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EFFECT OF PREWELD SURFACE MODIFICATION USING FRICTION STIR PROCESSING OF IN738 SUPERALLOY ON THE LIQUATION CRACKING OF AUTOGENOUS LASER WELDS

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Abstract

Heat affected zone (HAZ) liquation cracking is a major problem associated with fusion welding of precipitation hardened nickel base superalloys. For eliminating liquation cracking and improving weldability of IN738 superalloy, preweld friction stir processing (FSP) was used to provide a more crack-resistant microstructure at the surface. The liquation susceptibility of this surface layer is evaluated by narrow laser surface melting. The depth of melted layer is significantly smaller than the depth of friction stir processed zone. Scanning electron microscopy (SEM) studies revealed FSP led to a significant microstructure evolution such as grain refining and size reduction of secondary phases. Microstructural changes due to the FSP, for instance, reprecipitation of fine γ′ and redistribution of carbides provide a crack resistant microstructure to the extent required for the complete suppression of liquation cracking. This can be related to the faster solid state dissolution of the present secondary phase particles.
Key words: Friction stir processing, HAZ liquation cracking, nickel base superalloys

Introduction

HAZ liquation cracking

Heat affected zone (HAZ) liquation cracking is a major problem associated with fusion welding of nickel base superalloys. It is normally associated with local or partial melting in weld HAZ grain boundaries [1, 2]. Concurrent presence of liquid film and welding stresses and strains during weld cooling could result in HAZ liquation cracking by grain boundary separation [3, 4]. Liquation of grain boundaries may occur either by supersolidus melting or by non-equilibrium subsolidus melting. Subsolidus liquation

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may take place by constitutional liquation of second phase particles, eutectic melting of terminal solidification constituent of segregated cast structure and grain boundary liquation due to segregation of melting point depressing minor elements like boron and sulphur. Besides the occurrence of cracking due to the liquid film along the grain boundaries, re-solidified material could be brittle and contribute to subsequent cracking [1-4].

Liquation cracking of IN738 Nickel base superalloy and its elimination

INCONEL 738 superalloy is one of the most widely used superalloys in both land-based and aero gas turbine engines. The weldability of heat resistant nickel base superalloys has gained importance because of the wide use of welding to fabricate and repair service-damaged hot section components of gas turbines. Unfortunately, application of fusion welding to fabrication and repair of precipitation-hardened nickel base superalloys such as IN 738 has been severely restricted. This is because these alloys, especially those containing a substantial amount of Al and Ti (>6 wt.%), are highly susceptible to liquation cracking in the area of HAZ during welding. High susceptibility of these alloys to post weld heat treatment cracking has been also reported to correlate with high Al+Ti content and initiation of these cracks, mainly in the HAZ regions that had liquated during welding [4,5].

Microstructural characteristics of IN 738 are potentially detrimental in terms of increasing the grain boundaries liquation and consequently decreasing material resistance to HAZ cracking [6,7]. Substantial volume of possible liquating particles such as γ' precipitates which is the main strengthening phase of the alloy and other secondary solidification products such as carbides, borides, sulphocarbides and γ-γ' eutectic phase along the grain boundaries coupled with coarse grain structure and high level of segregation and inhomogeneity in the cast alloy contribute to high susceptibility of IN 738 alloy to liquation cracking during welding [8].

