Study on Welding Adaptability of Spray Formed 2195 Al-Li Alloy Filler Wires

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Abstract: Study on the weldability of Al-Li alloy indicates that the composition design of filler wires, and the morphology and content of the strengthening elements dominate microstructures, mechanical properties and defect control of fusion welding joint; and the welding process can actively correct the joint performances within limits. The filler wires of the both Al-Cu and Al-Cu -Zr alloy systems were developed and comparison and analysis were carried out to their adaptability along with study of the weldability of spray formed 2195 Al-Li alloy. The EDSD (electron back-scattered diffraction) detection method was applied to obtain the statistics of the microstructure fraction, grain size and small angle grain boundary of weld joints and their microstructures and correspondingly establish the interrelationship between the filler compositions and joint microstructure and performances; moreover, a microstructure matching based optimization approach was put forward to the fusion welding filter based on analysis of characteristics between weld joints and the base metal microstructures.

Keywords: Spray formed Al-Li alloy; Welding; Filler wire; Adaptability

Introduction

The third-generation Al-Li alloy has been being increasingly popular in aerospace structures since 1990s; moreover, research and development of their weldability and adaptable welding wires are still in progress, which can be summarized in two aspects[1-4]: 1) the material compositions shall be optimized to reduce the sensitivity of fusion welding cracks and improve the solid-liquid plasticity of the fusion zone and microstructures of the heat affected zone; and 2) the welding filler compositions shall be matching to not only reduce the sensitivity of cracks but also improve the overall performances of joints. In addition, The latter is of great significance to meet the engineering needs for manufacturing various types of welded structures.

Early research on filler wires for fusion welding Al-Li alloy mainly focused on the crack resistance of welds. Reddy et al. utilized the commercially available welding wires made of 4043, 2319, 5356 and so on to evaluate the thermal cracking sensitivity of 01441 alloy joints by means of the fish bone test method [5] and the corresponding results indicate that 4043 and 2319 welding wires rather than 5356 ones tend to be more easily cracking because the solidification range of 5356 eutectic liquid is large but their eutectic phase is discontinuously distributed along the grain boundaries so that more network metal bridges can be formed to reduce the thermal cracking sensitivity of 01441 alloy joints. L. S. Kramer et al. studied the weldability of Weldalite 049, 2090 and other alloys with various Cu contents by means of the spot verestraint test method [6] and their results show that any welding wire with more Cu can not only improve the solidification crack resistance of Weldalite 049 and 2090 alloys but also avoid liquefaction cracks in the fusion zone; unluckily, they failed to evaluate the overall performances of joints.

While National Aeronautics and Space Administration (NASA) developed storage tanks for Saturn V Project, a systematic study was carried out to the weldability of 2195 Al-Li alloy as the alternative of 2219 Al-Cu alloy and its fillers [7], where 5 commercial welding consumables (namely 2319 (Al-6.3Cu), 4043 (Al-5.3Si), 4047 (Al-12Si), 4145 (Al-10Si-4Cu) and 5356 (Al-5.0Mn)) were technologically tested and compared for welding a 2195-T8 plate (thickness: 5mm) and the test results indicate that 2319 welding wires rather than 4043 and 4047 ones are more preferential to eliminate thermal cracks but result in a smaller strength loss; on the other hand, 4043, 4145 and 5356 welding wires cannot meet the performance requirements of 2195 Al-Li alloy engineering applications. To this end, NASA, Lockheed Martin and McCook Metal Company jointly developed Al-Cu based welding wires called as B218 [8], whose chemical compositions ensure that the sensitivity of welding and repair welding of 2195 Al-Li alloy shall fall and its mechanical properties can exceed the joint performances with the currently available welding wires.

Although development and application of 2195 Al-Li alloy are still at an initial stage in China, research and development of filler wires have been being in progress to meet the needs development of the aerospace industry. Li Xiaohong et al. regulated compositions and successively developed 7 types of welding wires in 2 categories based in ER2319 filler wire [9], whose Cu contents were selected at about 6.0%. One category of filler wires (Sc content: 0.5-1%) include a little Mn while the other category of filler wires are free of Sc and the weld performances were regulated by means of Mg and Ag. The findings indicate that the joint tensile strength and elongation are 330MPa and 5.1%, respectively, while the Sc content is about 7%.

This study focuses on two aspects as follows:

1) Compared to forming of materials by means of the melt casting method, spray forming for preparation of 2195 Al-Li alloy (hereinafter referred to as S2195) can more accurately control its compositions; moreover, its rapid solidification ensures that its material grains shall basically be fine and equiaxed so that its occurrence probability of segregation can fall[10]; and

2) Analysis and comparison were carried out to the adaptability of 2 categories of filler wire independently developed with Al-Cu and Al-Cu-Zr alloy series for fusion welding of S2195. The statistics of the phase microstructure ratio, grain size distribution, angular grain boundaries and so on of weld joints were gained by means of the EDSD detection method to establish a quantitative interrelationship between the joint microstructures and performances. Thus, a method for evaluation and analysis of the adaptability and joint performances can be presented based on the state of their microstructures.

