Residual stresses in Inconel 718 electron beam welds

S. BISWAS
Gas Turbine Research Establishment, Bangalore-560093, India

G. M. REDDY*, T. MOHANDAS
Defence Metallurgical Research Laboratory, Hyderabad-500058, India
E-mail: gmreddy_dmrl@yahoo.co.in

C. V. S. MURTHY
Defence Research and Development Laboratory, Hyderabad-500058, India

Inconel 718, a precipitation hardenable Ni base super alloy, has excellent weldability quality unlike other alloys of the same group, due to its sluggish aging response resulting in reduction of the strain age cracking problem [1]. However it has a major limitation in the form of segregation of Niobium (Nb) in the interdendritic regions leading to laves phase formation and consequent mechanical property deterioration of the fusion zone [2]. In addition, this alloy is prone to heat affected zone (HAZ) microfissuring [3]. The segregation of Nb and HAZ microfissuring could be controlled to a large extent by weld cooling rates, which depends on the type of welding process with controlled heat input, welding technique that dictates liquid metal convection in the weld pool etc. [4, 5].

It is well known that residual stresses are induced during welding operation [6] and their presence may often be associated with permanent deformation [7]. Even when the weld can be produced successfully, the presence of residual stress fields must be accounted for estimating the useful working life, since the mechanical properties of welded joints can be impaired due to their presence. Residual stresses may promote brittle fracture, fatigue, stress corrosion cracking, and can even reduce buckling strength [7]. Therefore, containment of weld residual stress in the structural components is important. The residual stress in the weld is expected to vary with heat input, welding technique and process, as they change thermal history and consequently the microstructures. The present investigation is an attempt to investigate in to the influence of welding technique namely, conventional and oscillated electron beam welding on the microstructure and residual stresses in Inconel 718 in the welds.

Electron beam welding was carried out on 3 mm thick sheets in solution treated and aged conditions [980 °C/20 min/AC followed by duplex aging at 720 °C/8 hrs/FC to 620 °C at a rate of 55 °C per hrs/620 °C/8 hrs/AC (AC: Air cooling, FC: Furnace cooling)]. Micro structural study in the earlier investigation [5] revealed that amongst all the oscillated beams, elliptical oscillation is most effective in microstructure refinement, control of Nb segregation and laves phase formation, and therefore welding was performed with the electron beam in elliptical oscillation mode. For comparison, conventional welds were also investigated. The welding parameters used are listed in Table I.

Residual stresses were measured at the weld centre on the top surface of weld of both types of test coupons using XSTRESS-3000 machine in the welding direction (Fig. 1) with Cr K_α radiation. Stress measurement was performed with a 3 mm diameter collimator at an exposure time of 30 s. The samples subjected to standard metallographic sample preparation were employed for micro-structural examination under an optical microscope while, scanning electron microscopy (SEM) and electron probe microanalysis were employed (EPMA) for examining the distribution of Nb and laves phase.

Both the welds represented typical dendritic microstructures extending from fusion boundary to weld centre in as-weld condition. But oscillated beam microstructure was extremely fine and equiaxed compared to the unoscillated weld (Fig. 2a and b). Presence of laves phase was confirmed in the interdendriditic regions of welds (Fig. 3a and b). Coarse and highly interconnected laves particles were formed in the unoscillated beam weld. The oscillated beam weld consisted of fine and discrete particles of laves phase. The amount of laves was more in the unoscillated beam weld. 12 ± 1.2 vol% laves phase was present in the unoscillated beam weld, whereas it was only 4 ± 0.8% for the oscillated beam weld. Quantitative analysis was performed on the interdendritic laves particles and in the dendritic core regions in both the unoscillated and oscillated beam welds at a number of locations. The results of quantitative analysis are shown in Fig. 4. Oscillation was more effective in reducing the Nb segregation and extent of laves phase formation. The back scattered electron (BSE) image and corresponding X-ray Nb maps in EPMA suggest less segregation in the oscillated beam weld than the unoscillated beam weld (Fig. 5a and b). It was also observed that the Nb segregation regions are larger than the size of laves phase seen in BSE images. This indicates that laves particles are surrounded by Nb rich regions.

