

Article

Formation Mechanism and Control of Solidification Cracking in Laser-Welded Joints of Steel/Copper Dissimilar Metals

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Abstract: The solidification cracking behavior in laser welds of steel/copper dissimilar metals was systematically investigated. T2 copper and SUS304 stainless steel were used in the study. The results showed that the occurrence of solidification cracking in welds was the synergistic effect of ϵ phase liquation, inclusions and composition segregation. During the welding process, the liquation of grain boundaries substantially reduced the cohesion between adjacent grains, as well as the resistance for intergranular crack propagation. The composition segregation inside the grains could induce lattice distortion, thus reducing the plastic deformation capacity of the material itself and concurrently increasing the susceptibility to cracks. In addition, an effective solution for inhibiting solidification cracking was proposed by using an oscillating laser, and the inhibition mechanism was further discussed. Laser oscillating welding significantly promoted grain refinement, solute diffusion and the formation of uniformly distributed ϵ -Cu precipitated phases in welds. It can improve the intergranular bonding, reduce the susceptibility to solidification cracking and increase the resistance to plastic deformation. The tensile strength of joints using laser oscillating welding is 251 MPa, 35.7% more than 185 MPa using laser welding. Meanwhile, the strain of joints using laser oscillating welding is 3.69, a 96% increase compared to 1.88 using laser welding.

Keywords: solidification cracking; dissimilar metals; laser welding; composition segregation; inhibition mechanism



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1. Introduction

Dissimilar welded joints of stainless steel and copper have been widely applied in power generation and nuclear industries, heat transfer components, and automotive/electrical sectors, due to the coupling advantages of the excellent thermal and electrical conductivity of copper and the good mechanical strength and corrosion resistance of stainless steel [1–3]. However, the significant mismatches in physicochemical and thermo-mechanical properties between these two dissimilar materials make it challenging to join them together. The major problem is hot cracking in the copper-stainless steel transition zone owing to solidification cracking and liquation cracking [4–6]. The emergence of cracks will greatly weaken the mechanical properties of welded joints, decrease the joints life, and even make the components premature failure. Thus, it is important to investigate hot cracking in the welding of stainless steel and copper.

Lasers, as a kind of high-density energy source, have been used widely in the fields of welding, cutting and emerging additive manufacturing [7–10]. Dissimilar metal combinations can be realized by laser welding [11–13] and laser additive manufacturing [14–16]. In

the laser additive manufacturing of copper and steel, massive cracks and pores in the interface [14,15] and fractures in the bonding regions or the heat-affected zones [16] have been observed. Laser welding has been widely used for dissimilar metal because of its advantages such as small energy input, high energy density, narrow heat-affected zone and small deformation. However, the poor metallurgical compatibility between dissimilar metals normally limits the laser welding process and leads to potential defects, e.g., hot cracking. Many studies on hot cracking (including liquation cracking and solidification cracking) in the laser welding of stainless steel and copper have been carried out. Mai et al. [4] considered that the major problem in welding copper to steel was liquation cracking in the heat-affected zone of steel due to copper melting and penetrating into the grain boundaries of solid steel. Li et al. [6] studied the formation mechanism of heat-affected zone (HAZ) liquation cracking and deemed that the liquation cracking was closely related to the precipitation of Cu-Fe compounds at grain boundaries and grain boundary liquation. Rinne et al. [12] thought that one of the most common weld defects in copper-steel combination was solidification cracking in the weld metal due to liquid copper accumulation between the stainless steel grain boundaries, which could not withstand the tensile tensions while cooling down. Chen et al. [17] believed that solidification cracks in the weld zone were caused by a thermal stress mismatch between stainless steel and copper. Weigl and Schmidt [18] and Joshi and Badheka [13] reported the presence of the solidification cracks in the “welding-brazing mode”. They concluded that the compositional gradient within the weld area was the reason for the cracking, not the presence of Cu within the weld metal. Nguyen et al. [19] found that a clear discrepancy in the temperature gradients of the melt pool at the copper and stainless steel side increased the possibility of solidification cracking and changed the place and pattern of crack propagation.

