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ARTICLE

Microstructure and Tensile Property of Electromagnetic Stirring Assisted Laser Repaired Inconel718 Superalloy

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Abstract: Inconel718 superalloy samples with V-grooves were experimentally repaired by electromagnetic stirring assisted laser repairing (EMS-LR) under different magnetic field currents. The effects of the magnetic field current on morphologies of single pass repaired zone (RZ), microstructure and mechanical properties of multilayer RZ were experimentally investigated. Microstructure observations show that metallurgical bonding is obtained between the RZ and the substrate when the optimized process parameter is used. The microstructure in RZ is coarse columnar crystal when no electromagnetic stirring is used, which grows epitaxially along the deposition direction. With the increase of magnetic field current, the convection of liquid metals prompts the transformation from coarse columnar to fine equiaxed grains. The strong scour of liquid metal convection can affect the interdendritic γ+Laves eutectic reaction and prohibit the growth of Laves phase. Electromagnetic stirring can improve the spreading of liquid metal in a certain extent. The width and deposition height of the single trace were measured and it is found that the width and deposition height ratio changes from 3.26 when no electromagnetic stirring is used to 3.33, 4.14 and 5.14 when the applied magnetic field current is 20, 40 and 60 A, respectively, and the penetration is found to be decreased inversely. The tensile strengths of repaired components increase from 487 MPa to 510, 673 and 770 MPa for magnetic field currents of 0, 20, 40 and 60 A, respectively.

Key words: electromagnetic stirring; laser repairing; superalloy

Inconel718 superalloy has been widely used in aviation, aerospace, nuclear industry and other fields[1] for its high temperature strength, excellent creep and fatigue performance, good processing and welding performance. During its service, damages of expensive parts could not be avoided and it will cost a lot to replace it with a new one. The repairing of the damaged parts is economical for the user. Laser additive manufacturing technology (LAM) was developed in 1980s, which not only can be used for rapid manufacturing of metal parts, but also can be used for laser repairing (LR) of complex shape and large volume manufacturing defects, error processing damage or damage to parts in working[2,3]. However, for the repairing of superalloy parts, the formation of brittle Laves phase was found to be harmful to the mechanical properties of the repaired parts. The presence of second phase particles and metal carbides (MC) in γ grains was found to be responsible for hydrogen induced cracking[4]. Zhang et al observed a large number of Laves phase in the repaired zone and stress concentration was caused for the dislocations can not pass the Laves phase easily, which creates the possibility of crack source in the Laves phase and γ substrate interface[5]. Ming et al also found the brittle Laves phase between dendrites, which provides a favorable position and channel for the origin and propagation of the crack[6].

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Moreover, the laser repairing of the damaged parts could lead to the generation of the coarse grain structure, which also has a great influence on the plasticity of the repaired zone[7,8].

In the casting field, researchers have found that the adding electromagnetic stirring (EMS) can effectively refine the solidified grain structure, uniform the distribution of inclusions and improve the mechanical properties of materials[9-12]. By adding electromagnetic field to welding, the magnetic field have a significant effect in improving the welding quality to a certain extent, e.g. reducing defects, improving the uniformity of microstructure composition and reducing the residual stress in the testing process [13]. In the area of laser additive manufacturing, some researchers have also reported their application of EMS in rapid forming. Yu [14] et al. have studied the effect of electromagnetic stirring on microstructure of the laser solid formed GH4169 superalloy. They found EMS has caused the strong convection of liquid metal in the molten pool. The convection reduced the interdendritic eutectic Laves phase in the deposited state and increased the microhardness of the material. Yang [15] et al investigated the using of electromagnetic stirring device laser deposition forming of titanium alloy to modify the microstructure and the experiments showed that the magnetic stirring can refine the microstructure of the deposition layer and improve the mechanical properties of the deposition layer.

