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Heat Input Dependence of Weld HAZ Cracking in Aerospace Superalloy Haynes 282

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Abstract - A study of weld heat affected zone (HAZ) cracking and its dependence on heat input during laser beam welding of a newly developed γ' precipitation strengthened nickel-base superalloy Haynes 282 (HY 282) was carried out. Careful and detailed microstructural study of the nature of HAZ cracking in the alloy showed that the cracking is attributable to degradation of hot ductility of the alloy due to formation of liquid film along grain boundaries. An increase in the magnitude of laser heat input resulted in a considerable reduction in the HAZ cracking. The cracking variation with heat input is discussed in relation to the time that the subsolidus HAZ region spent at peak temperatures. The behavior is also discussed with the results of numerical simulation, which show that reduction in the magnitude of thermally induced strain rate gradient may contribute to reduced HAZ cracking that occurred with an increase in heat input**.**

Keywords – Joining; Laser Welding; Ni based superalloy

I. INTRODUCTION

The continual demand for improved efficiency of aero- and power generation gas-turbine engines by increasing the service temperature is encouraging the design and development of higher performance nickel-base superalloys used to produce gas-turbine components. Haynes 282 (HY 282) is a new γ' precipitation strengthened nickel-base superalloy with improved elevated temperature properties compared to some of the commonly used nickel-base superalloys like Inconel 718, Waspaloy and HY 263 [1]. Welding is a critical integral process in the assembling of simple to complex shaped turbine parts during fabrication. Also, hot-section turbine components are often subjected to complex combination of severe thermal and mechanical stresses for extended time periods, which normally cause cracking, wear and degradation of engine parts; these limits the components useful life. Owing to the high cost of parts replacement, it is increasingly becoming economically desirable to repair and rejuvenate service-damaged such as components. Conventional fusion welding process, such as gas tungsten arc (TIG) welding is one of the most commonly used techniques to fabricate new component and repair worn out parts. However, the high heat input associated with these processes often results in large heat affected zone (HAZ) size and undesirable distortion of welded parts. Laser beam welding (LWB) has attracted considerable interest in recent years for the fabrication and repair of advance high temperature alloys due to its speed, flexibility, high energy concentration and power transfer rate in order to produce low heat input welds with reduced heat affected zone and physical distortions. HY 282, like other γ' precipitation strengthened Ni-based superalloy is difficult to weld due to the occurrence of HAZ crack during laser beam welding [2]. There is, however, limited reported data on HAZ cracking behavior in the HY 282 superalloy. Understanding how the susceptibility to weld HAZ cracking is influenced by laser heat input is crucial to developing optimum welding procedure for preventing or minimizing the cracking problem and facilitates the application of laser beam for joining the newly developed alloy. Therefore, the objective of this research was to carefully study the fundamental dependence of weld HAZ cracking on laser heat input, as controlled by welding parameters. The results are presented and discussed in this communication.

II. MATERIAL AND EXPERIMENTAL

Wrought HY 282 superalloy with a nominal chemical composition of (weight %) 1.5Al, 2.1Ti, 10Co, 20Cr, 8.5Mo, 1.5Fe, 0.3Mn, 0.15Si, 0.06C, 0.005B, and balance nickel was used in this study. The alloy was received in the form of mill bright-annealed plates. Welding test coupons of dimension 65 x 15 x 5 mm, were machined by a numerically controlled wire electro-discharge machine (EDM) and subjected to a pre-weld solution heat treatment (SHT) at 1050ºC for 2 hours, followed by water quench. The pre-weld heat-treated specimens were surface ground, properly cleaned to remove surface oxides and then, autogenously welded by bead-on-plate single pass CO_2 laser beam using

TABLE I. LASER BEAM WELDING PARAMETERS

Sample No	Heat Input J/mm	Power (kW)	Speed (m/min)	Beam Focus	Shielding Gas Flow rate. Litre/min	Welding Gas Flow Rate. Litre/min
1	60	2	2	-2	30	25
2	120	2	1	-2	30	25

