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Formability study on the friction stir welding tailor welded blanks: A broad review

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Abstract
Friction Stir welding (FSW) tailor welded blank which consists of sheet metal having different thickness, material are butt welded together and then forming is carried out. FSW tailor welded blanks has become a major used in the automobile industries especially in the joining of different grades of aluminum alloys. The forming behavior of FSW joints is different from the forming of normal blanks. This paper is concern with the butt joining of different grades of aluminium alloy sheets using FSW process. The current research paper focus on the review of experimental and analytical study on formability of FSW tailor welded blank using bending, forming and drawing operation were discussed. The behavior of weld line movement and spring back study of joints were also discussed. The process parameter of FSW machine such as pin profile, tool rotational speed, feed rate, axial force, shoulder diameter etc. affecting the formability of FSW tailor welded blank is presented. The study on the various optimization technique used for optimize the process parameter to affect the formability of FSW joints is covered.

Keywords: FSW tailor welded blank, formability, bending die, FSW machine parameter, drawing process, spring back

Introduction

Friction Stir Welding (FSW) is a solid state joining method. This was invented at the Welding Institute of the United Kingdom in year 1991. It was generally used for the butt welding of aluminium alloys (AA). The FSW process uses a non-consumable rotating tool in which special designed pin and shoulder diameter. The diameter of the tool shoulder and pin depends on the material thickness. During the process the sheets are abutted together properly on the fixture so that there is no gap between the abutting surfaces as it may produce defects during welding. A backup plate is used on which the sheets are placed and rigidly clamped to the fixture for preventing the lateral movements of the sheets during process. After that the non-consumable rotating tool is plunged into the abutted edges of the sheets and traversed subsequently along the traverse line.

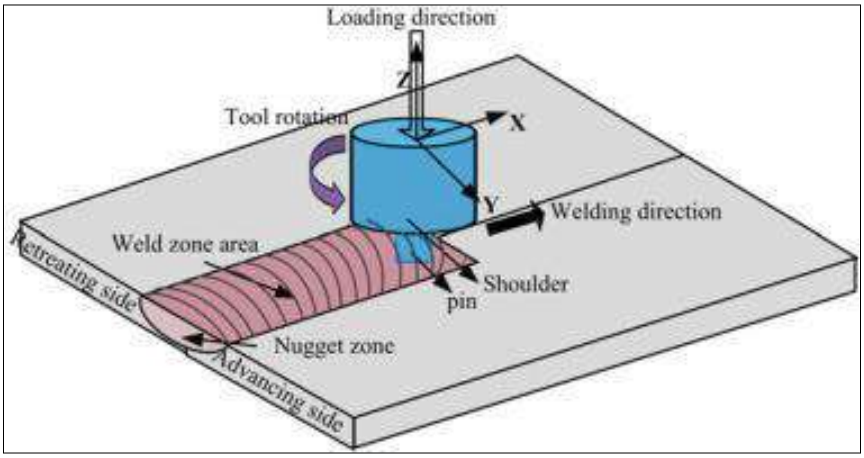

Fig 1: Schematic diagram of friction stir welding [1]

The tool rotation and travel direction provide the advancing side and retreating side orientations. The tool is rotating in counter clockwise direction and traverse from left to right direction, then the right side is the advancing side where the tool rotation direction and the tool traverse direction is same and the left side is the retreating side where the tool rotation direction and tool traverse direction are opposite [1].

2. FSW parameters and its effects on formability

2.1 Effect of process parameter of FSW on weld joint

W.B. Lee *et al*. [2] investigated the improvement of mechanical properties of friction-stir-welded A356 Al alloy with welding parameters, such as tool (including shoulder and screw-like shaped pin) materials, constant tool rotating speed (1600 rpm), welding speed (87 to 342 mm/min) and the angle of the tool constant at 30. The study concluded that sound joints were acquired below 187 mm min-1of welding speed when the tool rotating speed was fixed at 1600 rpm and hardness of the weld zone showed more homogeneous distribution in comparison with that of base material (BM).It was observed that the mechanical properties of the SZ were improved by the dispersed Si particle. H.J. Liu *et al*. [3] investigated the fracture position and mechanical properties of FSW joints of AA 2017- T351 aluminium alloy. In this research, 0.07 mm/rev of revolutionary pitch corresponding to the 1500 rpm of rotation speed and 100 mm/min of welding speed was used. This was found that the tensile properties of the joints are lower than those of the Base material. FSW joints are fractured near or at the interface between the weld nugget and the TMAZ on the advancing side. P. Cavaliere *et al*. [4] investigated the effect of welding parameters on mechanical and microstructural properties of AA6056 joints produced by FSW. The welding parameters, such as tool rotating speed and welding speed ranging from (500, 800 and 1000 rpm) and (40, 56 and 80 mm/min) respectively, having constant tool profile. This study concluded that the material ductility reaches maximum values with minimum travel speed and rotating speed, and decreases as the increases of travel speed and rotating speed. Khodir *et al*. [5] investigated of process parameter effects on FSW of dissimilar AA2024 and AA7075 aluminium alloys. For this study rotational speed and welding speed were taken as process parameters, where rotation speed was kept constant as 20s-1and welding speed was set at 0.7, 1.2, 1.7 and 3.3 mm/second. This study concluded that the rise in welding speed tended to the formation of kissing bond and pores especially when the AA 2024 was located on the retreating side. It was also observed that the minimum hardness were observed in the Heat affected zone (HAZ) both sides and their values increased with welding speed.

