Review and Analysis of Mechanical Properties of Friction Stir Welds of High Strength Aluminium Alloys

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Abstract
There have been significant advancements of recent in the studies of friction stir welding of high strength Aluminium alloys. These studies cover developments in the welded joint properties of these alloys. This paper reviews some available literature on evolving mechanical properties of friction stir welding of high strength aluminium alloys especially those of 7075 aluminium alloy which happens to be the most versatile member of the high strength aluminium alloy group. This review is aimed at establishing a correlation between the tensile behavior, plate thickness and temper conditions of the 7075 alloy when joined by friction stir welding (FSW) in both similar and dissimilar joints with other metals. The average values of reported ultimate tensile strength, yield strength, and percentage elongation have been calculated and presented. Comparative analysis was made between the tensile properties at different temper designation and plate thickness. The analysis revealed that temper conditions significantly affect the mechanical properties of both the similar and the dissimilar joints and that similar welding at T6 and T651 temper conditions gave higher weld efficiencies than dissimilar welding with other groups in the aluminium series. However plate thickness have little or no influence on the ultimate tensile behaviour, yield strength and elongation of the welds. The review also indicates that there is a range of temperature between which post weld heat treatment (PWHT) could be performed in order to obtain maximum tensile property. This paper is a significant approach to enhance high performance joining techniques and the reliability or otherwise of friction stir welding technology to join 7075 aluminium alloys under different heat treatment or temper conditions of the alloys for better industrial applications.

Keywords: Aluminium alloy, Friction stir welding, Mechanical strength and temper

1. Introduction
High strength aluminium alloys are naturally the 7000 series of aluminium alloy. The major alloying elements utilized in this series is zinc. When this is combined with little quantity of magnesium, the resulting alloy is a high strength, heat treatable alloy. A prominent and most commercially utilized member of this group is the 7075 [1], [2], [3], [4]. The use of these alloys is ever increasing due to their desirable properties. These properties include; high strength comparable to those of many sheets of steel and with a higher strength to weight ratio than steel, high fatigue strength and considerably good resistance to corrosion [5], [6]. These unique characteristics have made this alloy gained wide acceptabilities in applications such as the aerospace, marine, automotive and defense industries [7]. 7075 aluminium alloy is weldable and is available in different temper conditions depending on the area of applications.
There have been numerous research efforts on this alloy aimed at exploring its potentials for better utilization. One of such researches is on similar and dissimilar friction stir joining of the alloys. Friction stir welding is a joining technique recently advanced to join two materials together. Friction stir welding utilized a rotating tool made up of shoulder with a protruded part known as a pin. When the rotating tool is brought into contact with the workpiece, friction is generated which softens the workpiece. The stirring action of the rotating pin at the joint interface of the workpiece caused plastic deformation, material flow and mixing of the two materials which solidifies at the trailing edge of the tool to form the weld. Friction stir welding technology has been successfully utilized to weld aluminium and high strength aluminium alloys in particular and it remains one of the best ways of joining aluminium alloys. [8], [9], [10]. Significant amount of investigations have been done by researchers on the influence of factors such as tool rotational and welding speed, tilt angle, plunge depth and axial force on the friction stir welded joints of high strength aluminium alloys under different conditions such as corrosion and mechanical strength which consist of tensile, wear, hardness, fatigue, impact and bending tests [11], [12], [13]. However, only a few reports are available on the influence of various temper conditions on the mechanical properties of friction stir welded joints of similar and dissimilar high strength aluminium alloys. These reports include those of Yan et al [14] that studied the influence of temper conditions (W, T6, and T7) on mechanical properties of friction stir welded AA7050 alloy. Their result showed that welds in W temper conditions gave the highest ultimate tensile strength, elongation and yield strength than those welded in T6 and T7 condition. Given et al [15] also studied the influence of different temper state of O and T6 on mechanical behaviour and microstructure of FSW of AA7075. The authors revealed that welds carried out in T6 temper conditions produced greater ultimate tensile strength and yield strength than welds in O temper state. However, there is a considerable reduction in elongation in elongation in T6 compared to those of O temper state. Also, Shama et al [16]. investigated the mechanical properties and microstructure of FSW of AA7039 under three pre-weld temper state of T6, W and O. They reported that welds in W conditions showed considerably greater yield strength and elongation than those in T6 and O conditions, but exhibit similarity to T6 and O in terms of ultimate tensile strength. Another study on temper conditions impact on FSW was carried out by Lin et al [17]. They investigated the effects of initial temper conditions T6 and T4 on tensile properties, hardness, and microstructure of FSW of 7055 alloys. They reported that joints in T6 temper exhibited slightly lower hardness in the weld zone than those in T4 conditions. However, the UTS, YS, and elongation obtained in T4 joints are higher than those of T6 joints.

