Materials Research Express

PAPER

Effects of Sc on laser hot-wire welding performance of 7075 aluminum alloy

Shichun Li\(^1\), Wei Xu\(^1\), Gang Xiao\(^1,2,3,\ast\), Zhenhong Zhou\(^1\), Fei Su\(^1\) and Jianghua Feng\(^1\)

\(^1\) Hunan Provincial Key Laboratory of High Efficiency and Precision Machining of Difficult-to-Cut Material, Intelligent Manufacturing Institute of HNUST, Hunan University of Science and Technology, Xiangtan 411201, People’s Republic of China
\(^2\) Collaborative Innovation Center of Engineering Technology, Jiangxi University of Applied Science, Nanchang 330100, People’s Republic of China
\(^3\) CRRC Zhuzhou Institute Co., Ltd, Zhuzhou 412001, People’s Republic of China

\* Authors to whom any correspondence should be addressed.

E-mail: xg_hnu@163.com and li.shi.chun@163.com

Keywords: laser hot-wire welding, Sc element, metallographic structure, mechanical performance, weld pores

Abstract

In order to clarify the effects of Sc modification on laser hot-wire welding performance of 7075 high strength aluminum alloys, the changing rules of weld formation, microstructure, element loss, mechanical performances and pores of weld joints were investigated during laser fusion welding, laser hot-wire welding and Sc-modified laser hot-wire welding. Comparing with laser fusion welding, the filler wire in laser hot-wire welding brought welding material and hot wire energy, resulting in better weld formation and sufficient fused weld joint. In laser hot-wire welding, tensile strength and elongation of weld joint were enhanced, element loss of weld joint was dramatically reduced and weld pore was reduced slightly. However, grains in fusion zone were relatively coarse, which caused lower microhardness in laser hot-wire welding. In Sc modified laser hot-wire welding, Sc modification led to smooth and continuous weld joint. During solidification of weld joints, Sc could combine with base metal to form Sc-containing alloy phase, which could lead to the formation of refined and equiaxed grains, thereby enhancing the yield strength of microstructure and increasing the microhardness, tensile strength and elongation of weld joint. In addition, Sc modification could increase the fluidity of molten pool, which thus promoted the escape of bubbles from the molten pool and hindered the formation of weld pores.

1. Introduction

As a light alloy material with high strength and good plasticity, the 7075 high strength aluminum alloy is widely used in manufacturing of airplanes \([1, 2]\). However, the laser welding of aluminum alloy is exposed to the following welding problems \([3–9]\): (1) more heat input is required and the laser energy utilization is low during the laser welding of aluminum alloy due to the high thermal conductivity and reflectivity of aluminum alloy; (2) the weld deformations are readily observed since the coefficient of linear expansion of aluminum alloy is large; (3) the weld fusion zone tends to soften, and the softening phenomenon becomes more serious with the increase of energy input; (4) the elements of weld fusion zone can be lost easily, which will affect the formation of weld joint; (5) the weld formation is poor, and the defects (such as collapse, pores and cracks) are easy to generate, thus poor mechanical performance will be obtained. The utilization of wire in laser welding of aluminum alloy has greatly improved the welding quality. The main roles of welding wire include \([8, 9]\): (1) it provides necessary elements for weld joints, thereby enhancing welding performance and reducing weld joint defects such as cracks and weld softening; (2) it makes up for element loss and a full weld joint can be obtained; (3) it introduces nucleation particles to promote the refinement of microstructure of weld joint; (4) it reduces the requirement of assembly accuracy of the weld joint. However, in laser filler welding of aluminum alloy, because of the high heat conductivity and reflectivity of aluminum alloy base metal and wire, much higher laser energy is required for
welding to melt both welding wire and base metal. In addition, the input of much high laser energy may cause the unstable welding process and discontinuous wire filling process, which will leads to the generation of welding defects such as pores and discontinuous weld.