In order to obtain crack-free welded joints during the laser welding of steel/copper dissimilar metals, many methods were attempted to inhibit the occurrence of cracks. A defocused laser beam with an offset to stainless steel was used by Kuryntsev et al. [20] in order to melt stainless steel directly and melt copper via heat conduction. Chen et al. [17] found that liquid separation and microcracks in the fusion zone could be prevented in “welding-brazing mode” by laser beam inclination towards the stainless steel. The methods of laser beam offset or inclination towards stainless steel to minimize the melting of copper have also been adopted by other researchers to obtain sound welds without cracks between stainless steel and copper [19,21,22]. Contrary to the above investigations, an approach of applying laser beams towards copper was raised by Shen and Gupta [23]. They reported that no solidification cracks were detected when weld metal was enriched with copper (80% of copper in the weld zone). Hot crack clusters were observed along the austenite grain boundaries in stainless steel-HAZ. However, a high tensile strength was achieved despite the presence of these cracks. Sahul et al. [24] achieved high values of tensile strength up to 261 MPa by offsetting the laser beam towards the copper side due to intermixing of both metals. Rinne et al. [12] proposed different solutions to influence the copper dilution and the weld metal geometry for solidification crack prevention in the laser welding of copper-steel. A design of experiment approach and inline weld depth control was used for the lap weld configuration to limit the copper dilution below 10 wt. % in steel-dominated weld metals, and different power distributions were adopted for the butt weld configuration to control the shape and dimension of the weld metal and mixing behavior. Nguyen et al. [19] proposed that creating the appropriate temperature gradient during welding played a crucial role to effectively control solidification cracking at the fusion zone in order to reduce the heat conduction effect of the copper. In addition, a reduction in heat input during welding was also advised to effectively lower the susceptibility to liquation cracking at grain boundaries [6]. From the above-mentioned literature, the cracks can be inhibited by regulating welding conditions or process parameters. However, the cracks in welds have not been fully eliminated during the laser welding of copper to steel. Further research on effective solutions for hot cracking in welds still needs to be studied.

In this work, the butt welding of copper and stainless steel was conducted using fiber laser beams. The forming mechanism of solidification cracking was investigated. According to the studies, laser welding with beam oscillation can suppress porosity [25], mitigate macrosegregation [26], and improve the resistance to cracks in welds [27]. Therefore, an effective solution for inhibiting solidification cracking was proposed by using an oscillating laser, and the inhibition mechanism was further discussed. This research will be an attempt to evaluate the feasibility of the laser oscillating welding of dissimilar metals as a method to improve the microstructure in welded joints.

2. Materials and Methods

The laser welding experiments were carried out using SUS304 stainless steel plates and T2 copper plates. Table 1 shows the chemical compositions of the materials. The element content values in the table are taken from the manufacturer data. The dimensions of the experimental plates were 70 mm × 50 mm × 2 mm. Before the welding experiments, firstly the oxide films on the material surfaces were completely removed by milling, and acetone was also used to eliminate greasy dirt on the sample surfaces; then, the samples were tightly fastened in butt weld configuration without misalignments.

Table 1. Chemical compositions of the materials used in the experiments (wt%).

T2	Cu + Ag ≥99.90	Sn ≤0.002	Pb ≤0.005	Fe ≤0.005	Sb ≤0.002	S ≤0.005	O ≤0.06	As ≤0.002
304	C ≤0.08	Si ≤1.00	Mn ≤2.00	P ≤0.045	S ≤0.03	Cr 18.5	Ni 8.6	Fe Balance

The experimental setup and schematic diagram of laser welding of copper to stainless steel is shown in Figure 1. In the experiments, a RFL-C3000 fiber laser (Wuhan Raycus Fiber Laser Technologies Co., Ltd., Wuhan, China) was used. The specific parameters of the laser were listed as follows: a focus diameter of 0.3 mm, a focal length of 300 mm, and a wavelength of 1070 nm. The shielding gas used in the experiments was argon. The high-power fiber laser (HPFL) welding of stainless steel to copper required the control of four variables, namely, welding speed, laser power, the defocusing amount and the flow rate of argon gas. The process variables in the experiments are shown in Table 2.