The few available findings reviewed above specifically studied the temper influence on mechanical properties of high strength aluminium alloys. However, these findings are not sufficient enough for a comprehensive understanding of the influence of initial temper conditions on the mechanical properties of similar and dissimilar FSW of these high strength aluminium alloys especially the most widely utilized of the group which is the 7075 alloy. It has, therefore, become very essential to look into other works from various authors on FSW of 7075 alloys with a view to harness their findings on mechanical properties and relate it with the various tempers and other alloys differently employed in their studies.

This review, therefore, presents an analysis of the various documented values of mechanical property precisely the tensile behaviour obtained under different temper conditions, plate thickness and post weld heat treatment in both similar and dissimilar FSW of high strength aluminium alloy 7075. This is to further deepen the knowledge based on FSW of this alloy for
better understanding by researchers and manufacturers that would result in greater industrial applications.

2 Mechanical properties

This section captures the summary of reported ultimate tensile strength (UTS), yield strength (YS), and elongations of the pre-weld 7075 alloy and the friction stir welded alloy at different temper conditions as well as their analysis.

2.1 Tensile Strength

Tensile testing is a method widely used by researchers to evaluate the mechanical behavior of materials. Mechanical properties of 7075 alloy at different temper condition is indicated in table 1. While those from findings on FSW of 7075 aluminium alloys under different temper conditions, plate thickness, and post weld artificial aging and heat treatment from various authors have been summarized in table 2 to 8 as follows:

Table 1: Mechanical properties of 7075 alloy at different temper conditions

| Temper condition | Ultimate tensile strength (MPa) | Yield Strength (MPa) | Elongation (%) |
|------------------|---------------------------------|----------------------|----------------|
| T6               | 570                             | 350                  | 10             |
| T651             | 575                             | 462                  | 18             |
| T7               | 505                             | 305                  | 13             |

Table 2: Tensile Results for Similar and Dissimilar welds with 7075-T7

| Ref | Other Aluminium alloys welded with 7075-T7 | Material thickness (mm) | Ultimate Tensile Strength (Mpa) | Yield Strength (Mpa) | Weld elongation (%) |
|-----|--------------------------------------------|-------------------------|---------------------------------|----------------------|--------------------|
| [18] | AA2024                                     | 1.0                     | 451                             | 388                  | 10.0               |
| [19] | AA2024                                     | 3.1                     | 477                             | 316                  | 13.8               |
| [20] | AA2024-T3                                   | 9.5                     | --                              | 398                  | --                 |
| [21] | AA2024                                     | 2.5                     | 476                             | --                   | --                 |
| [22] | AA2024                                     | 6.0                     | 480                             | --                   | --                 |
| [23] | 7050                                       | 6.35                    | 473                             | --                   | 6.1                |
|     | Average                                    |                         | 471.4                           | 367.33               | 9.96               |
| [24] | Similar                                    | 8.0                     | 458                             | --                   | --                 |
| [25] | Similar                                    | 8.0                     | 346                             | 227                  | 4.6                |
|     | Average                                    |                         | 402                             | 227                  | 4.6                |
Table 3: Tensile Results for Similar Welds with 7075-T6

| Ref | Material thickness (mm) | Ultimate Tensile Strength (MPa) | Yield Strength (MPa) | Weld elongation (%) |
|-----|-------------------------|-------------------------------|----------------------|---------------------|
| [26] | 5.0                     | 311                           | -                    | -                   |
| [27] | 5.0                     | 567                           | 480                  | 8.2                 |
| [28] | 20                      | 401                           | 322                  | -                   |
| [29] | 20.0                    | 415                           | 255                  | 8.1                 |
| [30] | 6.0                      | 450                           | -                    | -                   |
| [31] | 4.0                      | 370                           | -                    | -                   |
| [32] | 5.0                      | 462                           | -                    | -                   |
| [33] | 6.35                     | 468                           | 312                  | 7.5                 |
| [34] | 7.0                      | 450                           | 325                  | 7.0                 |
| [35] | 10                      | 350                           | --                   | 6.5                 |

