial runs to the correct value. Due to the test piece being quite sensitive to changes in the stroke, even a small adjustment could cause fracture in the formed part. Three tests for each condition have been performed so as to ensure a good repeatability of the forming results.

To determine the mechanical properties of the TWB before and after HFQ®, hardness values were measured along the mid thickness of the blank using a Vickers Microhardness tester with a load of 200 g and a dwell time of 12 s.

3. Results and discussion

3.1. HFQ® dome test

3.1.1. Limit dome height

The limit dome height (LDH) is the position at which localised necking starts to occur on the formed component, and was used to compare the formability of the TWBs under HFQ® conditions. In general, the LDH increases with the decreasing blank thickness ratio and increases as the forming speed increases from 75 to 400 mm/s, although the increasing trend for the 2–1 mm TWBs is not as significant as the 1.5–1.5 mm TWBs. The premature fracture occurred at higher blank thickness ratios, because the localised strain primarily occurred in the thinner blank at higher circumferential stress levels. The increase in the LDH with increasing forming speed is due to the enhanced strain rate hardening effect at higher forming speed. In addition, the blank temperature was higher at fast forming speed due to less heat loss into the cold punch and air, which is beneficial for the formability improvement (Figure 3).

3.1.2 Deformation characteristics

Figure 4 shows the different features of localised necking (or cracking) for the TWBs with various thickness combinations. It can be seen from the 2–1 mm TWB in Figure 4a that the most severe plastic deformation occurred in the 1 mm blank parallel to the weld line. In this case, the failure is found at a small distance away from the weld line, which is referred to as parallel failure in the study.

For the 2–1.5 mm TWB shown in Figure 4b, two localised thinning regions are found in a mixture mode combining the parallel necking and the circumferential cracking. The cold die quenching was not effective due to the rough surface topography around the weld line, hence a higher blank temperature in this region has resulted in lower strength and thus localised necking took place along the weld line. The circumferential necking in the thin blank was due to the stress concentration in the thinner blank, as the circumferential stress within the blank is proportional to the ratio between the punch radius and blank thickness (*R/t*).

Figure 4c shows the circumferential necking occurring approximately halfway between the base and apex of the formed 1.5–1.5 mm TWB part. Since the two part of the TWB have similar thickness, the weld line stayed in the centre after forming and the stain distribution on either side of the weld line is

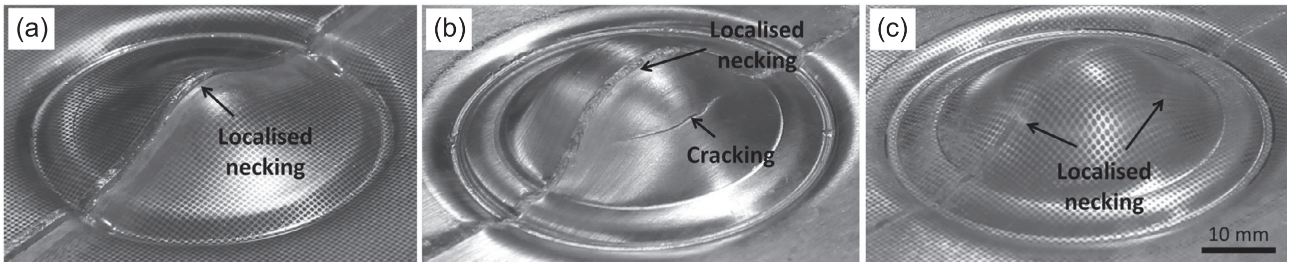

Figure 4. HFQ® formed parts of (a) 2–1 mm TWB, (b) 2–1.5 mm TWB and (c) 1.5–1.5 mm TWB.

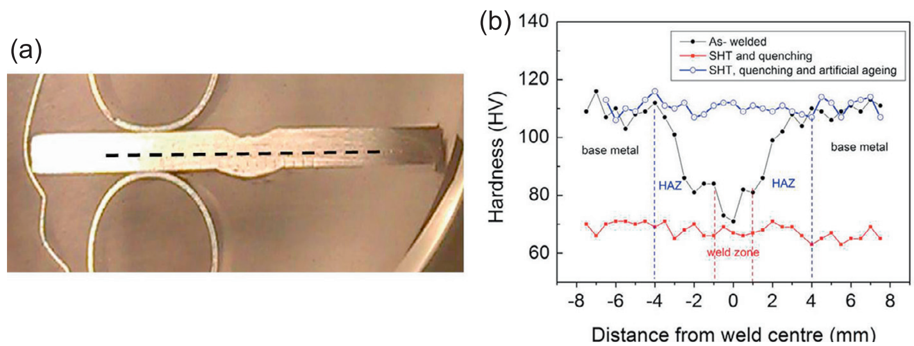

Figure 5. (a) Cross-section of a 1.5–1.5 mm TWB and (b) hardness profiles of the TWB at different heat treatment conditions.

symmetrical. The strain distribution will be detailed in Section 3.2.3.