As for the repair of damaged parts, high temperature heat treatment is not allowed for the maintaining of original microstructure of the substrate, therefore, the mechanical properties of the RZ metal will be affected by the as-repaired microstructure. For Inconel718 superalloy, Laves phase is a detrimental phase with high melting point and brittle nature. To improve the mechanical properties of the material, the morphology and fraction of Laves phase should be controlled to a certain extent. To achieve this, electromagnetic stirring may be a useful method. In this paper, laser repairing combined with electromagnetic stirring was used to repair Inconel718 superalloy samples. It is expected to enhance the density of the repaired structure, modify the structure of Laves phase, achieve the grain refinement, and improve the comprehensive mechanical properties of the repaired parts.

1 Materials and Experimental Procedures

1.1 Experimental materials and equipments

The laser repair equipment used in this experiment is a LDF-6000-60 laser additive manufacturing system built by Shenyang University of Aeronautics and Astronautics. The system is composed of six parts, which are made up of 6550 W fiber laser generator, optical path transmission system, inert gas processing room, powder transmission system, electromagnetic stirring system and numerical control table. The model of the electromagnetic stirring equipment is a self-developed 350 type and the stirring frequency is 15 Hz, and the electromagnetic stirring current is set to 0, 20, 40 and 60 A, respectively in this experiment.

The base material used in experiment was Inconel718 superalloy in solution heat treatment condition, and the metal powder prepared by plasma rotating electrode method was fed into molten pool to achieve the deposition of metals in RZ. The particle size is ~175 μm. The nominal chemical composition of Inconel718 superalloy and powder are listed in Table 1.

1.2 Experimental methods

Single track deposition experiments were carried out with applied magnetic field current of 0, 20, 40 and 60 A. The metal surface spreading of single track deposition can be used to represent the wettability of liquid metal during laser repairing and the width and penetration ratio (R) of single track deposition can represent the wettability the spreadability of reactive metal. With the increase of R, the spreadability of RZ becomes better [16,17]. As shown in Fig.1, RW, RH and RD mean the single track width, deposition height and penetration, respectively. R=RW/(RH+RD) stands for the spreading of the metal, and Y=RW/RD reflects for the penetration ratio of single track.

According to the crack damage characteristics of aeronautical thin-walled components of Inconel 718 alloy, the substrate is processed into a V type groove by the electric spark wire cutting. The samples were washed with acetone and sanding to clean the oil stain and oxides before repair. The V groove size of repaired components is 60 mm × 40 mm ×10 mm (length×width×height) and launch angle is 50°, as shown in Fig.2.

The Inconel718 alloy powder was dried in a vacuum furnace before laser repair. The drying temperature was 150 °C and the drying time was more than 4 h, and then cooled to room temperature in the vacuum furnace. The magnetic field current of 0, 20, 40 and 60 A are selected, and the processing parameters are listed in Table 2.

Metallographic samples were corroded by a mixture solution of 8 mL H_2O+4 mL HCl+2 mL H_2O_2+1 mL HNO_3

Table 1 Nominal chemical compositions of Inconel718 superalloy and powder (wt%)

Element	Inconel718	Powder
Nb	4.75	4.91
Cr	21	19.68
Ni	55	51.75
Al	0.3	0.63
Ti	0.75	0.97
Mo	2.8	3.18
Mn	<0.11	0.11
Si	<0.23	0.23
S	<0.001	0.001
P	<0.004	0.004
Fe	Bal.	Bal.

