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Hot stamping of AA6082 tailor welded blanks for automotive applications

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Abstract

Friction stir welded (FSWed) AA6082 tailor welded blanks (TWBs), with gauge combinations of 2.0-2.5 and 3.0-5.0 mm, have been prepared and successfully formed into automotive panel components. Experimental results indicated that the post-form strength, in terms of hardness, varied from location to location on the final parts. The strength is highly dependent on the blank gauges, with the average hardness values being HV 110 and HV 98 for the 2.0-2.5 and 3.0-5.0 mm TWB parts, respectively. Conventional FE simulation was built in PAM-STAMP and the prediction results were validated from experimental data in terms of strain distribution and temperature evolution. A typical continuous cooling precipitation (CCP) diagram for AA6082 was implemented into the verified simulation data to explain the strength variations. It is deemed that the temperature history during the stamping and quenching stages has played a major role on the post-form strength of the final parts.

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Keywords: Tailor welded blank; Hot stamping; Quenching; Cooling rate; Post-form strength

1. Introduction

Due to the pressing demands for weight reduction and fuel efficiency in land transportation, the usage of high-strength aluminium alloys has been increasing rapidly in recent years. Aluminium TWBs could make the

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components even lighter without compromising the structural complexity and strength requirements. In order to form the high-strength aluminium panel components, an advanced forming process involving hot forming and cold-die quenching, also known as HFQ®, has been developed [1]. The process has been able to perform both forming and heat treatment simultaneously in a single operation, and as such the degraded strength of the weldment in a TWB can be restored after forming.

However, the final strength of a high-strength aluminium component may still depend on many factors in the forming process, e.g. solution heat treatment (SHT), transferring time, quenching efficiency, artificial ageing, etc. Prediction of the post-form strength is also a challenge due to the effects of such factors. SHT is usually performed to dissolve the existing precipitates from the previous processes and uniformly distributes the alloying elements within the aluminium matrix [2]. After SHT, the blank is immediately transferred either manually or automatically to cold dies, which should be controlled in a matter of seconds to minimise the heat loss. The blanks are stamped into the die shape, and the formed components are held in the cold dies for a period of time under an appropriate holding force to quench it to a sufficiently low temperature. The rate of quenching must be fast enough to prevent second phase particles (i.e. precipitates) from coming out of the solution and to attain a supersaturated solid solution (SSSS) microstructure. The precipitation behaviour during cooling from solution heat treatment of Al-Mg-Si alloys has been investigated over a wide range of cooling rates, and maximum supersaturation after quenching should be reached to ensure maximum hardness after ageing [3]. The heat transfer from the formed component to the dies can be enhanced by increasing the holding pressure [4]. Furthermore, continuous cooling precipitation (CCP) diagrams have been developed to evaluate the quench sensitivity of aluminium alloys, such as for AA6xxx and AA7xxx [5]. The age-hardening responses of aluminium alloys are very significant and hence control of quenching efficiency as well as precipitation behaviour during forming is critical for attaining optimal material performance [6].

In this work, AA6082 TWBs (with gauge combinations of 2.0-2.5 mm and 3.0-5.0 mm) made from friction stir welding have been used and successfully formed into automotive panel components (B-Pillar section parts) under HFQ® conditions. The post-form strength, in terms of hardness, has been evaluated in simulations by adopting the CCP diagram. The effects of cooling rate/quenching efficiency on the formed TWB parts have been studied.

2. Experimental details

Aluminium alloy AA6082 sheets with thicknesses of 2.0, 2.5, 3.0 and 5.0 mm were used as the baseline material. The sheets were initially cut along the rolling direction (RD) and then joined together parallel to the RD into two thickness combinations, i.e. 2.0-2.5 and 3.0-5.0 mm welded blanks, as shown in Fig. 1(a). The widths of the weld zone in the two TWBs are 15 and 24 mm, respectively. The hardness values measured along the mid thickness section of the as-received TWBs are plotted in Fig. 1(b), showing decreased hardness at the weld and the thermal-mechanical affected zones.