To eliminate or reduce the occurrence of grain boundary liquation during the welding of nickel base superalloys, especially those containing large amounts of (Ti-Al) such as IN738 alloy, several approaches have been used. These include preheating, welding above the homogenization temperature, development of a preweld heat treatment, using very low heat input welding processes such as laser cladding and utilizing low strength filler alloys [6-9]. Jahnke [10] has suggested that electron beam welding with a preheating of the alloy to above the homogenization temperature of 1120°C and the subsequent use of hot isostatic pressing can be used to weld IN 738LC without the use of a filler metal. Ojo et al. [6-8] and Chaturvedi et al. [1,3] have reported several grain boundary liquation-related phenomena in precipitation-hardened nickel base superalloys. They have indicated high susceptibility of these alloys to grain boundary liquation in various prior heat treatments, several filler metals and different welding processes. A more conventional method to prevent weld cracking in these alloys, however, is to use lower strength and ductile solid solution strengthened fillers such as IN 625. However, the welds produced by these fillers, even if relatively crack free, have inferior mechanical properties. Attempts are, therefore, being made to carry out welding with the help of stronger age hardenable fillers that more closely match the base metal properties. However, the use of these fillers promotes the tendency to liquation cracking. The preweld heat treatment can improve the weldability of IN 738 alloy through a combination of improved ductility and a desirable microstructure but it is indicated that grain boundary liquation is not completely eliminated through the preweld heat treatments. Ojo et al. [6-8] and Chaturvedi et al. [1,3] have indicated high susceptibility of these alloys to liquation cracking in various prior heat treatments and different welding processes.

A new approach for elimination of IN738 liquation cracking

Significant efforts have been made toward eliminating the grain boundary liquation cracking of nickel base superalloys. However, none of them have been efficient and/or completely successful because they cannot completely alter the liquation related microstructural features of the alloy. For instance, it is known that various heat treatments cannot suppress the liquation cracking because by applying these treatments it was not possible to produce suitable microstructural conditions.

This work examines an alternative approach which can effectively change the detrimental microstructural features in terms of grain boundary liquation and, therefore, can produce a liquation resistant microstructure. The material at the surface of the as-cast part was processed in such a way that the liquation-related microstructural features such as second phase particles and segregation along the grain boundaries were altered and more crack resistant microstructure was produced. With the objective of altering the surface microstructure, friction stir processing (FSP) was used. FSP is often considered as a generic tool for microstructural modification [11]. Severe plastic deformation associated with FSP is expected to alter the liquation-related microstructural features. Using the FSP for improving fabrication weldability has not been reported in the literature. The liquation susceptibility of this surface layer and the as-cast base metal are evaluated by narrow laser surface melting. The depth of melted layer was significantly smaller than the depth of friction stir processed zone.

Experimental procedure

The cast alloy used in this study was Inconel 738, with the following composition (wt.%): 0.10C, 15.50Cr, 9.8Co, 3.04W, 2.27Mo, 0.70Nb, 0.09Fe, 4.36Al, 3.15Ti, 1.81Ta, 0.04Zr, 0.01B balance nickel. Single pass FSP was performed on 100 × 50 × 5 mm rectangular plates machined from the as-received cast billets. FSP was performed using a tungsten carbide base alloy tool that consisted of a 14mm shoulder diameter, 4mm probe diameter and 1.4mm probe length. After a number of test runs and producing a processed material with about 1.7 mm depth, the following parameters were selected: tool rotation speed of 800 RPM and tool travel velocity of 50 mm/min. The tool was tilted by 3°. Friction stir processed sample was then autogenously laser melted transverse to the direction of FSP as shown in Figure 1.

Figure 1 shows a schematic illustration of the experiment which was used in this investigation and observed sections and regions. As shown in this figure, laser melting was performed transverse to the direction of FSP pass. Therefore, in this manner, the region of as-cast base metal which has been laser melted can show the as-cast base metal liquation susceptibility. Also, the region of friction stir processed zone which has been laser melted may be susceptible to the FSPZ liquation.

A pulsed Nd:YAG laser with a maximum mean laser power of 400W was used. The focusing optical system composed of three lenses with 75 mm focal length. Pure argon gas at 160×10^{-6} m^3sec^{-1} flow rate was used for shielding. To achieve a laser fusion zone with depth much smaller than the FSP depth, the following laser conduction welding parameters were used: spot diameter of 1 mm; pulse frequency of 40 Hz; pulse duration of 10 ms; welding speed of 3 mm/s at an average power of 170 W.

