LASER WELDING OF SINGLE CRYSTAL NICKEL BASE SUPERALLOY CMSX-4

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ABSTRACT

In this paper, applicability of laser welding to joining process of single crystal nickel base superalloy turbine blades was investigated. Because heat input of laser welding is more precisely controlled than TIG welding, it is possible to optimize solidification microstructure of the welds. Since in single crystal nickel base superalloy the crystal orientation have a significant effect on the strength, it is important to control the solidification microstrucure in the fusion zone. A single crystal nickel base superalloy, CMSX-4, plates were bead-on welded and butt welded using a CO_2 laser. The effects of microstructure and crystal orientation on properties of the weld joints were investigated.

In bead-on welding, welding directions were deviated from the base metal [100] direction by 0, 5, 15 and 30 degrees. The welds with deviation angles of 15 and 30 degrees showed fusion zone transverse cracks. As the deviation angles became larger, the fusion zone had more cracking. In the cross section microstructure, the fusion zone grains in 0 and 5 degrees welds grew epitaxially from the base metal gains except for the bead neck regions. The grains in the bead neck regions contained stray crystals. As deviation angles increased, number of the stray crystals increased.

In butt welding, the declinations of the crystal orientation of the two base metals varied 0, 5 and 10 degrees. All beads had no cracks. In the 5 degrees bead, the cross section and surface microstructures showed that the fusion zone grains grew epitaxially from the base metal grains. However, the 10 degrees bead, the bead cross section and surface contained the stray crystals in the center of the welds.

Orientations of the stray crystals accorded with the heat flow directions in the weld pool. When the welding direction was deviated from the base metal [100] direction, cracks appeared in the area including the stray crystals. The cracks developed along the grain boundaries of the stray crystals with high angles in the final solidification regions at the center of the welds. The fracture surfaces were covered with liquid film. The cracks, therefore, found to be solidification cracks due to the presence of low melting eutectic. As the results, in both bead-on welding and butt welding, the deviation angles should be control within 5 degrees for preventing the fusion zone cracks.

To investigate the mechanical properties of the weld joints, high temperature tensile tests for bead-on welds with deviation angles of 0 and 5 degrees and the butt welds with declination angles of 0, 5 and 10 degrees were conducted at 1123K. The the tensile strength of all weld joints were more than 800MPa that is almost 80% of the tensile strength of the base metal. The strength of the laser weld joints were more than twice that of the TIG weld joints with a filler metal of Inconel 625. The results reveals that laser welding is more effective joining process for single crystal nickelbase superalloy turbine blades than TIG welding.

KEYWORDS

Laser welding, single crystal nickel base superalloy, CMSX-4, Microstructure, Solidification cracking,, Joint strength

1. Introduction

Nickel based superalloys are commonly used in both aircraft and land based turbine energy systems because of their excellent high temperature mechanical properties, in particular, their exceptional high temperature creep resistance. In recent applications, single crystal nickel based superalloys having no grain boundaries have been used so that high temperature creep performance is further improved1). However, the cost of a modern single crystal turbine blade is significantly higher than conventional equiaxed alloys. Therefore, it is important to study welding technology of single crystal nickel based superalloys for repairing turbine blades. For the effective use of welds, not only must the alloys be weldable, but there is also need for microstructural control so that welds perform adequately in service2). Although generally TIG welding, electron beam welding and diffusion bonding have been applied to welding of nickel base superalloys, in this paper, applicability of laser welding to joining of single crystal nickel base superalloy turbine blades was investigated. Because heat input of laser welding is more precisely controlled than TIG welding, it is possible to optimize solidification microstructure of the welds. In single crystal nickel base superalloys, the crystal orientation has a significant effect on the strength. So we investigated how the solidification microstructures and crystal orientations in the weld fusion zones changed when welding directions were deviated from the base metal [100] direction in bead-on welding and the declinations of the crystal orientation of the two base metals varied 5 and 10 degrees in butt welding. Then, in such cases, we clarified the effects of the weld microstructures on the mechanical properties of the weld joints in high temperature tensile tests.