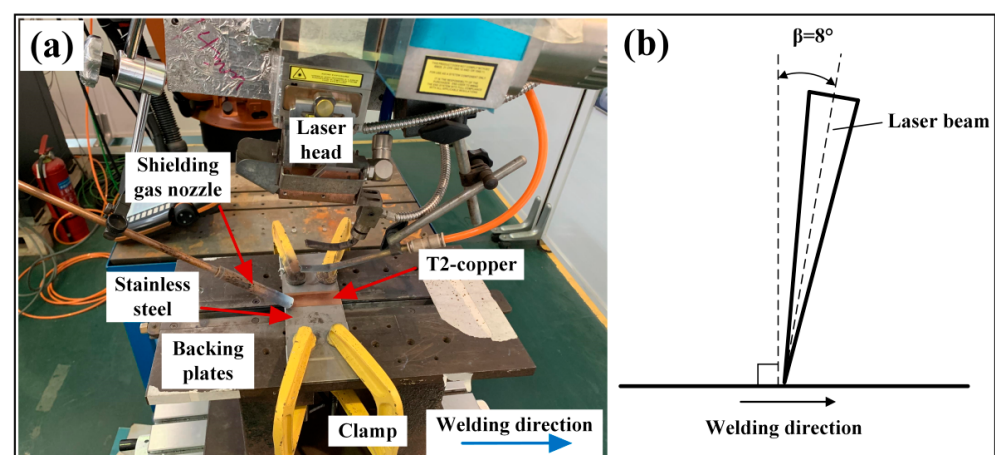


Figure 1. The experimental setup and schematic diagram of laser welding of copper to stainless steel: (a) the experimental setup; (b) the schematic diagram of the welding process.

Table 2. Process variables in the experiments.

Variables	Units	Levels
welding speed	m/min	1.8, 2.4, 3.0, 3.6
laser power	kW	3.0
defocusing amount	mm	0
flow rate of Ar gas	L/min	16.7

Transverse sectioning samples were taken at multiple locations of each welded specimen and polished using standard metallographic techniques. An etchant of 96 mL ethanol, 2 mL HCl, and 5 g FeCl₃ was used to etch prepared specimens for subsequent studies. The microstructures of welded samples were examined and analyzed using an optical microscope (Shanghai Cewei Optoelectronic Technology Co., LTD, Shanghai, China) with metallographic photo analysis software and a Sirion 200 scanning electron microscope (FEI Company, Hillsboro, OR, USA) equipped with an EDAX energy diffraction spectrum. High-speed videography (Photonfocus, Lachen, Switzerland) was used to prove the validity of the crack suppression method. Tensile testing was performed to determine the strength of the joints according to the GB/T 2651-2008 standard.

3. Results and Discussion

3.1. The Defects of Welded Joints

The microstructure of the steel/copper laser-welded joint can be clearly observed using a scanning electron microscope, as shown in Figure 2. In the figure, the abbreviation GB means grain boundary. It can be seen that the weld metal mainly consists of the ϵ -Cu phase (block or spherical structures), the α -Fe phase (columnar or granular structures) and the ($\alpha + \epsilon$) eutectoid phases (granular structures).

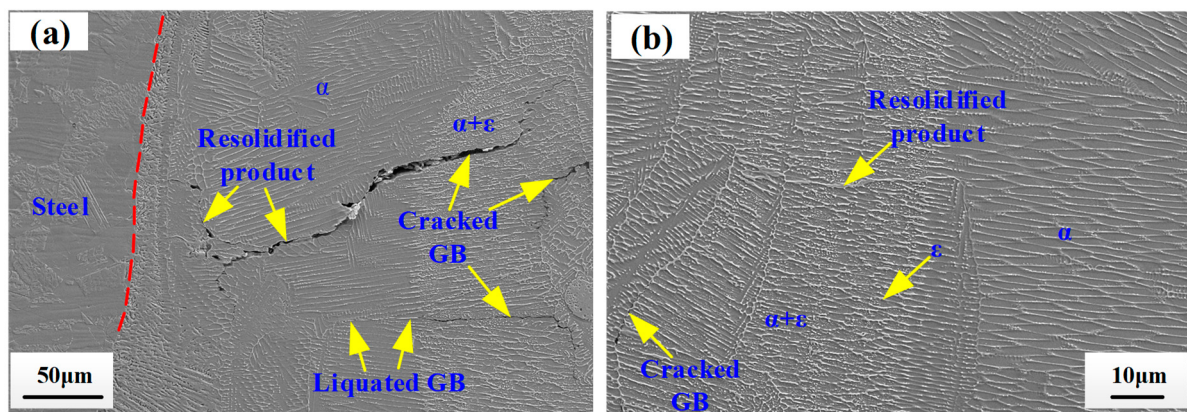


Figure 2. The microstructure of steel/copper laser-welded joint: (a) cracking along the grain boundary; (b) microcracks in the weld metal.

