Experimental study on the effects of incremental forming and friction stir welding on formability of AA5083 sheet

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Abstract. This article presents investigations on the effects of incremental forming and friction stir welding on the formability of AA5083 through comparison of experimentally predicted forming limit curves. Initially hemispherical dome stretching test was performed to predict forming limit curve for the parent sheet in conventional forming from plane strain to biaxial stretching strain path. Forming limit curve in case of single point incremental forming of parent sheet was also determined by conducting groove test. Formability in single incremental forming was found to be far better than that in conventional forming from the comparison of the forming limit curves for both the cases. Friction stir welded blanks were prepared by varying tool shoulder diameter, welding speed and tool rotational speed as input parameters following three levels of inputs parameters according to the central composite design matrix. Optimal welding parameters were selected based on the weld quality judged by bending angle of free bend test of the welded blanks and visual inspection. Forming limit curve for friction stir welded sheet was generated through incremental forming groove tests of the blanks made by optimal welding parameters. Formability of welded sheet was found to decrease compared to the parent sheet due to the severe plastic deformation and work hardening during the welding operation.

1. Introduction

Formability is the ease with a metal sheet can be deformed in desired shape without any failure. Lot of work has been done for formability of un-welded sheet in conventional forming as well as incremental forming. This study focuses on the formability of friction stir welded blank in single point incremental forming. Friction stir welding is a solid state joining process in which thin sheet metals get joined by plastic deformation and stirring action of material of the two weldments due to friction heating of rotating friction stir tool. The quality of weld joint in friction welding depends on a number of factors namely tool geometry, spindle speed, weld speed and others. Proper selection of process parameters is important to produce good quality weld. In past many researchers studied the formability of friction stir welded blank and conventional forming which are discussed in the following section.

Kim et al. (2002) studied the effect of different process parameters on the formability of Al-1050 sheet using groove test, experimentally. The authors used freely rotating ball which reduces friction along the tool and workpiece contact and hence increases formability. It was observed that formability increases with decrease in tool diameter and incremental depth. Finite element analysis was used to observe the effect of process parameters on the deformation. Kim et al. (2010)
investigated formability of friction stir tailor welded blank of different aluminium alloy and DP590-steel sheets taking various thickness. Formability was determined using simple tension test along different weld direction, hemispherical dome stretching test and cup drawing test. It was found that formability of FSTWB was highly depended on weld line arrangement. Janbakhsh et al. (2012) compared forming limit curves (FLCs) for AA2024-T3 and AA5083-H111 sheet, experimentally and theoretically. It was found that the formability of AA5083 sheet was higher compared to the formability of AA2024. Zhalehfar et al. (2013) studied the formability of AA5083 sheet varying strain path. The experiments were done using stretching over hemispherical punch for proportional and non-proportional loading paths. Uniaxial pre-straining increased the formability and moved the FLC to the left but biaxial pre-straining moved the FLC to the right and formability decreases for the specimen in rolling direction. Zhang et al. (2014) studied the influence of temperature and strain rate on AA5086 sheet. It was observed that the formability of AA5086 sheet decreased with increase in strain rate but increased with temperature. Kesharwani et al. (2015) investigated formability of friction stir welded blank taking optimal process parameters of AA5754 - H22 and AA5052-H32 with 2 mm thickness sheet using limiting drawing ratio. Limiting drawing ratio was found close with unwelded sheet metal which signifies that quality of the weld was good. Parente et al. (2016) evaluated formability of friction stir tailor welded blank for dissimilar alloy AA5182 and AA6061 of thickness 1mm by plotting FLC using Nakajima test with different blank width samples. Formability of tailor welded blank was found comparable to unwelded sheet and observed that formability of tailor welded blank was dependent on weld line direction. Entesari et al. (2017) studied formability of AA7075-T6 friction stir welded blank experimentally using hemispherical dome stretching test and numerically. The effect of welding process and temperature on formability was studied. It was found that formability decreases with welding and improves with temperature. Li et al. (2018) analysed the effect of tool path strategies on thickness distribution of deformed square cone for AA5052 sheet using multistage two-point incremental forming. The best strategy was selected for increasing the thickness distribution.

