Effect of friction stir processing on microstructures and mechanical properties of TIG cladding layer on AA7075

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Abstract
AA7075 is a precipitation strengthened Al-Zn-Mg-Cu alloy which has been widely used. As a common way to repair AA7075 components, tungsten inert gas (TIG) cladding generates coarse grains and defects. In addition, the use of other types of filler wires could lead to insufficient rigidity and strength of the cladding layer. In the present work, friction stir processing (FSP) has been applied to the TIG cladding layer on AA7075 to study the effect of process parameters on microstructures and mechanical properties. The macro/micro structural characteristics, elemental distribution, microhardness distribution and tensile properties have been investigated. The macroscopic defects in TIG cladding layer are eliminated and the size of grains is decreases to around 6 μm by FSP. FSP reduces the compositional difference between the stir zone and the base material. Higher rotational speed promotes the grain refinement while the lower traverse speed benefits the microstructural uniformity. FSP on the TIG weld bead brings improvement in tensile properties and hardness. All the fractures for TIG + FSP samples occur at thermo-mechanically affected zone of the advancing side. The tensile strength of the stir zone increases from 424.2 to 442.8 MPa with the increase in rotational speed and traverse speed.

1. Introduction
AA7075 is a precipitation strengthened Al-Zn-Mg-Cu alloy which has been widely used in the structural parts of aviation, aerospace, vehicle and other high-tech industries due to its low density, high strength, high fracture toughness and good corrosion resistance. Welding plays an important role in manufacturing large and complex components and structures. However, the fusion welding processes such as tungsten inert gas (TIG) and metal inert gas (MIG) are easy to generate coarse grain structure and defects like porosity, slag inclusion, crack, deformation and lack of fusion due to the heat concentration and high residual stress [1]. These drawbacks make it difficult to guarantee the welding quality, thus giving rise to the development of new welding methods or post-weld processing methods [2].

Friction stir welding (FSW) is a solid-state joining technique offering distinct advantages over conventional fusion welding in terms of the operability of microstructural control and the applicability of materials [3]. Friction stir processing (FSP) is developed from the basic principles of FSW, as one of the severe plastic deformation technologies, it forms fine-grained microstructure at a relative low processing temperature by the ultrahigh strain and strain rate [4–6]. FSP has been considered as a potential solid-state processing technique for not only microstructure modification but also superplasticity and in situ synthesis of composites or intermetallics [7–9]. In the last two decades, researches have extensively studied the effect of FSP parameters on microstructures and properties of the stir zone, and it is proved that the microstructural evolution during FSP depends on the pin profile, rotational speed and travelling speed [10–13]. Wang et al [14] reported the effect of FSP on microstructure, microtexture and mechanical properties of 2A14 aluminum alloy with different initial precipitation states (as-cast, homogenized, rolled, and T6 state). It was found that the initial states evidently
affect the morphology and distribution of precipitates and dislocations after FSP, leading to different mechanical performance that strengthened SZ for as-cast and homogenized states while softened SZ for rolled and T6 states. Recently, the microstructural evolution caused by FSW/FSP has been comprehensively reviewed [15]. The principal evolution mechanisms of grain structure during FSW/FSP depend primarily on crystal structure and stacking fault energy.

Due to the applicability and convenience, TIG cladding has been used to repair some metal products for the reduction of economic losses or timely remanufacturing. However, for the mending of AA7075, it is known that there are still no 7-series filler wires available at present. Thus, other types of filler wires such as ER5356 and ER4043 have been used as alternatives, leading to insufficient rigidity and strength of the cladding layer. In addition, the heat treatment on 5-series and 4-series aluminium alloys couldn’t obtain good strengthening effect. In the last few years, FSP has been considered as a feasible way to elevate the mechanical properties of TIG welded TA15 joints [16] and a low-cost technique for fusion welds repair and modification in AA6061 alloys [17]. Under the circumstances, it is attempted to improve the mechanical properties of TIG cladding layer by applying FSP to it. The process parameters of FSP have significant influences on the microstructures and mechanical properties of cladding layer, hence the correlation and influencing mechanism are important. With the understanding of mechanism, grains and phase particles can be designed with FSP at the sub-micro scale to achieve high-strength AA7075 remanufactured parts through a simple and effective surface modification strategy.