* Author to whom all correspondence should be addressed.

0022–2461 © *2004 Kluwer Academic Publishers*

TABLE I Welding parameters

Machine parameters	Without beam oscillation	With beam oscillation
Gun to work distance (mm)	275	275
Accelerating voltage (KV)	55	55
Beam current (mA)	22	25
Focus	Above the surface	On the surface
Speed (m/min)	1.5	1.5
Vacuum level (mbar)	10^{-4}	10^{-4}
Heat input (J/mm)	48.4	55

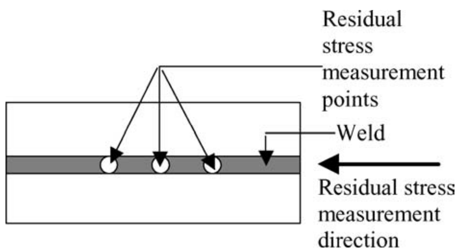

Figure 1 Residual stress measurement direction.

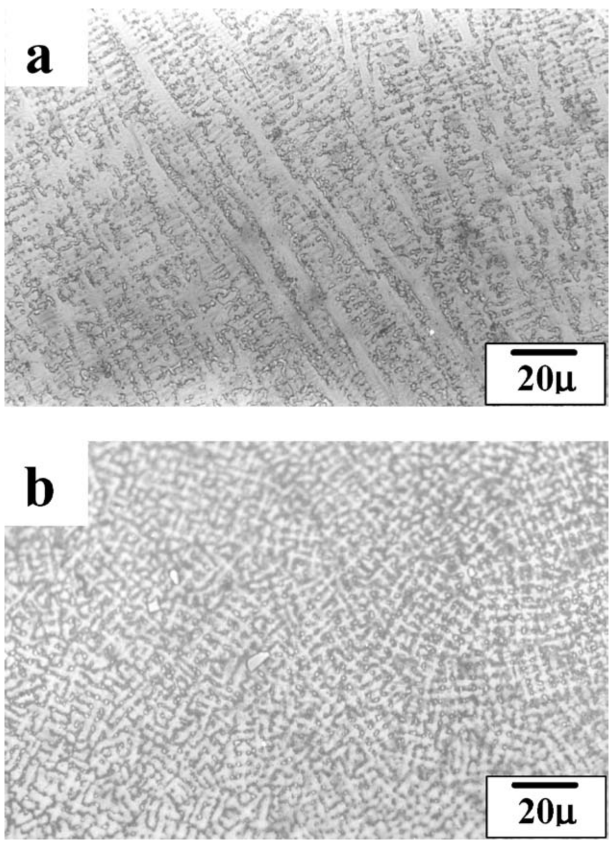

Figure 2 Optical microstructure: (a) Unoscillated beam weld and (b) Oscillated beam weld.

