Title of Publication *Edited by*
TMS (The Minerals, Metals & Materials Society), Year

STRAY GRAIN FORMATION IN NICKEL-BASE SUPERALLOY SINGLE-CRYSTAL WELDS

J. M. Vitek[1], S. S. Babu[1], J.-W. Park[2], and S. A. David[1]

[1]Oak Ridge National Laboratory
P. O. Box 2008, Oak Ridge, Tennessee, 37831-6096, USA
[2]formerly at Oak Ridge National Laboratory, now at Samsung Electro-Mechanic Co, Ltd.
Suwon, Kyunggi-Do, Korea 442-743

Keywords: Single crystals, dendritic growth, stray grains, nickel-based superalloys

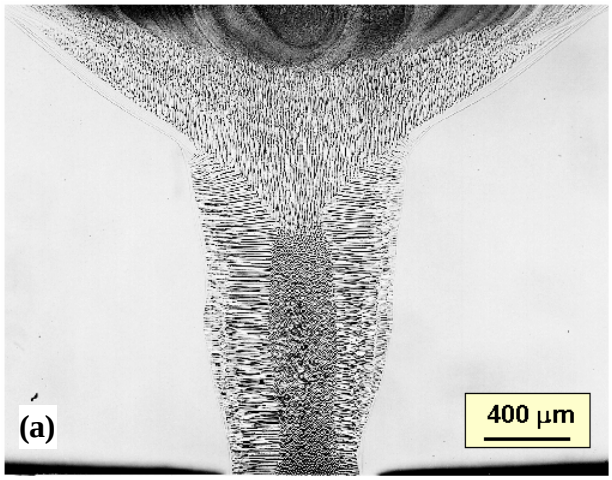
Abstract

A single-crystal nickel-based superalloy (alloy Rene N5) was welded using laser and electron beam processes. The resultant microstructure was examined by optical microscopy. It was found that extensive stray grain formation took place, and furthermore, the stray grain formation was not symmetrical with respect to the weld centerline. The results were interpreted with the use of the theories of Kurz and co-workers on dendrite tip growth and constitutional supercooling ahead of the advancing dendrite solidification front. It was found that the theories explain the observations quite well, and provide the basis for optimizing the weld conditions in the future so as to yield stray-grain free welds in single crystals.

Introduction

Welding of single-crystal nickel-base superalloys is a desirable technology that needs to be developed so that cost-efficient repair and refurbishment of expensive single-crystal components in turbine engines can be accomplished. The welding of single-crystal nickel-based superalloys is complicated by the fact that the formation of new grains (stray grains) can take place during solidification and these are likely to compromise weldment properties. The formation of stray grains is very strongly dependant upon the alloy composition and the welding conditions. This is demonstrated in Figure 1 where a weld made on a model Fe-Cr-Ni alloy is compared to a weld on a nickel-based superalloy. The microstructure of the Fe-Cr-Ni weld shows zones with different variants of the base metal <100> directions but the overall single crystal nature is maintained. In contrast, the nickel alloy weld shows extensive stray grain formation, thereby destroying the single crystal microstructure. In addition, the high angle grain boundaries associated with stray grains appear to be weak points in the microstructure since weld cracking typically follows along these boundaries (see Figure 1).

Earlier work on model Fe-Cr-Ni single crystal welds [1-4] showed that the welds consist of several zones with dendrite growth directions that are oriented along different variants of the easy-growth <100> directions. A geometric model was used to explain which dendrite growth directions are active at any given location on the liquid-solid interface [1,2]. This model was based on an evaluation of the dendrite tip temperature as a function of dendrite growth velocity, using the theory for dendrite growth advanced by Kurz and co-workers [5]. The theory indicates that as the growth velocity increases, the dendrite tip temperature decreases. Thus, the dendrite orientations with the slowest growth velocity have the highest dendrite tip temperature and extend furthest into the liquid. These same dendrites lie ahead of dendrites with less favorable orientations and therefore will prevail while the other orientations will be eliminated.