Laser hot-wire welding is a multi-heat source welding method, combining a laser heat source with a current heating welding wire [10–19]. The preheated welding wire can reduce the dependence of the welding wire on laser heat source and improve the utilization of laser energy [12]. Wen et al. [13, 17] studied the controllability of wire transfer behaviors in laser hot-wire welding. The transfer behaviors of welding wire could be controlled by preheating temperature. When the wire was fully preheated, the feeding stability and cladding efficiency could be improved and good welding quality could be obtained. Liu et al. [15] concluded that the relative position of welding wire and laser beam also had an impact on the stability of welding wire. Zheng et al. [18] observed the transition behavior of welding wire under different process parameters. The welding wire transition states could be divided into drop transition, fuse transition, continuous transition, and top wire transition. Sound weld was obtained when the welding wire was continuously fed and transferred. By precision control of the preheating temperature of welding wire, the transition stability of welding wire was controlled and then the welding quality was improved [15–18]. Nevertheless, few studies of laser hot-wire welding of aluminum alloys have been reported. Previously, we have investigated weld formations in laser hot-wire welding of 7075 aluminum alloy [19]. The results indicated that the laser power and current had a significant effect on the weld formation. As the temperature of welding wire increased, the weld formation quality became better and then deteriorates. Good weld formation could be obtained under the optimized process parameters, but the weld performance could be improved further.

In laser welding, by selecting suitable element of filling material, the fusion characteristics of filling material and base metal and the microstructure and performance of weld joint could be improved and the defects can be avoided [20–24]. Li et al. [22, 23] studied the effects of surface-active element sulfur on microstructure and properties of weld during laser welding of steel. The added active element not only affected the fluidity of molten metal but also had obvious influences on microhardness, metallographic phase and corrosion resistance. Braun [7] studied laser welding of Al–Mg–Si–Cu alloy filling Si-rich wire. The Si modification of welding wire not only improved the fluidity of the liquid metal and the filling ability of the welding wire, but also affected the formation of intermetallic compound of weld joint, thereby suppressing the pores, refining the grains, and improving welding performance [7, 20]. In the laser filler welding process, the Mg-containing welding wire could make up for the loss of Mg during welding and improve the mechanical performance of weld joint [20]. Cai et al. [9] studied the effect of Zr-containing wire on the microstructure and macrostructure of laser welding of 2524 aluminum alloy, and demonstrated that Zr could combine with Al to form Al3Zr phase, which played a heterogeneous nucleation during solidification. Croteau et al. [25] found that the heat cracks could be reduced during the selective laser melting of Zr modified aluminum alloy. Nie et al. [26] also demonstrated that the Zr element could disrupt the growth direction of dendritic grains and obtained a refined grains during selective laser melting of Zr modified Al-4.24Cu-1.97Mg-0.56Mn alloys. When the growth of dendritic grains was prevented, the formation of equiaxed grains could be promoted and the heat cracks could be reduced [9, 25–29]. For aluminum alloys, Sc modification and Zr modification had similar effects [30–33]. Liu et al. [30] compared the Sc and the Zr modified Al-6.2Mg alloy during selective laser melting and found that the mechanical performances of alloys under Sc modification might be even better than that under Zr modification. Yang et al. [28] added trace amount of Sc to an Al–Mg–Zr alloy during selective laser melting and found that the Al3Sc particles in remelting zone had promote the transformation of coarse columnar grain structure to refined columnar grains. Huang et al. [33] studied the effect of trace amount of Sc on weld joint of Al–Zn–Mg–Zr alloy during metal–inert gas (MIG) welding and demonstrated that Sc modification could significantly refine metallographic structures and improve mechanical performances of weld joint. However, few studies of laser hot-wire welding of 7075 high strength aluminum alloys with Sc modification have been reported.

In order to improve the weld properties and restrain the weld defects, a small amount of Sc powder was added in the laser hot-wire welding of 7075 high strength aluminum alloy (which contains no Sc element). The welding qualities were compared in laser fusion welding, laser hot-wire welding, and Sc-modified laser hot-wire welding of 7075 high strength aluminum alloy. The weld formation, microstructure structure, elemental composition, mechanical performance, pores distribution were analyzed to reveal the influences of Sc on welding performance. The results could provide guidance for the achievement of excellent welding performance of 7075 aluminum alloys.