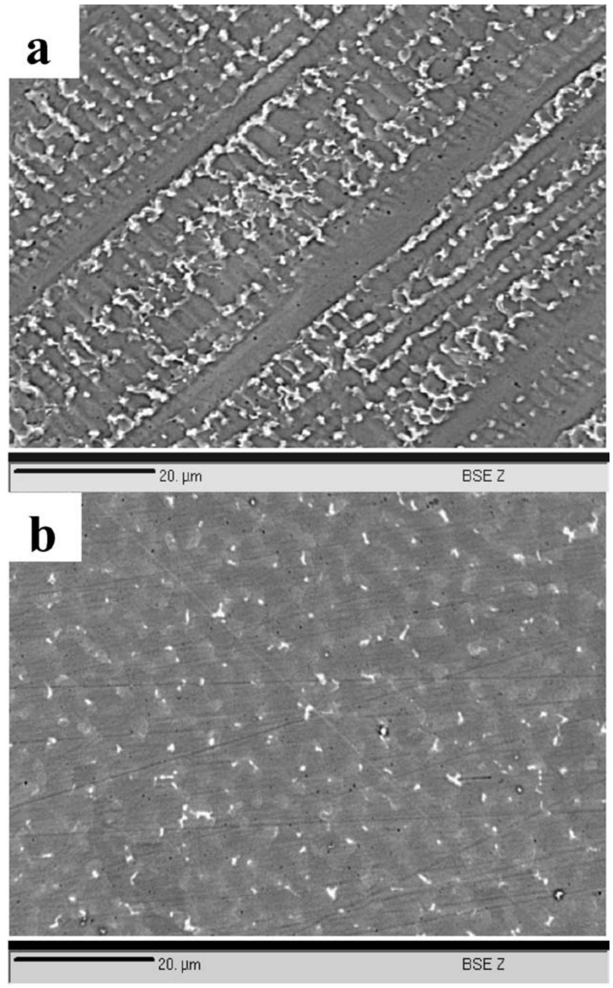

Figure 3 Back scattered scanning electron micrographs: (a) Unoscillated beam weld and (b) Oscillated beam weld.

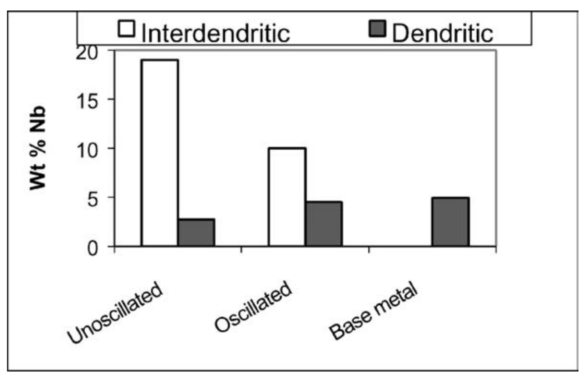

Figure 4 Nb contents in various 718 electron beam welds and base metal.

Beam oscillation is known to impart convection in the weld pool, and therefore better temperature distribution in the cavity formed by the electron beam; hence temperature gradient in the cavity will be less in this case compared to the unoscillated beam. Convection created by beam oscillation will also help in homogeneous mixing of the constituents. This helps in reducing Nb segregation.

Fig. 6 shows the data (average of 3 readings) on residual stresses in the fusion zone of oscillated and unoscillated beam welds in as-weld condition. It has been observed that for both the welds, the stress is compressive in nature at the weld centre. But the stress was less compressive in the case of oscillated beam weld as compared to the unoscillated beam weld, implying that Nb segregation regions and laves phase are responsible for the compressive stress.

During solidification, the dendritic core gets depleted of Nb [2] making the interdendritic zone enriched with this element leading to the formation of Nb segregated regions and hence the laves phase formation (at least 10–12% Nb is required) in interdendriditic regions. The mechanism for the laves phase precipitation is as

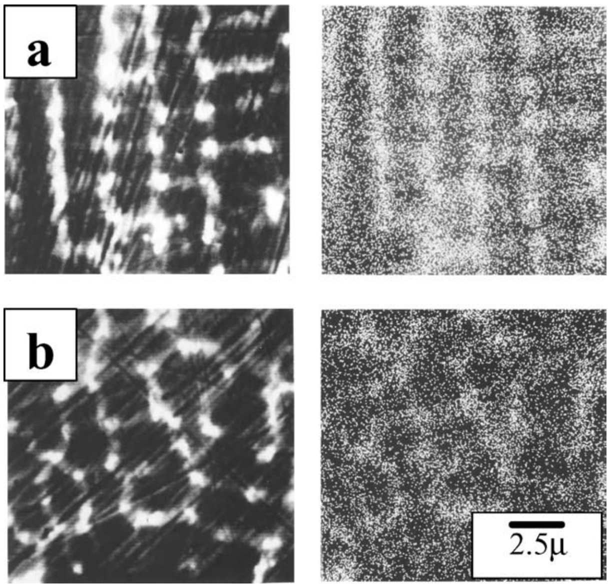

Figure 5 BSE images and corresponding X-ray Nb maps of weld fusion zones (as-welded): (a) Unoscillated beam weld and (b) Oscillated beam weld; Location: weld centre.