Tozaki *et al*. [6] investigated the effect of tool geometry on microstructure and static strength in friction stir spot welded aluminium alloys with a constant tool plunge rate of 20 mm/min and a shoulder plunge depth of 0.2mm with varied tool rotational speeds and the tool holding times, which were 2000, 2500 and 3000 rpm, and 0.2, 1 and 3 s respectively. This study concluded that the microstructures of welds varied depending on probe length, tool rotational speed and tool holding time. The tensile strength increased with increasing probe length. This was also observed that the cross section area of welded joint decreased and tensile strength increased, with increasing tool holding time and rotational speed. H. Bisadi *et al*. [7] investigated the influences of rotational and welding speeds on microstructures and mechanical properties of FSW AA-5083 joints. The process parameters such as tool rotational speeds of 600, 825, 1115 and 1550 rpm and welding speeds of 15 and 32 mm/min was taken. It is observed that the defects in FSW joint due to less frictional heat at very low welding speed. The maximum hardness of the copper side of the joint was observed at the weld stir zone because of its fine grain size. The ultimate tensile stresses decreased by increasing the process temperature. It is observed that highest value of the ultimate tensile stresses was about 78% of the Cu and also about 74% of the aluminium sheets parent material Speeds of 600, 825, 1115 and 1550 rpm and welding speeds of 15 and 32 mm/min was taken. It is observed that the defects in FSW joint due to less frictional heat at very low welding speed. The maximum hardness of the copper side of the joint was observed at the weld stir zone because of its fine grain size. The ultimate tensile stresses decreased by increasing the process temperature. It is observed that highest value of the ultimate tensile stresses was about 78% of the Cu and also about 74% of the aluminium sheets parent material.

Feistauer *et al*. [8] investigated the mechanical behavior of dissimilar friction stir welded tailor welded blanks (TWB) in Al–Mg alloys for Marine applications. The process parameters such as rotational speed (600 rpm), axial force (25 kN), welding speed (6 mm/s), tilt angle (10) for welding of dissimilar Al–Mg alloys and thicknesses (6 and 8 mm). This study concluded that the FSW process altered the central portion (SZ) of the dissimilar TWB. The mechanical properties of the TWB joints were approximately the same as those of the AA5059 BM used as the thinner sheet. Hasan *et al*. [9] investigated a simplified design of clamping system and fixtures for friction stir welding of aluminium alloys. Dissimilar sheets of aluminum alloys AA7075 and AA6061 of 3mm thickness was used for this study. Three tool rotational speed levels of 1000, 1100 and 1200 rpm with three travel velocities of 250, 300 and 350 mm/min were taken as parameters. This study concluded that the sound welds with smooth surface finish, gap and defects free and without geometric imperfections were effectively achieved. The maximum value of the UTS represents an efficiency of about 82% with respect to the UTS of the AA6061 alloy.