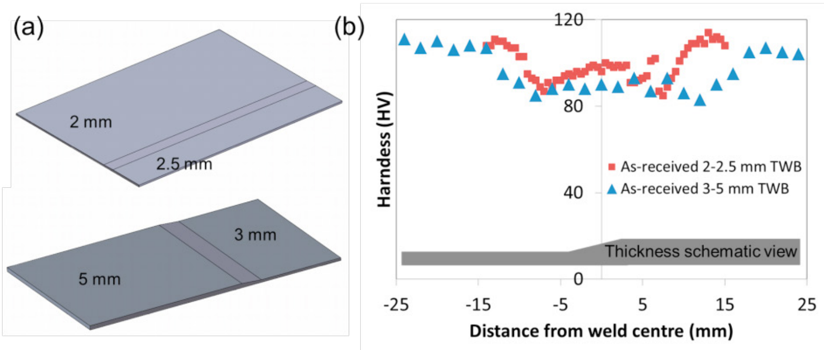

Fig. 1. Schematic of the FSWed 2.0-2.5 and 3.0-5.0 mm blanks and (b) hardness profiles of the corresponding TWBs.

Forming trials of the B-pillar sectional part were carried out on a 250 kN high speed hydraulic press with customised tool sets. Two sets of punches and dies were specially designed so as to accommodate the different thicknesses of the welded blanks. All the TWBs were initially heated to 525°C and maintained at the temperature for 3 min to ensure complete solution heat treatment. The hot TWB was then rapidly transferred to the cold die which was immediately closed to form the desired component. The transfer was completed within 10 s. A commercial graphite grease was used as the lubricant and was evenly applied to the tool surfaces to reduce the friction. Artificial ageing was conducted on the formed parts at 180°C for 8 hr. To determine the final mechanical properties after ageing, hardness values were measured on the formed parts using a Proceq® hardness tester. Each hardness value was an average of five readings.

3. Results and discussion

3.1. Forming trials

AA6082 TWBs (with gauges of 2.0-2.5 mm and 3.0-5.0 mm) made by friction stir welding have been successfully formed into automotive panel components (B-Pillar section parts), as shown in Fig. 2(a)-(c). The weight saving for the 2.0-2.5 and 3.0-5.0 mm blanks are 15%, compared to the monolithic blanks of 2.5 mm and 5.0 mm thickness, respectively. There are no visible defects or localised necking on the surfaces of the formed parts.

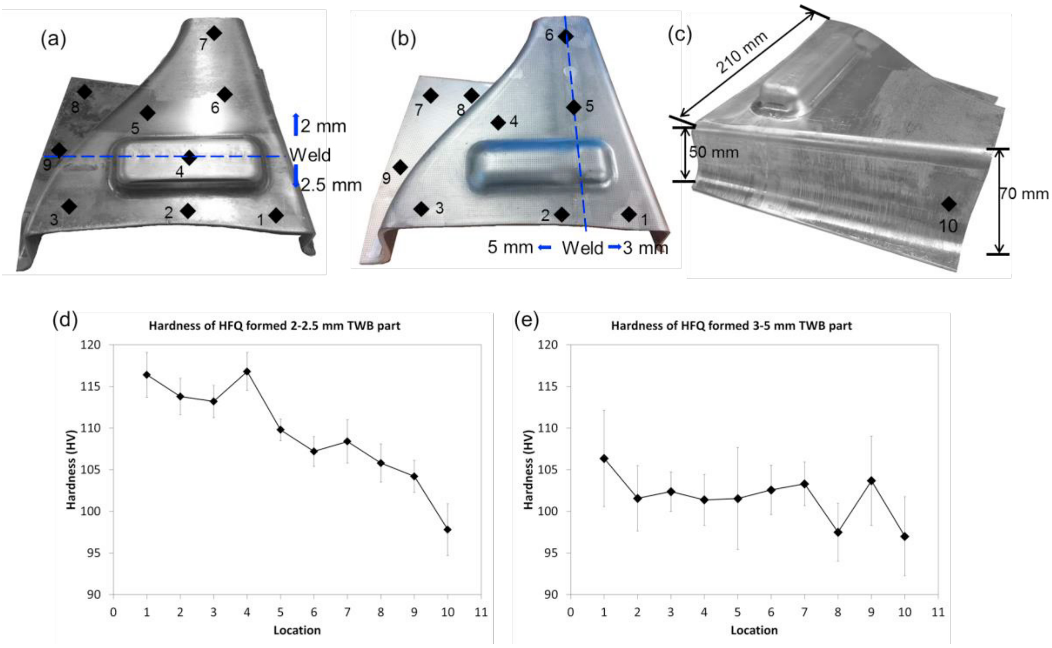

Fig. 2. HFQ® formed parts of (a) 2.0-2.5 mm TWB, (b) 3.0-5.0 mm TWB and (c) dimensions of the part, and hardness profiles for the (d) 2.0-2.5 mm and (e) 3.0-5.0 mm TWB parts.