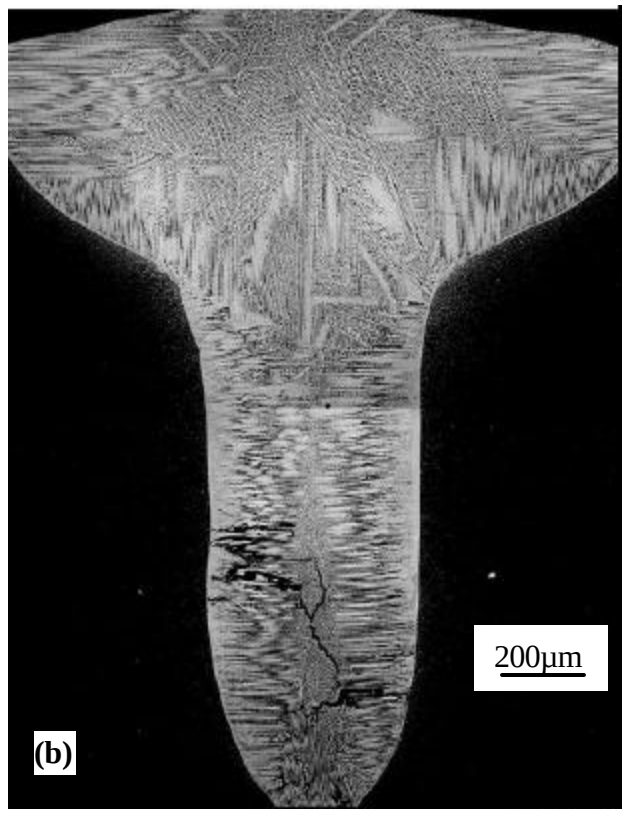


Figure 1: Transverse view micrographs of electron beam welds of single crystals: (a) Fe-15Cr-15Ni alloy showing zones of different dendrite growth orientations but no sign of stray grains, (b) PWA1480 nickel-based superalloy weld showing extensive stray grain formation throughout weld cross-section as well as cracking.

The geometric model also showed that dendrites most closely aligned with the solidification front normal will be the dendrites with the minimum growth velocities. Experimental results were in excellent agreement with the theoretical predictions [1-4]. This geometric model is critical when trying to evaluate the stray grain formation tendencies in single crystal welds.

Kurz and co-workers also advanced the theory to explain the extent to which stray grains can nucleate and grow during the solidification of single crystals [6,7]. The theory was based on the concept of constitutional supercooling ahead of the advancing dendrites. When these newly formed grains are oriented more advantageously than any of the six possible <100> growth variants in the base material then they will tend to be stable. Consequently, when the stray grains are stable and they grow, the single-crystal nature of the base material is lost.

The present paper will describe results from welds made on single crystal Rene N5, a commercial nickel-based superalloy that is used extensively in advanced turbine engines. The pioneering work of Kurz and co-workers that provided the basis for the geometric dendrite growth model and the stray grain formation model will be used to explain the results. The current work considers a partial penetration weld in which the orientations of the weld pool surface normal and thermal gradient vary along the entire solid-liquid interface. This is in contrast to the cladding-type configuration that was studied by Kurz and co-workers [8] where the thermal gradient and dendrite growth directions were nearly parallel and tended to be constant across the entire solidification front.

Theoretical Basis for Modeling Stray Grain Formation

Ahead of the advancing solidification front, constitutional supercooling may be extensive enough to promote nucleation and growth of grains with crystallographic orientations that are different from that of the base material. Kurz et al evaluated this phenomenon by considering the dendrite tip temperature and the solute field ahead of the dendrite [5-7]. By integrating the