1. Test conditions and welding process

1.1 Test materials and statistical characteristics of their microstructures

The measured compositions of the S2195 sheet of our study are shown in Table 1. Statistical analysis was performed to those microstructure features such as material phase structure, grain size distribution, grain boundary characteristics and microstructures with the help of the EBSD technique[11]. Its base microstructures (Figure 1) indicate that its base grains were rolled in a bundle/stripe distribution; also, their grain orientation reveals that the base preferentially grows Crystal Directions of <111> and <001> so that the rolled sheet shall be characterized as an anisotropic fiber texture. The characteristic statistics of its base microstructures are listed in Table 2.

Table 1 Chemical compositions of S2195 Al-Li alloy

Plate Number/Composition	Cu	Mn	Mg	Ag	Si	Fe	Zr	Li
S2195-17	3.66	0.0006	0.45	0.31	0.067	0.036	0.12	0.88
Reference American Standard	3.7-4.3	≤0.25	0.25-0.8	0.25-0.6	≤0.12	≤0.15	0.08-0.16	0.8-1.2

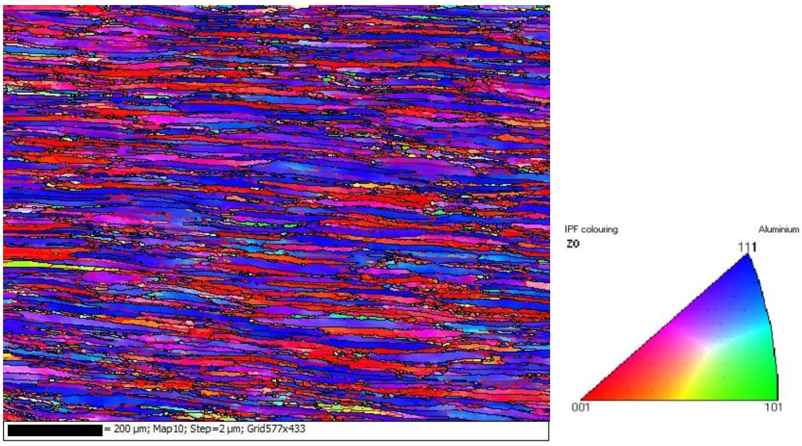


Figure 1 Grain orientation of S2195-T6 Al-Li alloy rolling plates

Table 2 Characteristics and statistics of S2195-T6 base microstructures

Recrystallization (%)	Substructure (%)	Deformed crystal (%)	Small angle grain boundary (%)	Average grain size/maximum μm	Grain size variance μm
6.1	13.1	80.8	17.9	12.5/120	7.3

Table 2 indicates that the average grain size of our S2195 base (state: T6) is 12.5μm, whose standard deviation is 7.3μm. Small-angle grain boundaries account for 16.48%; namely, another factor affecting properties of the polycrystalline material is directional and fibrous deformed microstructures (Figure 1) and the lamellar-type microstructures made up of large-angle grain boundaries are characterized although the grain size and distribution are relatively small and uniform. Thus, the base properties can be affected by a high proportion of large-angle grain boundaries and fiber microstructures.

Table 3 Mechanical properties of test S2195-T6 material

Base state*	σ_b/MPa	$\sigma_{0.2}$/MPa	A (%)	Remarks
S2195-T6	555	495	10.5	Rolling direction
S2195-T6	529	485	3.0	Vertical rolling

Notes: T6 solid solution: 505±3°C/70min; water quenching; ageing; 165°C/40h, air cooling.

1.2 Composition design of filler material

The compositions and adjustment of the filler wires were primarily focused on regulation and control of the content of Cu for intensification of solid solution and the combined effects of the Al_3M type transition group elements with refined grains and forming a dispersion hardening phase.

(1) Cu as the primary solid solution element, such as Al_2Cu as a strengthening and toughening phase can effectively improve the base strength. On the other hand, the excess Cu components generate a Cu-rich eutectic phase at the grain boundaries to adversely affect the strength and toughness as well as corrosion of the material resistance. For example, Al_7Cu_2Fe and other components can refine grains but they easily accumulative at the grain boundaries in form of a brittle phase to become a fracture source; moreover, the content of Cu in the filler shall be controlled at about 6% in view of consideration of the thermal cracking sensitivity and comprehensive performances of weld joints[12].

(2) Common characteristics of Zr, Ti and other transition group elements ensure that they can perform a series of peritectic reactions with Al to form refractory metal compounds such as Al_3Zr and Al_3Ti. While such elements are separately or jointly added into any filler, the dispersed, small and refractory aluminized material points may occur and become non-spontaneously solidified nuclei when the liquid metal solidification takes place; thus, the joint grains can be refined and the occurrence probability of solidification cracks can fall.

(3) Control of the Si content is in favor of removal of the low melting point eutectics and impurities at the crystal boundaries but becomes a a weak link due to correspondingly thickening the crystal boundaries. In addition, Si will result in the too large fluidity of the molten pool for Al-Li alloy so as to go against penetration and forming of joints.

