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Mechanical Properties of Laser Welded Joint of Copper and Steel Dissimilar Metals

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Abstract: In this research project, copper and stainless steel were connected by two laser welding methods: straight seam welding and swing welding. Then, electronic tensile test machine, X-ray diffractometer, scanning electron microscope and metallographic microscope were used to analyze the tensile properties, macroscopic and microscopic structure morphology and phase of the welded joint. Based on the experimental results, we determined that the strength of the straight seam welded joint was higher. Because of the intermetallic compound near the weld in the swing welding process, it leads to stress concentration, crack cracking and strength reduction. In addition, the oscillating laser beam also leads to the disorderly direction of columnar crystal and coarse structure, which makes the joint strength decrease.

Key words: copper steel dissimilar alloy; laser welding; mechanical properties

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0 Introduction

Because dissimilar material welding combines the benefits of two different materials and has its own advantages, composite materials made of copper and steel that are dissimilar metals are utilized frequently in daily life. It is challenging to weld these different materials together due to the material mismatches between copper and carbon steel, which include chemical and thermomechanical characteristics[1]. Therefore, it is very important to choose the right welding mode to obtain the ideal welding joint[2].

Laser welding[3,4] is generally considered to be superior to conventional welding methods for joining dissimi-

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lar metals[5]. The heat source of laser welding is the laser beam with high energy density. Its energy input is small and energy density is high, so the welding process is precise and the welding effect is better. Laser beam swing welding is a new welding technology which uses the beam of uniform spiral forward, so that the laser beam in the welding process on both sides of the base material area of the uniform melting expands to the laser action area, and because of the repeated action of multiple spots, the point of heat input is further increased. Therefore, it may lead to the coarsening of the microstructure and disordered direction of the welded joint, and correspondingly lead to the reduction of its mechanical properties. Laser beam straight seam welding is the laser beam walking smoothly, welding stability and reliability. At present, most of the literatures only analyze the laser welding of a single method, and do not compare the welding of metals with the same material in different ways.

In this paper, two laser welding methods of straight seam welding and swing welding are used to weld T2 red copper and 316L stainless steel. After the mechanical properties test, metallographic microstructure observation, X-ray diffractometer (XRD) test and electron microscope scanning (SEM) of the welded samples, the macroscopic microstructure, fracture morphology and phase of the welded joints were analyzed, and then the influence mechanism of the joint properties was speculated. By comparing the joint properties of two different laser welding methods, the mechanical properties of the joint can be seen more directly, and the mechanism that affects the joint properties can also be analyzed.

1 Experimental

1.1 Materials and Experimental Parameter

The materials used in this study are 100 mm×50 mm×2 mm copper plate and 316L stainless steel plate, whose specific parameters are shown in Tables 1 and 2.

Table 1 Main chemical constituents of T2 copper % (wt.)

Cu+Ag	Sn	Fe	Pb	Sb	Bi	S	O
⩾99.9	⩽0.002	⩽0.005	⩽0.005	⩽0.002	⩽0.001	⩽0.005	⩽0.06

Table 2 Main chemical constituents of 316L stainless steel % (wt.)

Fe	Cr	Ni	Mo	C	S
69.0	16.0-18.0	10.0-14.0	2.0-3.0	0.03	⩽0.03

The physical properties of the two materials are shown in Table 3.

Table 4 displays two samples of the laser welding process-specific parameters for 316L and bronze 2 mm plate butt welding.

Table 3 Basic physical properties of base metal

Material	Melting point /℃	Density /g·cm^{-3}	Thermal expansivity/10^{-6}·K^{-1}	Thermal conductivity /W·m^{-1}·K^{-1}
T2	1 084	8.90	17.64	352
316L	1398	7.98	16.0	166

Table 4 Laser welding process parameters

Sample	Power/ kW	Speed /m·min^{-1}	Swinging form	Amplitude/mm	Frequency/Hz	Declination	Spot allocation
d-01	4	3	—	—	—	Partial steel 10°	1:1
d-02Cu	4	3	0 clockwise	0.5	250	Partial steel 10°	1:1

1.2 Text Method

1.2.1 Laser welding

Prior to laser welding, a series of mechanical and chemical cleaning methods are usually required to remove the oxide film and contaminants on the substrate surface.