As shown in Figure 2a, slender columnar crystals are generated near the fusion zone of steel side. The growth of these crystals mainly depends on a larger temperature gradient along a certain direction. Only a few ϵ phases emerge at the grain boundary. The segregation of precipitated phases mainly lies on liquid separation reactions due to the great difference in physicochemical properties [28]. During the solidification of the weld, the α phase with the high melting point was preferentially precipitated and grew up quickly, whereafter the ϵ phase and inclusions with low melting points were formed at the grain boundaries. The structure inhomogeneity easily results in the anisotropy for the joint mechanical properties. The major defects near the fusion line were found to be cracks and microcracks. The continuous or semi-continuous cracks appeared in the weld zone (WZ), spreading along the grain boundary direction. It can be observed that liquated films occurred at grain boundaries, but the cracks failed to be generated during

the laser welding process. The occurrence of intergranular cracking mainly depends on metallurgical factors and mechanical factors. For mechanical factors, it can be directly determined by the competition results between intergranular cohesive and the thermal stress at interface. For metallurgical factors, it can be also influenced by grain size, grain boundary misorientation [29] and multi-component segregation [30].

As shown in Figure 2b, resolidified products appear at grain boundaries and large columnar crystals are formed in the middle weld. The presence of liquated films is closely associated with a low melting point phase and inclusions at the grain boundaries. These inclusions can easily liquefy at high temperatures owing to their low melting point. The presence of liquid films at grain boundaries weakens the binding force between grains during the solidification process, resulting in an increase of cracking susceptibility. As the binding force fails to counteract the welding thermal stress, solidification cracks begin to form at the grain boundaries. Coarse grains in the weld can greatly weaken the plasticity and ductility of materials, increasing the crack sensitivity of the joint. Therefore, it is very necessary to control the grain size and the composition segregation during the solidification process for reducing the cracking sensitivity.

3.2. Element Distribution Near the Interface

To further study the formation mechanism of solidification cracking, energy dispersive spectroscopy (EDS) analysis was performed on the welded specimens with solidification cracks. The element distribution of the crack on both sides using line scanning was demonstrated in Figure 3.

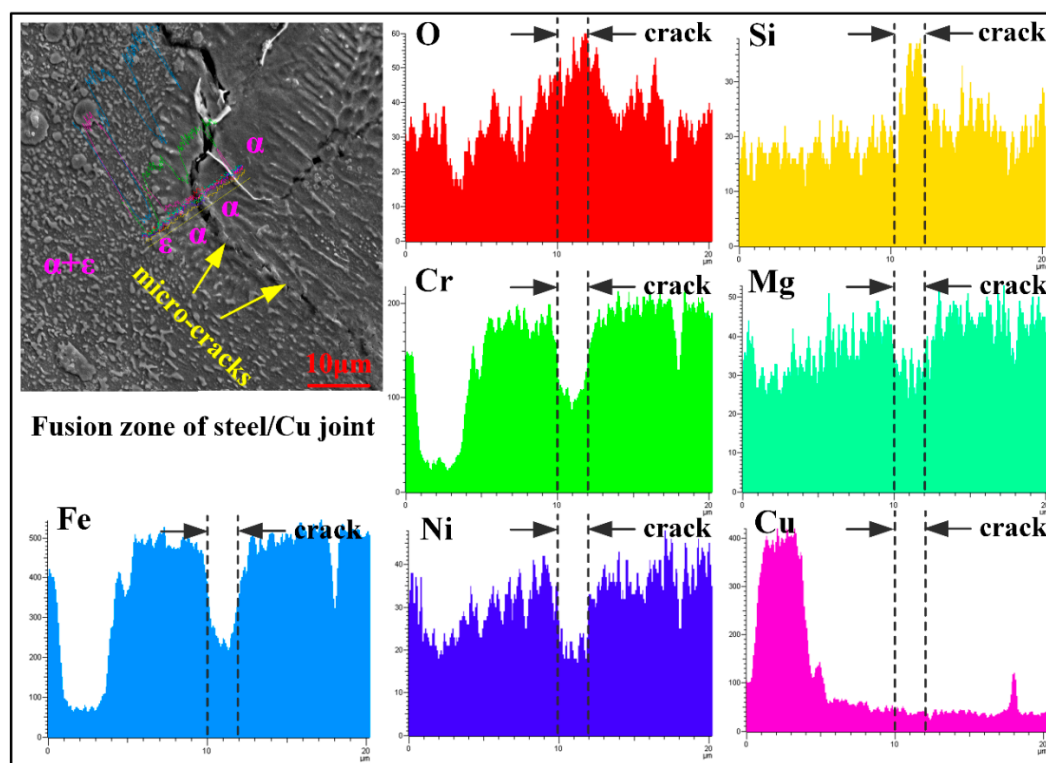


Figure 3. The element distribution of weld zones with solidification cracking.