The objective of this paper is to weld the sheet by friction stir welding taking different shoulder diameter tool, feed rate and spindle speed and after that compare the formability of AA5083 parent with welded sheet using groove test in single point incremental forming and hemispherical dome stretching test in conventional forming.

2. Experimental procedures
This section describes materials, equipment and design of experiment method for conducting experiments on friction stir welding, conventional forming using hemispherical dome stretching test and single point incremental forming of AA5083 sheet.

2.1. Material and equipment
Aluminium alloy AA5083 sheet is used for present study. It has been widely used in marine, aerospace and automotive industry. It has good formability, medium strength and excellent marine corrosion resistance. Table 1 shows the chemical composition of AA5083 sheet. The 1 mm sheet thickness is used for the fabrication of FWBs.

Table 1: Chemical composition of AA5083 sheet

| Element | Zn | Cu | Cr | Ti | Si  | Fe | Mn | Mg  | Al |
|---------|----|----|----|----|-----|----|----|-----|----|
| Weight %| 0.05 | 0.08 | 0.08 | 0.15 | 0.158 | 0.22 | 0.79 | 4.79 | Balance |
Experimental limit strains are calculated for conventional forming using Hemispherical dome stretching test for AA5083 sheet. The experimental setup of hemispherical dome stretching test is developed to deform the sheet as in Figure 1. The setup consists of a hemispherical punch, blank holder, base part and lower die. The sheet is firmly clamp in between the blank holder and lower die. The diameter of the developed punch is taken as 56 mm which is 45 % less compared to punch diameter taken in standard ISO 120004-2 test for forming limit curve determination [7]. The dimensions of samples considered for the hemispherical dome stretching test are also reduced to 45 % as in ISO 120004-2. The length of the sheet is taken as 110 mm for all samples and width taken as 68.75 mm, 82.5, 96.25 and 110 mm for four different samples (Figure 2). The different sample geometry gives the wide range of deformation from plane strain to biaxial stretching. All the samples are cut using the wire EDM machine (ELEKTRA CLPULS 55 2F).

The setup is developed to deform the sheet with different sample geometry using universal testing machine (Make: - BLUE STAR, Model: - BSUT-100T) as in Figure 1. The maximum load capacity of the machine is 1000 KN. The travel speed of the punch is taken as 2 mm/s during the test. Before the deformation of the sheet, the bottom surface of the sheet is marked with 3 mm uniform circle using electrochemical etching method prior to deformation. After the deformation, the circles marked near the necking and fracture region are converted in elliptical shape. The major and minor axes of ellipse give the major and minor strains respectively. The major and minor strains are measured using Mylar tape. The measured major and minor strains are plotted for the FLC prediction. The circular grids are converted in elliptical shape after the deformation of the samples tested. For each sample, the major and minor limit strains are measured from the major and minor axes of the ellipse that was located near the localized necking zone. Mylar transparent tape is used for measuring the major and minor limit strains.

![Figure 1: Experimental Setup for hemispherical dome stretching test on Universal Testing Machine.](image)
2.2. Design of experiment

Three factors each with three levels was taken as process parameters for conducting the experiments of friction stir welding and bend angle considering the preliminary experiment result. The process parameters and tool geometry for friction stir welding of AA5083 sheet are considered based on literature and its suitability for the materials to be welded. Pin diameter taken as 3 mm and 0.9 mm length for all three different shoulder diameters tools. The proportion of pin diameter to shoulder size is important in generating heat and stirring action for joining. The levels selected were also based on the conclusion of previous studies. Input variables and their levels for the central composite design were shown in Table 2.
Table 2: The ranges of input process parameters for FSW

| Sl. No. | Input process parameters (unit)       | Symbols | Levels   |
|---------|--------------------------------------|---------|----------|
|         |                                      |         | -1       |
| 1       | Tool rotational speed (RPM)           | N       | 2000     |
| 2       | Feed rate (mm/min)                    | f       | 100      |
| 3       | Tool shoulder diameter (mm)           | d       | 7        |
|         |                                      |         | 0        |
|         |                                      |         | 2500     |
|         |                                      |         | 150      |
|         |                                      |         | 11       |
|         |                                      |         | 3000     |
|         |                                      |         | 200      |
|         |                                      |         | 9        |