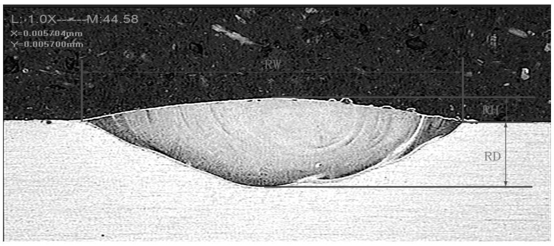

Fig.1 Morphology of cross section of a single track deposition

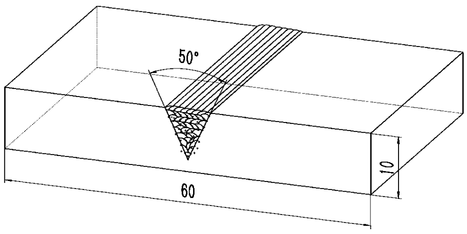

Fig.2 Sketch of substrate and laser repairing processing V groove crack damage model

Table 2 Processing parameters of laser repairing of Inconel718 superalloy samples assisted by electromagnetic stirring

Parameters	Value
Power/W	1400
Scanning speed/mm·s^{-1}	6
Powder feeding speed/g·min^{-1}	4
Shield gas flow/L·min^{-1}	6
Laser spot diameter/mm	3
Over laps/%	25
Deposition height of each layer/mm	0.3
Magnetic current/A	0, 20, 40, 60

after the rough grinding, fine grinding and polishing processing. Metallographic microstructure of repaired zone and transition zone were observed and analyzed.

Tensile specimens of EMS-LR Inconel 718 alloy were cut by electric spark wire along the direction perpendicular to the laser scanning direction and from the center of the repaired sample. The size of the tensile specimen, as well as the cutting position is shown in Fig.3. The tensile properties of the repaired specimens were tested on a WDE-E200D type tensile testing machine and the tensile rate was 1 mm/min.

2 Results and Discussion

2.1 Spreadability of laser deposited single track

The macro morphologies of single tracks deposited with different magnetic field currents are shown in Fig.4. The

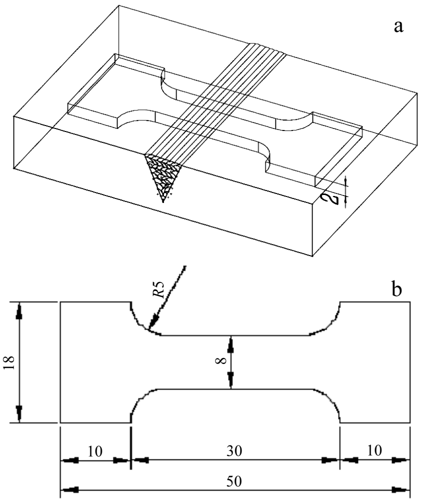

Fig.3 Diagram of interception position (a) and nonstandard tensile specimen of Inconel718 superalloy after electromagnetic stirring assisted laser repairing (b)

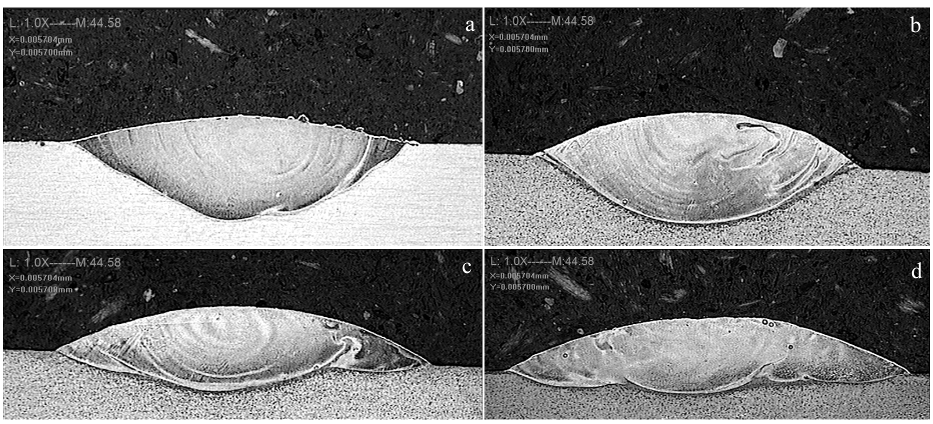

Fig.4 Macro morphologies of single tracks of Inconel718 samples deposited with different magnetic field currents: (a) 0 A, (b) 20 A, (c) 40 A, and (d) 60 A

liquid metal vortex traces appear evidently in the molten pool when electromagnetic stirring was applied. With the increasing of numerical magnetic field current, convection of liquid metal is more significant, and the vortex is clear after the solidification of liquid metal. The electromagnetic stirring is very intense when the magnetic field current reaches 60 A. The liquid metal spreading is very wide and no porosity or incomeplete fusion phenomenon appears as seen from Fig.4.