Thus, those factors such as the alloy composition, solidification temperature range, low-melting eutectic composition and quantity, and the properties and distribution of the second phase of the grain boundary of the filler wire dominate the fusion welding processability of S2195 and comprehensive performances of joints. Table 4 presents the compositions of our two categories of filler wires. Growth of contents of Zr and Ti in the Al-Cu-Zr welding wire was expected to lower eutectic phases which may occur due to possible existence of Fe and Mn in joints.

Table 4 Compositions of 2 categories of filler wire (wt. %)

Filter material	Cu	Si	Ag	Zr	Ti	Fe	Mn	Al
Al-Cu wire	5.6	0.015	0.013	0.10	0.10	0.378	0.327	Bal.
Al-Cu-Zr wire	6.32	0.089	0.36	0.34	0.30	0.080	0.0014	Bal.

1.3 Test conditions

Performances of filler wires were verified by a manual variable polarity TIG welder (model: Dynasty 700) powered by an AC pulse power source. Sizes of our welding test plates are as follows: thickness: 6.0mm; length: 300mm; and width: 150mm. The both sides of the plate were protected with high purity argon (purity: 99.999%) during the welding. The shielding gas flow rates for the welding torch and the back side are 12-16L/min and 20-25L/min, respectively. The butt joint form are as follows: bevel: 120°; blunt edge: 1-1.5mm; single-sided two-layer welding. Those grooves and their surrounding area (≤15mm) of those plates and their back surface oxide layers were fully scraped prior to welding. The welding environment temperature is 24-26°C and the relative humidity is 40-60%. Table 5 presents the primary welding process parameters.

Table 5 VP-TIG welding process parameters for S2195-T6 alloy plate

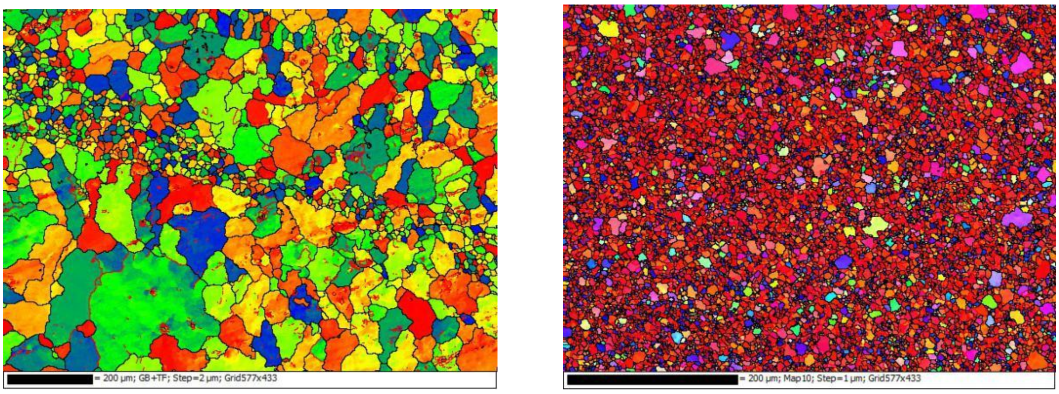
Root pass current / A	Root pass voltage / V	Capping current / A	Capping voltage / V	Capping layer travel speed / (mm/min)	Capping layer travel speed / (mm/min)	Heat input (kJ/mm)
195-200	13.5~15.0	170-175	15.5~16.5	120-130	110-120	Root pass: 1.3-1.4 Capping layer: 1.1-1.2

Those welding process factors such as welding specifications, preheating, joint form and welding sequences shall be optimized. The welding cracks shall be prevented to reduce the welding stress; on the other hand, the thermal cycle of welded joints shall be regulated to not only obtain better joint microstructures but also help removal of weld defects and improve crack resistance.

2. Interrelationship between weld microstructures and joint performances

2.1 Analysis of grain and grain boundary state of weld joints

During welding any Al alloy joint whose metals are in typical chilled crystalline microstructures, not only their crystallization and cooling speeds are fast but also the epitaxial growth of crystal grains occurs from the base substrate; in addition, the unique crystallization phenomens such as the directionality of grain growth occur along with movement of the welding heat source[13]. For the Al-Li alloy, Al_3Zr and other components can inhibit epitaxial growth of crystals to easily form fine equiaxed crystal layers. This is a unique phenomenon for welding a Al-Li alloy system. While any weld metal composition is segregated or the degree of subcooling is relatively large, local fine-grained bands often occurs. Figure 2 shows the morphologies of joint microstructures for application of Al-Cu and Al-Cu-Zr filler wires under the same welding process conditions, respectively.Table 6 presents comparison of characteristic statistics of joint microstructures for two categories of filler wires.



a. Application of Al-Cu filler wire b. Application of Al-Cu-Zr filler wire

Figure 2 Morphologies of joint microstructures

Table 6 Comparison of characteristic statistics of joint microstructures for two categories of filler wire

