Investigation on the formability of friction stir welded Al-TWB through incremental forming

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Abstract. In the quest for weight reduction, automobile industries introduced the technology of tailor welded blanks (TWB) which offered utilization of material as per functional requirement. In general, friction stir welding (FSW) is mostly used for fabricating aluminum based TWBs as fusion welding of Al—alloys are problematic. Recently, single point incremental forming (SPIF) gained popularity among researchers as well as in industry as a dieless flexible forming technique. Hence, in this study two aluminum sheets namely AA6061 and AA7075 of similar thickness were welded together using FSW with square pin. The formability of the TWBs were evaluated in terms of cup height, wall angle and fracture location through SPIF incorporating different tool geometries. To assess the effect of weld, similar welded Al blanks were also deformed in the similar condition. The formability of the similar welded blanks and corresponding parent metals did not differ much and fracture did not initiate at the weld. However, cup depth for the TWB was in between the cup heights of the parent metals and failure was not observed at the weld region. TWB cups did not show any weldline shift.

1. Introduction

In the case of incremental forming, complete deformation of sheets occurred through gradual localised deformation of the same, instead of simultaneous deformation of the complete sheet by the application of punch, die and binder. In general, small hemispherical tools are used to cause localised plastic deformation in the sheets, which is then extended all over the clamped sheet along the best suitable path to achieve the desired deformed shape [1,2]. On one hand, being a dieless forming process, incremental forming offers the flexibility to fabricate any shape by just changing CNC/robot programming to design the suitable tool path without the necessity of designing new die-punch sets. On the other hand, localised nature of deformation enables the sheet to sustain more amount of deformation compared to the conventional sheet metal forming. However, the major drawback of the process involves longer processing time of the components. Therefore, the process is being adapted in the industries for customised product development, batch production or rapid prototyping purposes [3]. Among the incremental forming processes, single point incremental forming is more flexible and popular due to involvement of less amount of tooling [4]. A detailed discussion on deformation mechanisms, springback and surface roughness in SPIF process was reported by Gatea et al. [2]. In general, it is observed that formability improves with increase in tool rotation speed and decreases with feed rate. The fracture is mostly observed at the corner region of deformed part due to equi-biaxial stretching condition. In a recent review article, Duflou et al. [4] discussed several other advancements in the SPIF process which enabled the SPIF to overcome its limitation and is being considered for applications like cranial implants, self-bearing roof structure, die making etc. Application of multistep tool path [5], heat...
assisted SPIF [6], electrically assisted SPIF [7] are the main advancements which further enhances the performance of SPIF process.

In the past decades, one of the major technology enhancements in the field of automobile industry to address the ever-restricting fuel efficiency norms was the development of tailor welded blanks (TWB). The TWBs are single blanks fabricated by joining two or more sheet metals with different grades, gauges or surface properties (coated/uncoated) in butt welding configuration mostly by laser/friction stir welding [8]. TWBs offers the advantage of placing right materials at the selected position as per the functional/design requirements. Thus weight reduction, optimised material utilisation, cost effectiveness etc. can be achieved. However, presence of different materials in terms of thickness or properties on either side of the weld makes forming of TWBs a challenging job. Several studies have already been reported on formability evolution of TWBs in various mode of deformation. Panda et al. [9] concluded that the formability of DP980-HSLA TWB reduced during stretch forming operation due to non-uniform deformation which led to failure in the weaker HSLA side. Reduction in formability of DP980-IFHS TWBs were also reported in case of deep drawing operation by Bandyopadhyay et al. [10]. The failure was always observed at the cup bottom, in the weaker material and parallel to the weld in case of deep drawing of TWBs. However, not only the reduction in formability, but also weld line movement due to non-uniform deformation is another typical problem associated with forming of TWBs. Bandyopadhyay et al. [10] also reported the severity of weld line movement in case of DP980-IFHS and DP980-DP600 laser welded blanks for deep drawing operations. It is observed that during stretching weldline shifts towards the stronger material as can be seen at the cup bottom for deep drawing [10], also at the pole for LDH testing [11] and weldline shifts towards the weaker material where compressive stress is predominant as can be seen at the flange or cup wall portion in case of deep drawing. Therefore, several techniques were proposed to restrict weldline movement and as a consequence to improve formability like split binder [12], clamping pin [13], proper placement of initial weldline [14]. However, most of the research on formability study of TWBs involves conventional sheet metal forming, and SPIF of TWBs are relatively rare in open literature. One of the preliminary study on SPIF of TWBs was successfully conducted by Silva et al. [15]. In the study, AA1050-H111 sheets with different thicknesses were combined to fabricate the TWBs which were then deformed under SPIF process using experimental benchmark tests. Tayebi et al. [16] also successfully performed SPIF on TWBs fabricated by joining AA6061 to AA5083 using FSW process. It was concluded that reduction in formability of TWBs in SPIF process can be avoided by selecting proper welding and SPIF parameters.