By measuring the track width, deposition height and penetration of single track with laser manual measuring instrument, the measured results are listed in Table 3. It is found that with the increase of magnetic field current, the width and penetration R and penetration ratio Y numerical value increases gradually, which indicates that the surface of repaired zone spreads better[18].

2.2 Macro morphologies and microstructure of laser repaired blocky specimen

The macro morphologies of the laser repaired blocky samples are shown in Fig.5. All the processing parameters used are the same except the magnetic field currents applied. The repaired sample without EMS is shown in Fig.5a, and Fig. 5b~5d are repaired samples deposited with magnetic field currents of 20, 40 and 60 A, respectively. Fig.5a shows the macro morphology of laser repaired sample without adding of magnetic field current, and it can be seen that there is a single track forming trajectory obviously. There is a shallow groove between adjacent single tracks due to the presence of a large surface tension of the molten metal which resulted in not fully expanding of the molten metal. The surface of the deposited layer is becoming smoother when the applied magnetic filed intensities increase, as shown in Fig.5b~5d. The smoothing was attributable to a case that Lorentz force was produced in liquid metal by electromagnetic stirring process and this made the liquid metal convert in molten pool sharply. The effect of convection overcomes the viscous resistance of surface tension and spreading, forming a relatively smooth surface. With the increase of magnetic field current to 20 A, the trace of single track becomes indistinct, but the last track of repaired morphology is still observed as shown in Fig.5b. It is not easy to observe the forming trajectory obviously in Fig.5c when the applied magnetic field current is 40 A, and the surface forming is uniform and smooth. The morphology of repaired sample with a magnetic field current of 60 A is irregularity surface and smooth forming relatively. It can be seen that with the increasing of the magnetic field current, the surface morphology is smoother. Electromagnetic stirring can achieve a significant improvement in the spreadability of the liquid molten metal. This agrees with the experimental results in Fig.4 and Table 3.

To compare the microstructures of laser repaired Inconel718 superalloy samples with or without magnetic stirring, optical metallurgical images were observed and the results are shown in Fig.6. Three regions can be divided from the repaired sample, i.e. the substrate, the heat affected zone (HAZ) and the repaired zone (RZ) from the left to right. As shown in Fig. 6a, the RZ has finecolumnar dendrite epitaxia lly growing from the substrate when no electro-magnetic stirring was used. There is no obvious metallurgical defect and the bonding with the substrate is good. The HAZ contains irregularly distributed crushing grains, forming a narrow transition zone between the substrate and the repaired zone. The grains in substrate are equiaxed. As shown in Fig.6b, no obvious grain boundaries are observed in HAZ that means the solution of precipitates and the coursing of the grain size, when the electromagnetic stirring was assisted tothe repair ing processing.

Table 3 Measurement results of dimensions of single track deposited with different magnetic field currents

Measured parameters	Magnetic field current, I/A			
	0	20	40	60
Width, RW/mm	3.03	3.11	3.45	3.96
Height, RH/mm	0.24	0.36	0.5	0.55
Penetration, RD/mm	0.69	0.57	0.33	0.22
Width to penetration ratio, R	3.26	3.33	4.14	5.14
Penetration ratio, Y	4.39	5.45	10.43	18.3