Average 424.40 338.80 7.46

Table 4: Tensile Results for Dissimilar Welds with 7075-T6

| Ref | Other Materials welded with 7075-T6 | Material thickness (mm) | Ultimate Tensile Strength (MPa) | Yield Strength (MPa) | Weld elongation (%) |
|-----|-------------------------------------|-------------------------|-------------------------------|----------------------|---------------------|
| [36] | 2024                                | 2.5                     | 572                           | 503                  | 11.0                |
| [37] | 2014AT651                           | 6.35                    | 443                           | --                   | 15                  |
| [38] | AA2024                               | 4.0                     | 434.7                         | --                   | 2.2                 |
| [39] | 6061-T6                              | 5.0                     | 209                           | -                    | -                   |
| [40] | 2024-T4                              | 4.0                     | 381                           | 302                  | 9.6                 |
| [41] | AA6063                               | 5.0                     | 154                           | -                    | -                   |
| [42] | AA2024                               | 5.0                     | 341                           | -                    | -                   |

Average 362.1 402.5 9.45
Table 5: Tensile Results for Similar Welds with 7075-T651

| Ref  | Material thickness (mm) | Ultimate Tensile Strength (MPa) | Yield Strength (MPa) | Weld elongation (%) |
|------|-------------------------|--------------------------------|----------------------|---------------------|
| [43] | 6.0                     | 568                            | 404                  | 19.9                |
| [44] | 6.0                     | 563                            | -                    | 11                  |
| [45] | 6.3                     | 468                            | 312                  | 7.5                 |
| [46] | 6.35                    | 473                            | -                    | 3.1                 |
| [47] | 5.0                     | 402.9                          | -                    | 3.6                 |
| [48] | 12.0                    | 335                            | 394                  | 12.0                |
| [49] | 6.0                     | 425                            | --                   | --                  |
| [50] | 6.5                     | 262                            | --                   | 8.66                |
| [51] | 10.0                    | 424                            | --                   | 6                   |
| [51] | 16.0                    | 330                            | --                   | 8                   |
| [45] | 6.35                    | 525                            | 365                  | 15.0                |
| [52] | 12.0                    | 394                            | 335                  | 12.0                |

**Average** 430.83 362 9.70

Table 6: Tensile Results for Dissimilar Weld with 7075-T651

| Ref  | Other Materials Welded with 7075-T651 | Material thickness (mm) | Ultimate Tensile Strength (MPa) | Yield Strength (MPa) | Weld elongation (%) |
|------|--------------------------------------|-------------------------|--------------------------------|----------------------|---------------------|
| [53] | 2024-T351                            | 6.35                    | 435                            | 290                  | 13.0                |
| [54] | 5754-H111                            | 5.0                     | 239                            | -                    | -                   |
| [55] | 5083-H111                            | 6.0                     | 371                            | 308                  | 9.9                 |
| [44] | 6082-T6                              | 6.0                     | 193                            | -                    | 4.0                 |
| [56] | 6061-T6                              | 6.0                     | 485                            | -                    | -                   |

**Average** 344.60 299 8.96
Table 7: Tensile Results for Post Weld Artificial Aging (PWAA) of Similar welds of 7075-T651

| Ref  | Other materials welded with 7075-T6 | Material thickness (mm) | Heat treatment condition | Ultimate tensile Strength (Mpa) | Yield Strength (Mpa) | Weld elongation (%) |
|------|-------------------------------------|-------------------------|--------------------------|--------------------------------|----------------------|---------------------|
| [30] | 2024-T4                             | 4.0                     | PWHT at 170°C for 12Hrs  | 443                            | 322                  | 5.6                 |