2. Experimental apparatuses and procedures

The laser used in the welding is the YLS–4000–CL fiber laser with a rated output of 400–4200 W and a laser wavelength of 1070 nm. The measured diameter of the focused spot containing 86.8% energy is 0.48 mm. A hot
wire-enabled feeder (TPS2700 by Fronius) was used during laser hot-wire welding. To heat the welding wire, the power positive electrode was in contact with the welding wire through the feeding head, and the negative electrode was in contact with the base metal. The temperature of welding wire was adjusted by adjusting current of feeder. The vertical distance of feeding nozzle from the workpiece was 10 mm, the horizontal distance from the contact point of welding wire and base metal to the feeding nozzle was about 20 mm, and the feeding angle was $30^\circ$. In the experiment, the welding wire was kept in contact with the base metal surface. The ABB IRB2400 six-axis robot is used to realize the synchronous control of the laser and the feeder during welding process.

During welding, the base metal upper surface and the lower surface are protected by Ar shielding gas with flow rate of 15 l min$^{-1}$. The front blowing angle on upper surface was $45^\circ$. To shield the lower surface, the Ar gas is blown into the welding groove below the plate. The laser hot-wire welding test arrangement is shown in figure 1. During Sc-modified laser hot-wire welding, the Sc powder is pre-filled in the gap of butt joint as shown in figure 1.

The base metal was 7075 aluminum alloy plate (size: 1.5 mm $\times$ 40 mm $\times$ 100 mm). The welding wire was 7075 aluminum alloy with diameter of 1.2 mm. The Sc powder was 200 meshes with 99.8 wt.%. Tables 1 and 2 summarize the chemical compositions of base metal, welding wire and Sc powder.

Before welding, surfaces and sides of base metal were sanded and wiped to remove oxides, oil and impurities. The parameters in laser fusion welding were as follows: laser power $= 1400$ W, welding speed $= 8$ mm s$^{-1}$, defocusing distance $= +8$ mm, gap width $= 0$ mm, gas flow rate $= 15$ l min$^{-1}$. The parameters in laser hot-wire welding and Sc-modified laser hot-wire welding were as follows: laser power $= 1400$ W, welding speed $= 8$ mm s$^{-1}$, defocusing distance $= +8$ mm, gap width $= 0.1$ mm, current $= 90$ A, feeding rate $= 0.6$ m min$^{-1}$, feeding angle $= 30^\circ$, gas flow rate $= 15$ l min$^{-1}$.

After welding, weld formations were observed and compared for laser fusion welding, laser hot-wire welding, and Sc-modified laser hot-wire welding. Then, the cross sections of weld joints and the samples for stretching were cut. The stretched sample is shown in figure 2. The cross section of weld joint was ground with abrasive paper and then polished with a diamond polishing agent with a particle size of 2.5 $\mu$m. Then, the cross section was etched by using a concentrated solution of 40% hydrofluoric acid, 38% concentrated hydrochloric acid, 68% hydrochloric acid, and distilled water at a volume ratio of 2: 1: 1:40. The digital optical microscope was used to observe the cross section morphology and metallographic structures of weld joints. The elemental compositions of weld fusion zones were tested by energy spectrum analyzer (EDS). The microhardness of weld joints was tested by using the HVS-1000 Vickers hardness meter and the tensile strength was tested by using the RG4100 electronic universal testing machine. Scanning electron microscopy (SEM) was used to observe the micromorphology of fractures. The digital optical microscope was used to observe the macroscopic morphology of fractures.

### Table 1. Chemical compositions of base metal and welding wires (wt.%).

|         | Si  | Fe  | Cu  | Mn  | Mg  | Zn  | Cr  | Ti  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Base metal | 0.40 | 0.50 | 1.50 | 0.25 | 2.50 | 5.80 | 0.26 | 0.20 | Bal. |
| Welding wire | 0.30 | 0.50 | 1.50 | 0.25 | 2.50 | 5.50 | 0.20 | 0.20 | Bal. |

### Table 2. Chemical composition of Sc powder (wt.%).

| Si       | Fe       | Cu       | Mn       | Mg       | Zn       | Ca       | W        | Ni       | Ta       | Sc       |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 0.0141   | 0.0650   | 0.0209   | 0.0002   | 0.0077   | 0.0097   | 0.0006   | 0.054    | 0.0191   | 0.0095   | Bal.     |
3. Results and discussion