extent of supercooling over the entire space in front of the dendrites, the tendency to form stray grains was quantified. The extent of supercooling was found to be a function of the solidification temperature range, the thermal gradient, and the dendrite growth velocity [5-7]. This theory readily explains the absence of stray grains in model Fe-Cr-Ni alloys, where the solidification temperature range is quite small (<10°C). In contrast, nickel superalloys have a much larger solidification temperature range and stray grain formation is more prevalent. The extent of stray grain formation was correlated with the alloy solidification temperature range earlier [9] and the results agreed with theoretical predictions. The analysis of supercooling ahead of the growing dendrite tips predicts that the extent of supercooling will be proportional to the quantity G^n/V where G is the thermal gradient, V is the dendrite growth velocity, and *n* is a constant that depends on the material. For a nickel-based CMSX4 alloy, comparable to Rene N5, *n* was found to be 3.4 [7]. In the case of a weld, the thermal gradient and interface growth velocity will vary with position along the solid-liquid interface. This is shown in Figure 2, where a schematic diagram shows the change in solidification front orientation across the entire weld. The orientation of the solidification front normal can be expressed in terms of the two angles, θ and ϕ.

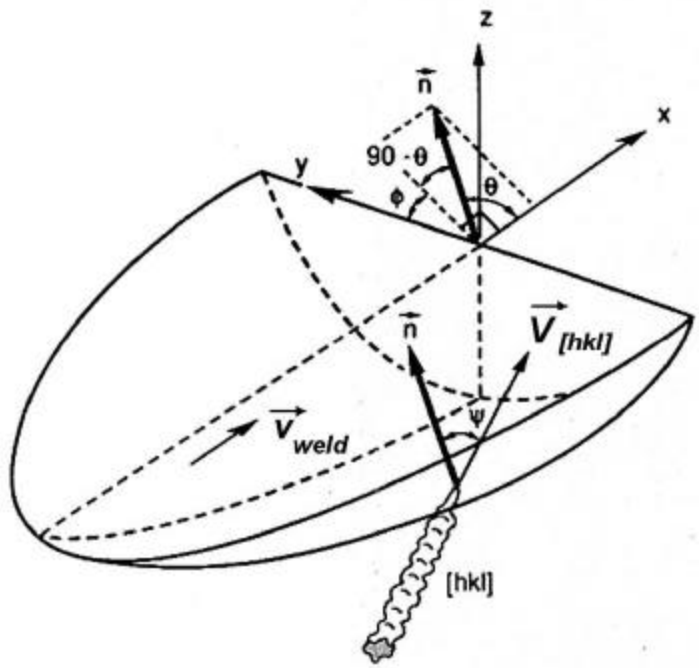


Figure 2: Schematic diagram of weld pool showing variation of solidification front normal direction with position and parameters used to identify the orientation.

A geometrical model based on a minimum undercooling criterion at the dendrite tip was developed to assess the effect of the variation of solidification front orientation on the dendritic growth [1-2]. The minimum tip undercooling criterion corresponds to a minimum dendrite growth velocity condition, based on the dendrite tip model of Kurz et al [5]. This geometric model was applied in the current study. The weld pool shape was determined with the use of a commercial heat and fluid flow software package [10] after modifying the heat source shape so that the predicted weld pool profile agreed with the experimentally observed profile [11]. Details are provided elsewhere [12].

Experimental Conditions

Autogenous laser and electron beam welds were produced on thin sheets (25.4 mm x 50 mm x 0.8 mm) of a Rene N5 alloy. The composition of the alloy was Ni-6.25Al-7.32Co-7.11Cr-6.38Ta-4.83W-2.88Re-1.41Mo-0.15Hf-0.053C (wt %). Three different combinations of weld speed and power were examined but because of space limitations, only one weld from each type of weld process will be presented here. Details on the other welds may be found elsewhere [12]. The laser weld was made using a 1.5 kW continuous wave Nd-YAG laser with argon gas shielding at a speed of 12.7 mm/s and a power of 804 W. The electron beam weld was made with a 15 kW electron beam welder at a speed of 21.3 mm/s and a power of 520 W. The welding direction was along the longitudinal direction of the original cast plate from which the thin sheet was cut and the welding plane was parallel to the original cast plate surface. The

weld direction and sheet normal were measured using Laue diffraction and were determined to be [0.141, $\overline{0.217}$, 0.966] and [$\overline{0.925}$, $\overline{0.376}$, 0.051], respectively. These directions correspond to deviations of 15° and 22° from the [0 0 1] and [$\bar{1}$ 0 0] directions, respectively. Orientation Imaging Microscopy (OIM) was used to identify the crystallographic orientations of grains within the welds.