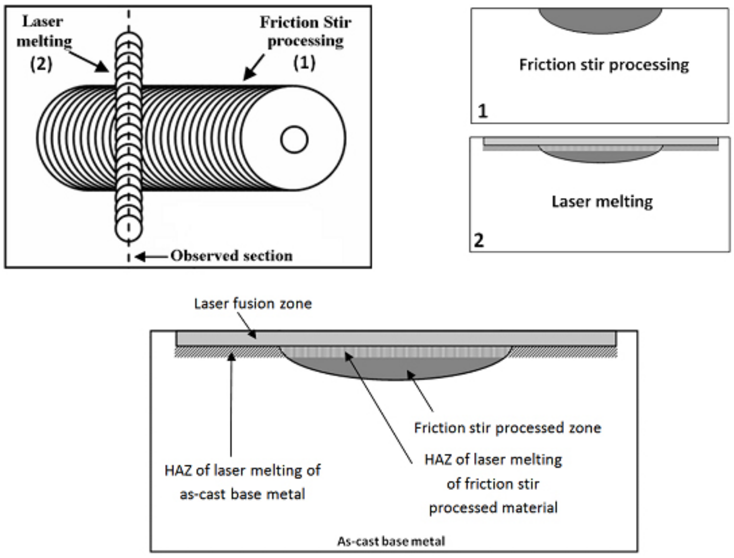

Fig. 1. Schematic illustration of the sequence of FSP and laser melting indicating plane of sectioning and the investigated regions.

The final laser melted specimen was sectioned longitudinally along the laser melting direction for microstructural examination (see Fig. 1). The prepared section was electrolytically etched with 12 ml H3PO4 +40 ml HNO3 +48 ml H2SO4 solution at 6 V for 5 s. The microstructure of as-cast base metal (BM), the laser fusion zone (FZ), the friction stir processed zone (FSPZ) and the laser melt heat affected zone in the regions outside and within the FSPZ were studied by optical and scanning electron microscope (SEM).

Results and discussion

Liquation susceptibility of as-cast base metal

Figure 2 shows an optical micrograph of the as-cast BM which has been laser melted. Shallow fusion zone with about 1 mm width and 225 μm depth is obtained.

The microstructural examination of the HAZ of laser melted as-cast BM showed that any grain boundary intersected the weld bead has cracked with resolidified products formed along them or has liquated, but has not cracked. The HAZ liquation cracks have extended into the BM to a distance varying from 20 to 110 μm. Some HAZ liquation cracks appeared to extend to some distance into the fusion zone.

Liquation susceptibility of friction stir processed zone

Figure 3 shows an optical micrograph of the friction stir processed material which has been laser melted. It is interesting to note that the microstructural examination of the HAZ of laser melted friction stir processed material showed that no grain boundary has been cracked.

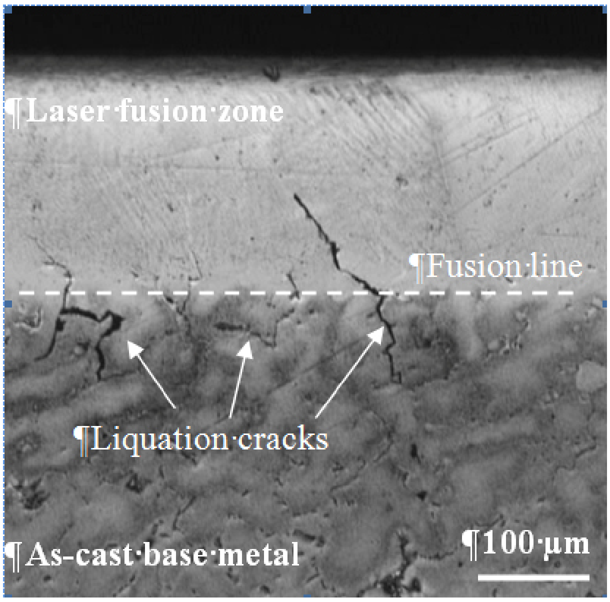

Fig. 2. Optical micrograph of the as-cast base metal which has been laser melted with HAZ liquation cracks.