2. Experimental Procedure

The material used in the present study was a single crystal nickel based superalloy, CMSX-4, subjected to a solution treatment and an aging treatment. The heat treatment conditions and chemical compositions of CMSX-4 are shown in Tables 1 and 2. Thickness of the plate was 2.0mm. Laser welds were made with 3kW CO_2 CW laser. Welding speed was 3000mm/min with a heat input of 50 J/mm. In the bead-on welding, welding directions were deviated from the base metal [100] direction by 0, 5, 15 and 30 degrees. In butt welding, the declinations of the crystal orientation of the two base metals varied 0, 5 and 10 degrees.

After welding, the weld bead crosssections were prepared for metallographic examinations and were mechanically polished. The solidification microstructure was observed by an optical microscope and crystal orientation analysis of the welded specimens was performed using electron backscattering pattern (EBSP). To investigate the mechanical properties of the weld joints, high temperature tensile tests for bead-on welds with deviation angles of 0 and 5 degrees and the butt welds with declination angles of 0, 5 and 10 degrees were conducted at 1123K with a strain rate of 5• 10^{-5}mm/s.

Table 1 Heat treatment conditions of CMSX-4

Sample	Heat treatment condition
Solution	**1553K-2H• 1563K-2H• 1593K-2H• GFC**
Aging	**1353K-4H• 1143K-20H• GFC**

Table 2 Chemical composition of CMSX-4

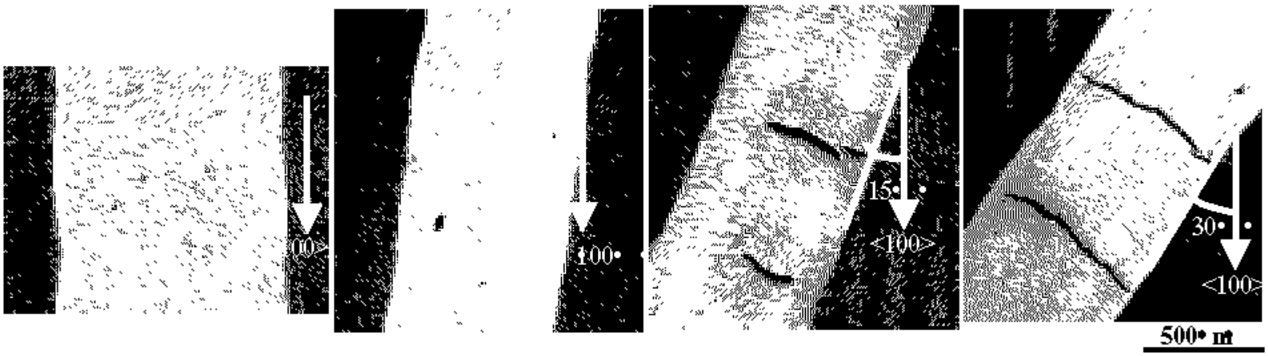
Sample	Chemical compositions (mass%)							
CMSX-4	C	Cr	Mo	Ti	Co	B	Al	Nb
	0.0018	**6.4**	**0.6**	**1.0**	**9.6**	**0.002**	**5.6**	**-**
	Ta	W	Zr	Hf	Re	P	S	Ni
	6.5	**6.4**	**-**	**-**	**3.0**	**<0.002**	**0.0002**	**Bal.**