Therefore, in the present study, formability behaviour of a particular Al-TWB with dissimilar material combination were studied under SPIF process. Unlike the previous studies, the sheet thicknesses of the materials are selected to be 1 mm. Further, in the present study a complex shape is chosen as the deformed geometry to understand the extent of formability under complex strain state. Finally, different shape and size of tools are employed to understand the effect of tool geometry on formability and corresponding force requirement.

2. Material and methodology
In the present study, two aluminium alloys AA6061 and AA7075 were selected for fabrication of the TWB and further formability study. Both the Al alloys were of 1 mm thickness. The mechanical properties of both the aluminium alloys are compared in the table below (Table 1) in terms of yield strength, and ultimate tensile strength.

| Material  | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) |
|-----------|----------------------|----------------------------------|
| AA6061    | 290                  | 327                              |
| AA7075    | 280                  | 304                              |
2.1. Friction stir welding process

Three sets of welded blanks were created using FSW process for which a linear CNC machine (make: ETA) was employed. Among them two were similar welded blanks fabricated by combining AA6061 to AA6061 and AA7075 to AA7075, respectively. The third one is the TWB fabricated by combining AA6061 with AA7075. The fixture and the tool geometry for the FSW process are shown in figure 1. The major challenge during welding of 1 mm blank was buckling of the sheet which was overcome by providing proper clamping. The shoulder diameter of the FSW tool was 15 mm and the cross-section of the tool pin was square with the side of 3.5 mm. The height of the tool pin was 0.9 mm. For all the three types of welding, the FSW parameters were kept same; the tool rotation was 500 rpm, the welding speed was kept at 100 mm/min and plunge depth was 0.05 mm with a tilt angle of 1°.

Figure 1. The fixture and tool for FSW process

2.2. Weld quality evaluation

The weld quality was assessed in terms of cross weld hardness test (figure 2a) and tensile test was performed keeping the weld perpendicular to the loading axis (figure 2b). Hardness in the weld zones were measured with a load of 100 g and dual time of 10s. The hardness at the weld was observed to be increased compared to the corresponding parent metals as can be seen from figure 2a. It is because finer grain size is obtained in FSW process and as per Hall-Petch equation hardness is inversely proportional
to the grain size. Tensile test shows the UTS of all the three-weld samples is around 200 MPa. The failed sample revealed that failure occurred from the heat affected region. In all the three welds, the weld efficiency was more than 60%. FSW process has successfully welded one mm thin aluminium alloy (similar and dissimilar) and with optimization of process parameters, weld efficiency can be further improved.

2.3. Incremental forming

The SPIF process was performed using a laboratory scale fixture with a forming window of 110×110 mm. The blank size required for the fixture was 150mm×150mm which had to be clamped between the blank holder and the backing plate using 12 numbers of screws. During experiment the complete SPIF set up was placed on a dynamometer (make: Kistler) for measuring the deformation force. In this study, two different shape of tools were used; one with hemispherical tip another with flat bottom.
Figure 5. The deformed cups obtained after SPIF process using a hemispherical tool with 10 mm diameter along with the failure location

For hemispherical tool two different tool diameter were considered; φ5 mm and φ10 mm. Flat bottom tool was of φ5 mm with corner radius of 1 mm. The tool path was designed and codified using Mastercam software which were later incorporated in the CNC system through memory card. In this study, a complex geometry (figure 3) developed by combining pyramid and conical shape was selected to be the deformed shape to understand the formability of welded blanks under more complex strain state with flat and curvilinear surfaces. The complete SPIF process was performed using a 4-axis CNC system (make: AMS V540). For the SPIF process, 4500 rpm was used as the tool rotation speed, feed rate was selected as 1000 mm/min with a step depth of 0.1 mm. The fixture, tools, and the complete experimental set up can be seen in figure 4. The SPIF process was continued till any appearance of crack in the deforming sheet. During the process, a mirror was placed under the deforming sheet to check appearance of crack. All the blanks were etched with circular grid marks and the grid marked surface was placed opposite to the tool facing surface. Circular grid marks were used to measure the strain of the deformed surfaces. During experimentation with parent metal, it was observed that formability drastically reduced at forming angle of 60º. Therefore, all the experiments were conducted at this angle. Some of the deformed cups after the SPIF process are shown in figure 5. Deformed cups from TWBs did not show any weldline movement.