Aissani *et al*. [10] investigated the design and Optimization of FSW Tool by testing on AA2024-T4 and AA7075-T6 aluminium alloys sheets with sheet thickness 1.6 and 5 mm respectively. The parameters were taken as different tool sizes (as per sheet thickness), shoulder diameters (20, 35 mm), rotational speed (1400, 2000 rpm) and tool pin profile with constant tool advancing speed (16mm/min). This study concluded that good strength of the weld joint made by tri-flute type pin tool with a conical threaded geometry. Better weld appearance without void, cracking, or distortion can be obtained with slow travel rate and recrystallization of the material occurs in the nugget zone region. Indira al. [11] investigated the effect of variation of tool geometry on FSW aluminium alloys. Two materials AA6351 and AA6061 were FS welded and for that modified tool is designed and fabricated. Various tool profiles were fabricated such as Tapered Profiled Tool, Threaded Cylindrical Profiled Tool and Square Profiled Tool with different parameters such as axial force, weld speed and tool rotational. This study concluded that the Square profiled tool facilitates the stirring action from tip to the collar. Using ANOVA it can be concluded that the tool rotational speed and welding speed had dominant influence on thermo-mechanical properties than the axial force. The tool shape, joints modification improved mechanical properties. Shape of the tool pin and shoulder had more influence in obtaining better mechanical properties for the weld joints. Zadpoor *et al*. [12] investigated mechanical properties and microstructure of FSW tailor-made blanks. In this study, FSW welds were made by using five different thickness/material combinations. AA2024-T3 and 7075-T6 sheets of different thicknesses were used for producing the welds. Rotational speed, welding feed, and inclination angle and pin/shoulder diameters were selected as process parameter. This study was observed that as the thickness ratio increases with decreases the tensile strength, yield strength, elongation and hardness value. It is also seen during microstructure view of FSW specimen, an Onion ring structure was formed in the weld nugget region.

2.3 Effect of process parameter on formability

Sato *et al*. [13] investigated post-weld formability of friction stir welded Al alloy 5052. In this study, process parameters was taken such as shoulder diameters of 9–15 mm, rotation speeds of 2000–4000 rpm and traveling speeds of 8.3–33.3 mm/s. The effect of microstructure on the fracture limit strain was examined in the stir zone of AA-5052. This study concluded that the fracture limit strain increased with increasing the grain size of mixing material up to 10 µm, beyond which it decrease. Zadpoor *et al*. [14] investigated the theoretical prediction of failure in forming of FSW blanks. Marciniak-Kuczynski method was used for the experiment to predict the formability of FSW specimen. Hemispherical punch having radius of 50.8mm, blankholder and die was used. The appropriate Forming limit diagrams (FLD) of the different zones of FSW blanks are determined. The experimentally and analytically study was made for the accurate failure prediction.

Ramulu *et al*. [15] observed the forming limit investigation of friction stir welded sheets on effect of influence of shoulder diameter and plunge depth. In this study, tool rotation speeds, welding speeds and plunge depth ranging from (800 to 1,600 rpm), (50 to 130 mm/min) and (1.5 to2.0 mm) respectively with three different shoulder diameters used. The BM was cut in different rolling directions like 0°, 15°, 30°, 45°, 60°, 75°, and 90°. This observation concluded that the friction stir welded sheets show signs of better formability than unwelded sheets. The forming limit of friction stir welded blanks has increased when plunge depth is increased from 1.85 to 1.9 mm. Hovanski *et al*. [16] investigated High-Speed FSW to enable aluminium TWB having AA5182-O sheets of 1.2 to 2.0 mm thickness to weld by taking tool variations such as different Shoulder-to-Pin diameter ratio (2.5:1, 3:1), Pin length (1.5, 1.75, 2.0) mm, Pin features (Taper, flats, threads), Shoulder features (One scroll, two scrolls).With parameters such as Plunge depth (1.85, 2.00) mm, Tool tilt angle (10, 00), Tool roll angle (3.820 (tangent), 30), Rotational velocity (1100, 1500, 1950) rpm. This study concluded that weight reduction, part reduction, and cost savings may be achieved using high-speed FSW to join aluminium TWBs at high volumes. Simulation of post weld formability was evaluated with three distinct fracture criteria, compared with as-welded and machined dissimilar blanks. Babu *et al*. [17] investigated the effect of differential heat treatment on the formability of aluminium tailor welded blanks using different materials namely AA6061 and AA2014 of 3mm sheet thickness. FSW joints using different process parameters which were rotational speed (900-1400 rpm), welding speed (16-32mm/min) and tool tilt angle (0-2 degree). They concluded with the study that the formability behavior of TWBs of two different materials namely AA6061 and AA2014.A uniform elongation on either side of the TWB was achieved on a sample that was solution treated and tested after five days of natural aging. Buffa *et al*. [18] investigated finite element studies on friction stir welding processes of tailored blanks. In this study a thermo-mechanical fully coupled 3D FEM analysis is performed for investigating the feasibility of the FSW of TWBs.

Zadpoor *et al*. [19] investigated the finite element modeling and failure prediction of friction stir welded blanks. Failure prediction and FEM modeling of the FS welded blanks was studied in this paper by using two different study cases, namely LDH test and S-rail problem. The forming limit diagrams of the different zones within the friction stir welded blanks were determined. Zadpoor *et al*. [20] investigated the effects of friction stir welding on the mechanical properties and microstructure of 7000 series aluminium tailor-welded blanks using three different thickness ratios such as 1, 1.3 and 1. The process parameters were taken at constant rotational speed and welding speed of 40 and 100 mm/min respectively. This study concluded that the formability, strength and heterogeneity of the properties within the blank are reduced.