3. Results and discussion

3.1 Microstructure

3.1.1 Bead-on welding

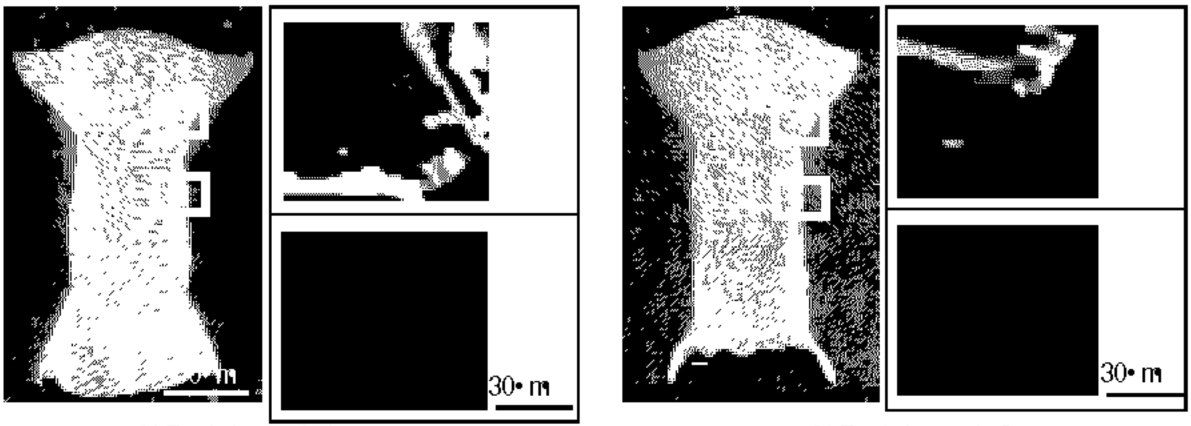
Figure 1 shows the top surface optical micrographs of the fusion zones in bead-on welding with welding directions being deviated from the base metal [100] direction by 0,5,15 and 30 degrees. As shown in Fig.1, the welds with deviation angles of 0 and 5 degrees had no cracking. However, the welds with deviation angles of 15 and 30 degrees included fusion zone transverse cracks. As the deviation angles increased, the fusion zone had more cracking.



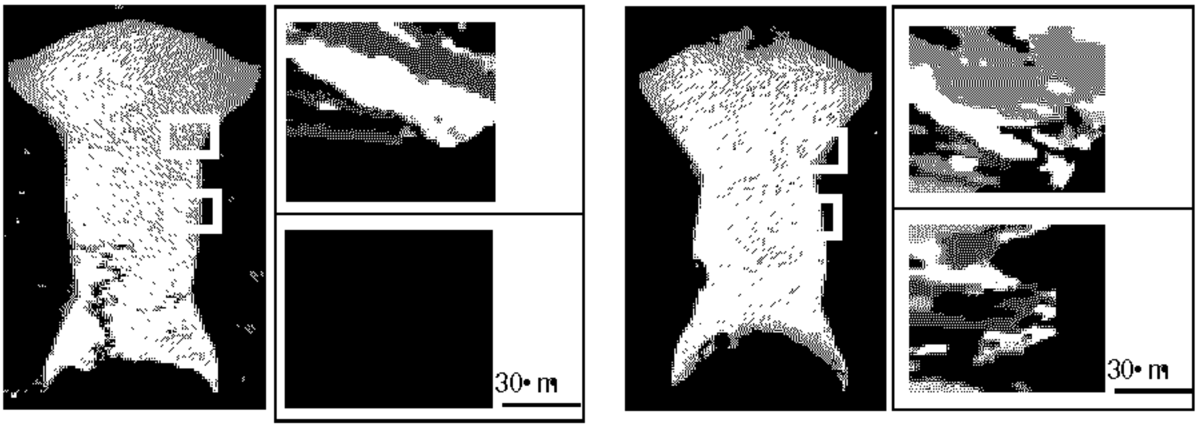
(a) Deviation angle:0• • (b) Deviation angle:5• • (c) Deviation angle:15• • (d) Deviation angle:30• •

Fig.1 Top surface optical micrographs of the bead-on welds in CMSX-4

Then, Fig.2 shows cross-sectional optical micrographs of the fusion zones and results of EBSP. In the EBSP maps dark and light graded regions exhibit grains having the crystal misorientation to adjacent grains lager than approximately 5 degrees. Thus, the black regions have the same crystal orientation as the single crystal base metal. The fusion zone crystals in the welds with deviation angles of 0, 5 and 15 degrees grew epitaxially from the base metal gains excepting the bead neck regions. The grains in the bead neck regions contained stray crystals whose orientations deviated from that of the base metal. As deviation angles increased, number of the stray crystals increased. This is because the deviation between the heat flow direction within the fusion zone in welding and the base metal [100] became larger with increasing deviation angles between welding direction and the base metal [100]. Although the bead neck regions contained stray crystals regardless of the deviation angles, it is possible to make the major part of the fusion zones the single crystal having the same crystal orientation as the base metal when deviation angles are within 5 degrees.