two heat input values, presented in Table 1: a low heat input corresponding to 60 J/mm and a high heat input of 120 J/mm. Laser beam welded specimens were sectioned transversely to the welding direction by the EDM to produce 10 sections from each test specimen, which were subsequently prepared by standard metallographic procedure for microstructural examination. Mounted sections of the welded specimens were etched by swabbing in a solution of 48g CuCl + 480 ml HCl + 40 ml H_20. The microstructure of the welded specimen was examined first by optical microscopy, using a ZEISS Axiovert 25 inverted-reflected light microscope, equipped with CLEMEX Vision 3.0 image analysis software. The measurement of fusion zone (FZ) and HAZ area were performed using the optical microscope. Detailed microstructural study was carried out by using a JEOL 5900 scanning electron microscope (SEM) equipped with an Oxford (Oxford Instruments, Oxford, United Kingdom) ultra-thin window energy dispersive spectrometer (EDS). The extent of HAZ cracking was determined by measuring the total crack length in 10 sections of each welded specimen using the SEM (operated in both secondary and backscattered imaging mode). In addition, numerical simulation by 2 dimensional thermal elasto-plastic finite element analysis was performed by using ANSYS 13 code to better understand the experimental results.

III. RESULTS AND DISCUSSION

Figure 1 shows an SEM micrograph of the preweld SHT alloy, which had an average grain size of 140 µm. The microstructure consisted of inter- and intragranular primary MC carbides based on titanium and molybdenum and chromium based secondary $M_{23}C_6$ carbides, all of which have been previously reported to form in the alloy [1]. An optical micrograph of a general laser weld region in HY 282, showing the fusion zone (FZ) and the HAZ is presented in Figure 2. No fusion zone cracking was observed in all section irrespective of the magnitude of the welding heat input. However, the HAZ suffered a varying degree of intergranular cracking. Most of the cracks were located in the neck region of the keyhole shape weld, in HAZ regions slightly away from the FZ (Figure 2 & 3). Some of the main features of the cracks include irregular zigzag morphology of fracture path and close association with widened grain boundaries, which are typical features that depict intergranular liquation cracking [3-4]. Grain boundary liquation cracking, which is caused by the formation of liquid phase along intergranular region and subsequent de-cohesion along one of the intergranular solid-liquid interfaces under the influence of tensile stress generated during weld cooling, has been reported in some nickel-base superalloys [3 - 5].

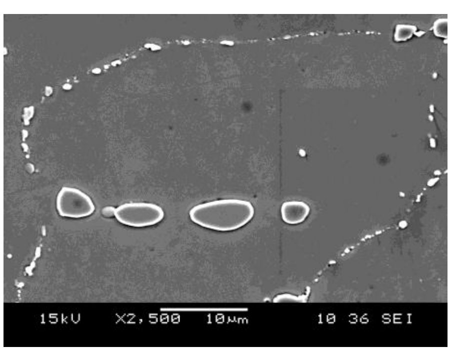

Figure 1: SEM micrograph of the SHT HY 282 superalloy

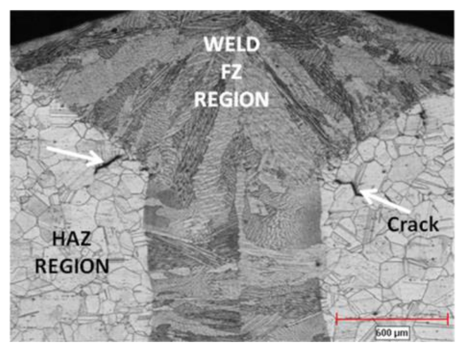

Figure 2: Typical general overview of the laser welded alloy HY 282

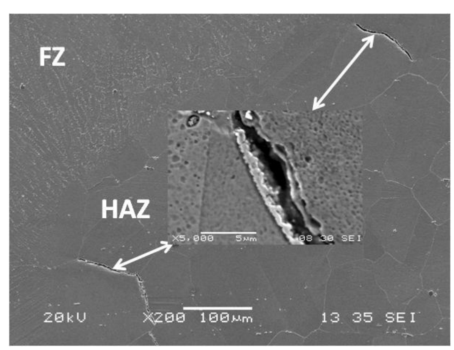

Figure 3: SEM micrograph of HAZ showing cracks and associated features

The effect of laser beam welding heat input on the magnitude of HAZ cracking and weld size is presented in Figure 4 and Table 2, respectively. The total crack length (TCL), depth of penetration, FZ area and the HAZ area were observed to vary with heat input, which is a function of welding speed and laser power. Since the size of the weld changed with heat input, in order to enable a more realistic comparable analysis of the cracking behavior of the welds based on different heat input parameters, quantitative index of cracking, CI, was calculated by normalizing the TCL with the HAZ area using a method reported by Richards et al [6]. The CI, which is a quantitative assessment of the length of crack per unit area, provides a meaningful comparison of the susceptibility of the alloy to HAZ cracking. The high heat input laser weld experienced a lower extent of cracking compared to the low heat input laser weld. The CI of high heat input weld (120 J/mm) was 0.33, which is appreciably smaller than CI of a low heat input weld (60 J/mm), 0.83 (Figure 5). Miller and Chawick [7] have related the tensile stress, $\boldsymbol{\sigma}$, required to cause cracking by overcoming the surface $\boldsymbol{\gamma_{sl}}$ tension at the solid-liquid interface on liquated grain boundaries to the liquid film thickness $\boldsymbol{h}$ by the equation:

$$\sigma = 2\gamma_{sl} / h \qquad (1)$$

The significance of equation (1) is that, any factor that reduces the thickness of the intergranular liquid could in effect improve resistance to cracking by increasing the magnitude of stress required to cause intergranular microfissuring. Grain boundary liquid film migration (LFM) is a fundamental mechanism by which a metastable intergranular film can be effectively removed through rapid solidification, thereby promoting resistance to liquation cracking. This solidification mode, which is controlled by a high diffusion rate in the liquid, is an alternative to lattice diffusion controlled and the normal dendritic solidification types. Reversed grain boundary curvature, which is a vital microstructural feature of LFM process, was observed in the HAZ in the present work (Figure 6). Weld HAZ is generally known to spend longer time at peak temperatures during high heat input welding compared to in low heat input welds. The longer time that the HAZ spent at peak temperatures in the high heat input welding could favour re-solidification via LFM and/or solute back-diffusion process and, thus, eliminate or reduce intergranular liquid film thickness compared to low heat input welding. According to equation (1), such reduction in the thickness of grain boundary liquid film thickness, which would increase the magnitude of tensile stress required for cracking, could be a contributing factor to the reduction of the HAZ cracking that is observed in high input welds.

Aside from the possible influence of heat input on the size of intergranular liquid film thickness, the magnitude of the driving force for cracking, welding stress can also be influenced by the level of heat input involved during welding. During welding, besides the effect of mechanical restraint, generation of thermally induced stress and associated strain is unavoidable. Therefore, the larger extent of cracking observed in the low heat input laser welds, in the present work, may be related to a greater level of thermally induced strain rate gradient generated during welding compared to the level in higher heat input laser welds. Tungsten inert gas (TIG) arc welding is known to be an inherent high heat input welding process [8]. In the present work, some HY 282 specimens were welded by TIG process with a high heat input of 490J/mm. Microstructural examination showed that both the FZ and HAZ in the TIG welded material were crack free, which corroborates the result obtained in the laser welds, in that, an increase in heat input reduces HAZ cracking. However, the TIG weld has large surface width (5.2mm) and was shallow (0.9mm depth) with a wide HAZ region.

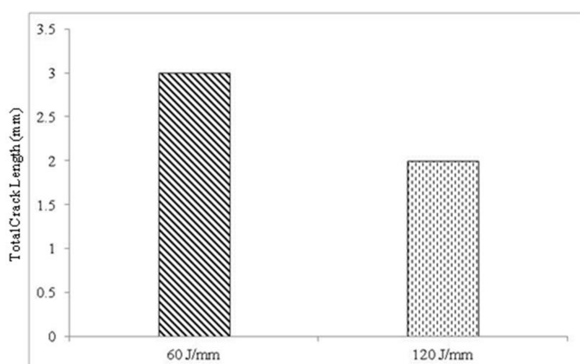

Figure 4: Effect of Heat Input on variation in Total Crack Length [TCL]

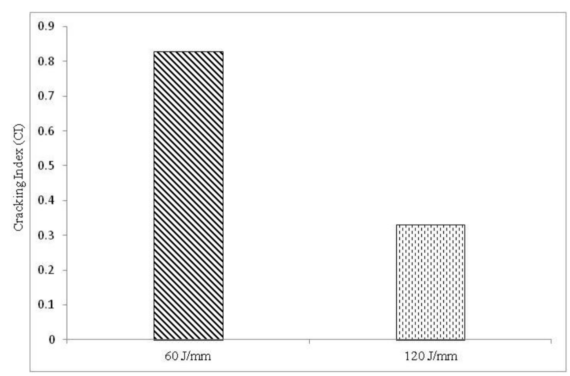

Figure 5: Effect of Heat Input on variation in Cracking Index [CI]