From the EDS results in Figure 3, it is clear that significant composition segregation takes place in the fusion zone (FZ) during the solidification process. It can be observed clearly that the irregular cracks, together with liquated films or inclusions, appear at the grain boundaries. It can be also discovered that, in comparison with intragranular element content, the oxygen and silicon element contents in the crack increase significantly; the copper element content remains largely stable; and iron, chromium, and nickel element

contents diminish drastically. The grain boundary involves more oxygen atoms, proving that the intergranular oxidation resistance is much weaker than the intragranular oxidation resistance. More seriously, the penetration of oxygen along grain boundaries can induce the emergence of grain boundary cracking [31]. The enrichment of silicon atoms means that the strength of α -Fe solid solution can be greatly enhanced by the effect of solution strengthening, leading to a reduction of toughness and a plasticity of materials. The evolution characteristics of the copper element mainly depend on its segregation during the solidification process. The first peak value is as a result of ϵ -Cu precipitation. Rich Fe areas are formed near the ϵ -Cu phase. An introduction of alloying elements such as Cr and Ni can improve the strength of solid solutions. Moreover, the presence of Cr at grain boundaries can effectively heighten intercrystalline oxidation resistance. The second peak value can be attributed to the migration of copper atoms along the grain boundary. Compared with α -Fe phase, the ϵ -Cu phase has a lower melting point. During the weld cooling process, liquated grain boundaries can be easily produced because of the generation of precipitated phases with a low melting point at grain boundaries, greatly reducing the binding force between the grains and increasing the grain boundary cracking susceptibility. As thermal stresses fail to be thoroughly eliminated by plastic deformation itself, the solidification cracking easily occurs at grain boundaries. Therefore, we determined that the occurrence of solidification cracking might be the result of the composition segregation. In order to inhibit the solidification cracking effectively, some measures should be adopted during the laser welding process to regulate precipitated phases such as low-melting-point phases or inclusions and subsequent gradient microstructures in the FZ.

3.3. An Effective Solution for Inhibiting Solidification Cracking

The study of FZ solidification cracking in laser-welded samples revealed that the liquation of ϵ phase and inclusions caused cracking, and there was obvious evidence of composition segregation along cracked grain boundaries. Hence, it appears that lower composition segregation in weld pools has great potential to decrease the susceptibility to solidification cracking.

In order to improve the performance of the welded joints, laser oscillating welding was performed on the steel/copper dissimilar alloys using circle C.W. mode. The laser oscillating frequency and oscillating amplitude were 150 Hz and 0.5 mm, respectively. The results of closer SEM examination, demonstrated in Figure 4, show that joints with good weld quality can be successfully obtained in available technological condition. No obvious defects, such as cracks, were found in the weld. As shown in Figure 4a, fine dendrites are formed near the fusion line owing to the stirring effect of oscillating laser on the molten pool. The grain orientations also change significantly. Evenly distributed microstructures involving α and ϵ in the FZ under the action of the oscillating laser can be also observed, as shown in Figure 4b. However, for the microstructures without oscillation mode (Figure 4c), an ϵ phase at the grain boundary is substantially broken and uniformly dispersed among the dendrites. The changes in the shape and distribution of the ϵ precipitated phase caused by the oscillating laser can greatly improve the cohesion between grains. During the welding process, solute migration and uniform distribution can be also greatly promoted, effectively reducing the composition segregation and crack source. Moreover, the grain refinement in welded joints contributes to a reduction in stress concentration and an increase in resistance to plastic deformation. Thus, it can be concluded that the resistance to intergranular crack propagation can be greatly improved by the driving effect of the oscillating laser. Compared with the steel/copper joints with massive cracks obtained by laser additive manufacturing [14,15], crack-free welded joints can be obtained using laser oscillating welding.