The YLS-30000 Yb fiber laser is used in this paper. The main parameters of the laser are as follows: defocus 0 mm, argon 1.2 m^3/h, spot diameter 2 mm (0 defocus position).

Heat and mass transfer can be controlled by adjusting the beam oscillation mode during welding. A high power fiber laser was used to weld copper and steel dissimilar metals through three variables: oscillation mode, amplitude and oscillation frequency. The swing welding head is mounted on an industrial robot (ABB) which drives the welding head to the clamped sample at a given welding speed. Pure argon with a flow rate of 1.2 m^3/h is transported to the weld through copper pipes as a protective gas. Finally we get the sample. The laser welding is shown in Fig. 1.

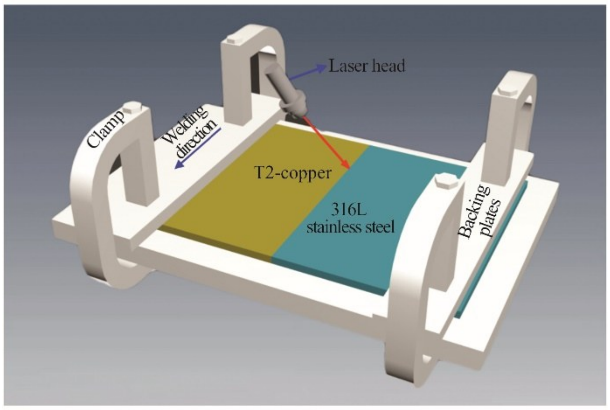

Fig. 1 Illustration of laser welding configuration

1.2.2 Mechanics performance testing

The tensile properties of the samples were tested by using a tensile test prototype. Proper mounting of the specimen requires the selection of a suitable fixture. The specimen clamping should not be subject to tension or compression, otherwise it will affect the test results. The mechanical properties of welded joints were evaluated by tensile test, and the microstructure evolution mechanism affecting the joint properties was analyzed.

1.2.3 Metallographic microstructure observation

Metallography first evaluates the macroscopic and microscopic structural characteristics of the weld. The sample after laser welding is cooled in air, cut to appropriate size by machine tool, and then cut out from the laser welding joint by wire cutter. Tiny samples with only welds are taken and inlaid using a metallographic sample inlay machine. Because the sample is too small to be handheld, white corundum powder is used for inlaying, and the inlaying temperature is 135 ℃.

The inlaid sample is roughed. In the process of rough grinding, attention should be paid to opening the water valve and cooling with water to prevent overheating of the sample and change the organization.

After grinding 1 200#, the sample was polished on a polishing machine to achieve mirror effect, and then cleaned with alcohol and observed under a metallographic microscope. After that, the corrosion was carried out and washed by 4% nitric acid alcohol, the hair dryer was blown dry, and the corrosion was observed under a metallographic microscope.

Metallographic microscope can be used to clearly see the shape, size, alignment direction and weld width of the grain near the weld, compare the differences between the two welding methods, and analyze the impact of the differences on the mechanical properties of the weld.

1.2.4 XRD analysis

The samples were analyzed by XRD in Shimadzu, Japan. The result was analyzed by JADE and Origin and compared with the standard PDF card to determine the phase. The phase type was determined according to the Angle between the crystal cell parameter ABC and the crystal cell, and the influence of the relative mechanical properties of the material was analyzed.

1.2.5 SEM analysis

The fracture and microstructure were observed by SEM (FEI-Sirion 200). The fracture morphology of the two samples was compared to analyze the size and depth of the dimple, so as to compare and judge the toughness and strength of the samples with two welding methods.

2 Results and Discussion

2.1 Mechanics Performance Testing

In order to study the influence of laser welding mode on joint performance, a series of comparative tests were carried out on the specimens under two welding conditions: straight seam welding and swing welding. According to GB/T 228.1-2010, all samples for tensile test were prepared by wire cutting and stretched at a stretching rate of 1.0 mm/min. The experimental results are shown in Fig. 2. It can be observed from Fig. 2 that both samples passed through a peak value at the maximum tensile stress before the occurrence of tensile failure. Beyond this stress area, the specimens began to fail in tensile until fracture.