(a) Deviation angle:0• • (b) Deviation angle:5• •

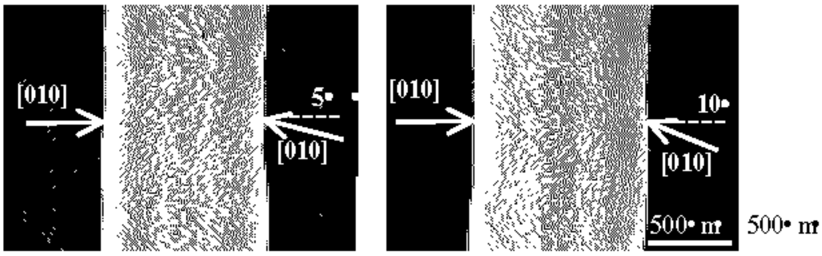


(c) Deviation angle:15• • (d) Deviation angle:30• •

Fig.2 Results of EBSP analysis of the weld bead cross-sections of bead-on welds in CMSX-4

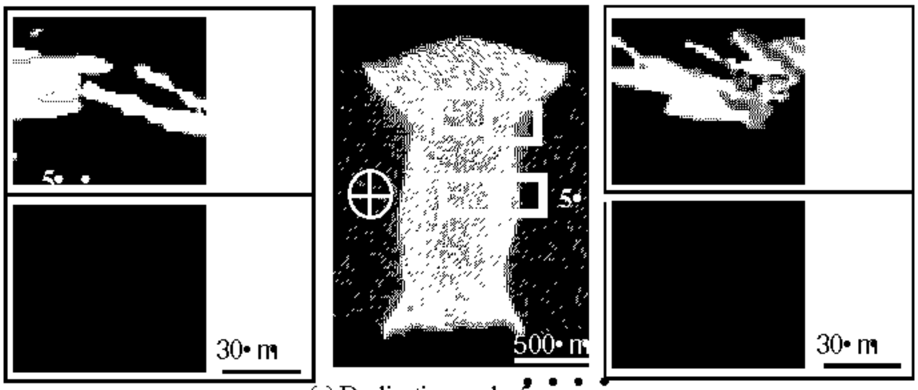
3.1.2 Butt welding

Figure 3 shows the top surface optical micrographs of the fusion zone in butt welding with the declinations of the crystal orientation of the two base metals varying 5 and 10 degrees. Both beads had no cracks. Figure 4 shows the results of EBSP analysis of the weld bead cross-sections. In the 5 degrees bead, the cross section and top surface microstructures showed that the fusion zone crystals grew epitaxially from the base metal grains except for the bead neck regions. However, in the 10 degrees bead, the bead cross-section and surface contained more stray crystals also in the center of the welds. As shown in Figs. 3 and 4, since the fusion zone grains grew epitaxially from each base metal toward the bead center, the declinations of the crystal orientation of the two base metals resulted in a crystal misorientation between the grains encountering each other at the center of the fusion zone. Therefore, the center of the fusion zone was small angle boundary with a misorientation angle of 5 or 10 degrees.

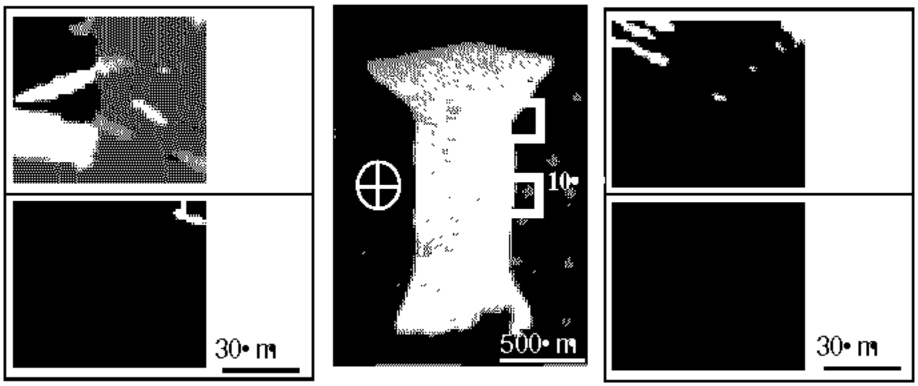


(a) Declination angle: 5• • • • • (b) Declination angle: 10• •

Fig.3 Optical micrographs of the weld bead surface of butt welds in CMSX-4



(a) Declination angle: 5• • • •



(b) Declination angle: 10• •

Fig.4 Result of EBSP analysis of the weld bead cross-sections of butt welds in CMSX-4