2.4 Effect of process parameter on springback using bending and formability test

Katre *et al*. [21] investigated the experimental study on the springback of FSW sheet of AA 5052-H32 and AA 6061-T6 of a thickness of 2.1 mm to determine the influence of welding speed and tool rotational speed. The Springback evaluated during V-bending and analyzed and compared. Hill’s 1990 yield criterion in the finite element model for springback prediction was used. Springback effect reduction of FSW sheets is observed at higher rotational speed and welding speed, which they co-relate with the changes in y/*E* ratio and *n* value of weld zone. They show a close agreement between experimental and predicted values of springback effect. The range of tool rotational speed was from 600-800 rpm and tool translation speed varied from 80 mm/min to 120 mm/min. V bending test were performed on all the welded blanks This study concluded that the ultimate tensile strength (UTS) decreases with the increase in welding speed, at a constant rotational speed of 800 RPM. There is also some improvement in the ductility of the weld zone with increase in welding speed and rotational speed with increase in welding speed and rotational speed the ductility of weld zone increases. This happens because of enhancement of strain hardening exponent of weld zone at higher rotational speed and welding speed. Reduction in springback effect of FSW sheets was observed at higher welding speed and tool rotational speed. Rao *et al*. [22] investigated the effect of shoulder diameter, rotational speed and welding speed on springback effect of FSW sheets such as 6061-T6, 5052-H32 of thickness of 2.1mm.Springback evaluated in V-bending of friction stir welded sheet 6061-T6/5052-H32 and 6061T6/6061T6 and it was found that with increases the value of shoulder diameter, rotational speed and welding speed the springback effect of friction stir welded sheets was reducing, and is totally independent of the material combinations joining. Even by reducing the nose radius of punch, the springback effect of FSW sheets can be reduced. This was concluded that the increase in all relevant condition (as described shoulder diameter, rotational speed, and welding speed) within given conditions the springback of FSW sheets was decreased. In all weld condition, 6061-T6 gives a better springback performance. Katre *et al*. [23] Investigated the springback behavior and formability of FSW sheets of AA 6061-T6 and AA6061. The V-bending setup without tension used for springback experiment and LDH setup used for formability experiments. This was concluded that the increasing the following factors such as shoulder diameter, plunge depth, and tool rotation speed, the peak temperature was increased and it is totally opposite for welding speed. At higher rotational and welding speed reduction in springback occur. Simoncini *et al*. [24] studied on post welding forming operation of FSW aluminium of AA1050 thin sheet. The tests are followed in such a manner given as tensile test processed at room temperature. Formability test were conducted at room temperature by using hemispherical punch. For bending test V-punch and U-die were used at room temperature with a constant angle of 60˚and with different nose radii (0.5, 4,6mm).This study was concluded that the mechanical properties of the joints are hardly affected by speed of welding. FSW process increase in flow stress and decrease in strain. The springback ratio of the joints were lower than that of unwelded blanks.

Amir A. Zadpoor *et al*. [25] found that the springback behavior of FSW tailor-made blanks. The tailor- welded blanks and base metal both have totally different springback behavior. In this research, Numisheet 96 S-rail benchmark problem taken and considered as case of the study to investigate the problem. After reviewing case study, it was concluding that implementation of weld details remarkably enhance the springback accuracy prediction and mechanical properties of heat affected zone has very less impact over springback behavior of FSW sheet. Park *et al*. [26] conducted a study that focused on AA5052-H32 automotive sheets of 1.5mm thickness and experimentally as well as scrutinized the improvement in these properties. Different variables were taken at the time of experiment. For the experiment three different probe sizes of 5mm, 8mm, and 10mm were used to get different surface friction stirred zones. These probes were rotated at different advancing speeds. Each of these probes penetrated to the depth of 0.11mm, 0.12mm, 0.16mm respectively. Plastic deformation increased with increasing the probe size (0.65mm, 0.78mm, 0.94mm respectively) resulting in improved formability an spring-back. As the probe size was increased the hardening characteristics of stirred zones were of lower strength with increased strain. This was due the fact that it faced annealing effects at increased temperatures resulting in recovery of original mechanical properties. Limit dome height test was done on an Ericson test machine. Two different sizes of rectangular specimens were selected for the test with longitudinal and traverse rolling directions. When compared with the base sheet the punch height at failure increased or the longitudinal type while it decreased for the traverse type. Unconstraint bending test was done, which resulted in slight improvement in the spring-back for the stirred sheets as compared to the base sheet. Finite element analysis was also done for both the tests. This study concluded with the findings that with increased probe size ductility gets improved as long as it is aligned with along the longitudinal direction and it decreased if aligned in traverse direction. Spring back got better irrespective of the aligned direction.