Based on the above all, FSP has been applied to TIG cladding layer on AA7075 in the present work and is expected to improve the mechanical properties of the weld bead. The macro/micro structural characteristics, elemental distribution, microhardness distribution and tensile properties have been investigated. The correlations among process parameters, microstructures and mechanical properties have been discussed.

2. Experimental procedure

AA7075-T6 aluminum alloy rolled plates with dimensions of 160 mm × 80 mm × 5 mm were used as base material in the experimental work. TIG cladding was firstly conducted in the base material by using the preferred parameters in table 1. ER5356 aluminum alloy wire with a diameter of 1.2 mm was used as the filler wire. The chemical compositions (in wt%) of AA7075 and ER5356 are listed in table 2. The weld bead was polished and cleaned as preparation for FSP by a vertical numerical control friction stir welding machine FSW-LM-BM16. The stirring tool is H13 steel with the geometry of a threaded tapered tool pin. The diameter of the shoulder is 15 mm, the diameter of the root diameter, head diameter and pin length of the stirring pin is 6 mm, 4 mm and 5.

### Table 1. TIG cladding parameters.

| Arc length (mm) | Current (A) | Argon (L/min) | Travel speed (mm/s) | Feed speed (m/min) |
|----------------|-------------|---------------|---------------------|-------------------|
| 3.2            | 150         | 25            | 3                   | 2                 |

### Table 2. Chemical compositions (in wt%) of AA7075 and ER5356.

| Material | Zn  | Mg  | Cu  | Si  | Cr  | Mn  | Fe  | Ti  | Al  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| AA7075   | 5.70| 2.50| 1.60| 0.40| 0.20| 0.30| 0.50| 0.15| Bal.|
| ER5356   | 0.05| 5.00| 0.08| 0.15| 0.13| 0.12| 0.20| 0.13| Bal.|

- **Figure 1.** Extraction scheme of sampling location and tensile sample.
During FSP, the stirring tool was slightly inclined to the vertical axis by 2.5° and the plunge depth was kept as 0.2 mm. FSP was carried out along the weld bead at rotational speeds of 600 and 1000 rpm, traverse speeds of 100 and 130 mm min$^{-1}$, respectively. There are brief expressions for samples, for example, the TIG cladded sample followed by FSP at rotational speed of 600 rpm and traverse speed of 100 mm min$^{-1}$ is expressed briefly as TIG + FSP-600–100.

The block samples containing weld zone were cut, ground, polished and then corroded by Keller reagent. The cross-section microstructures were characterized by ZEISS optical microscope (OM) and ZEISS Sigma 500 scanning electron microscope (SEM). Distribution of elements was analyzed by energy dispersive spectroscopy (EDS). The grain sizes were measured using the linear intercept technique by the ImageJ software. Chinese standard GB/T 27552–2011 was used for the micro-hardness tests taken along the horizontal line (1 mm depth from the upper surface) of cross-section by applying a load of 100 g with a dwell time of 10 s on an HVS-1000A.
Vickers microhardness tester, the interval of measuring points was set as 0.5 mm. Planar dog-bone tensile samples were machined across and along the processing zone with the guidance of the GB/T 2651–2008 standard, with outline dimensions as shown in figure 1. The tensile properties were tested on an electronic universal testing machine operating at a constant crosshead speed of 1.0 mm/min. After testing, the gage length change of failed specimens was measured to determine the ductility. Three measurements were taken to calculate the mean value as performance data.