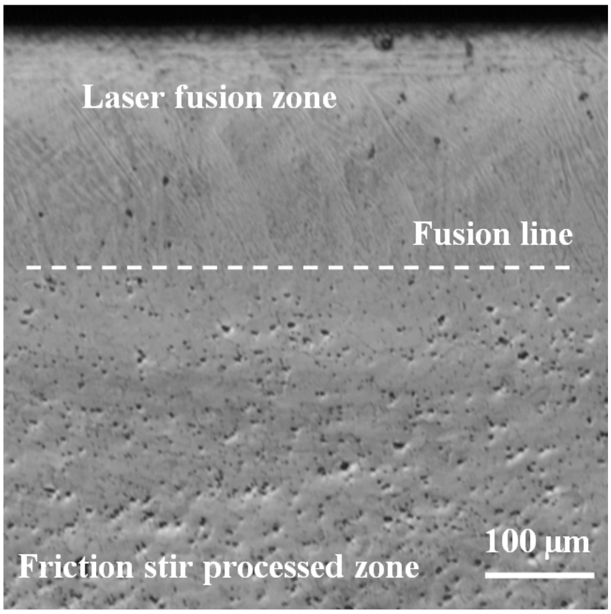

Fig. 3. Optical micrograph of the friction stir processed material which has been laser melted. Liquation cracking did not occur in the HAZ.

The correlation between liquation susceptibility and microstructural characteristics of as-cast base metal and FSP zone

Complete suppression of HAZ liquation cracking in the laser melted friction stir processed material and severe liquation cracking of the laser melted as-cast base metal can be related to distinct difference between microstructural characteristics of as-cast base metal and friction stir processed zone as discussed below.

Ojo et al. [6-8] have discussed the second phase particles capable of liquating, microstructural features of different liquation phenomena involved and characteristics of the liquid film contributing to high susceptibility of IN738 alloy to the HAZ liquation cracking in various preweld heat treatments such as solution or overaged heat treatments. In brief, it has been recognized that the basic requirement for constitutional liquation is that the particles should exist at temperatures equal to or above their eutectic temperature on heating. Therefore, the susceptibility of a second phase to constitutional liquation in the weld HAZ will depend upon its solid state dissolution behavior, as a complete dissolution prior to reaching the eutectic temperature will preclude the occurrence of liquation. Due to the rapid heating during welding, the dissolution behavior of second phase is expected to deviate from equilibrium. Hence, the limited integrated time available for homogenization by the diffusion process can cause relatively larger second phase particles to survive well above their solvus to temperatures above their eutectic reaction temperature of the alloy. Also, the mere occurrence of liquation is not sufficient to produce a crack susceptible microstructure. Susceptibility to cracking depends on penetration and wetting of grain boundaries, liquid film thickness and its stability to temperatures at which sufficient thermal and mechanical stresses are generated on cooling [9,10]. As shown by previous researches, the microstructural features of the as-cast BM (Fig**.** 4) used in the present work exacerbate the grain boundary liquation.

The most important microstructural characteristics of IN738 superalloy which can affect the liquation susceptibility are as follows:

(1) the microstructure of the as-cast IN738 alloy was cored dendritic (Fig. 2 and 4), with enriched interdendritic regions which consisting of several secondary solidification constituents such as carbides and γ-γ′ eutectic due to microsegregation that occurred during solidification. It is recognized that these particles can be capable of constitutional liquating [7],

(2) most of carbides formed along grain boundaries are coarse and semicontinuous. The observed coarse particles along the grain boundaries in the as-cast BM lead to higher susceptibility to the constitutional liquation,