As shown in Table 5, the maximum tensile strength of straight seam welding joints is 187.86 MPa, the maximum tensile strength[6] of swing welded joint is 187.28 MPa. In contrast, the tensile strength of the swing laser welding joint is reduced by 0.31%. The elongation of the sample under straight seam welding is 1.12%, and that under

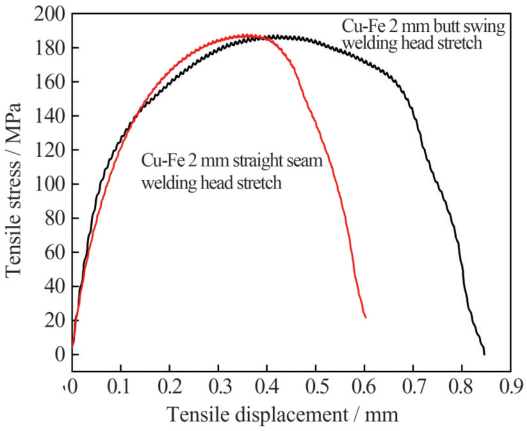

Fig. 2 Tensile stress-displacement diagram of Cu-Fe joint with two welding methods

swing welding is 1.32%. The elongation of the swing welding joint increases correspondingly.

Figure 2 shows the tensile stress and displacement of the straight seam welding joint and the swing welding joint after stretching. It is obvious that the maximum tensile stress of the straight seam welding joint is slightly higher than that of the swing welding joint. This is due to the oscillation of the laser beam from one side to the other during the oscillation welding process, the coarse columnar structure in the joint weld is replaced by a fine dendritic tissue[7], the lumpy structure is also transformed into spherical or granular structure, and the refinement of the microstructure increases the number of grains and the grain boundary area. Under the action of external forces, dislocation movement in grains is hindered by grain boundaries with large deformation energy.

Table 5 Tensile parameters of straight seam welding joint and swing welding joint

Item	Max force /kN	Max tensile displacement /mm	Max tensile strain /%	Tensile stress at max force /MPa
Straight seam welding joint	3.46	0.36	1.12	187.86
Swing welding joint	3.52	0.42	1.32	187.28

The accumulation of grain boundary dislocations leads to stress concentration[8], and cracks[9] tend to occur at grain boundary locations, making grain boundaries weak and extending to the degree of crack cracking, and also producing brittle phase fracture[10], so it has a great impact on the mechanical properties of welds. Therefore, compared with straight seam welding, the mechanical properties of swing welding joints are worse. Then, according to Table 5, the maximum tensile stress of swing welding seems to be slightly different from that of straight seam welding. The reason is that the tensile fracture position of swing welding joint is slightly deviated from the weld center, and the fracture position is in the copper biased position.

From the abscissa of Fig. 2, it is obvious that the tensile displacement of the swing welding joint is larger than that of the straight seam welding joint. Therefore, the toughness of the swing welded joint is better than that of the straight seam welding. The reason for the change in toughness of the swing welding joint is that the driving effect of the laser beam oscillating back and forth and oscillating accelerates the full transfer of alloying elements, which effectively reduces the composition bias within the grain and improves the intragrain plastic deformation, and the composition bias in the weld increases the crack susceptibility[11] and the inhomogeneity of the joint properties, resulting in better shaping of the swing welding joint.

2.2 Metallographic Microstructure Observation

Figure 3 shows the macroscopic morphology of the front and back sides of the straight seam welding joint and the swing welding joint. It can be found that the copper and steel in the weld are staggered in sheet-like distribution, and the flow phenomenon of the molten pool[12] in the weld is also clearly visible. Through the comparison in terms of weld width, it can be found that the width of swing welding weld is slightly higher than that of straight seam welding weld and the swing welding joints are more uniform. The reason is that in the process of moving forward, the swing welding moves forward evenly, so the area scanned by the laser on both sides will be very large. The larger the scanning area is, the more heat the master material can absorb. Therefore, the melting amount of the matrix metal also increases accordingly, making the width of the weld wider and more uniform[13].