3. Results and discussion

3.1 Macrostructures
Figure 2 shows the appearances of TIG cladding layer and TIG + FSP region. The TIG cladding direction is perpendicular to the plate rolling direction. It is observed from the surface morphology in figure 2(a) that a great part of cladding layer (or weld bead) is free of macroscopic cracks, instead, cracks only appear in the end part of the weld bead. It indicates that the current set of cladding parameters is the preferred one among the alternatives which have been attempted. One of the TIG + FSP plates as given in figure 2(b) shows that the friction stir processing along the cladding direction is achieved with a good surface quality.

The typical cross-section macrographs of TIG cladded and TIG + FSP areas for samples are shown in figure 3. It can be seen from figure 3(a) that the surplus height of weld bead is about 1 mm. The macrostructure presents different characteristics including the weld zone (WZ) with equiaxed grains, fusion zone (FZ), heat affected zone (HAZ) and base material (BM) with fibrous tissues. A few gas holes, voids and small cracks can be found in the WZ. These defects formed due to factors such as air flow, heat concentration and high residual stress during the fast melting and solidification processes. The width of HAZ is estimated to be about 600 μm.

After FSP, the macrostructure in figures 3(b) and (c) can be divided into different areas including stir zone (SZ), thermo–mechanically affected zone (TMAZ), HAZ and BM. There is a sharp interface between SZ and TMAZ at the advancing side (AS) and a fuzzy one at the retreating side (RS), owing to the fact that AS has larger gradients of strain and temperature [18, 19]. In addition, the slope of interface between SZ and TMAZ at AS is larger than that at RS, which can be attribute to the different material flow on both sides which is relevant to the 2.5° back tilt of the tool [14]. The SZ exhibits an upside-down ‘bucket hat’ shape, which consists of a basin-like bottom region and an outward-extending upper part. There is a little difference between figures 3(b) and (c) in the shape of the upper region of SZ, indicating the influences of heat and strain rate originated from the different rotational speeds of 600 and 1000 rpm. The outline of SZ is similar to that of the nugget zone commonly observed in FSW joints [4, 12, 20]. The macrograph also reveals a homogenously fine grain structure without defects such as cavities, cracks and tunnels in the SZ. The typical onion-ring structure appears in the middle and bottom of SZ in figures 3(b) and (c), which has been correlated to the precipitation response and crystallographic texture in some of the friction stir processed aluminum alloys [21].

Figure 4. Microstructures of different regions in TIG cladded sample.
3.2 Microstructures and elemental distribution

The microstructures of different regions in TIG cladded sample are shown in figure 4. Figures 4(a) and (c) exhibit the microstructures of WZ and FZ from the view of OM at 200 × magnification. FZ is a semi-molten area between WZ and HAZ during welding process preserving severe chemical and physical inhomogeneity, which shows the transition tissue like the discontinuous banded structure. Figure 4(b) clearly shows the equiaxed dendrites microstructure with grain size of 30–70 μm in diameter. The average composition of the marked precipitates analyzed by EDS is 72.9%, 20.6%, 3.8% and 2.7% (in wt%) for Al, Cu, Zn and Mg, respectively. The microstructures of HAZ are shown in figures 4(d) and (e), which are composed of elongated grains formed by rolling. It is obvious that the tissue distribution in HAZ is nonuniform and the grains are coarsened compared with that in FZ. The uniform distribution of precipitates in the deformed grains can be found and associated with the T6 heat treatment on the as-rolled base material. High temperature and rapid cooling during TIG cladding could lead to the decrease of most strengthening phases in SZ and HAZ by redissolution. While the saturated solid solution results in the re-precipitation of other phases with relatively low dissolved or precipitated temperatures in subsequent natural aging [22].