3.1. Formation of weld joint

Figure 3 illustrates surface and cross section morphology of weld joints in laser fusion welding, laser hot-wire welding and Sc-modified laser hot-wire welding. The cross section of weld joint in laser fusion welding is ‘V’-shaped with an insufficient fusion of bottom, and the weld reinforcement does not appear on the upper surface of weld joint. It can be seen that there was a loss of material during laser fusion welding. The cross section morphology of weld joints in laser hot-wire welding and Sc-modified laser hot-wire welding are both ‘I’-shaped with a sufficient fusion of bottom, and the weld reinforcement appears on the upper and lower surface of weld joints. Compared with laser fusion welding, in the laser hot-wire welding and Sc-modified laser hot-wire welding, the filled wire brought the resistance heat which promoted the penetration and full fusion of weld joint, also the filled wire supplemented the lost material of the weld joint. In addition, the applied current in the welding process have a stirring effect on the welding pool, so as to improve the stability of the welding pool and increase the depth of weld [34, 35]. Compared with laser hot-wire welding, surface formation of weld joint was improved and the fish scales of the upper surface were uniform and continuous in Sc-modified laser hot-wire welding.

3.2. Microstructure of weld joint

Figure 4 shows the metallographic structure of base metal. As observed, the base metal exhibits rolling grain morphology. The grains are distributed in a fiber-like structure along the rolling direction and there are a large number of granular secondary phases with a uniform distribution, as marked in figure 4. These granular secondary phases mainly play a role in strengthening the microstructure and ensuring high strength of base metal. Figures 5–7 illustrate the metallographic structures of weld joints in laser fusion welding, laser hot-wire welding, and Sc-modified laser hot-wire welding, respectively. Dendritic grains and equiaxed grains are observed in the fusion zones obtained by the three welding methods, which indicates a cast metallographic morphology and are finer than that of base metal, as marked in figures 5–7. The dendritic grains grew along the temperature gradient during the rapid cooling process of weld joint. The temperature gradient near the center of
the weld joint was smaller than that near the boundary. The molten metal at the center of the weld joint might be super cooled, thus the crystal nucleus was formed in the molten metal and the nucleation grew to form equiaxed grains.

Figure 4. Metallographic structures of base metal.

Figure 5. Metallographic structures of weld joint in laser fusion welding (a) heat affected zone; (b) fusion zone.

Figure 6. Metallographic structures of weld joint in laser hot-wire welding (a) heat affected zone; (b) fusion zone.
Dendritic and equiaxed grains are mixed in fusion zone in laser fusion welding, dendritic grains are dominant in fusion zone in laser hot-wire welding, and equiaxed grains are dominant in fusion zone in Sc-modified laser hot-wire welding. By contrast, the fusion zone grains in laser hot-wire welding are relatively thick, while those in laser fusion welding and Sc-modified laser hot-wire welding are similar in size. This is because the heat input in laser fusion welding was relatively small and the cooling rate was faster, therefore the crystal nucleus grew into thin grains with a mixed crystal. Compared with laser fusion welding, the heat input and the cooling time for weld pool increased in laser hot-wire welding. Thus, crystal nucleus grew along the temperature gradient to form thicker dendritic grains, while equiaxed grains appeared near the center of weld joint. During Sc-modified laser hot-wire welding, Sc precipitated during the cooling of weld joint and combined with aluminum to form the Al3Sc phase [30–33], which attached to the grain boundary and hindered grain growth, resulting in refined equiaxed grains.

In all the three cases, grains in the heat affected zones of weld joints are columnar. Compared with grains of base metal, grains in heat affected zones are coarser. This is because that the temperature at heat affected zone was above the recrystallization temperature of original grains, which promoted the original grain to form coarse grain structure. The width of heat affected zone in laser fusion welding is about 0.6 mm, and is about 1.0 mm both in laser hot-wire welding and Sc-modified laser hot-wire welding (data can be seen below section). In conclusion, the input of hot wire increased the width of heat affected zone during welding process.

Elemental scanning analysis was performed on the fusion zone in the three welding modes by using an energy spectrum analyzer. Six different zones in the fusion zone for each weld joint were analyzed. Then, the average value of the detected data was obtained. The final results of elemental compositions are shown in table 3.