It can be observed from Fig. 4 that the welding joint in Fig. 4(b) is more uniform, but the thickness is relatively small. Because of the large width of the weld,

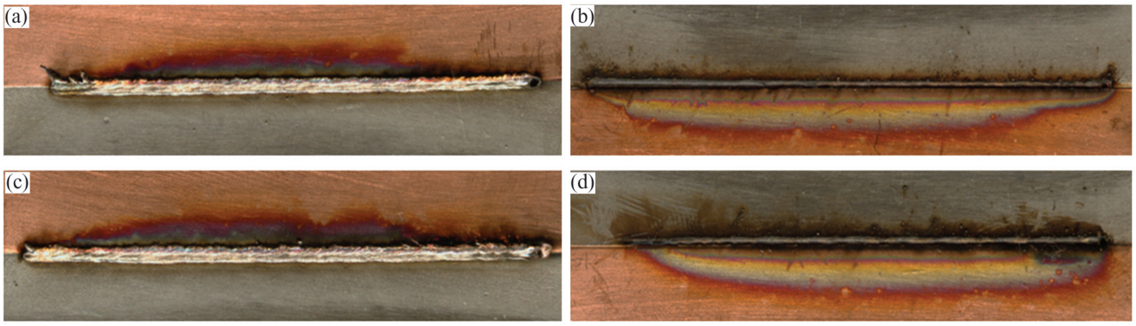

Fig. 3 Macroscopic morphology of weld seam

(a) and (b) The front and back sides of the straight seam welding joint; (c) and (d) The front and back sides of the swing welding joint

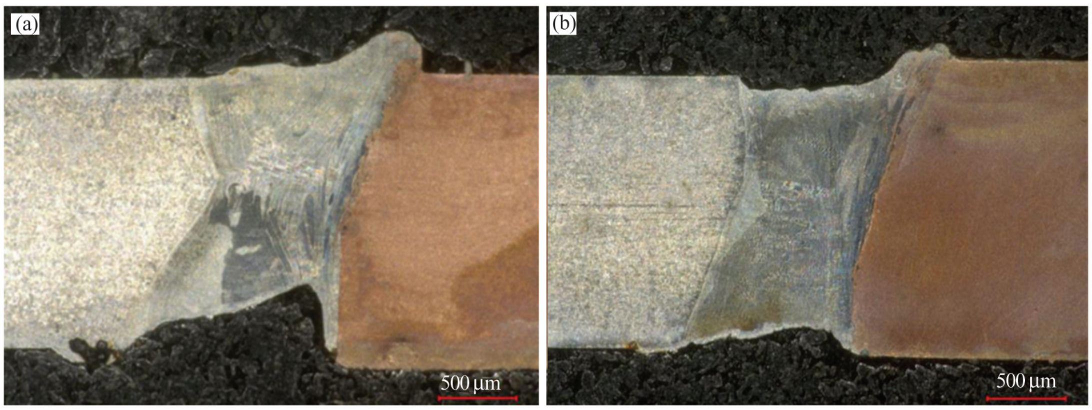

Fig. 4 Macroscopic morphology of welding joint

(a) Macroscopic morphology of straight welding joint; (b) Macroscopic morphology of swing welding joint

there are many defects in the weld, which affect the strength of the joint. The swing laser welding will lead to the decrease of the strength of the welding joint.Metallographic examination of welded joints was carried out to determine internal defects. Using the wire-cut method, the sample is cut down as required, and after cleaning the oil, the intercepted specimen is inlaid, preground, polished and etched under a metallographic microscope, and the following images are obtained after observation by the objective lens.

Microstructure changes are directly related to the mechanical properties of the joint[14,15], and the change in the weld organization directly affects the mechanical properties of the joint. From Fig. 5, it can be seen that there are cylindrical crystals in both welding methods. The cylindrical crystal in the center of the weld is because the welding temperature is much higher than the melting point of the metal in the center of the weld. During the welding process, the melting pool is overheated, the grain grows quickly, and the cooling gradient is relatively large, so it is easy to form cylindrical crystals in the center of the weld. Laser welded copper-steel dissimilar metal joints have distinct boundaries due to the obvious differences in the physicochemical properties of copper and steel[16].