3. Results and discussion

Samples prepared with friction stir welding are shown in figure 3. These samples are gone through free bending test for measuring bend angle. Welding samples after bending test are shown in Figure 4. Figure 5 shows the samples after bending test in which first two welded samples are not fractured during test when it welded with proper parameters but last two welded samples get fractured at the root in welded zone during bending test.

![Figure 4: Friction stir welded samples with different process parameters combinations.](image)

![Figure 5: Samples after bending test.](image)

The value of bend angle decreases as feed rate increases for selected process parameters of FSW. The maximum value of bending angle of friction stir welded sheet in free bend test is obtained for a medium value of shoulder diameter and minimum value of tool rotational speed within the considered process parameters.

Optimized process parameters for friction stir welded sheet are matching with sample that was predicted using free bend test. Now, using this optimized set of parameters i.e. spindle speed 2000 rpm, feed 100 mm/min and tool shoulder diameter of 9 mm, friction stir welded sheet are produced and groove test is done for welded sheet and parent sheet metal. Figure 6 and Figure 7 shows the sheet deformed after groove test for parent and welded sheet, respectively.
Forming limit curve (FLC) are plotted for unwelded sheet and welded sheet using groove test. Figure 8 a and 8 b shows FLC plotted for parent and friction stir welded sheet, respectively. The plotted FLC is a straight line with negative slope in positive region of principal major and principal minor strain. Figure 9 shows the comparison of FLC for parent sheet and welded sheet. Forming limit curve of welded sheet is found to be less compare to parent sheet. The possible reason for less formability is work hardening of the welded region through friction stir processing.

![Figure 6: Groove test of parent sheet.](image)

![Figure 7: Groove test of friction stir welded sheet.](image)

![Figure 8: Forming limit curve for (a) parent sheet (b) Friction stir welded sheet.](image)
Figure 9: Comparison of Forming limit curve for parent and friction stir welded sheet.

Figure 10 shows the comparison of forming limit curve parent and welded sheet in single point incremental forming (SPIF) with parent sheet in conventional forming. It is observed from the figure that formability of both parent and welded sheet in incremental forming is higher than conventional forming. Formability of welded sheet in SPIF is closer to the conventional forming for biaxial stretching strain path.

Figure 10: Comparison of Forming limit curve for conventional forming and parent and friction stir welded sheet SPIF.
4. Conclusions
In the present study, the effects of friction stir welding and incremental forming on the formability of sheet metal compared to the conventional forming have been investigated through experiments. Friction stir welded sheets were produced taking optimized process parameters, i.e., minimum feed rate and rotational speed with medium tool shoulder diameter determined through free bend test of the FSW blanks and visual inspection. Forming limit curves of the parent sheet were predicted by hemispherical dome stretching test and incremental forming groove test and compared. FLCs of parent sheet and welded sheet in SPIF were also compared. The following points were inferred from the experimental observations.

- The good quality friction stir welded thin sheet joint of AA5083 was fabricated with the combination of 2000 rpm rotational speed, 100 mm/min welding speed and 9 mm tool shoulder diameter.
- Formability in single point incremental forming was found better than that by conventional forming as evident from the comparison of FLCs for the cases. Formability in incremental forming increased due to the occurrence of progressive local plastic deformations at the smaller tool job contact area.
- Comparison of FLCs showed that formability got reduced in case of welded sheet compared to that of parent sheet. The reason behind the lower formability of FSWB is work hardening of the welded region through friction stir processing.
- FLCs of welded and parent sheet in incremental forming were compared with FLC for conventional forming from plane strain to biaxial stretching strain path and found to be higher for incremental forming compare to conventional forming but closer for welded sheet in incremental forming with conventional forming for biaxial strain path.

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