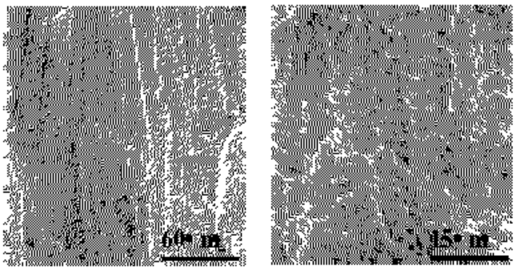
3.2 Stray crystals and cracks

EBSP analysis was performed on the vicinity of the fusion zone cracks in the bead-on weld with the deviation angle of 30 degrees. Figure 5 shows the optical micrograph and the results of EBSP analysis. The <100> direction of the stray crystals may accord with the heat flow directions in the weld pool. When the welding direction was deviated from the base metal [100] direction, cracks appeared in the area including the stray crystals. The cracks developed along the grain boundaries of the stray crystals with large misorientation angles in the final solidification regions at the center of the welds. Consequently, the welds with the deviation angles of 0 and 5 degrees, which includes few stray crystals, have no fusion zone transverse cracks.

Fig.5 Results of EBSP analysis of the bead-on weld with the deviation angle of 30 degrees

The fracture surface of the fusion zone crack was observed using scanning electron microscope (SEM). Figure 6 shows SE image of the fracture surface of the crack. The fracture surface had the dendritic nature and the traces of liquid film. The cracks are, therefore, found to be solidification cracks as the result of the presence of a low melting eutectic.

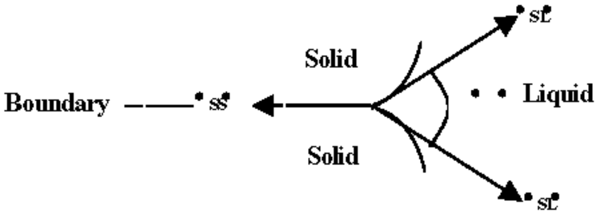
Thus, segregation at the grain boundaries was investigated. Chemical composition analysis with electron prove micro analyzer (EPMA) was performed at grain boundaries of the stray crystals and those of the epitaxial crystals from the base metal. Ti,



(a) Low magnification (b) High magnification

Fig.6 SE images of fracture surfaces of solidification crack

Al and Ta, which were formation elements of • ’• phase, segregated at both dendrite boundaries. It is believed from the results that • /• ’• eutectic existed as the residual liquid phase in the final solidification regions at the dendrite boundaries. However, no significant difference in the extent of the segregation was found between the two kinds of the dendrite boundaries. Thus, the cause of generating solidification cracks is considered to depend on interfacial energy ratio of solid phase and residual liquid phase. Figure 7 shows a schematic diagram of interfacial energy balance at the liquid/solid interface. As the difference in crystal orientations of adjacent grains is larger, the solid/solid interfacial energy • $_{ss}$• increases and thereby the solid/liquid contact angle • decreases. Smaller • will result in enhancing wetting between the liquid phase and solid phase. This promotes penetration of liquid phase to the grain boundaries. Thus formed liquid film along the grain boundaries will enhance the sensitivity to solidification cracking. Consequently, since the grain boundaries of the stray crystals with large misorientation angles have high interfacial energy, solidification cracking tends to occur at the grain boundaries. As the results, in both bead-on welding and butt welding, the deviation angles should be control within 5 degrees for preventing the solidification cracks.