As can be seen from Fig. 5(a), samples welded by straight seams have more isoaxial crystals at the center of the weld and are evenly distributed. This is due to the characteristics of the process of straight seam welding: during the welding process, the branches of each grain are laped firmly, and the growth of each grain is close to the same in all sides, forming more isoaxial crystals[17]. Therefore, the mechanical properties of straight welding joints are better.

For Fig. 5(b), there are more columnar crystals in the center of the weld, and the grains are thick and distributed disorderly. This is because in the process of swing welding, the laser beam swings evenly, so that the direction of the grain formed after melting the base metal on both sides is different, so the direction of the columnar crystal is disordered, the structure is thick, and there are weak surfaces, which affects mechanical prop-

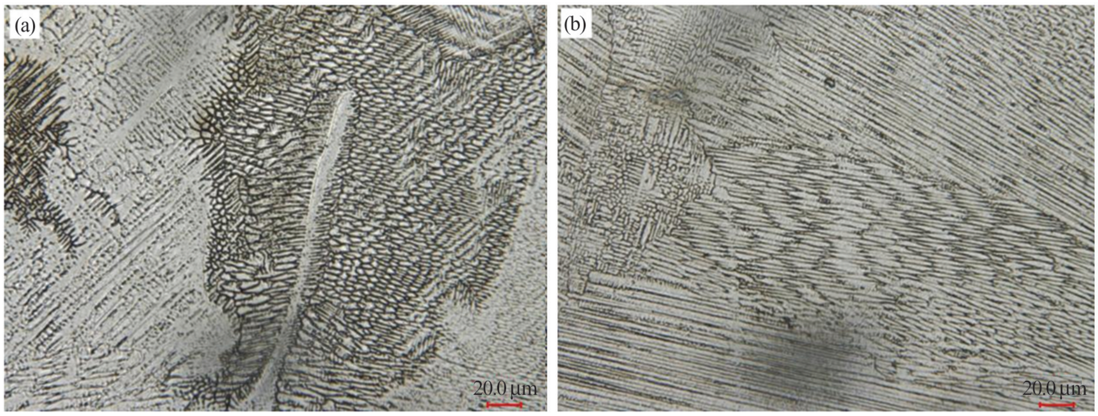

Fig. 5 Microstructure of the center of the weld under metallurgical microscope

(a) Straight seam welding center; (b) Swing welding center

erties[18,19]. Therefore, the mechanical properties of swing welding joints are poorer.

2.3 XRD Analysis

The surface of the welded joint was first polished with 500# sandpaper, and then the sample was measured and analyzed XRD with a scanning angle of 10°-120° and a scanning speed of 4°/min.

Figure 6 shows the XRD pattern at the weld of the laser welded joint between T2 purple copper and 316L stainless steel. From Fig. 6(a), the presence of ε-Cu phase and α-Fe phase in the weld can be observed. From Fig. 6(b), in addition to the ε-Cu phase, we can observe that the intermetallic compound FeN also appears during the welding process.

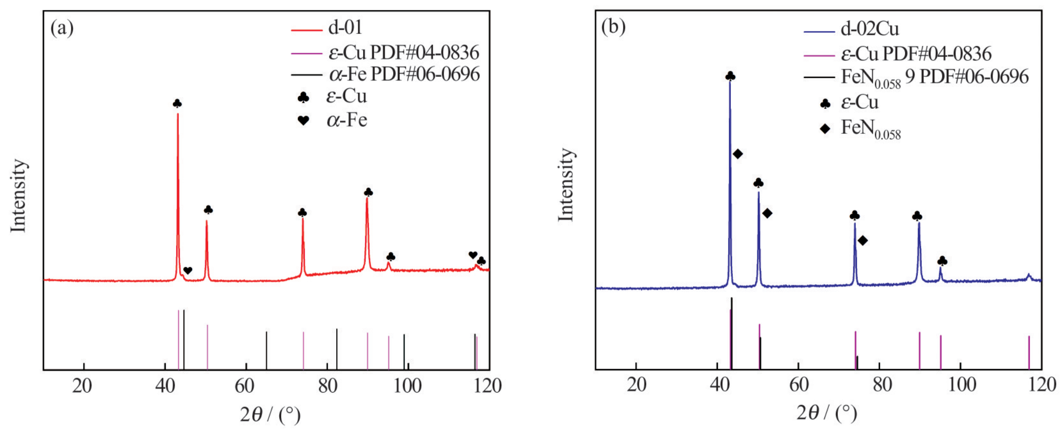

Fig. 6 XRD pattern at the weld of the laser welded joint

(a) The weld of the straight seam welded joint; (b) The weld near the copper side of the swing welding joint