TABLE II. DIMENSION OF LOW AND HIGH HEAT INPUT LASER WELDS

Speed m/min	Power kW	Heat Input J/mm	Depth of Penetration mm	Top Width / Depth Ratio	Area FZ mm^2	Area HAZ mm^2
2.0	2.0	60	3.9	0.5	3.2	4.2
1.0	2.0	120	4.6	0.7	5.9	8.6

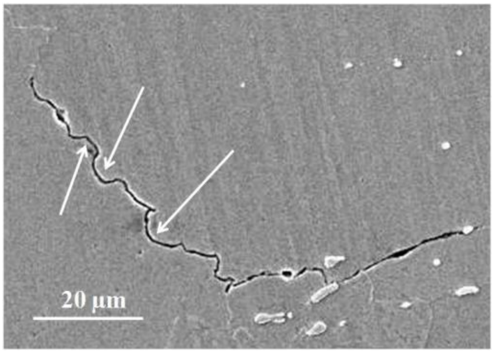

Figure 6: Typical Liquid Film Migration feature along intergranular region

Although, it is apparent in the present work that increasing the heat input leads to reduction in the overall cracking susceptibility, generally, low heat input laser welds are preferred due to the associated better weld shape and size in terms of its penetration, width and reduced material distortion. Therefore, an additional investigation, using numerical simulation, was performed to enable a better understanding of the dependence of the magnitude of HAZ cracking on the welding heat input during the low heat input laser beam welding, which may prove useful in understanding how to prevent or minimize HAZ cracking in the newly developed alloy HY 282. In its basic form, heat input, Q_1, is dependent on the power of the welding heat source power, P, and welding speed, ν, through the equation;

$$Q_1 = k\frac{p}{v} \tag{2}$$

where k is a constant. Accordingly, the magnitude of welding heat input can be varied by either changing the laser power or welding speed. In the present numerical simulation study, both the laser power and welding speed were varied, exclusive of each other, to analyze the effects of heat input on weld characteristic during laser beam welding. Also, cracking generally occurs when significant amounts of thermal strains are generated during weld cooling. The rate at which thermal strain develop at different weld locations, thus, become important in evaluating the propensity to HAZ liquation cracking.

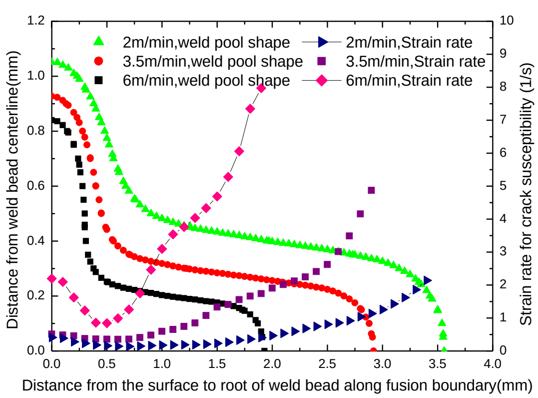

Figure 7: Simulated variation of strain rate along the fusion boundary of laser welds produced at different value of welding speed at constant power

The numerical model, developed in this work was used to calculate the strain rates generated at various locations along the weld fusion boundary and how these values are influenced by welding speed and laser power. Figures 7 and 8 show numerically calculated variation of strain rate along the weld profile for different values of welding speed and power, during the laser welding. The abscissa shows the distance from the weld top surface to the root of the weld, along the weld fusion boundary. The right side ordinate shows the distance from weld centerline, along the weld top surface, while the left side ordinate shows the strain rate. The results show that while the increased welding speed caused a significant increase in strain rate, an opposite effect is produced by increasing power. The two trends show the same influence of heat input on the rate at which thermal strains are generated along the weld profile, starting from the weld surface to the weld root.

A careful study of the calculated results, presented in Figures 7 and 8 shows another interesting behaviour in terms of variations of the strain rate along the weld profile. A reverse in the strain rate behaviour occurs at the neck region of the nail-shaped weld profiles. The strain rate initially decreases from the weld surface to the neck region, however, starting from the neck region, the rate increases towards the root of the weld. Experimental observation in the current work showed that the HAZ liquation cracks concentrate around the neck region of the welds. The strain rate gradients within the neck-region in welds produced by different welding conditions were numerically calculated to compare the propensity to cracking. As shown in Figures 9 and 10, increase in heat input, either by reducing the welding speed or increasing the power, reduces the magnitude of the strain rate gradient. In concurrence with the numerical analysis results, the results of the crack measurement in the current work also show that an increase in heat input caused reduction in the extent of HAZ liquation cracking. Therefore, the strain rate gradient within the weld-neck region appears to be an important mechanical driving factor that influences the occurrence of the HAZ liquation cracking during the laser beam welding.