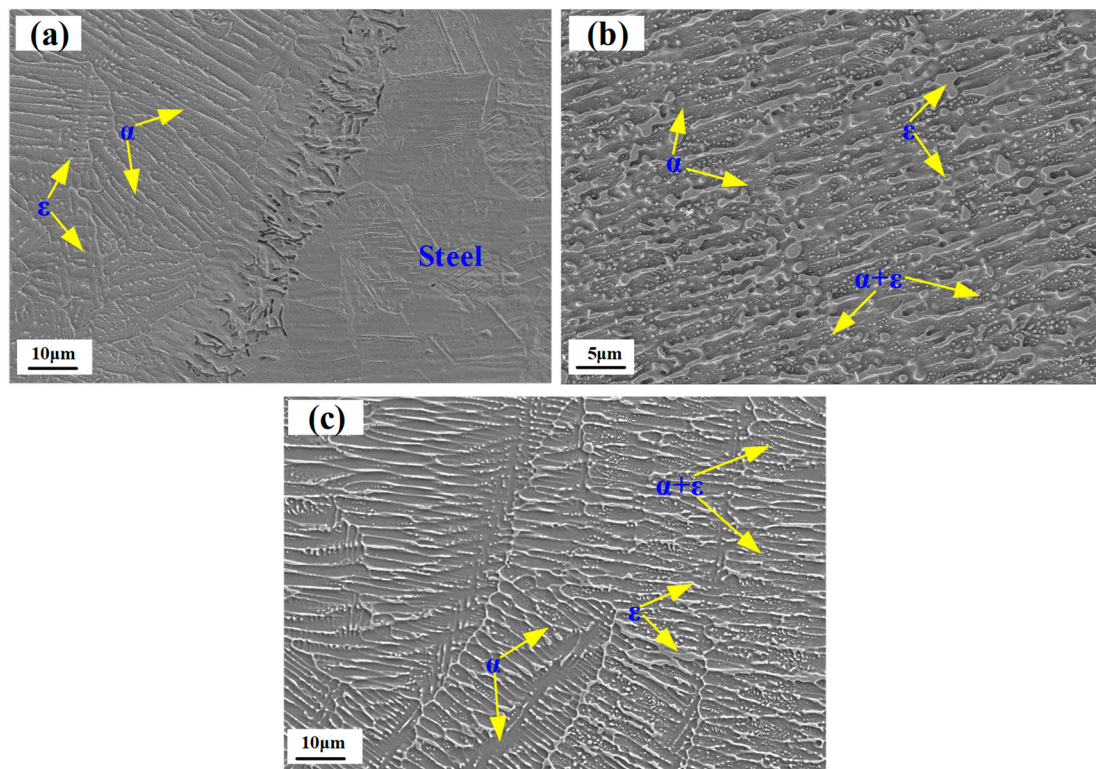


Figure 4. Microstructures of welded joints using different laser modes: (a) fusion zone near steel in the laser oscillating welding; (b) weld zone in the laser oscillating welding; and (c) weld zone in the laser welding.

The tensile properties of the tested samples under different processes are presented in Figure 5. As shown in Figure 5, the tensile strength of tested samples using laser oscillating welding is 251 MPa, 35.7% more than 185 MPa using laser welding. Meanwhile, the strain of tested samples using laser oscillating welding is 3.69, 96% more than 1.88 using the laser welding. The improvement of joint strength mainly depends on the microstructures of the welds. As seen from Figure 4a,b, fine columnar crystals instead of coarse dendrites are produced in the fusion zone because of the stirring effect of the oscillating laser. Grain refinement can significantly increase the area of the grain boundary. Under external force, dislocation motion is hindered at the grain boundary because of large distortion energy. The entanglement of the dislocation can greatly improve the deformation ability of the material and endure a greater force. In addition, the refined grains can effectively reduce stress concentration at the grain boundary, resulting in the inhibition of the occurrence of cracks at the grain boundary and a quick extension along the grain boundary. In such a condition, the strength and toughness of the joints can be enhanced significantly. Compared with the steel/copper joints with the tensile strength of 220 MPa obtained by laser additive manufacturing [15], the tensile strength of 251 Mpa is higher using laser oscillating welding.