Category of filter wire	Recrystallization %	Substructure %	Deformed crystal %	Small angle grain boundary %	Average grain size / max. μm	Standard deviation μm
Al-Cu	10.9	32.0	57.1	16.9	24.6/131.5	19.2
Al-Cu-Zr	39.7	11.4	48.9	13.6	5.7/27.5	2.3
Base metal T6 (for reference)	6.1	13.1	80.8	17.9	12.5/120	7.3

The characteristic inspection statistical results (Table 6) of the joint microstructures can present the following understanding:

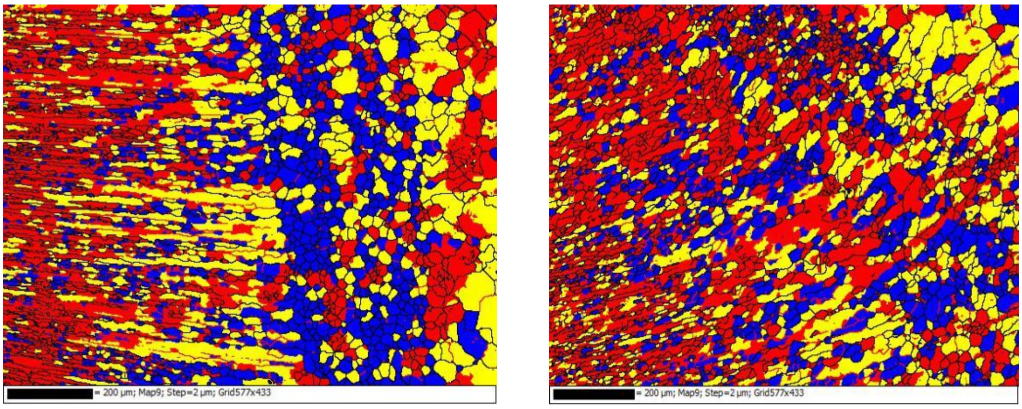
(1) The grain morphology and size are the basic characteristic parameters for description of microstructure. Based on analysis of the statistical distribution of the grain characteristics of joints, the characteristics of joints and base microstructures are relatively close for application of the Al-Cu filler wire; moreover, there is a small gradient in their microstructures and grain size distributions; in addition, their mechanical factors such as strength and flow stress are characterized as macroscopic uniformity.

(2) In terms of the proportion of the small grain boundary angle, the joint and base are also similar for application of the Al-Cu filler wire; and such case indicates that dislocation aggregation and slipping of the microstructures are better compatible on the two sides of the fusion line of a joint while it is deformed under any external force.

(3) In view of analysis of the joint microstructures, the proportion of recrystallized grains greatly affects the strength and elongation of the fusion zone. As for joint microstructures for application of Al-Cu filler wire, the percentage of recrystallized grains are similar to that of the base, which is significantly lower than that of joints for application of Al-Cu-Zr filler wire.

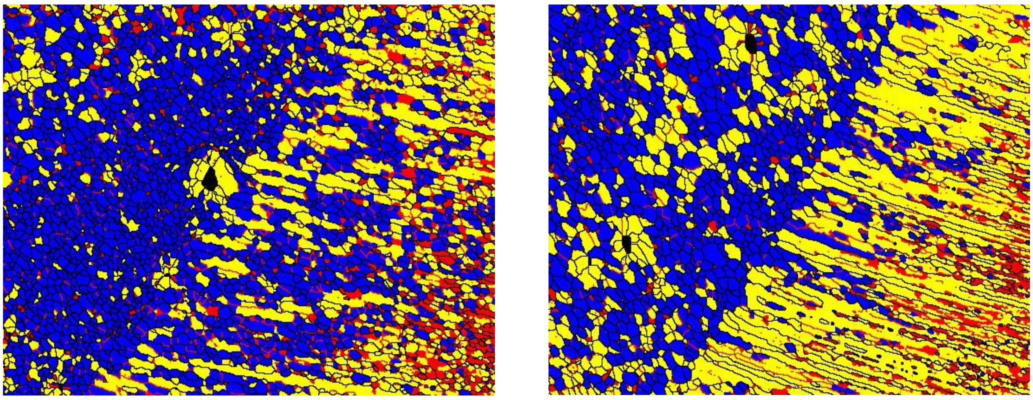
2.2 Analysis of microstructures in the fusion zone of joint

The welded joint is subject to thermal cycling during the welding process to result in uneven joint microstructures and corresponding performance changes. For example, the nucleus arcuates of grains grow based on their original grains at the recrystallization temperature and above to form some recrystallized grains. Figure 3 presents the microstructure photos of the bond coating and cover layer for application of Al-Cu and Al-Cu-Zr filler wires, respectively. Table 7 indicates that the recrystallization percentages and microstructures are significantly different at the both sides of the fusion line for application of Al-Cu and Al-Cu-Zr filler wires.