• $_{SL}$•: interfacial energy (solid-liquid)

• $_{SS}$•: grain boundary energy (solid-solid)

• : •contact angle of interface (solid-liquid)

$$\gamma_{SL} / \gamma_{SS} = \frac{1}{2\cos(\theta / 2)}$$

Fig.7 Relation between contact angle and interface energy at solidification interface

3.3 Mechanical property

To investigate the mechanical property of the weld joints, high temperature tensile tests for bead-on welds with deviation angles of 0 and 5 degrees and the butt welds with declination angles of 0, 5 and 10 degrees were conducted at 1123K. Figure 8 shows the results of the tensile tests of the CMSX-4 weld joins. The tensile strength of all laser weld joints was more than 800MPa that is almost 80% of the tensile strength of the base metal, and was also more than twice that of the TIG weld joint with a filler metal of Inconel 625.

Then we observed the fracture paths using optical microscope (Fig. 9) and the fracture surfaces using SEM (Fig.10) for the butt welds with the declination angles of 0 and 10 degree. In both welds, the fracture surfaces of area • •that correspond to the fracture paths of the top of the fusion zones showed the granular nature and those of area • •that correspond to the fracture path along approximately 45 degree direction to the [010] loading axis had the shearing feature. Therefore, it is considered that the fracture of area • •occurs at the grain boundaries of the stray crystals and/or the columnar grains encountering at the bead center. In the weld with the declination angles of 10 degree the latter should be dominant fracture path because of the crystal misorientation at the bead center. Thus, the fracture may initiate at the top of the fusion zone including misoriented grain boundaries and propagate to the bottom side where the sheared fracture along the {111} slip planes occurs. Since even the weld with the declination angle of 0 degree includes the grain boundaries of the stray crystals in the top portion, the declinations between the two base metals up to 10 degrees have no significant effect on the strength of the weld joints.

Consequently, when the deviation between the welding direction and the base metal in the bead-on welds is within 5 degrees and the declinations of the crystal orientations of the two base metals is within 10 degrees, the beads have no fusion zone transverse cracks and their tensile strengths were more than 800MPa that is almost 80% of the tensile strength of the base metal. The results reveals that laser welding is more effective process than TIG welding as joining process of single crystal nickel base superalloy turbine blades.

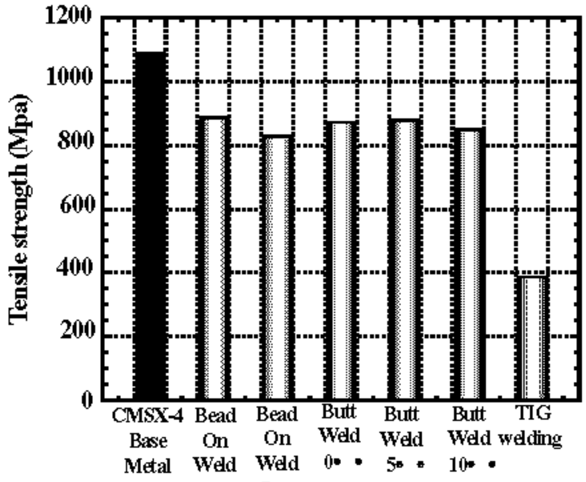
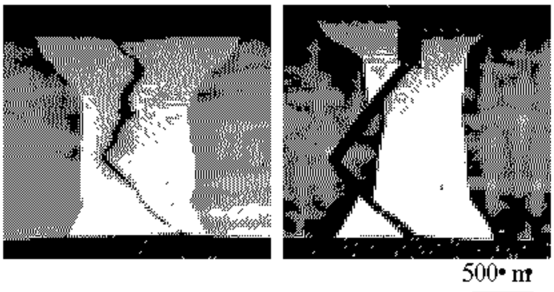
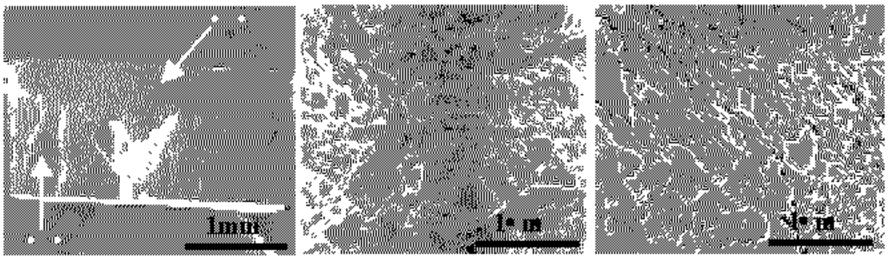


