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An overview of Friction stir welded alloys: Microstructure and properties

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ABSTRACT:*FSW is considered to be the most significant development in metal joining in a decade and is a ''green'' technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. When desirable, dissimilar aluminum alloys and composites can be joined with equal ease [8-10]. In contrast to the traditional friction welding, which is usually performed on small axis symmetric parts that can be rotated and pushed against each other to form a joint [11], friction stir welding can be applied to various types of joints like butt joints, lap joints, T butt joints, and fillet joints [12]. A unique feature of the friction-stir welding process is that the transport of heat is aided by the plastic flow of the substrate close to the rotating tool [13]. The heat and mass transfer depend on material properties as well as welding variables including the rotational and welding speeds of the tool and it's Geometry.*

1. INTRODUCTION

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining , hot shear joining technique, and it was initially applied to aluminum alloys [1-2]. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint (fig 1). The tool serves two primary functions: (a) heating of work-piece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the Work-piece and plastic deformation of work-piece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of

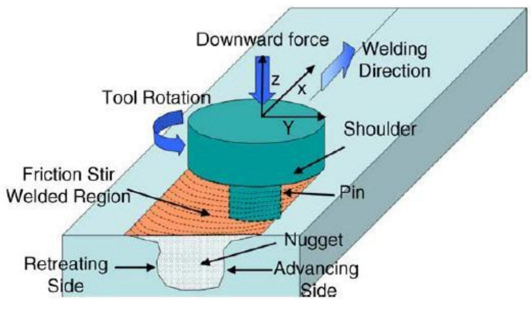
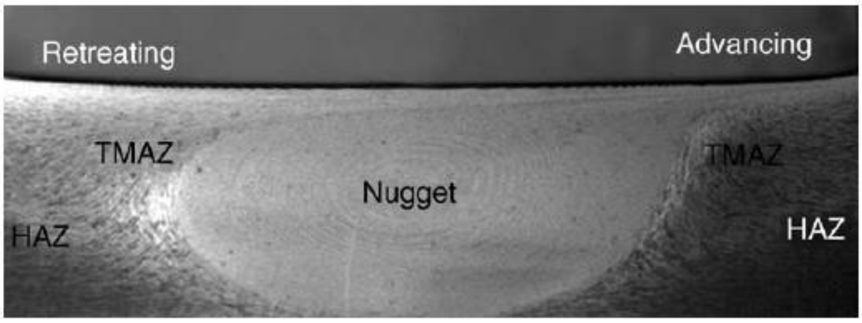


Fig. 1. Schematic drawing of friction stir welding.

the pin to the back of the pin. As a result of this process a joint is produced in 'solid state'. Because of various geometrical features of the tool, the material movement around the pin can be quite complex [3]. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains [4-7]. The fine microstructure in friction stir welds produces good mechanical properties.

2. MICROSTRUCTURE OF FS WELDED ALLOYS



The contribution of intense plastic deformation and high-temperature exposure within the stirred zone during FSW/FSP results in recrystallization and development of texture within the stirred zone [7,8,14-19] and precipitate dissolution and coarsening within and around the stirred zone [8,14,16,18,19]. Based on micro structural characterization of grains and precipitates, three distinct zones, stirred (nugget) zone, thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ), have been identified as shown in fig.2. The micro structural changes in various zones

Fig. 2. A typical macrograph showing various microstructural zones in FSP 7075Al-T651 (standard threaded pin,
400 rpm and 51 mm/min).

have significant effect on postweld mechanical properties. Therefore, the microstructural evolution during FSW/FSP has been studied by a number of investigators. Nugget zone :-

Intense plastic deformation and frictional heating during FSW/FSP result in generation of a recrystallized fine-grained microstructure within stirred zone. This region is usually referred to as nugget zone (or weld nugget) or dynamically recrystallized zone (DXZ). Under some FSW/FSP conditions, onion ring structure was observed in the nugget zone . In the interior of the recrystallized grains, usually there is low dislocation density [4,5]. However, some investigators reported that the small recrystallized grains of the nugget zone contain high density of sub- boundaries [20], subgrains [21], and dislocations [22]. The interface between the recrystallized nugget zone and the parent metal is relatively diffuse on the retreating side of the tool, but quite sharp on the advancing side of the tool [23].