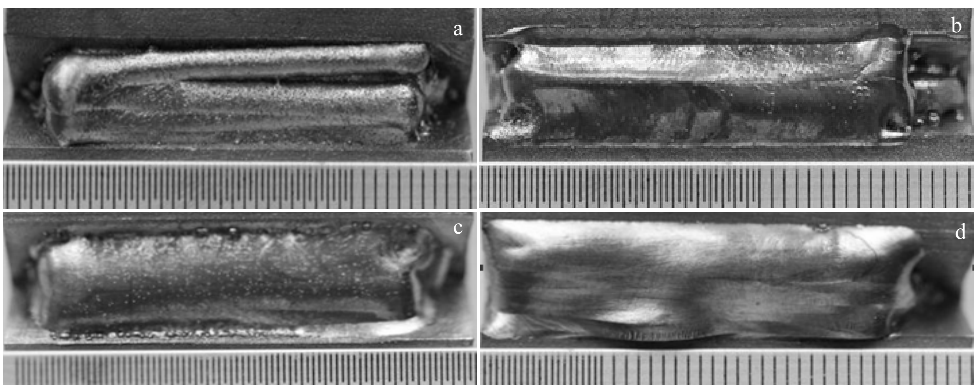

Fig.5 Macro morphologies of laser repaired Inconel718 superalloy samples deposited with different magnetic field currents: (a) 0 A, (b) 20 A, (c) 40 A, and (d) 60 A

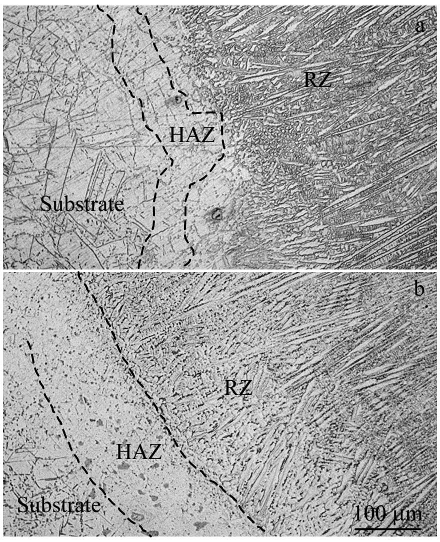

Fig.6 Microstructure of repaired Inconel718 superalloy samples deposited without (a) or with magnetic field stirring with a magnetic field current of 60 A (b)

The solidification process of Inconel718 alloy can be reduced to L→γ+ L → (γ+ NbC) + L →γ+ L →γ+ Laves[19]. Therefore, the solidification process of molten pool in laser repaired Inconel 718 alloy will also form γ phase, NbC phase and γ+Laves eutectic phase orderly. Fig.7 shows the scanning electron micrographs of laser repaired Inconel718 alloy with different magnetic field currents. Obviously, there are a large number of continuous strip eutectic Laves phase in the sample without adding of electromagnetic stirring, as shown in Fig.7a, and these Laves phase are located in the interdendritic areas because the eutectic action occurs in the last period of the solidification. Fig.7b and 7c show after the application of electromagnetic stirring, the morphology of eutectic Laves phase changes from continuous distribution to discontinuous distribution with a smaller size. The eutectic Laves phase has transformed to fine particles and its fraction decrease apparently when the magnetic field current is 60 A, as shown in Fig.7d. The results show that the convection of liquid metal with magnetic stirring under the solid/liquid interface can change the morphology of the interdendritic eutectic microstructure with the increase of magnetic field current. The strong scouring of liquid metal convection can affect the interdendritic γ + Laves eutectic reaction and prohibit the rapid growth of Laves phase.

2.3 Tensile properties of laser repaired specimens

Fig.8a shows the fractured EMS-LR samples and longitudinal section in as-repaired condition after tensile testing at room temperature. With the increase of the magnetic field current, the ductility of the repaired samples increases. The plastic deformation is the biggest when the magnetic field current is 60 A. According to fracture location of longitudinal section it can be seen that all repaired specimens are broken in the repaired zone. Though the crack initiation areas are located in the fusion zone or heat affected zone as shown, their crack propagations mainly occur in the repaired zone, and generally along the arc lines as shown. This indicates that the discontinuous microstructure at the arc lines of two adjacent passes can lead to stress concentration and cracks.