Figures 5 and 6 exhibits the microstructures of different regions in sample TIG + FSP-600–100 and TIG + FSP-1000–100, respectively. Figure 5(b) and figure 6(b) show the microstructures in SZ where the equiaxed grains with diameter of about 6 μm can be observed. Under the impact of mechanical agitation and friction heat, the weld bead is softened, thus the severe plastic deformation takes place and fine equiaxed grains

3.2 Microstructures and elemental distribution

Figure 5. Microstructures of different regions in sample TIG + FSP-600–100, TMAZ at AS (a)(d), SZ (b) and TMAZ at RS (c)(e).

Figure 6. Microstructures of different regions in sample TIG + FSP-1000–100, TMAZ at AS (a)(d), SZ (b) and TMAZ at RS (c)(e).
form by dynamic recrystallization in SZ [23]. Compared with figure 4(b), it is evident that the coarse grains in TIG cladded WZ have transformed into fine grains during FSP. It is well known that the TMAZ microstructure forms under the combined influence of low stress and high temperature during FSP. As shown in figures 5(a)
Zn increases from 3.6 to 6.1 wt%. This result is correlated to the composition of ER5356 and (c). The microstructures of TMAZ at the AS in figure 5(d) and figure 6(d) clearly show the grains in TMAZ are distorted and elongated on the base of as-rolled microstructure, similar to that at the RS in figure 5(e) and figure 6(e). On the one hand, the insufficient plastic deformation occurs on the grains within TMAZ due to rotational friction and shear deformation of the stirring tool, and thus the dynamic recovery and dynamic recrystallization occurred in a few grains. On the other hand, the elongation of grains along the rotating direction results from the effect of temperature gradient and strain rate. These features are similar to those in the welds of FSW [24]. According the study of Duan et al [25], the dissolution of mass precipitates and grain growth of the FSW joints increase the possibility of intergranular fracture occurrence, leading to the deterioration of plasticity and toughness of the joints compared with BM.

In order to investigate the elements distribution among different regions, EDS was applied in map scanning mode on the marked areas as shown in figures 3(a) and (b). The results are summarized in table 3 and the distribution images for major elements in WZ and SZ are given in figures 7(a) and (b), respectively. It can be found in figure 7(a) that the Al content on the grain boundary is less than that within the grain. Moreover, the component analysis by point scanning reveals that the content of Cu rises to around 45 wt% and 22 wt% while that of Mg and Zn slightly changes at the locations for each kind of precipitations, respectively. Figure 7(b) indicates the major elements are more evenly distributed in SZ after FSP compared with that in WZ. The component evolution along with the distance from center can be found in table 3. For TIG cladded sample as shown in figure 3(a), the average content of Al decreases from 92.1 wt% in WZ to 89.3 wt% in BM while that of Zn increases from 3.6 to 6.1 wt%. This result is correlated to the composition of ER5356 filler and 7075 BM. After FSP, the compositions in the center of SZ (area 1 in figure 3(b)) can be found 1.5 wt% less in Al content while 1.4 wt% more in Zn content compared with those in the center of WZ (area 1 in figure 3(a)). The result can be explained as the mechanical agitation of pin dragging 7075 BM into the SZ, similar phenomenon and explanation are prevalent in FSW of dissimilar materials [26]. The element content barely changes in TMAZ, HAZ and BM.

The comparison of microstructures in SZ for the experimental samples has been given in figure 8. The existence of voids in SZ is associated with the insufficient heat input which will weaken the flow of metal, leading to the incomplete filling of cavities behind the stirring pin. For one thing, the sufficient stirring effect by high rotational speed is conducive to the fragmentation and the uniform dispersion of particles throughout the SZ. For another, high heat input within limit gives the effective recrystallization and more homogenous temperature distribution in SZ, which facilitate the grain refinement and enhance the homogeneity of microstructure [27]. As a consequence, it is observed that the microstructures of TIG + FSP samples with the lower traverse speed of 100 mm min$^{-1}$ (figures 8(a) and (c)) are relatively homogeneous, which implies the sufficient dynamic recrystallization during FSP.