2.1 Aluminium alloys:-

Many aluminium alloys are strong by virtue of precipitation hardening through natural or artificial ageing from the solution-treated condition. The heat associated with welding changes the microstructure of the material. In Fig. 3, HV_{min} and HV_{max} represent the hardness in the solution-treated and precipitation hardened states. The effect of welding is to cause a drop in hardness from HV_{max} towards HV_{min} as the peak temperature experienced increases, curve (a), fig 3. This is because precipitates will coarsen and reduce in number density in regions remote from the heat source, and will re-enter solution when the peak temperature is sufficiently high [24]. Some re- precipitation may occur during the cooling part of the thermal cycle, resulting in a hardness value beyond HV_{min}, curve (b), fig.3. The ultimate result is the continuous line with a minimum in hardness somewhere in the heat- affected zone, due to the competing effects of dissolution and re-precipitation [25]. But in contrast to age hardenable AA 6082, where a minimum hardness occurs in the HAZ, FSW of non-hardenable AA 5082 results in uniform hardness across the weld [25].

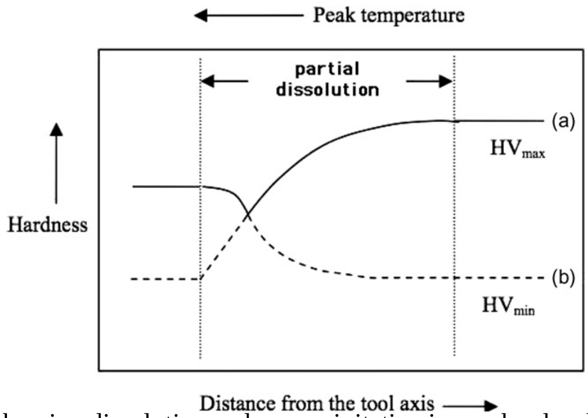


Fig. 3. A schematic diagram showing dissolution and re-precipitation in age-hardenable aluminium alloys. HV denotes the Vickers hardness number. Adapted from [25].

2.2 Magnesium alloys:-

Magnesium alloys, normally produced by casting, may find significant applications in the automotive and aerospace industries with rapid growth particularly in die-cast vehicle components because of their better mass- equivalent properties [26-29]. They are used for light-weight parts which operate at high speeds. The motivation for using FSW for magnesium alloys is that arc welding results in large volumes of non-toxic fumes [30]. On the other hand, solid-state FSW does not result in solute loss by evaporation or segregation during solidification, resulting in homogeneous distribution of solutes in the weld [31]. Also, many magnesium alloys in the cast condition contain porosity which can be healed during FSW.

The hardness and strength can be retained after friction-stir welding [33]. There is no significant precipitation hardening in the alloy studied (AZ31, ’Mg–3Al–1Zn wt.% wrought) and the net variation in hardness over the entire joint was within the range 45–65 HV, with the lower value corresponding to the base plate [32-34]. In the same system, a higher starting hardness of 70 HV leads to a substantially lower hardness in the nugget (50–60 HV); the variations in hardness appear to be consistent with measured variations in grain-size in accordance with the form of the Hall–Petch relationship [32,35]. The grains in both the nugget and TMAZ tend to be in a recrystallised form, and tend to be finer when the net heat input is smaller (for example at higher welding speeds).

2.3 Copper alloys:-

Copper which has much higher thermal diffusivity than steel cannot easily be welded by conventional fusion welding techniques. Heat input required for copper is much higher than conventional FSW because of the greater dissipation of heat through the work-piece. Still, FSW has been successfully used to weld very thick (50 mm) thick copper canisters for containment of nuclear waste [36].

In FSW process hardness of copper alloy is depend on thickness of plate, and grain size[13].When 4 mm thick copper plates with average grain-size of 210 μm were welded at high rpm (1250) and low welding speed (1.01mm s^{-1}) [37], nugget had lower hardness (60–90 HV), compared to base metal (105–110 HV). Even though grain-size decreased from 210 to 100 μm, hardness decreased slightly due to reduction in dislocation density relative to base metal [37]. On the other hand, when 2 mm thick copper plates with average grain-size of 30 lm were welded at 1000 rpm and 0.5 mm s^{-1} low welding speed, nugget (128–136 HV) was harder than the base metal (106–111 HV) due to reduction in average grain-size to 11μm [38].