Kim *et al*. [27] selected 4 different sheet materials aluminium 6111-T4, 5083-H18, 5083-O and dual-phase DP590 steel sheets, each in two thicknesses. Similar materials with same thickness (Same gauge, SG) and with different thickness (Different gauge, DG) were welded together by FWS method. Cylindrical bending test was conducted for spring-back analysis. No lubricant was applied, also there was no blank holder involved in the test since it was unconstraint. Bending angle for all the materials was constant. Measurements were taken after unloading the components and lager angle in the sheet meant larger spring-back. Finite element analysis was also done for the same. 2-D drawing test was conducted next. Blank holder was used and sheets were sprayed with a lubricant, WD-40 oil. In this case spring back was measured by the cross sectional shape of the formed component after unloading. OSU draw bend test was done, the schematic diagram of test and obtained component is shown in the figure. Numerical simulations through FEA were also run. All the test results showed that numerical simulations shoed approximately same results as actual experiments. Spring-back of a material depends on its yield strength, Young's Modulus and thickness of sheet. Weld direction has negligible effect on the spring-back. Proper description of reverse loading in the 2-D draw test and OSU bending test were significant in predicting the spring-back. OSU bending test concluded that spring-back decreased with increased tension on the component. Fowler *et al*. [28] inspected behavior of low alloy steel DH36 sheets which were joined together by FSW technique. Metallographic tests were run before and after the experiments for detailed evaluation. Tensile, fatigue and bending test were done in the experiment. FSW process lead to grain size reduction therefore increasing yield strength. The component had ductile fracture and plastic deformation. The welded joint has detrimental effect on fatigue performance, while all welded sheets did well in the bending tests. The study concluded that although the FSW process improves performance in bending and tensile strength related function it is not suitable under fatigue conditions.

2.5 Effect of optimization technique on formability of FSW tailor welded blank

Some of the researchers have optimized the process parameter using different design of experiment technique such as Taguchi, response surface methodology, artificial neural network, Grey relational analysis [29-36]. The design of experiment is a mathematical and statistical technique to develop the empirical model and improve the optimizing processes parameters. The optimized process parameter such as rotational speed (RS), travel speed (TS), shoulder diameter (SD), Pin diameter (PD), Tilt angle (TA), Plunge depth (PL), Pin geometry (PG) to predict the optimized result in the form of output response such as tensile strength, yield strength, elongation, formability, micro hardness and microstructure etc. In literature review [29-36], there is combination of dissimilar aluminium alloys sheet having different thickness were used. The optimization technique is used to predict the best run for the formability, bending etc.

Table 1: Design of experiment technique used in FSW tailor welded blank

Material for FSW	Sheet Thickness	Optimization Technique	Process parameter used	Ref.
AA5052-H32 /AA5754-H22	2	Taguchi grey relational technique	RS, TS, SD, PG	[29]
AA6061-T6/5083-H12	1.2	Response surface methodology(RSM)	RS, TS, PD, SD	[30]
AA5083-H12/AA6061-T6	1.5	RSM with Box- bhenken Method	RS, TS, SD, TA	[31]
AA6061/AA2014	3	Taguchi and ANOVA	RS, TS, TA	[32]
AA5754-H22/AA5052-H32	2	Grey Relational Analysis	RS, TS, SD, PG	[33]
AA5083-H12/AA6061-T6	1.5	RSM	RS, TS, SD, PD	[34]
AA2014-T6/AA2014-T6	2	RSM	RS, WS, TA, PG	[35]
AA 5083/AA5083	2	RSM	RS, TS, PL	[36]

3. Conclusions

In the review of study of formability of FSW tailor welded blank, a satisfactory understanding of the formability and spring back effect on FSW joints parts. This review help to figure out the effect of process parameter such as welding speed, rotational speed, tilt angle, plunge depth, pin diameter, shoulder diameter etc. on the output responses like tensile strength, yield strength, limiting dome height test, elongation, hardness etc. Therefore this paper concluded that the friction stir welding process is the environment friendly, easy and economically process used in automobile, aerospace and marine application. This study estimated the entire knowledge of FSW and it is useful to selection of the welding process parameter and optimization technique. It helps to decreasing the defects in weld zone region, improving the weld quality, make a reliable weld, and produced a good strength in weld nugget zone region of the FSW tailor welded blank.

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