Fig.8 Results of tensile tests of CMSX-4 weld joins



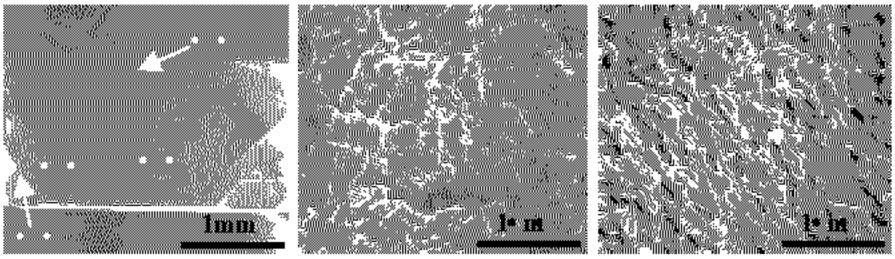
(a) Butt welds (declination angle:0•) • • • (b) Butt welds •declination angle:10• • • •

Fig.9 Optical micrographs of fracture path



(a) Low magnification • (b) High magnification• • • (c) High magnification
• • • • • • • • • • • of • •• • • • • • • • • • • of • ••• • • • • •

(•) Butt welds (declination angle: 0•)



(a) Low magnification (b) High magnification• • • (c) High magnification • •
• • • • • • • • • • • • of • •• • • • • • • • • • • of • ••• • • • • • • • •

(•) Butt welds (declination angle: 10•)

Fig.10 SE images of fracture surfaces of tensile test specimens

4.Conclusions

In this study, applicability of laser welding to joining process of single crystal nickel base superalloy turbine blades was investigated foundamentally. In bead-on welding, welding directions were deviated from the base metal [100] direction. In butt welding, the declinations of the crystal orientation of the two base metals varied 0 and 10 degrees. We investigated the solidification microstructure in the fusion zones, mechanical property of the welds.

1. In the bead-on welding, the welds with deviation angles of 0 and 5 degrees had no cracks. But the welds with deviation angles of 15 and 30 degrees showed fusion zone transverse cracks. As the deviation angle increased, the welds had more cracks. The fusion zone crystals in the welds with deviation angles of 0, 5 and 15 degrees grew epitaxially from the base metal gains excepting the bead neck regions. The grains in the bead neck regions contained stray crystals. As deviation angles increased, number of the stray crystals increased. It is possible to make the major part of the fusion zones the single crystal having the same crystal orientation as the base metal when deviation angles are within 5 degrees.
2. The fusion zone cracks developed along the grain boundaries of the stray crystals with large angles in the final solidification regions at the center of the welds. Since Ti, Al and Ta segregated at the dendrite boundaries, the cracks found to be solidification cracks as the result of the presence of the low melting eutectic of • /••'.•
3. In the butt welding, all beads with declination angles within 10 degrees had no cracks. Since the fusion zone grains grew epitaxially from each base metal toward the bead center, the declinations of the crystal orientation of the two base metals resulted in a crystal misorientation between the grains encountering each other at the center of the fusion zone. Therefore, the center of the fusion zone was a small angle boundary with misorientation angle of 5 or 10 degrees.
4. The tensile tests for bead-on welds with deviation angles of 0 and 5 degrees and the butt welds with declination angles of 0, 5 and 10 degrees were conducted at the 1123K. The tensile strength of all laser weld joints was more than 800MPa that is almost 80% of the tensile strength of the base metal, and was also more than twice that of the TIG weld joints with a filler metal of Inconel 625. The declination angles up to 10 degrees had no significant effect to the strength of the weld joints. The results reveals that laser welding is more effective process than TIG welding as joining process of single crystal nickel base superalloy turbine blades.•

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