The intermetallic compound[20, 21] mostly appears during the welding process and usually consists of more than one element, but it also has the basic characteristics of metal. It is often due to the rapid cooling speed during the welding process, the molten pool of the weld in the crystallization, the chemical composition of the molten pool has solidified before it has time to diffuse evenly, resulting in the emergence of intermetallic compounds[22]. The intermetallic compound FeN occurred in the welding process of copper steel makes the stress concentration and crack cracking at the joint, leading to the strength reduction at the weld joint and weak mechanical properties. Therefore, the mechanical properties of the weld in the swing welding joint are worse than those in the straight welding joint.

2.4 Fracture Morphology

Figure 7 shows that the straight seam welding fracture has more dimple[23]. Figure 7(a) and (b) can be judged that the fracture is a dimple fracture. It is evident that the dimple at this fracture is incredibly erratic. The small dimple is both deep and shallow and it is contained within the larger dimple. As a result, it is thought that the straight seam welding joint has better toughness.

Figure 8 is a partial morphology of the fracture of the swing welding joints. Figure 8 shows the shape of the fracture of the swing welding joint. Observing these two pictures, it can be found that the dimple of the tensile fracture of the swing welding joint is relatively uniform, which is a typical ductile fracture. In addition, Fig. 7(b) and Fig. 8(a) are the fracture shape of straight seam welding and swing welding under the same magnification multiple. It can be seen intuitively that the dimple in Fig. 8(a) is relatively large. However, the smaller the simple, the greater the resistance, so the strength of the swing welding joint is higher. However, the white particles[24] that appear in Fig. 8(b) may be the intermetallic compound FeN. The appearance of FeN will cause stress concentration and crack cracking, so the strength of the swinging welding joint will decrease.

In summary, the strength at the weld of a straight seam welding joint is slightly higher than that at a swing welding joint.

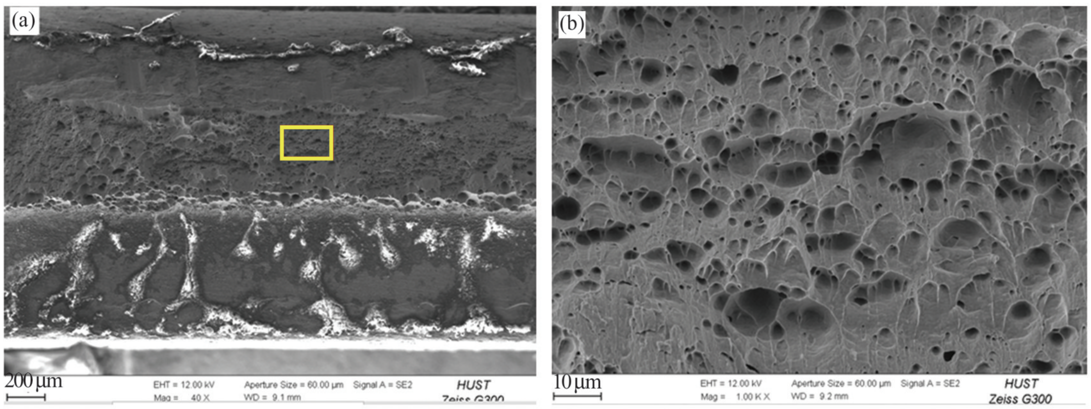

Fig. 7 Straight seam welding fracture shape

(a) Overall shape of straight seam welding fracture; (b) The enlarged view of the part circled in (a)