a. Root pass b. Capping layer

Application of Al-Cu filler wire



a. Root pass b. Capping layer

Application of Al-Cu-Zr filler wire

Figure 3 Comparison of microstructure states in the fusion zone

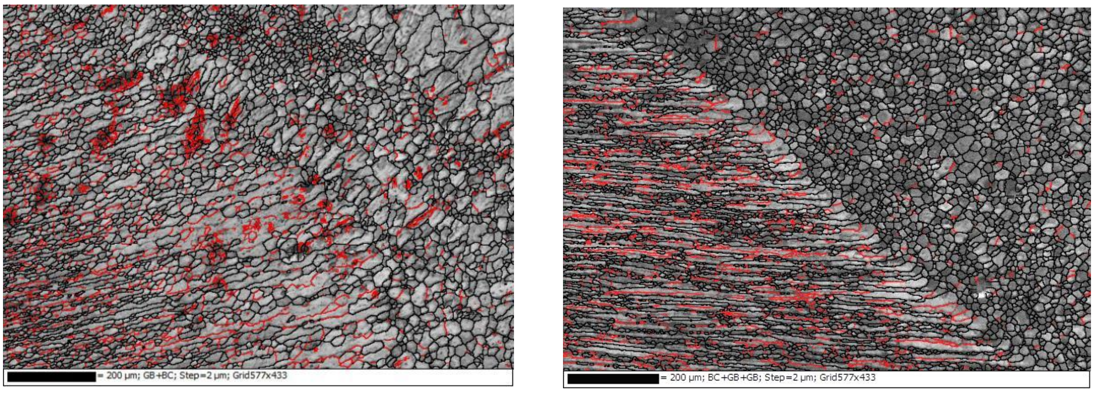
Notes: Blue - Recrystallized grains; Yellow: Substructure; and Red: deformed grains)

Table 7 Statistics of microstructures in the fusion zones

Joint position / Microstructure fraction	Root pass (Al-Cu)	Capping layer (Al-Cu)	Root pass (Al-Cu-Zr)	Capping layer (Al-Cu-Zr)
Recrystallized grains	27.4 %	25.5 %	56.5 %	39.1 %
Substructure	34.7 %	29.3 %	33.0 %	52.5 %
Deformed grains	37.9 %	45.2 %	10.5 %	8.4 %

Those results in Figure 3 and Table 7 indicate that a highly concentrated recrystallized zone appears on the fusion joint line while the percentage of the substructure microstructures is also high after the cover layer on the fusion base side for application of Al-Cu-Zr filler wire. Moreover, the grain morphologies are significantly different on the both sides of the joint fusion line; there are fine and small equiaxed crystals on the joint side while fiber microstructures remain in the base side. There is no any remarkable transition zone between the joint and based sides. All the above indicates that the percentage of the small angle grain boundaries made up of dislocations and sub-grains is significantly higher than that for the joint side of the fusion line to lead to a "discontinuity" phenomenon of mechanical properties due to sudden changes in microstructures and increase the slip blocking and stress concentration of external force based dislocations. The joints of tensile specimens Are easily cracking along their fusion lines and tend to expand to their joint sides. Their elongations shall be greatly affected although their tensile strength can remain about 350MPa.

As for application of Al-Cu filler wire, there are only a few fine crystal bands on the joint side of the fusion line and the stress level between the grains is low and they are relatively evenly distributed. The proportion of recrystallization is relatively small. The characteristics of welded microstructure and base are relatively close (Figure 4). After performance of a rational welding heat input and two thermal cycles, joints have higher tensile strength and elongation. In addition, the deformed grains with an originally higher percentage changed to the substructure on the base side of the fusion line due to effects of thermal cycles during welding (Table 2).



a. Application of Al-Cu filler wire   b. Application of Al-Cu-Zr filler wire

Figure 4 Comparison of the grain topographies on the both sides of the fusion line

2.3 Analysis of joint performances

Table 8 presents comparison of joint performances for application of the both categories of filler wire under the same welding process conditions. Under a certain welding condition, the microstructure characteristics due to composition of the filter material are related to those metallurgical factors such as the gradients, the gradient of the grain state change and transformation microstructures. As for application of Al-Cu filler wire, its tensile strength and elongation can be up to 67.5% and 90% of the corresponding parameters of the base, respectively. In contrast, its elongation can only be 53% of that of the base as for application of Al-Cu-Zr filler wire though it has the same tensile strength as that for application of Al-Cu filler wire. Besides, most of the tensile samples for application of Al-Cu filler wire are fractured in their heat affected zones while all tensile samples for application of Al-Cu-Zr filler wire are fractured on their fusion lines.