The formed parts after artificial ageing were labeled by nos 1 to 9, as shown in Fig. 2, where hardness measurements have been carried out correspondingly. As can been seen in Fig. 2, the highest hardness values for the 2.0-2.5 and 3.0-5.0 mm TWB parts are found at *Location* 1 with the values of HV 116 and 106, respectively. Generally, the hardness of the 2.0-2.5 mm TWB surface (*Locations* 1-6) is higher than that of the 3.0-5.0 mm TWB surface. During stamping and quenching stages, the material in these locations was pressed directly by the punch and die under a die closing force of 250 kN. The difference in the hardness between the 2.0-2.5 mm TWB and the 3.0-5.0 mm TWB may come from the variations in the heat transfer of different thicknesses, although the contact area is assumed to be similar. Compared to the as-received weld zone in Fig. 1(b), the weld (e.g. *Location* 4 in Fig. 2(a)) after forming possesses a much higher hardness value. The degraded strength of the weld was restored after forming.

For the blank holder area, especially at *Locations* 8-9, the hardness values are lower than those at the part top surfaces (*Locations* 1-6). This is due to the efficiency of the quenching/cooling process. As the area is just located at the blank holder, the materials was firstly contacted by the blank holders with a blank holding force of 20 kN, which may be not sufficient to attain a rapid cooling. The sliding of the material between the blank holders and die during the stamping process also removed the lubricant from the blank surfaces, and thus reduced the heat transfer as well as the quenching efficiency.

The *Location* 10, which is illustrated in Fig. 2(c), is located at the vertical side wall of the formed TWB parts. The lowest hardness values are located at this area. It is well accepted that a higher contact pressure on the blank surface will enable the material being quenched at a higher rate due to the higher heat transfer induced. At the vertical side wall, the contact pressure between the blank and die is very small, because the die closing force was hardly applied on the area along the force direction.

3.2. Finite element simulation

Finite element (FE) simulations of the stamping at HFQ® conditions were conducted using the commercial software PAM-STAMP and a developed temperature and strain rate dependent material model [1]. As shown in Fig. 3, the simulation model comprises of a punch, die, TWB, and the blank holder sets. The tools (i.e. blank holder, punch and die) were modelled using rigid elements, and especially, a stepped surface was made on the punch facing towards the TWB so as to accommodate the different thicknesses of the TWB. For a real friction stir welded blank, there usually exists a thickness transition in the weld zone due to the nature of the welding process. The thickness transition zone was modelled by shell elements with pre-defined thicknesses, as shown in Fig. 3(b). A friction coefficient of 0.2 was chosen to account for surface interaction between the sliding sheet and the die assembly [7].

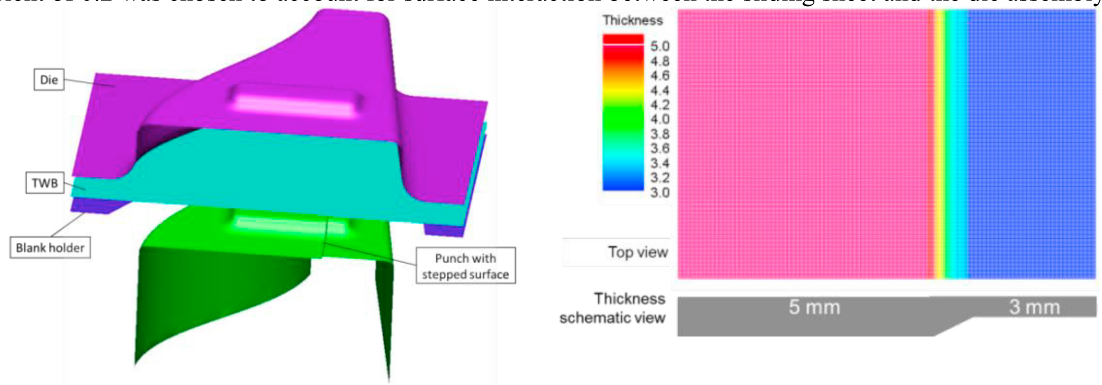

Fig. 3. (a) Pam-Stamp simulation model and (b) shell elements for the 3.0-5.0 mm TWB with thickness schematic view.