3.1.3. Microhardness

Microhardness values of the as-welded specimen show a typical V-shape, as plotted in Figure 5, where the lowest value is located in the centre of the weld zone. After solution heat treatment at 525 °C and the subsequent water quenching, all the hardness decreased significantly but were at a consistent level at different measured locations. An artificial ageing treatment (190 °C for 9 h) strengthened the material, and as a result, achieved the full hardness (HV > 110) of the alloy.

3.2. Finite element simulation

3.2.1. Simulation model

Finite element (FE) 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 Figure 6, the simulation model comprises of a punch, TWB, and the blank holder sets. The tools (i.e. blank holders and punch) were modelled using rigid elements. The TWB was defined using the built-in feature provided by PAM-STAMP. Since the HFQ® forming process could eliminate the welding effects and restore the mechanical properties of the weld zone, no special consideration was taken for the weld zone and the weld section mesh was set to the same as that of base material. The initial blank temperature was set to be 450 °C, which is identical to the experimental condition. A friction coefficient of 0.35 was chosen to account for surface interaction between the sliding sheet and the die assembly.

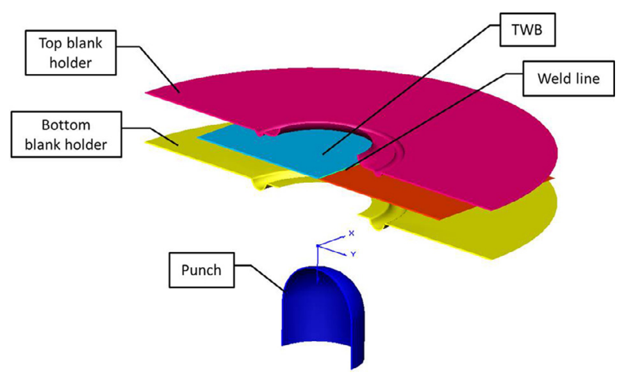

Figure 6. PAM-STAMP simulation model (cross-sectional view).

3.2.2. Temperature evolution

The HFQ® process is a hot sheet forming operation that incorporates part of the thermal tempering process required for heat-treatable aluminium alloys [15]. The hot blank is formed and held between cold dies, during which a rapid quenching is performed. The temperature of the deforming sheet is not uniformly distributed, which makes the deformation more complicated.

Figure 7 shows the temperature history during HFQ® at a forming speed of 75 mm/s. Temperature data at two points of the formed component was recorded using a data logger at a frequency of 6 Hz. The blank temperature was at 450 °C when the stamping started. The temperature at Point 1 dropped

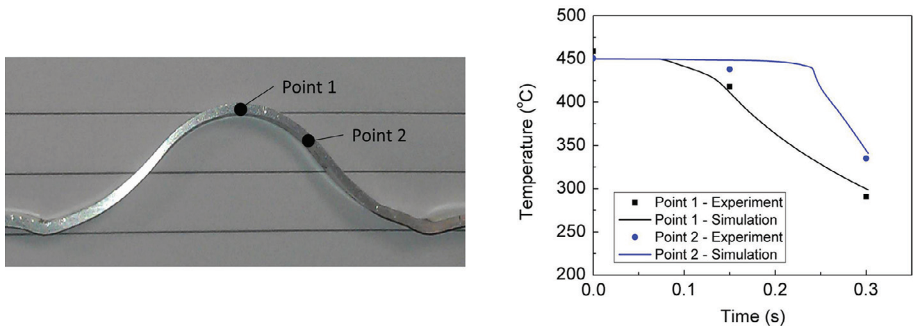

Figure 7. Temperature history during HFQ® forming at 75 mm/s between experiment and simulation.

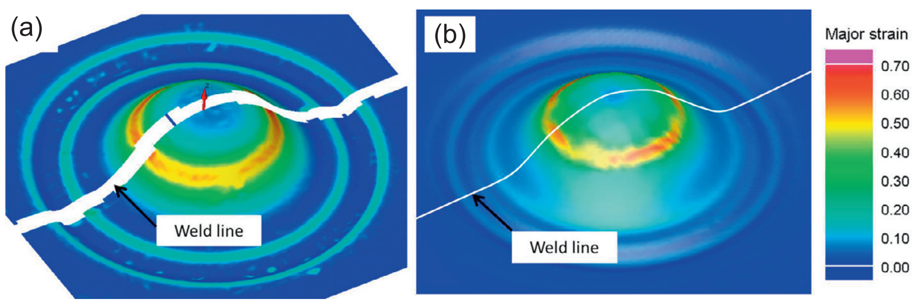

Figure 8. Comparison of strain distributions in the 1.5–1.5 mm TWB between (a) experiment and (b) simulation.

rapidly when the punch firstly contacted the blank at the dome apex, but there was some delayed temperature drop at Point 2 due to the later contact between this point and the punch. The predicted temperature evolution from simulation, see Figure 7, has a good agreement with the experimental measurements.