Table 8: Tensile Results for Post Weld Heat Treatment (PWHT) of Dissimilar welds of 7075-T6

| Ref  | Other materials welded with 7075-T6 | Material thickness (mm) | Heat treatment condition | Ultimate tensile Strength (Mpa) | Yield Strength (Mpa) | Weld elongation (%) |
|------|-------------------------------------|-------------------------|--------------------------|--------------------------------|----------------------|---------------------|
| [57] | 2024-T4                             | 4.0                     | PWHT at 170°C for 12Hrs  | 443                            | 322                  | 5.6                 |
2.2 Analysis of Reported mechanical properties

2.2.1 Effects of temper conditions on ultimate tensile strength and elongation

2.2.1.1 T7 Temper Condition

The average UTS obtained for similar friction stir welding of 7075-T7 is 402MPa. This indicates a weld efficiency of 79.6%. The weld efficiency is a measure of the ratio of the average UTS to that of the base alloy expressed in percentage. Welding of this alloy with other aluminium alloys shows higher average values of 471MPa with a corresponding 9.96% elongation representing a weld efficiency of 93.2% which is higher than those of similar welds. There is no sufficient information from similar welds reported in the literature as reviewed in table 2 to justify why higher UTS was obtained in dissimilar welds. However, the overaged conditions of T7 temper 7075 alloys could be a factor when similarly welded together. The results obtained generally implies that the performance of the welds in both similar and dissimilar joints with other metals is considered reliable. This further affirm the effectiveness of FSW technology in joining high strength aluminium alloys.

2.2.1.2 T6 Temper Condition

Under T6 temper condition, the average values obtained for similar welds is 424MPa translating to an efficiency of 74.4%. The dissimilar average UTS value is 362MPa indicating an efficiency of 63.52% which is lower than that of similar welds. This could be attributed to the low strength of the other base alloys joined to the 7075-T6 which are mainly from group 2 and 6 series of aluminium alloys as reported by the various authors.

2.2.1.3 T651 Temper Condition

Welds in this temper show average UTS value of 430MPa and efficiency of 74.8% respectively when similarly welded. These are higher than the average UTS of 344MPa and efficiency of 59.8% obtained for dissimilar welds. This could also be due to lower strength of the dissimilar metals joined to the 7075-T651 alloy. The dissimilar metals as shown in table 6 are alloys from group 2, 5 and 6 of the aluminium series. Thus, failure is likely to occur on the side of these low strength alloys leading to decrease in UTS and weld efficiency.

2.2.2 Effects of heat treatments

The effects of heat treatments on the high strength aluminium alloy can be grouped into two, viz: PWAA and PWHT. This has been briefly explained in the next section.
2.2.2.2 Effects of PWAA

PWAA reported in table 7 for T651 temper condition indicate that the artificial aging of the welded joints affects the tensile behaviour of the welds. The aging temperature and the number of hours the weld was soaked in heat can increase or decrease the mechanical strength. The tensile strength obtained ranges from 347MPa to 354MPa which translate to between 60.3% to 61.6% which are lower than those obtained from as weld condition. Although the overall aim of PWAA on high strength aluminium alloys is not to increase the strength but rather to improve exfoliation and stress corrosion cracking.

2.2.2.3 Effects of PWHT

PWHT reported in table 8 was done by only one author. While the PWHT increase the tensile strength at heat soaking time of 16 hours, the tensile strength reduced when the soaking time is further increased to 20 hours. This indicates that there is a range of temperature between which PWHT could be carried out on dissimilar FSW of high strength aluminium alloys to maximize the mechanical properties.

2.3 Effects of Plate thickness on the UTS

The results of the UTS, YS, and elongations presented in table 2 to 8 show no correlation with the thickness of the plates joined. Both high and low UTS values were obtained under different thickness, indicating no particular trend. Thus, the UTS, YS and the elongation of the welded alloys as seen in the reported results from various authors are independent of the alloy thickness used for the experiment.

3 Conclusions

Conclusions from this literature survey and analysis can be drawn as follows:

- The temper conditions of the 7075 aluminium alloy before welding significantly affects the tensile strength of the weld both in similar joint or dissimilar joint with other metals.
- FSW remains a reliable technique of joining 7075 alloys at all temper conditions
- Similar welds of the 7075 alloy at T6 and T651 temper conditions exhibit better tensile behaviour than the dissimilar welds.
- There is a range of temperature between which PWHT could be performed in order to obtain maximum tensile property.

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