Fig. 4 shows the strain comparison of the 3.0-5.0 mm TWB between experiment and simulation formed at a speed of 250 mm/s. The strain distributions are able to depict deformation characteristics of this TWB, indicating that the deformation is mainly located at the small rectangular feature. Although there exists thickness difference in the TWB, the weld line didn't move as that in conventional forming [1]. This is because that the stepped punch surface, which was in direct contact with the TWB, restricted the movement of weld line during stamping. Therefore, small strains were observed along the weld zone. As the blank was drawn into the die, the material at the circled area was stretched by the punch and die, resulting in a much higher strain at the corner.

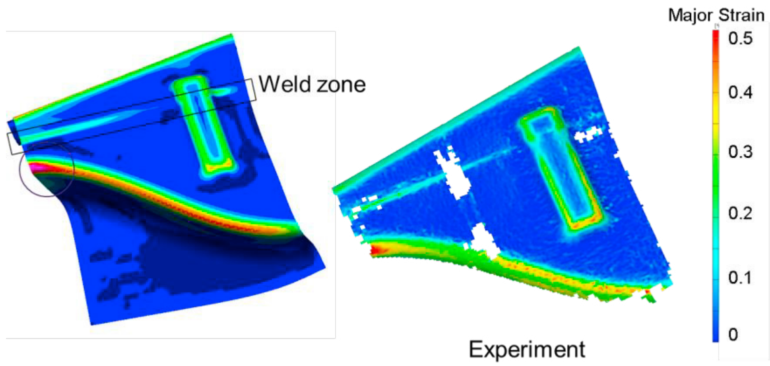

Fig. 4. Comparison of strain distributions in the 3.0-5.0 mm TWB between (a) simulation and (b) experiment.

The HFQ® process is a hot sheet forming operation that incorporates part of the thermal tempering process required for heat-treatable aluminium alloys. 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. Fig. 5 shows the temperature contours predicted by simulation during the quenching stage, from which the variations of the temperature distribution are observed.

The temperature profiles for the corresponding elements are plotted in Fig. 6. During stamping, the hot blank was stamped into the die at a speed of 250 mm/s, and the blank temperature at the selected point maintained at a stable level with only about 1°C decrease due to the short time period. The temperature started dropping rapidly at the subsequent quenching stage after the deformed blank was held by the die and punch with a force of 250 kN. The predicted temperature evolution from simulation has a very good agreement with the experimental measurements.

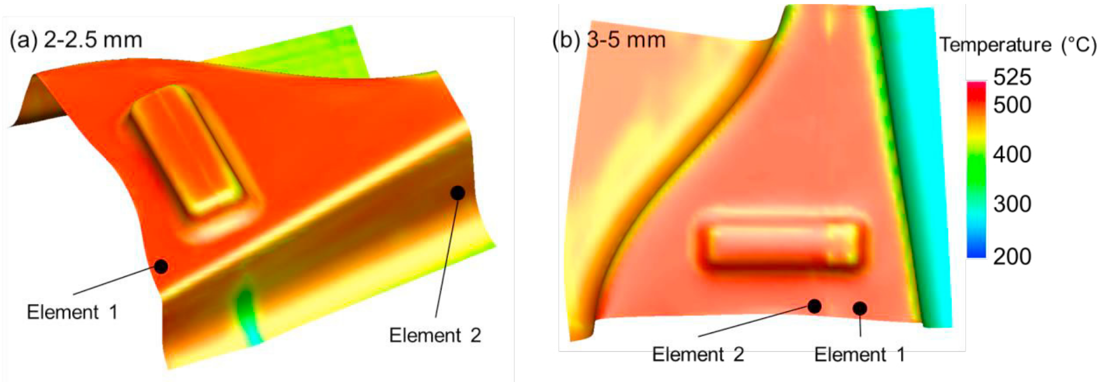

Fig. 5. Predicted temperature distribution during quenching of the formed parts: (a) 2.0-2.5 mm and (b) 3.0-5.0 mm.