Table 8 Joint mechanical properties for application of the both categories of filler wire

Filler wire	Tensile strength R_m/MPa	Elongation A(%)
Al-Cu	364 (365,375,375,335,370)	6.3 (7.2,6.1,6.9,4.3,6.7)
Al-Cu-Zr	359 (349,380,349)	3.7 (3.0,5.0,3.0)
Base metal T6 (for reference)	539	7.0

Table 8 offers the further understanding of the interrelationship between those metallurgical factors such as the filter wire compositions and microstructures and the mechanical properties, whose primary expressions are as follows:

(1) The proportion of small-angle grain boundaries in the fusion zones of welded joints can be up to no less than 20% for application of Al-Cu filler wire; in particular, the proportion of small-angle grain boundaries in the bond coating microstructures can be up to 44.7%. As for single-sided two-layer welded joints, those adverse effects of the back joint grain-boundary weakness, coarse grains and so on on the mechanical properties can be eliminated. In the overall view of grain sizes, the average grain sizes and the standard deviation are about 18μm and 12μm regardless of bond coatings or cover layers, respectively; and the better microstructure continuity which come out from joints to their fusion zones as well their heat affected zones can effectively prevent any abrupt change in performance and ensure that a few joints of tensile samples are fractured in the softened zones of their base so that such joints shall have higher comprehensive mechanical properties.

(2) The recrystallization ratio in the joint fusion zones is about 26% and the recrystallized microstructures are dispersively distributed on the both sides of their fusion lines for application of Al-Cu filler wire. In contrast, the recrystallization ratio in the joint fusion zones can be 40-50% or above and the recrystallized microstructures can form a large amount of dislocation pile-ups for application of Al-Cu-Zr filler wire; moreover, the stress concentration occurs on the joint sides of the fusion lines; thus, the elongation falls.

(3) Changes from the original deformed grains on the base sides to the corresponding substructures are related to the dynamic recrystallization under the thermal stress during the solidification of joints; moreover, the recrystallized nuclei can further change into recrystallized grains during the plastic deformation of joints. This phenomenon is significant in the joint fusion zones and it is particularly remarkable on the base sides of the fusion lines in bond coatings for application of Al-Cu-Zr filler wire.

(4) The welding findings indicate that Al-Cu filler wire are more sensitive to thermal cracks at the arc striking or extinguishing zones; and such case is related to the lower contents of Zr, Ti and Ag but the higher contents of Fe and Mn.

3. Conclusions

Al-Cu and Al-Cu-Zr filler wires were utilized here to study of the adaptability of spray formed 2195-T6 Al-Li alloy under the TIG welding process conditions. The metallurgical mechanism and mechanical behaviors of their adaptability were discussed based on analysis of joint microstructures and crystallographic differences and comparison of mechanical properties. The following conclusions are obtained:

(1) During the multiple thermal cycles and their corresponding stress-strain processes for fusion of joints, compositions of filler wires dominate the grain sizes and distribution, microstructure states and corresponding evolutions of various regions of joints. As for evaluation of the weldability of any material, it shall be taken into account that the metallurgical and mechanical behaviors may be anisotropic due to application of various welding wires so that a basis can be formed to verify the adaptability of filter wires.

(2) A welded joint shall be regarded as a large gradient region formed by means of a series of continuous changes due to the thermal cycle of welding. Our EBSD microstructures and crystallographic characterization method help to obtain not only the quantitative statistical analysis and comparison of various zones of any joint but also the further understanding of the adaptability mechanism of filter wires and comprehensive control of the joint quality.

(3) As for the fusion joints of spray formed 2195 Al-Li alloy by Al-Cu filler wires, the statistics of characteristics such as the grain size and microstructures indicate a better adaptability for the base. Moreover, they were verified by means their mechanical property measurements.

(4) The thermal cracking resistance is superior for application of Al-Cu-Zr filler wire rather than Al-Cu filler wire; but the too small joint grain size and the higher percentage of recrystallized microstructures in the fusion zones result in the lower joint elongation. Further adjustment of contents of Zr, Ti and other elements in filler material shall be taken into account.

(5) In terms of welding process factors, the joint microstructures welding stress states are mainly improved from those aspects such as welding specifications, preheating, joint forms and welding sequences to suppress occurrence of welding cracks. The welding process parameters can directly affect not only the solidification imbalance and microstructure states but also the strain growth rate and cracking during the solidification process. The strict control of welding conditions and optimization of parameters need regulation and control of statistical characteristics of joint microstructures.

Declarations

- Availability of data and materials

  The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

- Competing interests

  The authors declare no conflicts of interest.

- Funding

  This research did not receive any financial support.

- Authors' contributions

  Conceptualization, Y.M.; methodology, G.W.; validation, Y.M.; formal analysis, Y.M.; investigation, G.W.; writing—original draft preparation, Y.M.; writing—review and editing, G.W.