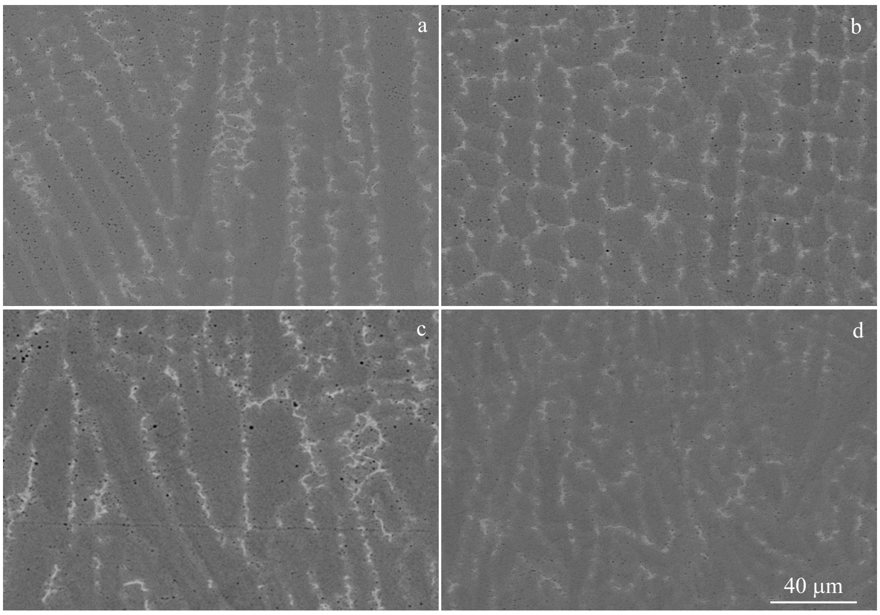

Fig.7 Morphologies of Laves phase in RZ of laser repaired Inconel718 superalloy samples with different magnetic field currents: (a) 0 A , (b) 20 A, (c) 40 A, and (d) 60 A

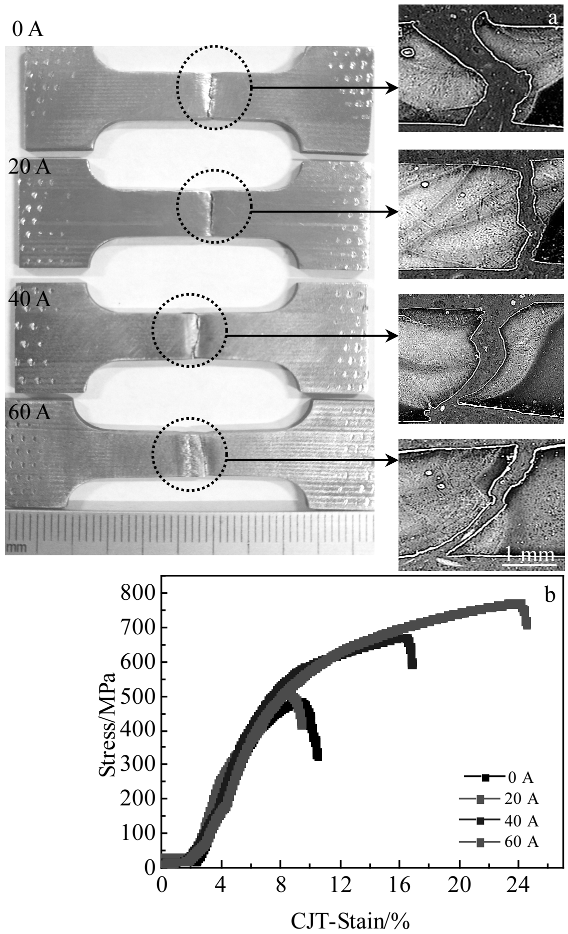

Fig.8 Fractured samples (a) and their stress-strain curves (b) of laser repaired Inconel718 superalloy samples deposited with different magnetic field currents