3. Results and discussions

3.1. Forming height

The forming heights of the deformed cups were measured using a 3D scanner (Make: Artec Eva) after dismounting the deformed samples from the fixture. All the cup heights are reported in Table 2. It can be observed that tool with hemispherical tool tip delivered higher cup height compared to that obtained by the flat bottom tool. In case of AA6061 cups, almost 72% cup height reduction was observed for flat bottom tool compared to the highest cup height that was achieved for the material. Similarly, 71.5% reduction was observed for AA7075 material. The highest cup heights were observed in case of hemispherical punch with 10 mm diameter for both the parent materials. This results corroborated well with previous studies [17]. Application of hemispherical tool with 5 mm diameter resulted in reduction of around 20% cup height for AA661 and 10% cup height for AA7075 compared to the corresponding maximum cup height. In case of the welded blanks, the cup heights were almost similar to the corresponding parent metals, without any significant reduction in cup height due to presence of the weld. In this regard it was also observed that none of the failure in the deformed cups were in the weld or in
the vicinity of the weld though failure was observed at the weld zone during tensile testing. Similar to the observation made for the parent metals, the maximum cup heights for the welded blanks were obtained with hemispherical punch with 10 mm diameter and the reduction in cup height due to application of hemispherical tool with 5 mm diameter followed the similar trend as reported for the parent metals. For the case of TWB, the cup height was observed to be in between the cup heights reported for the combining parent metals whenever hemispherical tools were used.

| Material                | Tool Geometry      | Tool Diameter (mm) | Forming Angle | Fracture Height (mm) |
|-------------------------|--------------------|--------------------|---------------|----------------------|
| AA6061                 | Hemispherical      | 10                 | 60°           | 11.075               |
|                         | Hemispherical      | 5                  | 60°           | 8.875                |
|                         | Flat Bottom        | 5                  | 60°           | 3.075                |
| AA7075                 | Hemispherical      | 10                 | 60°           | 12.575               |
|                         | Hemispherical      | 5                  | 60°           | 11.275               |
|                         | Flat Bottom        | 5                  | 60°           | 3.575                |
| AA6061+AA6061          | Hemispherical      | 10                 | 60°           | 11.375               |
| (Welded blanks)         | Hemispherical      | 5                  | 60°           | 8.575                |
|                         | Flat Bottom        | 5                  | 60°           | 2.875                |
| AA7075+AA7075          | Hemispherical      | 10                 | 60°           | 11.875               |
| (Welded blanks)         | Hemispherical      | 5                  | 60°           | 10.575               |
|                         | Flat Bottom        | 5                  | 60°           | 3.475                |
| AA6061+AA7075          | Hemispherical      | 10                 | 60°           | 11.575               |
| (TWB)                  | Hemispherical      | 5                  | 60°           | 9.575                |
|                         | Flat Bottom        | 5                  | 60°           | 3.075                |

3.2. Force analysis

During the SPIF experimentation, the force measurements were performed employing a dynamometer for comparing the force requirement with different tool shapes and sizes. The obtained Z-direction force data with all the three types of tools are plotted for both the parent metals in figure 6a, b. For the TWB, force data are plotted for the case of 5 mm hemispherical tool (figure 6c). It can be delineated from the plots that force required for the deformation increased when hemispherical tool diameter increased from 5 mm to 10 mm. This can be related to the localized area under the tool which is being deformed. In case of 10 mm tool diameter, the localized deformation zone was higher compared to that of the 5 mm tool diameter. Therefore, higher force was recorded with the 10 mm diameter tool. The lowest force was recorded for the flat bottom tool. The deformation region was quite small in this case as the corner diameter of the flat bottom tool was 1 mm. It can also be observed that the force requirement for AA6061 was relatively higher compared to that of AA7075. This can be correlated to the corresponding material strength reported in section 2. In case of the TWB, the force data reflected the load requirement for either side of the parent metal for which two distinctive force data is visible. This indicates the force requirement corresponds to that of the AA6061 while the tool travel in the AA6061 side, and vice-versa. Similar observation was also made for hemispherical tool with 10 mm diameter and the flat bottom tool.
3.3. Strain analysis