Compared to those in base metal, the contents of Mg and Zn in fusion zones decreased in all weld joints. It was indicating severe element loss of Mg and Zn in laser fusion welding. Although there were some Mg and Zn lost in laser hot-wire welding and Sc-modified laser hot-wire welding, the filled wire could compensate for the reduction of element. The Sc content of weld joint in Sc-modified laser hot-wire welding was 0.4 wt.%, indicating that trace Sc could significantly improve the quality and enhance the mechanical performance of weld joint (see below for details).

![Figure 7. Metallographic structures of weld joint in Sc-modified laser hot-wire welding (a) heat affected zone; (b) fusion zone.](image-url)

### Table 3. Results of energy spectrum analysis (wt.%).

| Element | Laser fusion welding | Laser hot-wire welding | Sc-modified laser hot-wire welding | Base metal |
|---------|----------------------|------------------------|-----------------------------------|------------|
| Al      | 90.34                | 89.32                  | 88.78                             | 88.59      |
| Mg      | 1.88                 | 2.32                   | 2.42                              | 2.50       |
| Zn      | 4.52                 | 5.36                   | 5.40                              | 5.80       |
| Cu      | 1.62                 | 1.55                   | 1.52                              | 1.50       |
| Si      | 0.32                 | 0.36                   | 0.33                              | 0.40       |
| Ti      | 0.16                 | 0.14                   | 0.13                              | 0.20       |
| Cr      | 0.22                 | 0.22                   | 0.20                              | 0.26       |
| Mn      | 0.24                 | 0.20                   | 0.22                              | 0.25       |
| Fe      | 0.70                 | 0.53                   | 0.60                              | 0.50       |
| Sc      | No                   | No                     | 0.40                              | No         |
3.3. Microhardness of weld joint

Figure 8 shows the results of the microhardness of weld joints in the three welding modes. The softening of weld fusion zone is observed in the three kinds of weld joints. The base metal has the highest hardness and the average hardness is 182 HV0.05. The hardness of heat affected zone shows a decreasing trend from the area closing to the base metal to the fusion zone. The fusion zone has the lowest hardness. The metallographic morphology analysis shows that the fusion zone indicated the as-cast metallographic morphology and the microstructure was expanded. Therefore the hardness is lowest. The metallographic structure of base metal is rolled and compacted, densely organized and has enhanced mechanical performance. Thus, it has highest hardness. Although the grain size of the weld fusion zone was smaller than that of base metal, which had a strengthening effect to the weld fusion zone, but it still cannot make up for the low hardness of the as-cast structure.

The test results show that the average hardness of the fusion zone in laser fusion welding is 124 HV0.05, while that in laser hot-wire welding is 107 HV0.05, and that in Sc-modified laser hot-wire welding is 116 HV0.05. During laser fusion welding, the fine grains and the rapid cooling process promoted the hardening tendency of fusion zone. Therefore, the hardness was highest among the three kinds of weld joints. In laser hot-wire welding, the grain size of fusion zone was relatively larger, thus the hardness of fusion zone was decreased. In Sc-modified laser hot-wire welding, Sc promoted the growth of finer grains of fusion zone, which strengthened the weld joint structure. Therefore, the hardness of fusion zone is higher than that in laser hot-wire welding.

3.4. Tensile strength of weld joint

Table 4 summarizes tensile strengths of the base metal and the three kinds of weld joints. The tensile strength of base metal is 321 MPa, and the fracture is at the middle of the test specimen. The tensile test specimens of the three kinds of weld joints are all broken at the fusion zone. The tensile strength of weld joint in laser fusion welding is 160 MPa (about 49.8% of base metal), while that in laser hot-wire welding is 206 MPa (about 64.2% of base metal), and that in Sc-modified laser hot-wire welding is 223 MPa (about 69.5% of base metal). The elongation of base metal is the largest and is much larger than the elongations of all the three weld joints. The elongation of weld joint in laser fusion welding is the smallest, which is about 1/4 of base metal. The elongation of weld joint in laser hot-wire welding is about 1/3 of base metal. Sc-modified weld joint has larger elongation than the other two weld joints.