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  Not applicable

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Figures

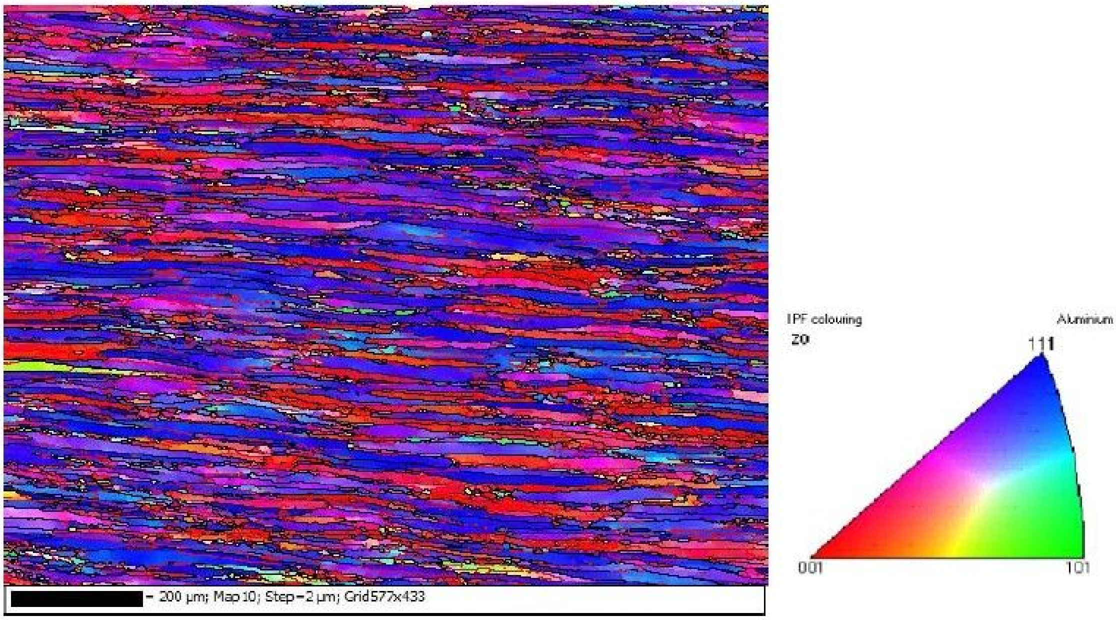
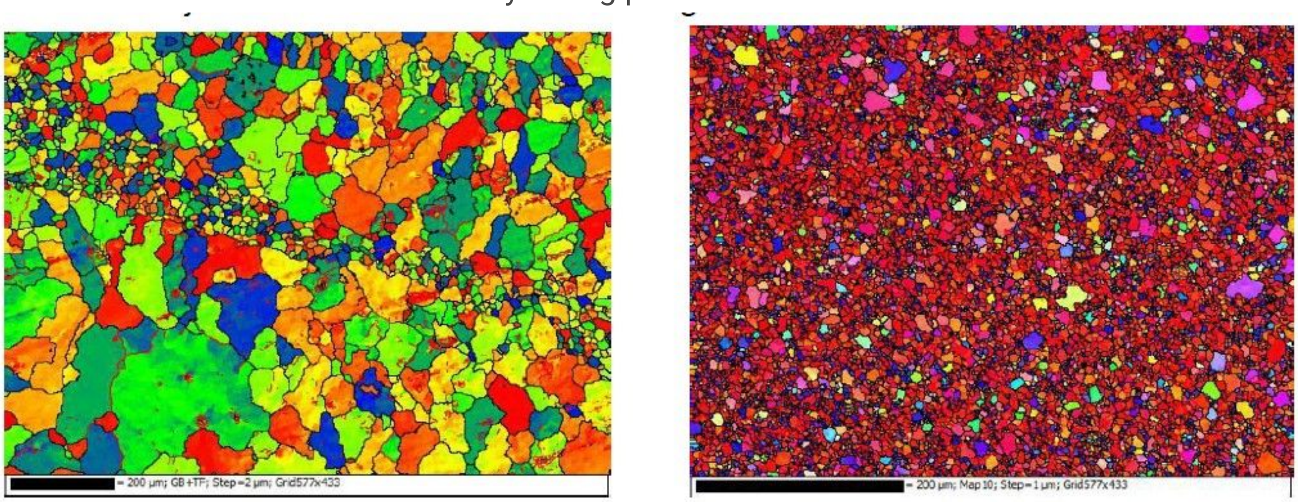


