Friction Stir Welds Strength under Two-Dimensional Stress State Conditions

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Abstract. The friction stir welding (FSW) is a solid-state joining technique. This process is normally used for different aluminum and magnesium alloys. FSW provides joint mechanical properties superior to arc welding. This properties estimation is a result of uniaxial tension test. In the vast majority of cases the welded plate structures are operated under biaxial stress state. This paper aims at establishing a relationship between biaxial loading conditions and mechanical properties in welding of 5083 type aluminum alloy using friction stir welding. The biaxial stress state was formed due to particularly designed samples. The specimens with different geometry and location of the pairs of raisers stresses are considered. All calculations were performed in ANSYS. The experimental verification of the numerical simulation results is presented.

1. Introduction
Friction stir welding (FSW) is a solid phase welding process in which the metal to be welded is not melted during welding, thus the crack and porosity often associated with fusion welding processes are eliminated [1, 2]. The advantages of FSW for welding aluminum can be summarized as excellent mechanical properties, competing strongly with welds made by other processes [3, 4]. It is often stated that the tensile properties of friction stir welds generally equal or exceed those reported for fusion welds. On numerous occasions aluminum alloys tensile strength is typically about the same as found in the parent material in the annealed condition, although significant improvements can be made by minimizing the thermal cycle. Joint efficiencies exceeding 90% have been reported in 7xxx alloys. Liu et al. [5] reported joint efficiencies as high as 82% for 2017-T351. Sato and Kokawa [6] report an inverted top hat profile for yield strength, the trough in the nugget and HAZ being 50% of the parent T5 condition for 6063Al. Upon post-weld aging 95% of parent strength in the weld region was recovered, although the fracture location remained unchanged. For work hardened non-heat-treatable alloys (e.g. 5xxx alloys in the H1xx, H2xx or H3xx conditions), failure of cross-weld tensile specimens normally occurs in the centre of the weld, where the hardness is at minimum. For example, the AA5454 joint has failed at a kissing bond [7]. Despite this, the failure stress and elongation is only some 10% less than the parent. For AA1050-H24 failure was on the advancing or retreating side, with the distance from the weld centre decreasing with decreasing pitch in correspondence with a narrowing troughs in hardness [8]. The failure stress observed is typically close to the annealed strength of the material, although higher values can be obtained if the heat input is minimized.
Elongation values are normally a little below the parent value, but the reduction is less than in heat-treatable alloys. Failures are fully ductile, with extensive necking. For annealed non-heat-treatable alloys (e.g. 5xxx in the O condition), failure of cross-weld tensile alloys can occur anywhere on the sample, although they usually occur away from the weld in the parent material. Elongation is therefore typically the same as the parent material, and the failure mode is invariably very ductile. Thus joint efficiencies of 100% can be obtained. One advantage often quoted for tensile properties in friction stir welds is the very consistent performance from weld to weld. This is perhaps well illustrated by data from Lockheed Martin [9], where the analysis of a large number of welds in a 2xxx alloy showed that FSW gave rise to a small increase in average tensile strength, but a very much reduced scatter band. As design of the component in question was based on minimum strength which can be guaranteed, the higher repeatability of friction stir welds allowed an extra 20% strength to be used in the design, even though the average strength of the friction stir welds was not much more than that of fusion welds. It should be noted that this is due to the low variability in weld properties rather than the incidence of defects. It has been realized that in the vast majority of cases the tensile properties were established according to standard uniaxial testing [10]. The tensile testing, also known as tension testing, is a fundamental science test in which a sample is subjected to uniaxial tension until failure. The results from the test are commonly used to select a material for application, for quality control, and to predict how a material will react under other types of forces. Properties that are directly measured via a tensile test are ultimate tensile strength (UTS), maximum elongation (EL %). Meanwhile it is a matter of common knowledge that thin wall metal constructions are often used in the biaxial stress state operation conditions. The metal durability in this case is different from uniaxial loading metal durability. There is no reliable academic failure criterion for plane stress state of metal. For this reason the in situ method of material testing is the best. This method must be based on the direct examination of material properties. Existing testing equipment for biaxial stretching is of limited availability and very expensive. The aim of this study is to design a unique specimen, which permits to produce biaxial stress state under the common tensile test condition and apply that specimen for friction stir welded properties estimation.

2. Experimental procedure

There are many researchers, who designed special specimens for simple tension in recent years [11-14 et al.]. As a rule, the plane stress state in these specimens was formed due to stress raisers location. In some cases elastic strain-stress specimen displayed the state that take place in the tube, i.e. situation with principal stresses ratio close to 0.5 [15]. The general form of these specimens is shown in figure 1.

![Figure 1. Specimen geometry and advanced strain area.](image-url)
The desired results are obtained due to corresponding geometry and location of the two symmetrical pairs of stress raisers. The base material used in this study was a 5083 aluminum alloy plate of 5mm thick, whose chemical compositions is 5.2 wt.% Mg, 0.5 wt.% Mn, 0.5 wt.% Si, 0.5 wt.% Fe, 0.2 wt.% Zn, 0.1 wt.% Ti, 0.005 wt.% Be and the rest Al. The rolled plate was cut by power hacksaw and machined into rectangular welding samples longitudinally butt-welded, using FSW machine. Conventional milling machine with appropriate fixture developed for FSW has been used for given experimental investigation. Aluminum plates are located by a slotted base plate of fixture. It constrains the movement of aluminum plates against the tool rotation and also provides accurate and unique position of the plates every time. Aluminum plates should be fully constrained at all times to prevent any movement. Clamps provide locking forces to hold the aluminum plates in place, once they are located. A totally restrained aluminum plates are able to remain in static equilibrium to withstand all possible processing forces or disturbance. Non-consumable tool, made of high carbon, high chromium steel, H-13 was used to fabricate the joints. Tool material has been purchased under annealing condition and machined as per tool design and finally heat treated to get required hardness. Tool has been heated at 1010 ºC for 30 minute and then air cooled. The initial hardness was 17 HRC which after heat treatment had been changed to 44 HRC. Experimental process parameters were constant. The designated welding tool size and welding parameters are listed in table 1.