As discussed above, in laser fusion welding, the fusion of the weld bottom was insufficient, which could decrease the strength of weld joint. More importantly, Mg and Zn elements, which are the key strengthening elements of 7075 high strength aluminum alloy, were severely lost in the laser fusion welding. As a result, the tensile strength of weld joint in laser fusion welding was greatly reduced. During laser hot-wire welding, the lost element of weld joint was very small and the weld formation was good, so the weld joint with higher tensile strength was obtained. Compared to laser hot-wire welding, the tensile strength of weld joint in Sc-modified laser hot-wire welding was further improved. The reason is that the Sc-modified weld joint had refined grains and the solid phase Al3Sc could be formed at grain boundary [30–33]. These two aspects were both beneficial for
enhancing the strength of weld joint. Therefore, much higher tensile strength of Sc-modified weld joint was obtained.

Figure 9 shows the micromorphologies of the fractures observed by SEM. The fracture of base metal has larger dimples, deeper dimple depth and tearing edges around the dimples. It can be deduced that the base metal presents ductile fracture morphology. Furthermore, broken particles can be observed in the dimples in fracture of base metal. The broken particles are the granular secondary phases observed in the metallographic image of base metal, which acts to increase the base metal strength. In all three kinds of weld joints, the dimples and tearing edges were observed in the fractures, which indicates that the three kinds of weld joints are mainly ductile fracture morphology. In contrast, the dimple depths in fractures of the three weld joints are smaller than that of base metal, which indicates that the elongations of the three weld joints are less than that of base metal.

The dimples in fracture of weld joint in laser fusion welding are uneven in size. Partial dimples are large and have a certain depth; partial dimples are very fine and very shallow. These indicate that the weld joint undergone a limited plastic deformation before fracturing. Therefore, the smallest elongation of weld joint in laser fusion welding was obtained. The reason is that the microstructure of weld joint in laser fusion welding had a high microhardness and high quench hardening tendency, therefore the plasticity decreased.

The dimples in fracture of weld joint in laser hot-wire welding have a uniform size, a certain depth and clear tearing edges. These demonstrate that the fracture occurred after adequate plastic deformation. Compared to laser fusion welding, the microstructure of weld joint in laser hot-wire welding had a low microhardness and low quench hardening tendency, thus the plasticity and the elongation were increased.

Compared to laser hot-wire welding, the dimples in fracture of weld joint in Sc-modified laser hot-wire welding are slightly dense, and the depth of dimple is deeper and uniform. These imply that the weld joint has a larger plastic deformation and larger elongation than the other two weld joints. This can be attributed to the fact that the refined grains of Sc-modified weld joint and the Sc-containing alloy phase (Al3Sc) precipitated at the grain boundary enhanced the difficulty of crystal slippage and improved the yield limit. The larger yield limit allowed the weld joint to produce a greater plastic deformation in the stretching process.
3.5. Porosity of weld joint

Figure 10 shows the macromorphologies of the fractures of the three kinds of weld joints. The pores appear near the bottom of all the three weld joints. The main reasons for pore generation are as follows: (1) the pores produce by the gas in the environment which is mixed into the molten pool; (2) the pores produce by the collapse of welding keyhole; (3) when the impurities containing hydrogen on the aluminum alloy surface are inhaled by the molten pool, the hydrogen will precipitate to form hydrogen pores during cooling process. Pores appearing in the weld joints may be attributed to the first two factors above, and the small pores produce by the first factor, while the large pores produce by the second factor. In addition, there are two reasons to cause the pores only generated near the bottom. First, the upper part of molten pool absorbed more heat during the welding process, resulting in a slow solidification speed of molten pool. Therefore, the bubbles were easier to escape from the upper part of molten pool. Secondly, in the form of butt welding, the bottom of molten pool was more likely to mix into the environment gas to form pores.

Among the three weld joints, the weld joint of laser fusion welding has the largest number of pores in different sizes. This can be attributed to the high cooling rate of weld joint in laser fusion welding, which caused more bubbles to be constrained thereby forming pores. The number of pores in the weld joint of laser hot-wire welding is reduced, and the pores are mainly large-sized pores. These are because that the higher energy input, the slower cooling rate and the stirring effect of electric field on molten pool in laser hot-wire welding promoted the escape of bubbles. Compared with the former two, the number of pores in the weld joint of Sc-modified laser hot-wire welding is greatly reduced. This suggests that Sc modification might make the fluidity of molten pool increased and further promote the escape of bubbles from molten pool on the basis of laser hot-wire welding.