(3) the as-cast BM consisted of high volume fraction of second phase particles capable of liquating such as coarse and semicontinuous carbides which formed along the grain boundaries and also the low melting point γ-γ′eutectic and γ′ particles,

(4) the large grain size of as-cast (about 400μm) BM results in smaller grain boundary area which promotes the existence of large volume of coarse carbides and other liquating phases with the attendant detrimental semicontinuous distribution along the grain boundaries,

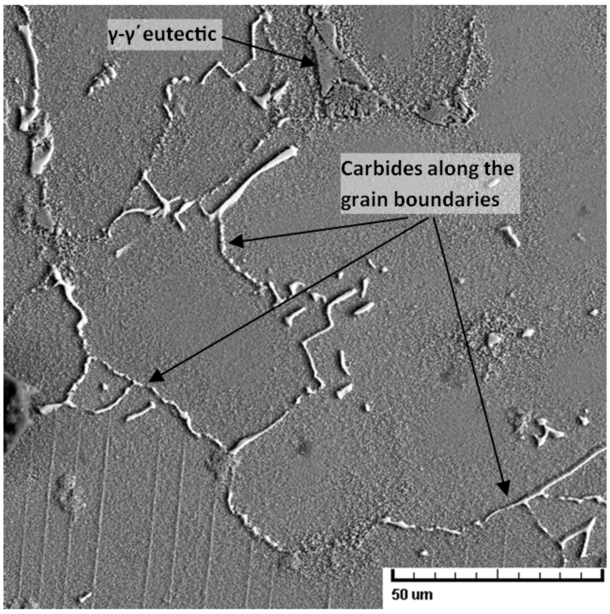

Fig. 4. SEM micrograph showing microstructure of as-cast base metal.

(5) high level of grain boundary segregation of melting point depressing elements (such as boron) might have an additional detrimental effect [7],

(6) constitutional liquation of the main strengthening phase of precipitation-hardened nickel-base superalloys, γ′ precipitates, was reported recently by Ojo et al. [8]. The size of γ′ in the interdendritic regions of the as-cast BM which is used in this study is about 0.45 μm. The liquation of these coarse γ′ can be seen in the microstructure. The constitutional liquation of this phase was reported to significantly affect the HAZ liquation due to its high volume fraction [8].

All of these microstructural characteristics would contribute to the severe liquation cracking when the cast microstructure becomes the HAZ.

In contrast, a single FSP pass dramatically alters the microstructure of the stir zone from that of the as-cast metal. During this process, the intense plastic deformation and thermal exposure the material undergoes, results in a significant evolution in the local microstructure.

During FSP process microstructure of IN738 was significantly changed:

(1) as shown in Figure 5, FSP resulted in a breakup of both the semicontinuous carbides and the segregated dendritic structure of as-cast BM,

(2) it can be seen that these finer carbides in the FSP zone have relatively less association with the grain boundaries,

(3) distribution and size of other secondary solidification constituents capable of liquating is also expected to be significantly changed,

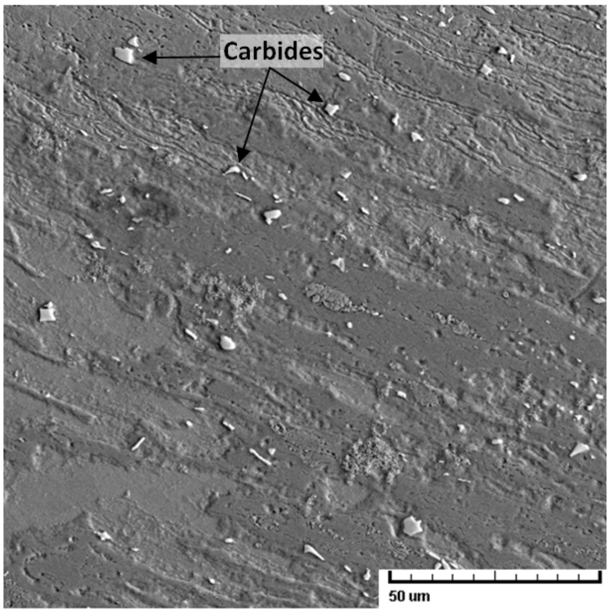

Fig. 5. SEM micrograph showing microstructure of friction stir processed zone.