Figure 6. Comparison of forming forces for (a, b) parent metals and (c) TWB

Figure 7. (a) The location and measurement direction for strain, (b) the measured major and minor strain
The complex geometry selected for the deformed shape, in this study, has three distinct regions; three flat surface (part of the pyramid shape), one conical face, and the corner regions. Therefore, the strain measurement was performed at three different regions as can be seen in the figure 7a. Strain values were measured from the cup center to the flange region along three different lines to cover all the distinct region. The measured major and minor logarithmic strain data for the samples deformed with 10 mm hemispherical tool are plotted in figure 7b. It can be inferred from the figure that regions with flat surfaces (location 2) follows a plane strain condition during deformation as minor strain was negligible. However, the strain measured across the conical face (location 1) showed major strain to fall between 0.4-0.5 and the minor strain to be around 0.02, indicating strain state to be in the biaxial stretching zone. Significant rise in both major and minor strain was observed in the corner region (location 3) which indicates a biaxial mode of stretching. The failure location of the various deformed samples as was shown in figure 5 can well be corroborated with the measured strain state. The failure was always observed close to the cup corner which experienced biaxial mode of stretching. The results can be well correlated to the results reported by Basak at al. [18] where it was clearly shown that fracture limiting strain are lower in the biaxial region. For other deformed samples, which were deformed using the 5 mm diameter hemispherical tool and the flat bottom tool, fracture was observed to initiate at the corner and then propagated to the flat surfaces. In case of the TWB, no strain differences across the weld were observed in the flat un-deformed portion and the weld remained at initial position. From this it can be inferred that localized mode of deformation did not affect the complete blank in SPIF process and the weldline shift was not observed. However, in the case of conventional forming, complete TWB deforms simultaneously in eccentric manner due to strength difference and weldline shifts.

4. Summary
In this study, TWB fabricated with 1 mm thick AA6061 and AA7075 were successfully deformed using SPIF process. From this study following conclusions can be drawn

1. With selection of proper parameters, and proper fixture design, sound friction stir welded blanks can be obtained even with sheet thickness of 1 mm. A weld efficiency of more than 60% was achieved in the study which can be further enhanced with parametric optimisation.

2. In case of SPIF process the tool geometry, and tool size have significant influence on force requirement during deformation. It was observed force requirement was more for hemispherical tool tip with 10 mm diameter compared to 5 mm diameter. Force requirement for deformation was lowest with flat end tools. For TWB two distinct force curve were observed which corresponds to the force related to the component blanks.

3. Cup heights for the similar welded blanks were similar to the corresponding parent metals and no failure was observed at the weld zone. Hence, presence of friction stir weld did not affect the cup height. However, cup height for the TWB was in between that of the component blanks.

4. In case of SPIF process of TWB, no weld line movement was observed due to localised nature of deformation. Hence, no complex set up development is necessary for weld movement restriction like conventional sheet metal forming processes.

References

[1] Silva MB, Skjoedt M, Martins PAF, Bay N. Int J Mach Tools Manuf. 2008;48(1):73–83.

[2] Gatea S, Ou H, McCartney G. Int J Adv Manuf Technol. 2016;87(1–4):479–99.

[3] Emmens WC, Sebastiani G, van den Boogaard AH. J Mater Process Technol. 2010;210(8):981–97.
[4] Duflou JR, Habraken A-M, Cao J, Malhotra R, Bambach M, Adams D, et al. *Int J Mater Form.* 2018;11(6):743–73.

[5] Verbert J, Belkassem B, Henrad C, Habraken AM, Gu J, Sol H, et al. *Int J Mater Form.* 2008;1(1):1203–6.

[6] Ambrogio G, Filice L, Manco GL. *CIRP Annals* 2008;57:257–60.

[7] Adams D, Jeswiet J. *Proc Inst Mech Eng Part B J Eng Manuf.* 2014;228(7):757–64.

[8] Merklein M, Johannes M, Lechner M, Kuppert A. *J Mater Process Technol.* 2014;214(2):151–64.

[9] Panda SK, Hernandez VHB, Kuntz ML, Zhou Y. *Metallurgical and Materials Transactions A.* 2009;40(8):1955-67.

[10] Bandyopadhyay K, Panda SK, Saha P, Padmanabham G. *J Mater Process Technol.* 2015;217.

[11] Kumar A, Gautam V, Kumar DR. *J Manuf Sci Eng.* 2018;140(3).

[12] Ahmetoglu MA, Brouwers D, Shulkin L, Taupin L, Kinzel GL, Altan T. *J Mater Process Technol.* 1995;53(3–4):684–94.

[13] Kinsey B, Liu Z, Cao J. *J Mater Process Technol.* 2000;99(1–3):145–53.

[14] Mennecart T, Güner A, Khalifa N Ben, Tekkaya AE. *Key engineering materials* 2014;611;955-962.

[15] Silva MB, Skjoedt M, Vilaça P, Bay N, Martins PAF. *J Mater Process Technol.* 2009;209(2):811–20.

[16] Tayebi P, Fazli A, Asadi P, Soltanpour M. *CIRP J Manuf Sci Technol.* 2019;25:50–68.

[17] Kim YH, Park JJ. *J Mater Process Technol.* 2002;131:42–6.

[18] Basak S, Prasad KS, Sidpara AM, Panda SK. *Int J Mater Form.* 2019;12(4):623-42