4. Conclusions

In this paper, weld formation, microstructure, element loss, mechanical performance and pores have been studied during laser fusion welding, laser hot-wire welding and Sc-modified laser hot-wire welding. The following conclusions have been drawn:

(1) Compared to laser fusion welding, the hot wire in laser hot-wire welding supplemented the material and brought energy for weld joint, which improved the weld formation and promoted the sufficient fusion of weld joint. Sc modification further increased the quality of weld formation in Sc modified laser hot-wire welding process.

(2) The weld fusion zones obtained in laser fusion welding, laser hot-wire welding, and Sc-modified laser hot-wire welding were mainly the as-cast metallographic structures. The heat affected zone was columnar grains. The weld fusion zones in laser hot-wire welding and Sc-modified laser hot-wire welding had a similar small grain size. The weld fusion zone in laser hot-wire welding has a relatively larger grain size than the two above. The width of heat affected zone was the smallest and the losses of Mg and Zn were the largest in laser fusion welding. Sc modification could further refine the weld joint grains and promote the generation of equiaxed grains.

(3) The tensile strength, elongation and microhardness of the three kinds of weld joints were both smaller than that of base metal. The microhardness of weld joint in laser fusion welding was the highest but the tensile
strength and elongation were the lowest among the three kinds of weld joints. Sc modification could further improve the microhardness, tensile strength and elongation of weld joint, since the Sc modification had refined the grains and promoted the generation of Sc-containing alloy phase, which were both benefited to the strengthen of weld joint. The tensile strength of Sc modified weld joint reached 69.5% of base metal.

(4) In laser fusion welding, a large number of pores were observed near the bottom of weld joint. In laser hot-wire welding, the pores near the bottom of weld joint were reduced slightly due to the higher energy input, slower cooling rate and the stirring effect of electric field on molten pool. While, Sc modification have significantly reduced the internal pores, which implied that Sc modification might increase the fluidity of molten pool and further promote the escape of bubbles.

Acknowledgments

This research was supported by the Natural Science Foundation of Hunan Province of China (No. 2018JJ3178), the National Natural Science Foundation of China (No. 51505145 and 52075159), the China Postdoctoral Science Foundation (No. 2019M652755), and the Open Foundation of Guangxi Key Laboratory of Processing for Non-ferrous Metals and Featured Materials, Guangxi University (No. 2020GXYSOF16).