The stress-strain curves of laser repaired specimens under different magnetic field currents are shown in Fig.8b. The maximum tensile strength of repaired sample in as-repaired condition is 487 MPa when no electromagnetic stirring was used. The tensile strengths of repaired components increase from 487 MPa to 510,673 and 770 MPa for magnetic field currents of 20, 40 and 60 A, respectively. The tensile strength of repaired specimens are visibly improved by electromagnetic stirring. This is because the increase of the magnetic field currents, which intensifies the convection of the laser melting pool, and accelerates the cooling rate of the melt pool, making the microstructure of the repaired zone be refined and improving the tensile strength of the repaired specimen. Due to the high content of Nb in the superalloy, a large number of brittle Laves phase and MC carbides are formed, and Nb is also consumed, which reduces the precipitation of the strengthening phase. However, the liquid metal convection of electromagnetic stirring can affect the interdendritic γ +Laves eutectic reaction and prohibit the growth of Laves phase. The plasticity of the repaired specimens is visibly improved, due to the fact that the volume fraction of Laves phase is visibly decreased as shown in Fig.7a~7d.

Fig.9 shows the fracture surfaces of the samples after tensile testing at room temperature. From the SEM images of fracture, whether or not there is a magnetic field applied during laser repair, all the fractures are typical ductile fracture. Fracture originates from micro cracks and inclusions of repaired samples. The fracture is mainly divided into two areas: the fibrous zone and shear zone. The area of fibrous zone gradually increases and the area of shear zone increases with the increase of magnetic field current. Fig.10 shows the higher magnification images of the fracture surfaces. The fibrous zones of EMS-LR samples have a large number of

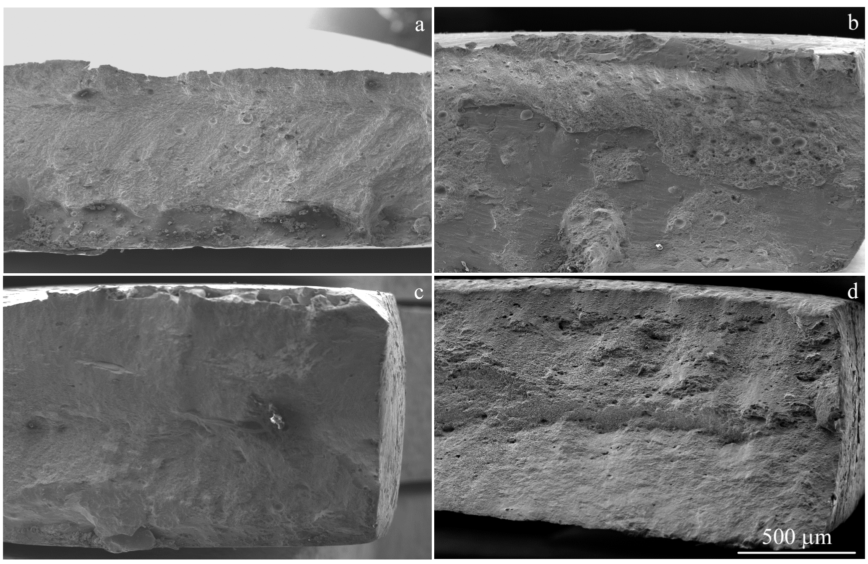

Fig.9 Fracture surfaces of laser repaired Inconel718 superalloy samples deposited with different magnetic field currents: (a) 0 A, (b) 20 A, (c) 40 A, and (d) 60 A