The average grain size is 6.6, 6.0, 5.8 and 5.6 μm for figures 8(a)–(d) respectively. The heat input and mechanical stirring have been considered the major factors for grain size of SZ [28]. Husain et al has reported that the temperature at the center of the TIG + FSP welded joint is increasing gradually with the increase of rotational speed from 800 to 1600 rpm [29]. When the rotational speed increases, grain size decreases, this
observation has been given the satisfactory amount of assurance [30]. Under the certain rotational speed which ensures the sufficient dynamic recrystallization, the peak temperature of SZ will decrease with the increase in traverse speed, leading to the decrease in grain size by restraining the growth of recrystallized grains as has been reported by Li et al [31]. Accordingly, the TIG + FSP samples rotated at 1000 rpm exhibit finer grains compared with corresponding ones rotated at 600 rpm.

3.3 Mechanical properties
Figure 9 gives the hardness profiles of cross-section under different process parameters. The different feature areas along the horizontal direction for samples have been distinguished according to the macrostructural characterization. Therefore, the variation of microhardness can be associated with the microstructural evolution. The fluctuations in microhardness values indicate the inhomogeneity of microstructures. For TIG cladded sample, the center of WZ preserves the lowest hardness of around 88 HV, which is considered a combined result of composition and microstructure in the ER5356 cladding layer. There is an increase in hardness with the increasing distance from centerline, due to the compositional variation towards base material. Then the region with the lower hardness than BM appears as known as HAZ, owing to the grain coarsening. The hardness for BM is around 106 HV.

It is noticed the hardness distribution patterns for TIG + FSP samples are similar, but different from the TIG cladded one. The non-uniform distribution of hardness in the SZ could be explained by the pulsating
actions and the inadequate material flow generated around the square pin [10]. The hardness values of the TIG + FSP samples are higher than those of the TIG sample within 8 mm from the centerline. Compared with WZ, the average hardness in SZ increases notably by around 25 HV due to the dynamic recrystallization. The hardness shows increase followed by decrease in TMAZ with the maximum of 138.3 HV, on account of the distorted and nonuniform microstructure. There is a descending trend of the hardness values to the lowest point of 88.5 HV followed by the increase. According to previous studies of the FSW joint of Al alloys [12, 32], it is deduced that the strengthening phases get partly dissolved or coarsened in HAZ together with the grain coarsening, resulting in continuous decline of hardness in HAZ. As can be seen, it is proved that the HAZ has been enlarged by FSP. Each of the hardness distribution pattern matches up well with the corresponding microstructural feature and the elements distribution shown in figure 3 and table 3.

Figure 10 presents the tensile properties for samples across the processing zone. The direction of tensile stress is parallel to the rolling direction. The tensile strength (TS) and elongation (EL) of the TIG cladded sample is 336.8 MPa and 8.3%, respectively. According to the post-fracture observation in figure 11(a), the fracture locations of TIG cladded specimen are always at the center of gauge length, which indicates the WZ is the weak area with regard to the repair of AA7075 by TIG welding. It is noticed that the TS of WZ is quite lower than AA7075-T6 base material, which results from the ER5356 filler, coarse grains, defects, as well as the dissolution of mass precipitates in WZ.

As shown in table 4, the TS of the cladding layer has been greatly enhanced by FSP, which can be related to the grain refinement. Based on the macrographs of the cross-section shown in figure 3, the fracture locations displayed in figures 11(b–e) and the macrostructure given in figure 11(f), it is identified all the fractures for TIG + FSP samples occur at TMAZ of the AS, illustrating TMAZ is the weak area. According to the heat transfer study of TIG + FSP welded joint of aluminum alloys [33], the temperature at AS is higher than the RS. It has been reported that the mechanical properties of the AS are generally slightly lower than the RS in the single-sided FSW [34]. The above results reveal the important role of TMAZ on mechanical properties of friction stir processed TIG cladding layer. It has been reported that the TMAZ is characterized by the dissolution of most precipitates [32]. In view of the high stress concentration and the sharp grain size gradient in this region, the emergence of the lowest mechanical properties in TMAZ is reasonable. The fractures at TMAZ could be connected with the distorted, nonuniform microstructure and the heat effect. It has been proposed that both of the defect and the redissolution of precipitates originated from insufficient and overmuch heat input.