2.4 Titanium alloys:-

Titanium alloy have high strength (above 1000 MPa). Pure titanium in its hexagonal close-packed a-form is interesting because there is also a tendency for deformation by mechanical twinning during friction-stir welding [6]. The nugget region of an FSW joint is found to contain a large density of dislocations and mechanical twins, with transmission microscopy showing an elongated fine-structure, but the overall grain shape seem to remain equiaxed on the scale of optical microscopy. It is speculated that recrystallisation must have occurred during welding but was followed by a small amount of plastic deformation. The HAZ simply revealed grain-growth, a consequential lower hardness, and hence was the location of fracture in cross-weld tests. There was no clearly defined TMAZ(Thermo- mechanically affected zone) .

2.5 Steels:-

The friction-stir welding of steels has not progressed as rapidly as for aluminium for important reasons.

First, the material from which the tool is made has to survive much more strenuous conditions because of the strength of steel. Second, there are also numerous ways in which steel can be satisfactorily and reliably welded. Third, the consequences of phase transformations accompanying FSW have not been studied in sufficient depth. Finally, the variety of steels available is much larger than for any other alloy system. FSW will become a commercially attractive method for the fabrication of ships, pipes, trucks, railway wagons and hot plate has not yet come to fruition.

The TMAZ should become fully austenitic at some stage of its thermo-mechanical history. It is likely that the severe deformation in this zone causes the austenite to recrystallise, perhaps repeatedly, prior to its transformation during subsequent cooling. This can result in a finer and consequently somewhat harder microstructure than the HAZ

3. PROPERTIES OF FS WELDED ALLOYS

3.1 Residual stress:-

It affects distortion behavior and sustainability of applied load. Compressive stresses are beneficial but due to tensile stresses get cracks. As in ordinary welds, residual stresses develop in constrained assemblies during FSW due to expansion during heating and contraction during cooling; a feature unique to FSW is the additional stress caused by the rotational and translational components of the tool so that the welding parameters of FSW must affect the final state of stress [39]. The stirring action of the tool is believed to relieve some of the stresses within the thermo mechanically affected zone [40]. A higher welding speed enhances the longitudinal residual stress but reduces it along the lateral direction.

3.2 Hardness :-

Aluminum alloys are classified into heat-treatable (precipitation-hardenable) alloys and non heat- treatable (solid-solution-hardened) alloys. A number of investigations demonstrated that the change in hardness in the friction stir welds is different for precipitation-hardened and solid-solution hardened aluminum alloys. FSW creates a softened region around the weld center in a number of precipitation-hardened aluminum alloys [5,7,10,20,41,42]. It was suggested that such a softening is caused by coarsening and dissolution of strengthening precipitates during the thermal cycle of the FSW . [5,7,10,20,41,42] Sato et al. [20] have examined the hardness profiles associated with the microstructure in an FSW 6063Al-T5. They reported that hardness profile was strongly affected by precipitate distribution rather than grain size in the weld. A typical hardness curve across the weld of FSW 6063Al-T5 is shown in fig.4. The average hardness of the solution-treated base material is also included in fig.4 for comparison. Clearly, significant softening was produced throughout the weld zone, compared to the base material in T5 condition. Further, fig 4 shows that the lowest hardness does not lie in the center part of the weld zone, but is 10 mm away from the weld centerline.