Figure 6 shows fractographs of tested samples at room temperature under different welding processes. As shown in Figure 6a, it can be clearly observed that multi-size dimples and torn edges emerge in joint fracture. The size of dimples varies from 1.8 μm to 14.4 μm . The emergence of typical features is closely associated with the microstructure in the welds. The microstructure mainly consists of α -Fe and ϵ -Cu in the weld zone. The hardness of the precipitated α -Fe phase is higher than that of the precipitated ϵ -Cu phase. Generally speaking, the presence of precipitated phases with high hardness can lead to the stress concentration, so it is quite adverse to the plastic deformation of the material. Moreover, the inhomogeneous distributions of these precipitated phases easily lead to the anisotropy of the mechanical properties of materials, which significantly induces the occurrence of the cracks.

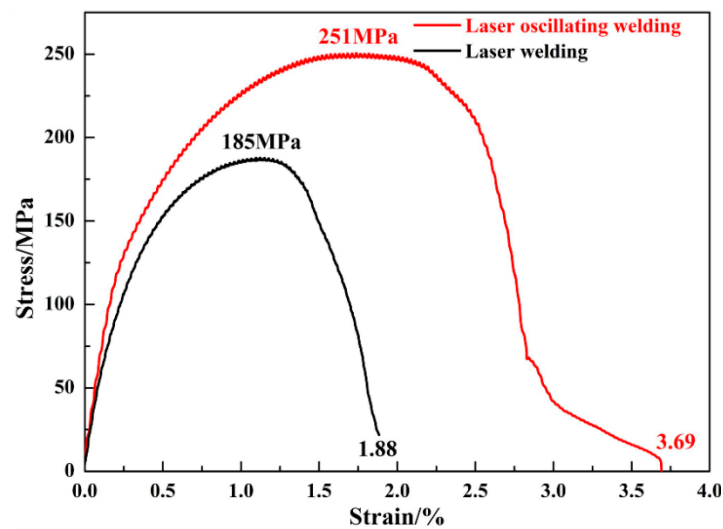


Figure 5. The stress-strain curves of the welded joints under different welding processes.

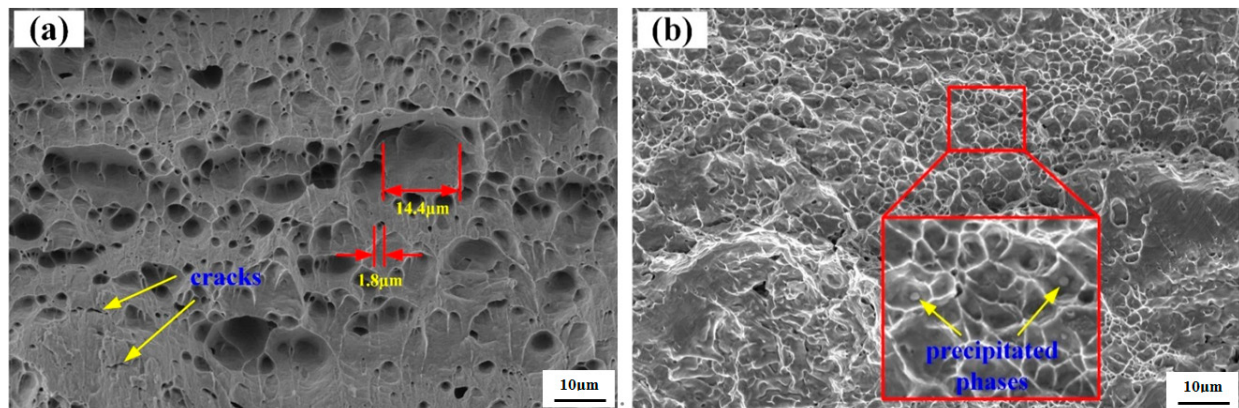


Figure 6. Fractographs of tested samples at room temperature: (a) laser welding; (b) laser oscillating welding.

As demonstrated in Figure 6b, it can be observed that more even-sized dimples are formed in the fracture, indicating that the fracture mode belongs to ductile fracture. The size of dimples has no noticeable change, signifying that a uniform microstructure is produced in the weld under the action of the oscillating laser beam. Grain refinement can increase the number of grain boundaries and reduce local stress concentration. The thermal stresses can be successfully eliminated by the plastic deformation capacity of the material, effectively inhibiting the occurrence of cracks. It can be clearly observed that the secondary precipitation phases are generated at the bottom of the dimples. These precipitated phases can also enhance the tensile strength of welded joints because they block the movement of the dislocation. Therefore, it can be concluded that the strength and toughness of welded joints can be significantly improved by means of the oscillating laser.