| Table 4 Summary of tensile properties. |
|-------------------------------------|
| TIG      | TIG + FSP-600–100 | TIG + FSP-600–130 | TIG + FSP-1000–100 | TIG + FSP-1000–130 |
|----------|--------------------|--------------------|--------------------|--------------------|
| Across   |                    |                    |                    |                    |
| TS (MPa) | 336.8              | 418.0              | 388.2              | 383.8              | 407.3              |
| EL (%)   | 8.3                | 9.7                | 8.0                | 8.7                | 7.9                |
| Fracture | WZ                 | TMAZ               | TMAZ               | TMAZ               | TMAZ               |
| location |                    |                    |                    |                    |
| Along    |                    |                    |                    |                    |
| TS (MPa) | 339.1              | 424.2              | 433.5              | 439.3              | 442.8              |
| EL (%)   | 9.0                | 9.6                | 9.4                | 9.8                | 9.5                |
| Fracture | WZ                 | TMAZ               | TMAZ               | TMAZ               | TMAZ               |
| location |                    |                    |                    |                    |

Figure 12. Tensile properties of samples along the processing direction under different process parameters.
individually, have a negative effect on the joint performance [25]. Therefore, the joint with the optimum mechanical properties is obtained by moderate heat input for sample with rotational speed of 600 rpm and traverse speed of 100 mm min\(^{-1}\).

In order to compare the tensile properties of the SZ under different process parameters, tensile properties were tested along the processing direction and the results are shown in figure 12. The TS and EL of the WZ is 339.1 MPa and 9.0\%, respectively, which are quite different compared with the corresponding values of 280 MPa and 29.5\% for AA5356 fabricated by TIG arc additive manufacturing [35]. This is due to the properties of the cladding layer lies between that of AA5356 and AA7075. It can be seen that the EL of WZ has also been improved by FSP. The TS of SZ increases from 424.2 to 442.8 MPa with the increase in rotational speed and traverse speed, on account of the decreasing grain size. It is noticed that samples processed at the lower traverse speed of 100 mm min\(^{-1}\) exhibit the better plasticity, which could be related to the better uniformity of microstructure and composition as has been discussed in section 3.2. Among all samples, the TIG + FSP-1000–130 preserves the best tensile properties, suggesting the sufficient stirring effect and the suitable heat effect in SZ.

4. Conclusions

In the present work, friction stir processing (FSP) has been applied to the layer deposited by TIG cladding on AA7075 to study the effect of process parameters on microstructures and mechanical properties. The main conclusions are listed as follows.

(1) The macroscopic defects in WZ are eliminated and the size of grains is decreases to around 6 \(\mu\)m by FSP. FSP reduces the compositional difference between SZ and BM. The element content barely changes in TMAZ, HAZ and BM.

(2) The TIG + FSP samples with the rotational speed of 1000 rpm exhibit finer grains in SZ compared to those rotated at 600 rpm. Microstructures in SZ of samples with the lower traverse speed of 100 mm min\(^{-1}\) are more homogeneous compared to 130 mm min\(^{-1}\), which implies the sufficient dynamic recrystallization during FSP.

(3) Compared with WZ, the average hardness in SZ increases notably by around 25 HV. The WZ is the weak area with regard to the repair of AA7075 by TIG welding, while TMAZ of the advancing side turns to be the weak area after FSP. FSP on the TIG weld bead brings noticeable improvement in tensile properties and hardness. The TS of SZ increases from 424.2 to 442.8 MPa with the increase in rotational speed and traverse speed.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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