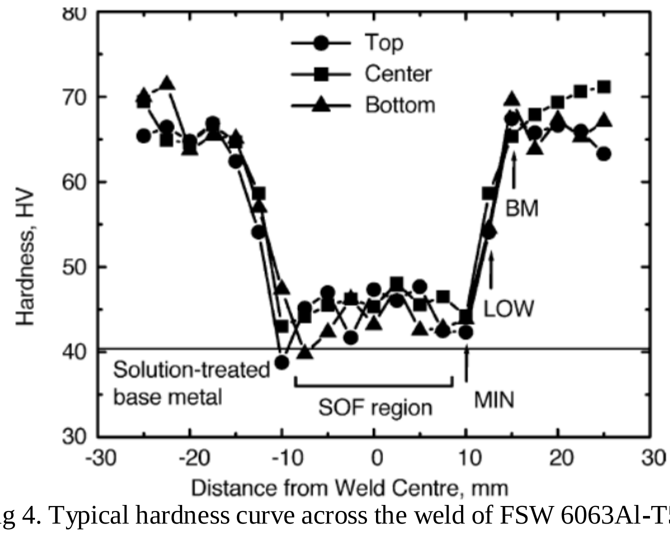


Fig 4. Typical hardness curve across the weld of FSW 6063Al-T5 [20]

3.3 Strength and

ductility :-

FSW affects the tensile properties of materials as e.g
7075Al-T651. Table. 1
Longitudinal tensile properties of weld nugget in friction stir welded 7075Al-T651 at room temperature [43]

Condition	UTS (MPa)	YS (MPa)	Elongation (%)
Base metal, T651	622	571	14.5
As-FSW	525	365	15
Postweld age treatment	496	455	3.5

Tensile specimens were machined from the nugget zone in two directions, parallel (longitudinal) and normal (transverse) to the weld. Longitudinal tensile specimens contained only fully recrystallized grains from the nugget zone, whereas transverse tensile specimens contained microstructures from all four zones, i.e., parent material, H AZ, TMAZ, and nugget zone.table.1 summarizes the longitudinal tensile properties of nugget zone. As-welded samples show a reduction in yield and ultimate strengths in the weld nugget, while elongation was unaffected. Mahoney et al.[43] attributed the reduced strength to the reduction in pre-existing dislocations and the elimination of the very fine hardening precipitates [4]. In order to recover the lost tensile strength of the nugget zone, Mahoney et al. [43] conducted a post weld aging treatment (121 8C/24 h) on the FSW sample. As shown in table.1, the aging treatment resulted in recovery of a large portion of the yield strength in the nugget, but at the expense of ultimate strength and in particularly ductility. The increase in the yield strength of post weld samples was attributed to the increase in the volume fraction of fine hardening precipitates, whereas the reduction in the ductility was accounted for by both the increase in the hardening precipitates and the development of precipitate-free zones (PFZs) at grain boundaries [43]. The tensile properties in transverse orientation of FSW 7075Al-T651 are summarized in table.4. Compared to un-welded parent metal, samples tested in transverse direction show a significant reduction in both strength and ductility. Furthermore, the strength and ductility observed in transverse orientation are also substantially less than those in longitudinal orientation. The post weld aging treatment did not restore any of the strength to the as-welded condition and further reduced ductility. In both as-welded and aged condition, failures occurred as shear fracture in the HAZ. As reported before, the tensile specimens in the transverse orientation cover four different microstructures, i.e., parent material, HAZ, TMAZ, and nugget zone. The observed ductility is an average strain over the gage length including various zones. The HAZ has the lowest strength due to significantly coarsened precipitates and the development of the FPZs. Thus, during tension, strain occurs mainly in the HAZ. The low-strength HAZ locally elongated to high levels of strain (12–14%), eventually resulting in necking and fracture, whereas the nugget zone experiences only 2–5% strain. Therefore, fracture always occurred in the HAZ, resulting in a low strength and ductility along transverse orientation of the weld.

Table .2 Room-temperature tensile properties in transverse orientation of friction stir welded 7075Al-T651[43]

Condition	UTS (MPa)	YS (MPa)	Elongation (%)
Base metal, T651	622	571	14.5
As-FSW	468	312	7.5
Postweld age treatment	447	312	3.5

4. CONCLUSION

Friction-stir welding technology has been a major boon to industry advanced since its inception. In spite of its short history, it has found widespread applications in diverse industries. Hard materials such as steel and other important engineering alloys can now be welded efficiently using this process. Significant progress has also been made in the fundamental understanding of both the welding process and the structure and properties of the welded joints. The understanding has been useful in reducing defects and improving uniformity of weld properties and, at the same time, expanding the applicability of FSW to new engineering alloys. At the current pace of development, FSW is likely to be more widely applied in the future.

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