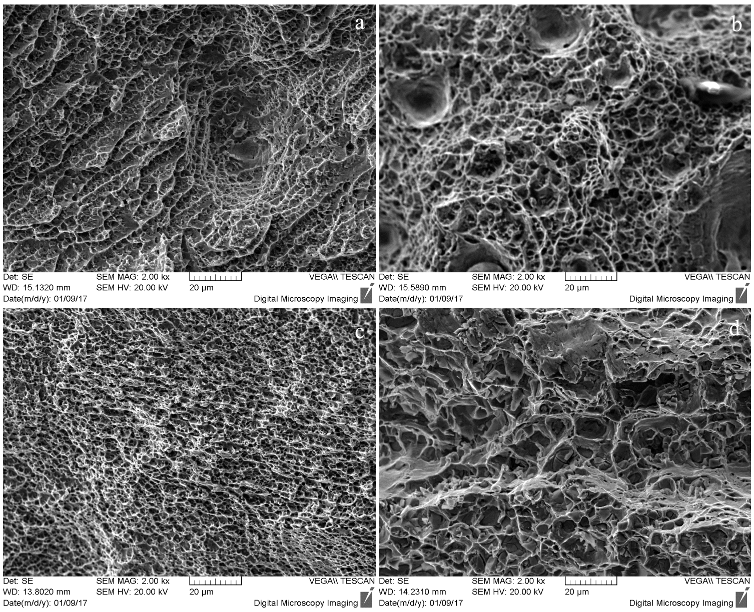

Fig.10 Fracture surfaces of laser repaired Inconel718 superalloy samples deposited with different magnetic field currents: (a) 0 A , (b) 20 A, (c) 40 A, and (d) 60 A

dimples, including non directional dimples (Fig.10b) and obvious direction arrangement dimples (Fig.10c). There are some obvious dimples from the four samples and small particles are observed in some dimples. This is because of the second phase particles unstuck with the matrix metal under shearing loads, and this may cause the early formation of micro cracks which could reduce the ductility of the sample. And for most conditions, these particles are large sized Laves phase in the interdendritic areas.

3 Conclusions

1) Electromagnetic stirring can enhance the spreadability of liquid metal to affect the formation of single track. The width and deposition height ratio of cladding pool changes from 3.26 when no electromagnetic stirring is used to 3.33, 4.14 and 5.14 when the applied magnetic field current is 20, 40 and 60 A, respectively.

2) Electromagnetic stirring has an effect on the heat transfer and narrow the heat affect zone of the repaired sample. The strong scour of liquid metal convection can affect the γ+Laves eutectic reaction in the interdendritic area and inhibit the formation of Laves phase.

3) Electromagnetic stirring can improve the tensile property of laser repaired Inconel718 alloy samples. The tensile strengths of repaired components increase from 487 MPa to 510, 673 and 770 MPa under magnetic field currents of 20, 40 and 60 A.

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电磁辅助激光修复 Inconel718 高温合金的组织及拉伸性能

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摘　要：以镍基高温合金 Inconel718 为研究的修复材料，对损伤 V 型槽添加不同磁场电流进行了电磁搅拌辅助激光修复试验，研究了不同磁场电流对单道修复形貌和多层修复区组织性能的影响。显微组织表明：优化工艺参数后使激光快速成形的修复区和基体形成了致密的冶金结合，未施加电磁搅拌的修复区组织为沿沉积方向外延生长的粗大柱状晶，随着磁场强度增大，液态金属的对流作用加剧，液态金属强烈的对流作用对枝晶间 γ+Laves 共晶反应有影响，抑制 Laves 相的生长。电磁搅拌在一定程度下可以提高液态金属的铺展性，未添加磁场时单道的沉积宽度与沉积高度比为 3.26，随着磁场强度（20、40 和 60 A）增大，高度比分别为 3.33、4.14 和 5.14。对修复件进行了拉伸性能测试，未施加磁场时，修复件的抗拉强度最高为 487 MPa，随着磁场强度（20、40、60 A）增加，抗拉强度逐渐得到提升，分别为 510、673 和 770 MPa。

关键词：电磁搅拌；激光修复；高温合金

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