3.2.3. Strain distribution

Figure 8 shows the strain comparison of the 1.5–1.5 mm TWB between experiment and simulation at the onset of localised necking. The strain distributions are able to depict deformation characteristics of this thickness combination. As shown in Figure 4c, the failure type was circumferential necking occurring approximately halfway between the base and apex of the formed part. As the stroke increased, the punch stretched the sheet material to a higher strain level, and the eventual failure was initiated by necking from excessive strain in a circumferential location. The good agreement between experiment and simulation also indicates the feasibility of the FE simulation in prediction of the deformation behaviour, e.g. localised necking, weld line movement, etc. for other TWBs.

3.2.4. Weld line movement

Due to blank thickness mismatch, the weld line shifts during the dome tests of TWBs. The weld line moves towards the thicker blank side because the thinner blank section has been stretched more by the moving punch than the thicker blank section. Table 1 lists the maximum displacement of the weld in the HFQ® formed TWBs with different thickness combinations. For each TWB type, the stamping stroke was maintained at the same level. It was found that the weld line displacement

Table 1. Weld line displacement at the dome apex (unit: mm).

	Experiment	Simulation
2–1 mm TWB	1.0	1.04
2–1.5 mm TWB	0.6	0.576
1.5–1.5 mm TWB	0	0

was nearly independent of the forming speed. Thus, only the displacement of the weld line at a forming speed of 250 mm/s was presented here.

FE simulation is a useful method to evaluate the displacement of a whole weld line. As can be observed from Figure 9, the amount of weld line movement on the punch surface tends to increase as the thickness ratio is increased from 2–1.5 to 2–1. The maximum movement for the 2–1 mm TWB is found in the centre of the weld line at the dome apex. For the 2–1.5 mm TWB, the maximum values are found along the weld line in the centre area. In addition, there is localised necking occurring parallel to the weld line for the dissimilar thickness TWBs, as shown in Figure 4. This is because most of the stretching is concentrated on the thinner blank section with lower strength. The deformation is not uniformly distributed and the weld line shifts towards the thicker side, finally leading to parallel localised necking in the thinner blank section.

The blank thickness ratio in a TWB is an important factor impacting the movement of weld line. A lower thickness ratio (less thickness variation within the TWB) could have a more uniform deformation during forming. In real applications, the orientation and the position of the weld line can be adjusted according to the FE simulation. Clamping force may be

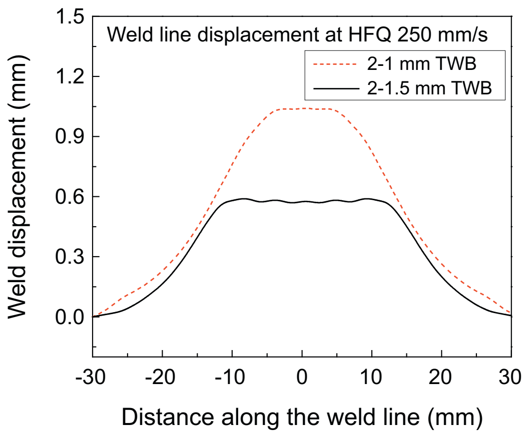

Figure 9. Predicted displacement of weld line for HFQ® formed TWBs with different thickness ratios.

applied on the weld line to eliminate the tearing failure (or localised necking) and produce a more uniformly distributed strain distribution in the thicker and thinner gauges of TWBs [6].

Conclusions

AA6082 tailor welded blanks with various thickness combinations have been used in the HFQ® forming process. The mechanical properties of the TWB have been restored after solution heat treatment, subsequent quenching and artificial ageing, indicating the advantages of the HFQ® process. The HFQ® formed TWBs exhibited different failure modes: localised necking parallel to the weld line for the 2–1 mm TWB, circumferential necking for the 1.5–1.5 mm TWB, and mixture of the parallel and circumferential necking for the 2–1.5 mm TWB. Thickness ratio has an important effect on the extent of the weld line movement and it was found that the weld line shift increases as the thickness ratio is increased. The non-uniform deformation may result in localised failure in the TWBs. Therefore, it is very important to identify the failure location, especially for the forming of complex-shaped components. The simulation of the HFQ® process could be further developed to predict the failure occurrence as well as to facilitate the forming process design.

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