Figure 1 Grain orientation of S2195-T6 Al-Li alloy rolling plates

Figure 1

Grain orientation of S2195 T6 Al Li alloy rolling plates



a. Application of Al-Cu filler wire

b. Application of Al-Cu-Zr filler wire

Figure 2 Morphologies of joint microstructures

Figure 2

Morphologies of joint microstructures

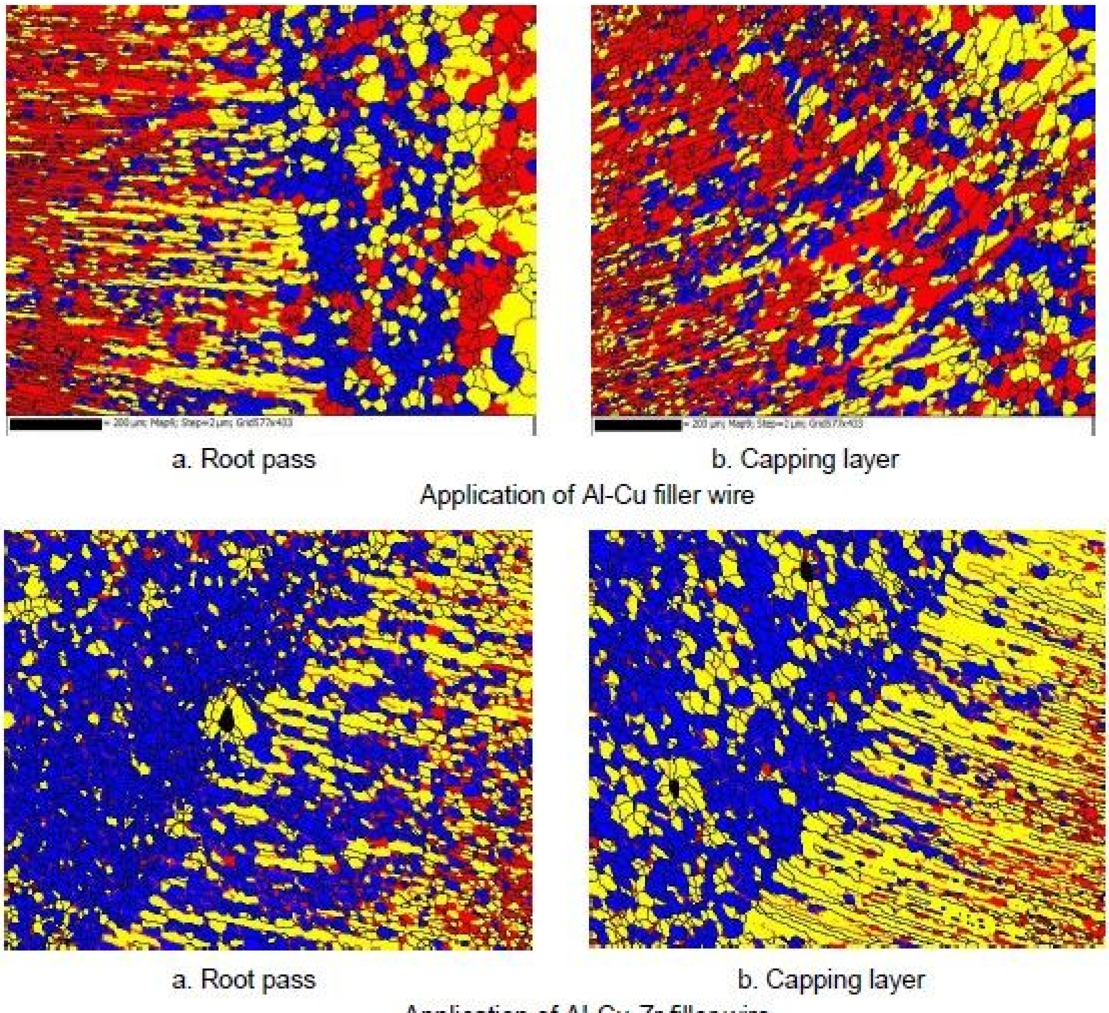


Figure 3 Comparison of microstructure states in the fusion zone
Notes: Blue - Recrystallized grains; Yellow: Substructure; and Red: deformed grains)

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Comparison of microstructure states in the fusion zone Notes: Blue Recrystallized grains; Yellow: Substructure; and Red: deformed grains)

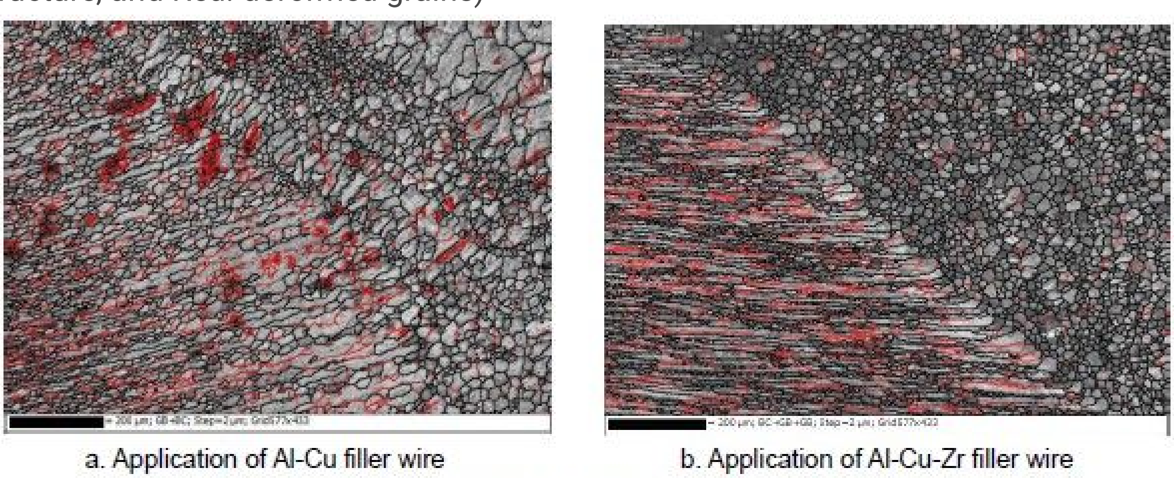

Figure 4 Comparison of the grain topographies on the both sides of the fusion line

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