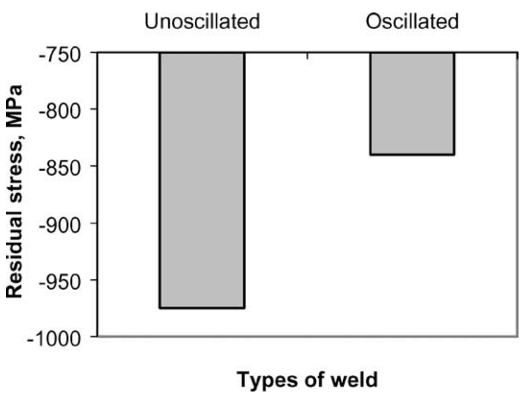

Figure 6 Residual stresses in different types of weld.

follows:

$$\text{Liquid} \longrightarrow \text{Liquid enriched with Nb} + \gamma$$

$$\text{Liquid enriched with Nb} \longrightarrow \gamma + \text{Laves}$$

The transformation of Nb rich liquid to $\gamma +$ Laves is a eutectic reaction and it terminates the solidification process.

Laves phases form a homeotect structure type set [8] (a family of different stacking variants of identical unit slabs) i.e., constructed by stacking identical unit slabs one on top of another (topological close packing). Laves phase in the present system is known to possess a Zn_2Mg structure [9] (with Pearson symbol hP12). The laves phase has higher co-ordination number (∼12.5) as compared to the normal stacking (maximum 12). This higher co-ordination number may result in an efficient packing of the atoms, and thereby reduce volume occupied by this phase. This difference in the volume of the phases results in residual compressive stress in the weld. This compressive stress is possibly more than the tensile stress due to thermal shrinkage after solidification for both the cases leading to residual compressive stress in the weld.

It can therefore be concluded that

(i) Inconel 718 electron beam welds are associated with residual compressive stresses.

(ii) Nb segregation and laves phase formation at the interdendritic regions are responsible for the compressive stresses in the weld.

Acknowledgments
The authors express their gratitude to the Defence Research and Development Organization for the financial support to carry out this program and to Dr. D. Banerjee, CCR&D (AMS) for his continued encouragement. The authors are thankful to Director, DMRL for permission to publish these results. One of the authors (Swati Biswas) is grateful to Director, GTRE for permission to carry out this work. The help extended by the members of SFAG and MJG of DMRL is also acknowledged.

References
1. D. S. DUVALL and W. A. OWCZARSKI, *Weld. Res. Suppl.* **48** (1969) 10s.
2. J. N. DUPONT, C. V. ROBINO and A. R. MARDER, *ibid.* **77** (1998) 417s.
3. Y. M. YAMAN and M. C. KUSHAN, *J. Mater Sci. Lett.* **17** (1988) 1231.
4. CH. RADHAKRISHNA and K. PRASAD RAO, *J. Mater. Sci.* **32** (1997) 1977.
5. C. V. SRINIVASA MURTHY, "Electron Beam Welding of Inconel 718—A Study on the Effects of Different Beam Oscillation Techniques," MS Thesis, IIT, Madras, India, 2003.
6. I. C. NOYAN and J. B. COHEN, in "Residual Stress and Stress Relaxation, Sagamore Army Materials Research Conference Proceedings," edited by E. Kula and V. Weiss, p. 1.
7. K. MASUBUCHI, in "Residual Stress and Stress Relaxation, Sagamore Army Materials Research Conference Proceedings," edited by E. Kula and V. Weiss, p. 49.
8. T. B. MASSALSKI, in "Physical Metallurgy," edited by Cahn and Hassen (1996) p. 176.
9. C. T. SIMS, in "The Superalloys," edited by Sims and Hagel (John Wiley & Sons, New York, London, Sydney, Toronto, 1972) p. 260.

Received 2 March
and accepted 21 April 2004