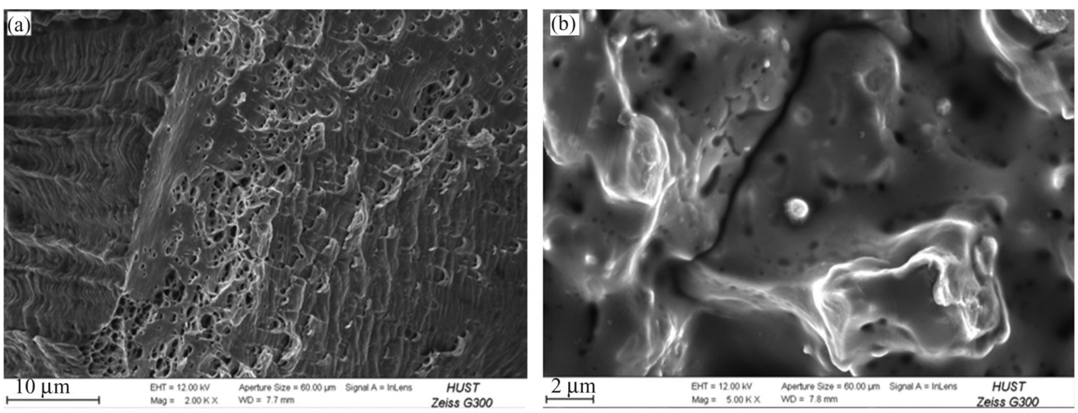

Fig. 8 Swing welding fracture shape

(a) The fracture morphology of the swing welded joint under the same magnification multiple as Fig. 7(b); (b) Partial enlargement of (a)

3 Conclusion

1) Laser beam swing welding can significantly increase the width of the weld compared with straight seam welding. Due to the large area swept by the swing welding beam along the weld, the heat absorption of the master material increases, resulting in an increase in the overall melting capacity, so the width of the weld also increases.

2) Metallographic microscope observation shows that the isoaxial crystals at the center of the joint weld are more and evenly distributed during straight seam

welding, and the mechanical performance is good. However, the grains in the center of the swing weld are thick, in many directions and messy distribution, which affects the overall strength of the joint, but the toughness is good.

3) By analyzing the XRD spectrum, it can be found that the appearance of FeN decreases the mechanical properties of the joint, so the strength of the straight seam welding joint is slightly higher. In the process of swing welding, the swing of the laser beam improves the structure segregation and grain orientation, so the plasticity of the swing welding joint is better.

4) Through the tensile property test, it is found that the change of columnar structure at the weld of the swing welding joint leads to the refinement of the microstructure, the accumulation of dislocations at the grain boundary and the concentration of stress, which makes the strength of the swing welding joint decrease.

5) By analyzing the fracture shape, it was found that the dimple at the joint was small and uniform, but the strength of the joint was reduced due to the presence of intermetallic compound FeN. Therefore, the strength of straight welding joints is slightly higher than that of swing welding joints.

References

[1] Yao C W, Xu B S, Zhang X C, *et al*. Interface microstructure and mechanical properties of laser welding copper-steel dissimilar joint[J]. *Optics and Lasers in Engineering*, 2009, **47** (7/8): 807-814.

[2] Yan F, Qin Y, Tang B K, *et al*. Effects of beam oscillation on microstructural characteristics and mechanical properties in laser welded steel-copper joints[J]. *Optics & Laser Technology*, 2022, **148**: 107739.

[3] Antony K, Rakeshnath T R. Dissimilar laser welding of commercially pure copper and stainless steel 316L[J]. *Materials Today*: *Proceedings*, 2020, **26**: 369-372.

[4] Zhao H Y, Niu W C, Zhang B, *et al*. Modelling of keyhole dynamics and porosity formation considering the adaptive keyhole shape and three-phasecoupling during deep-penetration laser welding[J]. *Journal of Physics D*: *Applied Physics*, 2011, **44**(48): 1-13.

[5] Chen J Y, Wang X N, Lü F, *et al*. Microstructure and mechanical properties of welded joints of low carbon steels welded by laser beam oscillating welding[J]. *Chinese Journal of Lasers*, 2020, **47**(3): 143-150(Ch).

[6] Gu X Y, Cui Z W, Gu X P, *et al*. Wire-feeding laser welding of copper/stainless steel using different filler metals[J]. *Materials* (*Basel*, *Switzerland*), 2021, **14**(9): 2122.

[7] Hu C J, Yan F, Zhu Z W, *et al*. Effects on microstructural refinement of mechanical properties in steel-copper joints laser welded with alternating magnetic field augmentation[J]. *Materials Characterization*, 2021, **175**: 111059.