ORCID iDs

Shichun Li https://orcid.org/0000-0002-2728-2568

References

[1] Vijaya Kumar P et al 2015 Microstructure, mechanical and corrosion behavior of high strength AA7075 aluminium alloy friction stir welds-effect of post weld heat treatment Defence Technology 11 362–9
[2] Liu B et al 2010 Recent development and prospects for giant plane aluminum alloys The Chinese Journal of Nonferrous Metals 20 1705–15
[3] Yang X et al 2019 Microstructure and stress distribution of narrow-gap rotating laser welding thick Al–Mg alloy joint J. Laser Appl. 31 022002
[4] Zhang M et al 2020 Understanding root humping in high-power laser welding of stainless steels: a combination approach Int. J. Adv. Manuf. Tech. 106 5353–64
[5] Xiao R et al 2014 Problems and issues in laser beam welding of aluminum–lithium alloys J. Manuf. Process 16 166–75
[6] Yang B et al 2019 Microstructure and fracture toughness properties of CMT repairing welded 7075–T651 Mg welding joint Mater. Res. Express 6 126506
[7] Liu J et al 2019 Effect of graphene on corrosion resistance of micro-arc oxidation coatings on 6061/7075 dissimilar laser–Mg hybrid welded joint Mater. Res. Express 6 066521
[8] Li J et al 2017 Effect of Filler Wire on Laser Welding Process Laser & Optoelectronics Progress 54 48–58
[9] Cai H et al 2014 Process and microstructure properties of laser beam welding of thin 2524 aluminum alloy sheet with filler wire Transactions of the China Welding Institution 35 24–8
[10] Näsström J et al 2018 Arc formation in narrow gap hot wire laser welding Weld J 97 171–8
[11] Näsström J et al 2015 Hot-wire laser welding of deep and wide gaps Phys. Proc. 78 247–54
[12] Kadoki K et al 2011 Development of high–efficiency/high–quality hot-wire laser fillet welding process Quarterly Journal of the Japan Welding Society 29 62–5
[13] Wen P et al 2016 Control of wire transfer behaviors in hot wire laser welding Int. J. Adv. Manuf. Tech. 83 2091–100
[14] Ohnishi T et al 2013 Butt welding of thick, high strength steel plate with a high power laser and hot wire to improve tolerance to gap variance and control weld metal oxygen content Sci. Technol. Weld. Jai 18 314–22
[15] Liu W et al 2015 Experimental and numerical investigation of laser hot wire welding Int. J. Adv. Manuf. Tech. 78 1485–99
[16] Zhang Y et al 2013 Research on gap margin in laser butt welding of high-strength automobile steel with hot wire filler Chin. J. Lasers 40 100–6
[17] Wen P et al 2011 Experimental research on laser narrow gap welding with filling hot wire Chin. J. Lasers 38 104–9
[18] Zheng S et al 2014 Research on wire transfer and its stability in laser hot wire welding process Chin. J. Lasers 41 109–16
[19] Li J et al 2018 Weld formation in laser hot-wire welding of 7075 aluminium alloy Metals 8 909
[20] Qu Y et al 2011 Research on high speed high power CO2 laser welding of 6061-T6 aluminium with filler wire Chin. J. Lasers 38 85–90
[21] Zhao Z et al 2013 Effect of Sc, Zr, Er in ER5356 welding wire on mechanical properties of welded joint of 7A52 aluminum alloy Chinese Journal of Materials Research 27 287–91
[22] Li J et al 2017 Microstructure and properties of weld joint during 10 kW laser welding with surface-active element sulfur Appl. Surf. Sci. 426 704–13
[23] Li J et al 2018 Effects of active sulfur powder on weld formation during high power laser welding Transactions of The China Welding Institution 39 65–70
[24] Li J et al 2018 Influence of CO2 shielding gas on high power fiber laser welding performance Metals 8 449
[25] Croteau J R et al 2018 Microstructure and mechanical properties of Al–Mg–Zr alloys processed by selective laser melting Acta Mater. 153 35–44
[26] Nie X et al 2018 Effect of Zr content on formability, microstructure and mechanical properties of selective laser melted Zr modified Al-4.24Cu-1.97Mg-0.56Mn alloys J. Alloy. Compd. 764 977–86
[27] Rogal I et al 2013 Characterization of semi-solid processing of aluminum alloy 7075 with Sc and Zr additions Mat. Sci. Eng. A-Struct. 580 362–73
[28] Yang K V et al 2018 Columnar to equiaxed transition in Al–Mg–(Sc)–Zr alloys produced by selective laser melting Scripta. Mater 145 113–7
[29] Zeng Y et al 2016 Effects of ZrB2 on substructure and wear properties of laser melted in situ ZrB2p/6061Al composites Appl. Surf. Sci. 365 1–9
[30] Li R et al 2017 Selective laser melting of a novel Sc and Zr modified Al-6.2Mg alloy: processing, microstructure, and properties Powder Technol. 319 117–28
[31] Spierings A B et al 2017 Microstructural features of Sc– and Zr–modified Al–Mg alloys processed by selective laser melting Mater. Design 115 52–63
[32] Tzeng Y C et al 2018 Effects of trace amounts of Zr and Sc on the recrystallization behavior and mechanical properties of Al–4.5Zn–1.6Mg alloys Mater. Lett. 228 270–2
[33] Huang X et al 2015 Effect of minor Sc on microstructure and mechanical properties of Al–Zn–Mg–Zr alloy metal–inert gas welds J. Alloy. Compd 629 197–207
[34] Xiao R S et al 2006 CO2 laser beam welding of aluminum alloy with additional current via filler wire Transactions of the China Welding Institution 27 9–12
[35] Xiao R S et al 2001 New approach to improve the laser welding process of aluminum by using an external electrical current J. Mater. Sci. Lett. 20 2163–5