3.4. Inhibition Mechanism for Solidification Cracking

High-speed video images of the molten pool under different welding modes are captured to further explore the crack inhibition mechanism. The results of high-speed videos are shown in Figure 7. The acquiring frequency of the high-speed camera is 5000 frames per second, and the photos are captured at 200 μ s intervals.

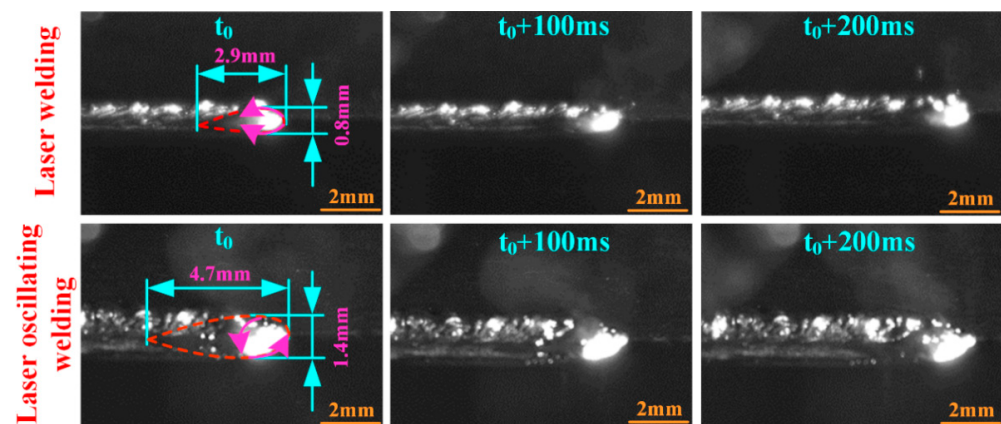


Figure 7. Images of the molten pool under different welding modes.

Compared with laser welding, the area of molten pool surface can be obviously enlarged using laser oscillating welding. As the same heat input is exerted on dissimilar metals during the welding process, the average energy density can be greatly decreased because of an increase in the laser radiation area. The lower energy density in the welding process can effectively restrict the growth of dendrites and cellular crystals. More grains are produced in such a condition. Thus, the cohesions between grains can be greatly improved on account of the grain boundary strengthening. In addition, the increase of weld pool volume can broaden the solidification interval of the molten pool and promote the full diffusion of the solutes at high temperatures. The temperature gradient can be also greatly diminished due to laser oscillating during the weld cooling process, thus decreasing the thermal stresses in welds [32]. It can be also observed that the weld pool rotates periodically during the laser oscillating process. The driving force produced by the oscillating laser can break dendrites and promote the solute migration. The full diffusion of the solutes can effectually enhance the matrix and eliminate the composition segregation, greatly reducing the susceptibility to solidification cracking. During laser welding, the synergy between liquid films and thermal stresses contributes to the occurrence of solidification cracking. Therefore, it is concluded that the solidification cracking in welds can be properly inhibited by reducing the composition segregation and the thermal stresses during laser oscillating welding.

4. Conclusions

The microstructure of the laser-welded steel/copper dissimilar metals was carefully studied in order to clarify the cause of solidification cracking, and then an effective solution of laser oscillating welding for inhibiting solidification cracking was proposed. The achieved conclusions can be summarized as follows:

- (1) Resolidified products were clearly observed along cracked grain boundaries in the fusion zone of welded steel/copper dissimilar metals. Grain boundary liquation and inclusions were the major factors responsible for solidification cracking in welds.
- (2) FZ solidification cracking in a welded sample proved that the occurrence of cracking was because of liquation of ϵ phase and inclusions associated with the composition segregation. The liquation of grain boundaries greatly weakened the cohesion between adjacent grains and reduced the plastic deformation capacity of the material itself.
- (3) The solidification cracking in welds could be effectively inhibited by reducing the composition segregation and thermal stresses using laser oscillating welding. It was mainly attributed to the adequate migration of solutes and a reduction of stress concentration because of the driving effect produced by the oscillating laser beam.
- (4) The tensile strength and strain of joints using laser oscillating welding are 251 MPa and 3.69, respectively, 35.7% more than 185 MPa and 96% more than 1.88 using laser welding, respectively.

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