[8] Wang T H, Mishra R. Effect of stress concentration on strength and fracture behavior of dissimilar metal joints [C]// *The Minerals*, *Metals & Materials Series*. Cham: Springer International Publishing, 2019: 33-39.

[9] Nguyen Q, Azadkhou A, Akbari M, *et al*. Experimental investigation of temperature field and fusion zone microstructure in dissimilar pulsed laser welding of austenitic stainless steel and copper[J]. *Journal of Manufacturing Processes*, 2020, **56**: 206-215.

[10] Sun L, Xu Z T, Peng L F, *et al*. Effect of grain size on the ductile-brittle fracture behavior of commercially pure titanium sheet metals[J]. *Materials Science and Engineering*: *A*, 2021, **822**: 141630.

[11] Ebrahimzadeh H, Mousavi S A A. Investigation on pulsed Nd: YAG laser welding of 49Ni-Fe soft magnetic alloy[J]. *Materials & Design*, 2012, **38**: 115-123.

[12] Gao M, Zhang Y Z, Meng Y F. Interface homogenization and its relationship with tensile properties of laser-arc hybrid welded Al/steel butt-joint via beam oscillation[J]. *Journal of Materials Science*, 2021, **56**(25): 14126-14138.

[13] Chen S H, Huang J H, Xia J. Influence of processing parameters on the characteristics of stainless steel/copper laser welding[J]. *Journal of Materials Processing Technology*, 2015, **222**: 43-51.

[14] Kuryntsev S V, Morushkin A E, Gilmutdinov A K. Fiber laser welding of austenitic steel and commercially pure copper butt joint[J]. *Optics and Lasers in Engineering*, 2017, **90**: 101-109.

[15] Chen S H, Huang J H, Xia J, *et al*. Microstructural characteristics of a stainless steel/copper dissimilar joint made by laser welding[J]. *Metallurgical and Materials Transactions A*, 2013, **44**(8): 3690-3696.

[16] Phanikumar G, Manjini S, Dutta P, *et al*. Characterization of a continuous CO_2 laser-welded Fe-Cu dissimilar couple[J]. *Metallurgical and Materials Transactions A*, 2005, **36A**: 2137-2147.

[17] Hagenlocher C, Sommer M, Fetzer F, *et al*. Optimization of the solidification conditions by means of beam oscillation

during laser beam welding of aluminum[J]. *Materials & Design*, 2018, **160**: 1178-1185.

[18] Bahrami Balajaddeh M, Naffakh-Moosavy H. Pulsed Nd: YAG laser welding of 17-4 PH stainless steel: Microstructure, mechanical properties, and weldability investigation[J]. *Optics & Laser Technology*, 2019, **119**: 105651.

[19] Ozsoy A, Tureyen E B, Baskan M, *et al*. Microstructure and mechanical properties of hybrid additive manufactured dissimilar 17-4 PH and 316L stainless steels[J]. *Materials Today Communications*, 2021, **28**: 102561.

[20] Tomashchuk I, Sallamand P, Andrzejewski H, *et al*. The formation of intermetallics in dissimilar Ti_6Al_4V/copper/AISI 316L electron beam and Nd: YAG laser joints[J]. *Intermetallics*, 2011, **19**(10): 1466-1473.

[21] Shamsolhodaei A, Oliveira J P, Schell N, *et al*. Controlling intermetallic compounds formation during laser welding of NiTi to 316L stainless steel[J]. *Intermetallics*, 2020, **116**: 106656.

[22] Mai T A, Spowage A C. Characterisation of dissimilar joints in laser welding of steel-kovar, copper-steel and copper-aluminium[J]. *Materials Science and Engineering A*, 2004, **374**(1): 224-233.

[23] Han Y L, Xue S B, Fu R L, *et al*. Effect of hydrogen content in ER5183 welding wire on the tensile strength and fracture morphology of Al-Mg MIG weld[J]. *Vacuum*, 2019, **166**: 218-225.

[24] Li J M, Cai Y Z, Yan F, *et al*. Porosity and liquation cracking of dissimilar Nd: YAG laser welding of SUS304 stainless steel to T2 copper[J]. *Optics & Laser Technology*, 2020, **122**: 105881.

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