| Tool size and process parameters. | Shoulder diameter (mm) | Pin diameter (mm) | Pin height (mm) | Rotation speed (rpm) | Welding speed (mm/min) | Tilt angle, (deg) |
|----------------------------------|-----------------------|------------------|-----------------|----------------------|------------------------|-----------------|
|                                  | 19                    | 6                | 4.8             | 710                  | 50                     | 2               |

The welded joints have been sliced using laser cutting and then machined to the required dimensions. From each joint, three tensile specimens extracted from the mid-length of the joint with dimensions of 200 mm×60 mm×5 mm were followed to prepare the specimen. The types of tensile specimen geometries prepared in this investigation are shown in figure 2.

**Figure 2.** Tensile specimen types: a) rectangular welded specimen with smooth edges; b) welded specimen with raisers (principle stresses ratio equal to 0.5); c) welded specimen with raisers (principle stresses ratio equal to 0.3); d) reference specimen; e) base metal specimen (principle stresses ratio equal to 0.5); f) base metal specimen (principle stresses ratio equal to 0.3).
Smooth tensile specimens were prepared to evaluate an ordinary 0.2 offset yield strength, tensile strength, elongation and joint efficiency. First specimen (figure 2a) is used for the common uniaxial friction stir welded tensile strength determination. Two other specimens (figure 2b, 2c) are serving for biaxial stress state representation. The specimens number 2 and 3 produced plane states with principle stress ratio ($\sigma_2/\sigma_1$) equal to approximately 0.5 and 0.3 correspondingly. Three last specimens (figure 2d, 2e, 2f) repeated previous tests but for base metal. Numerical simulation method was offered as the prime tool for specimen designing. Numerical experiment was conducted under ANSYS. PLANE182 four node finite elements were used. There were two degrees of freedom in each mode. Five millimeters aluminum alloy AA5083 plates were used for numerical simulation and experimental verification. For every specimen configuration, the principal stresses ratio fields were plotted as it is shown on figure 3. Variations of shape and size of the stress raisers were performed as specified in the articles [14, 15].

![Figure 3. Results of numerical simulation of the principal stresses ratio for two type tensile specimens (the fourth part of each specimen is shown).](image)

Tensile test was carried out under a load of 500 kN on an electro-mechanically controlled universal testing machine (ИР 5145-500-11, Russia). The tensile tests were carried out at room temperature at a crosshead speed of 5 mm/min. The 0.2% offset yield strength, tensile strength, and the elongation at failure were recorded. Three tensile specimens has been fabricated to evaluate the tensile strength of each type specimen. The arithmetical average of three tests was taken as a result.

### 3. Results and discussion

The results of tensile tests of different specimen are listed in the table 2. It can be seen from the table that the tensile properties of each joint are all lower than those of the base material.

| Specimen number | Elongation at failure (%) | 0.2 offset yield strength (MPa) | Ultimate tensile strength (MPa) | Notes |
|-----------------|---------------------------|---------------------------------|---------------------------------|-------|
| 1               | 8.2                       | 293                             | 343                             | figure 2a |
| 2               | 3.5                       | 302                             | 339                             | figure 2b |
| 3               | 3.7                       | 280                             | 318                             | figure 2c |
| 4               | 3.9                       | 271                             | 339                             | figure 2e |
| 5               | 4.3                       | 302                             | 340                             | figure 2f |
| 6               | 19.6                      | 305                             | 336                             | figure 2d |

Especially, the elongation of the joint is far lower than that of the base material, and its maximum is merely 8.2%. The sample № 6 (table 2, figure 2d) was chosen as reference. Some examples of fractured piece are shown in figure 4. The fracture of all specimens happened as ductile fracture and is shearing strain in nature. As it is followed from the tests, the friction stir weld presence operates considerably larger on elongation than on strength. The elongation degreases is no less than twofold in the case of friction stir weld presence. It appears that the residual welding stresses make the plane stress state in the fracture area. Complex stress state occurrence prevents the plastic strain beginning.
and thus decreases the samples elongation. The same influence on elongation is rendered with raisers presence (tests 2, 3, 5 and 6).

Figure 4. Plastic fracture: smooth specimen with friction stir weld (a, d); base metal specimen with stress raisers (b, d).

Meanwhile all samples were shown high joint efficiency. The minimum welded specimen strength is no less than 95% of base metal.

4. Conclusion
In order to reveal the friction stir welds plastic deformation behaviors under multi-axial stress conditions and determine the yield function of the present sheet metal, bi-axial deformation behaviors were investigated. For that purpose, we have developed a particularly designed specimen. In this specimen, biaxial stress states with different principal stresses ratio are represented during uniaxial tensile loads. For biaxial stress state to obtain, specimens with two couples of raises were designed. Displacement and raiser sizes were developed using numerical simulation. For a comparison between uniaxial and biaxial friction stir welded behavior six types of specimen were utilized in the present research. From the comparisons of the tensile test results is follows that the presence each of friction stir weld and complex stress state displayed considerable decreasing of the elongation and insignificant changing in strength. It can be inferred that stress state type has an appreciable influence on tensile properties of welded joints and requires more research.

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