3.3. Post-form strength analysis

Precipitation behaviour of Al-Mg-Si alloys has been reported to be temperature- and time-dependent [3], and the post-form strength can be determined by the temperature evolution in a specific range. Continuous cooling precipitation (CCP) diagrams describe the precipitation behaviour of aluminium alloys during cooling from solution state as a function of temperature and time. In this study, a typical CCP diagram for AA6082 was adopted and plotted in Fig. 6. A maximum hardness value can be obtained as long as the cooling was performed faster than the specific range of the CCP diagram.

According to the hardness distributions, the highest hardness for the 2.0-2.5 and 3.0-5.0 mm TWB parts are found at *Location* 1 (Fig. 2) with the values of HV 116 and 106, respectively. The elements, labeled as *Element* 1, in the simulations correspond to the areas with highest hardness values, while the *Element* 2 in the 2.0-2.5 mm part represents for the one at the side wall. The temperature profiles for the corresponding elements are plotted in Fig. 6. It is clear that a very fast cooling was performed on the *Element* 1 of the 2.0-2.5 mm TWB, thus high supersaturation of the precipitation elements can be obtained during quenching [3], leading to a high hardness value after the subsequent artificial ageing. For the side wall *Element* 2, it initially underwent a fast temperature decrease during stamping. The temperature then dropped gradually, as shown in Fig. 6, in the quenching process. The loss of hardness for *Element* 2 is therefore attributed to the decreased cooling rate.

For the 3.0-5.0 mm parts, *Element* 1 corresponds to the area with a hardness value of HV 106. As shown in Fig. 6., its temperature profile is very close to the CCP diagram, which is just beyond upper critical values for the slowest cooling rate at which completion of supersaturation in solid solution is reached [3]. *Element* 2 is selected at the area where the temperature was measured experimentally. The cooling rate for *Element* 2 is lower than the critical rate, as compared to the CCP diagram. Therefore, the supersaturation is assumed to be not sufficient which would eventually weaken the material after artificial ageing.

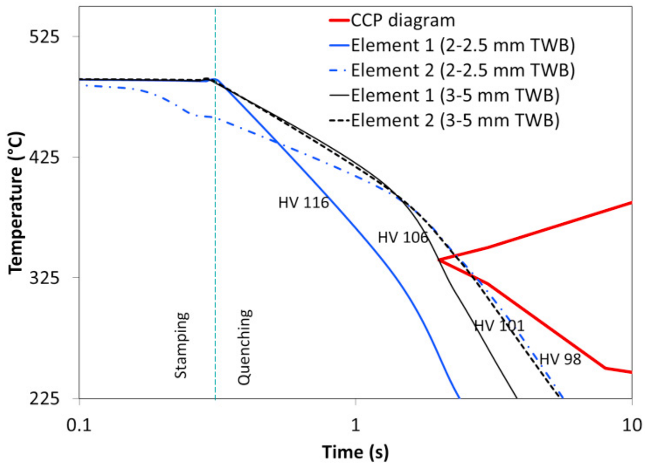

Fig. 6. CCP diagram of typical AA6082 [3] and temperature history for the selected elements in Fig. 5.

Conclusions

AA6082 tailor welded blanks made from friction stir welding with various thickness combinations have been successfully formed by the HFQ® process into vehicle panel components. The stepped punch surface, which was in direct contact with the TWB, could restrict the movement of weld line during stamping. The post-form strength, in terms of the hardness in this study, is highly dependent on the cooling rate/quenching efficiency during the stamping and quenching stages. Moreover, the degraded hardness of the TWBs can be completely restored after forming and the subsequent ageing process, as long as the cooling was performed faster than the specific critical cooling rate of the alloy. Advanced finite element simulation has been established to evaluate the quenching efficiency and the post-form strength by integrating the temperature- and time-dependent precipitation behaviour using a proper CCP diagram.

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