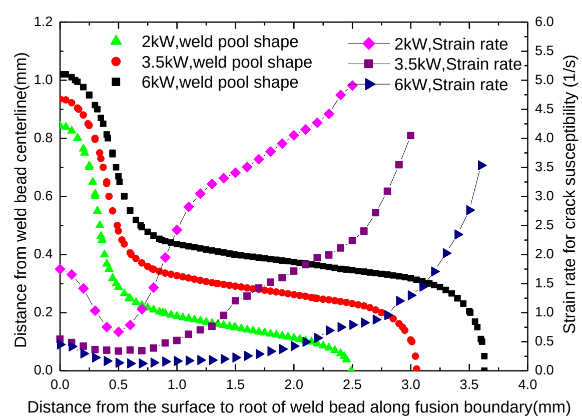

Figure 8: Simulated variation of strain rate along the fusion boundary of laser welds produced at different value of laser power at constant speed

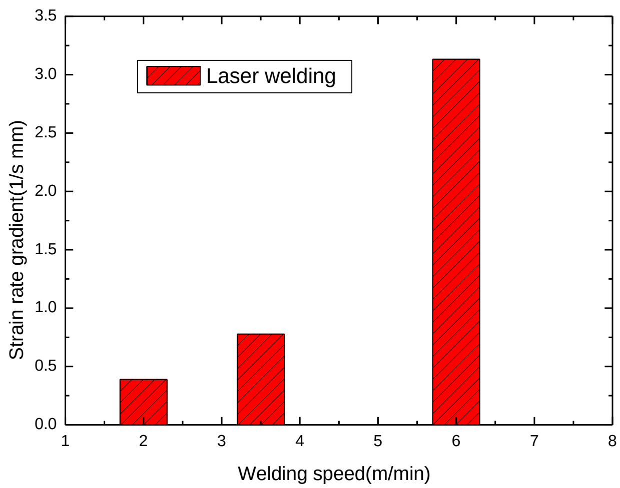

Figure 9: Strain rate gradient in the neck region of laser weld using different welding speed at constant power

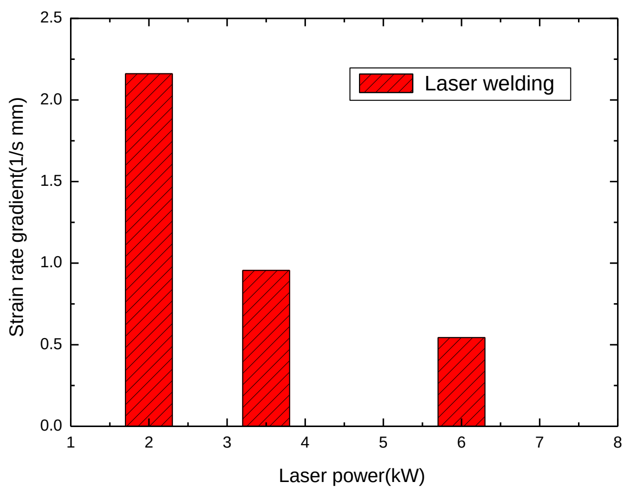

Figure 10: Strain rate gradient in the neck region of laser weld using different power at constant welding speed.

IV. SUMMARY AND CONCLUSIONS

1. HAZ cracking in the superalloy Hayne 282 during laser beam welding is attributable to grain boundary liquation, which degrades hot ductility of the material and reduces its capability of accommodating welding stress.

2. An increase in the magnitude of heat input during welding resulted in reduction in the extent of HAZ cracking. This can be related to a combination of (i) possible increase in the magnitude of tensile stress required to induce cracking due to reduction in intergranular liquid film thickness which is enabled by longer available time for re-solidification in high heat input welds and (ii) lower level of thermally generated stress due to shallower temperature gradient in the HAZ associated with high heat input welds.

3. The numerical simulation model results reveal that thermally generated strain rate gradient within the weld-neck region increases with reduction in heat input, which can be correlated with the observed increase in cracking at lower heat input.

4. Therefore, the strain rate gradient that is thermally generated within the weld-neck region during weld cooling appears to be an important mechanical driving factor that influences cracking during the laser beam welding.

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