(4) in addition, FSP results in the generation of very fine and recrystallized grains of about 5-10μm. It is known that the fine grained structure leads to higher resistance to the liquation cracking,

(5) it is not unreasonable to expect these new grain boundaries to constitute less segregation as compared to considerably coarse dentritic structure of the BM formed during the solidification process,

(6) furthermore, the finer grains results in the availability of more grain boundary area and hence lower concentration of liquation-inducing material at the grain boundaries of the FSP zone,

(7) the size of γ' in the FSP zone is about 0.05 μm. The observed fine γ' particles in the FSP zone lead to less susceptibility to the constitutional liquation. The size and morphology of γ' particles of base metal and FSP zone are shown in figure 6. The smaller size of γ' in the FSP zone may result in solid-state dissolution of these particles during heating cycle of laser melting instead of their constitutional liquation.

Through studies done about the relationships between microstructural characteristics and liquation of second phases and liquation cracking [1-10], it is known that obtained microstructural features of FSP zone, observed in the present work, for instance, small second phases and fine grains structure have led to increasing the resistance of an alloy to HAZ liquation cracking.

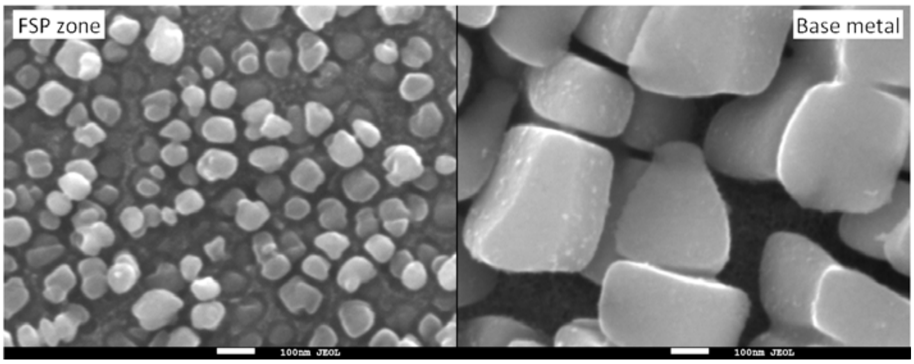

Fig. 6. The size and morphology of γ′ particles in base metal and FSP zone.

As mentioned earlier, during welding, smaller second phases such as fine carbides which observed in the FSP zone can dissolve completely prior to reaching the eutectic temperature and consequently the occurrence of liquation is precluded. The resistance to the grain boundary liquation is greatly influenced by fine and smaller second phase particles such as carbides and especially γ′ precipitates which are produced during the FSP. The size of γ′ in the interdendritic regions of the as-cast BM is about 0.45 μm as compared to the FSP zone with the fine γ′ particles of average size about 0.05 μm. The particle size has a significant effect on its solid-state dissolution behavior and consequently the susceptibility of it to constitutional liquation.

Therefore, the complete dissolution of fine γ′ in the FSP zone is much faster than γ′ particles of the as-cast BM and hence, it can be reasonably expected that the fine γ′ of the FSP zone is likely dissolved prior to reaching the eutectic temperature and consequently the occurrence of its constitutional liquation is precluded.

Conclusion

Combination of very large deformations and heating associated with the friction stir processing of the as-cast IN738 superalloy can change its grain boundary liquation crack susceptible microstructure to the crack resistant microstructure to that extent required for the complete suppression of liquation cracking in the laser conduction welding. Microstructural features of FSP zone observed in the present work, specially, small second phases and fine grains structure have led to increasing the resistance of IN738 to grain boundary liquation and the attendant cracking.

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