Results and Discussion

Representative optical micrographs of the laser and electron beam welds are shown in Figures 3 and 4. Both a transverse view and top-surface view are shown for each weld. The micrographs show several features that are characteristic of the welds. First, as shown in the top surface view, transverse cracking was observed in both types of welds. Second, the cracking was clearly asymmetrical with respect to the weld centerline in both cases. Third, distinct zones of dendritic growth representing different variants of the base metal <100> directions are found, in agreement with observations on other single crystal welds (see Figure 1 and refs. 1-4, 13). Finally, higher magnification transverse views (Figures 3b, 4b) show that stray grain formation is common, but the density of stray grains is asymmetrical with respect to the centerline, with more stray grains appearing on the same side as the cracks. The same trend was observed in welds made at other speeds [12]. Furthermore, the tendency to form stray grains and cracks was greater in higher speed laser welds [12]. The asymmetrical presence of stray grains is graphically shown in Figure 5, which is an OIM image of the top surface of the laser weld.

A detailed description of the weld crystallography and thermal conditions is not possible in this paper. However, when the optical results are combined with a heat and fluid flow model analysis of the thermal conditions, it is found that the stray grain formation decreases as the parameter G^n/V increases [12]. Since the weld direction and weld surface normal are not along the symmetrical [100] and [001] directions, the dendritic growth conditions are also not symmetrical. Thus, even though the heat and fluid flow conditions are equivalent on both sides of the welds, and the solidification front velocities and maximum thermal gradients are also symmetrical, one must consider the actual crystallographic effects and resolve the velocities and gradients along the active dendrite growth directions at various locations. When this is done, one finds that the growth conditions are no longer symmetrical and the observed effects can be explained [12]. It should be noted that not only do the resolved velocities and gradients vary for different <100> dendrite growth variants, but even in regions where the same growth

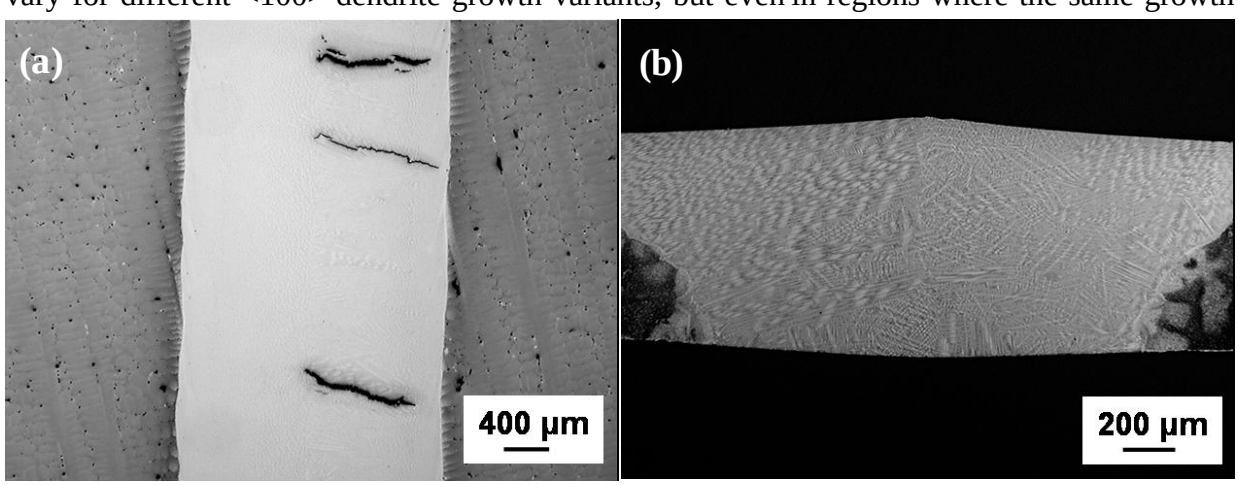


Figure 3: Optical micrographs of laser-welded Rene N5: (a) top-view and (b) transverse view.

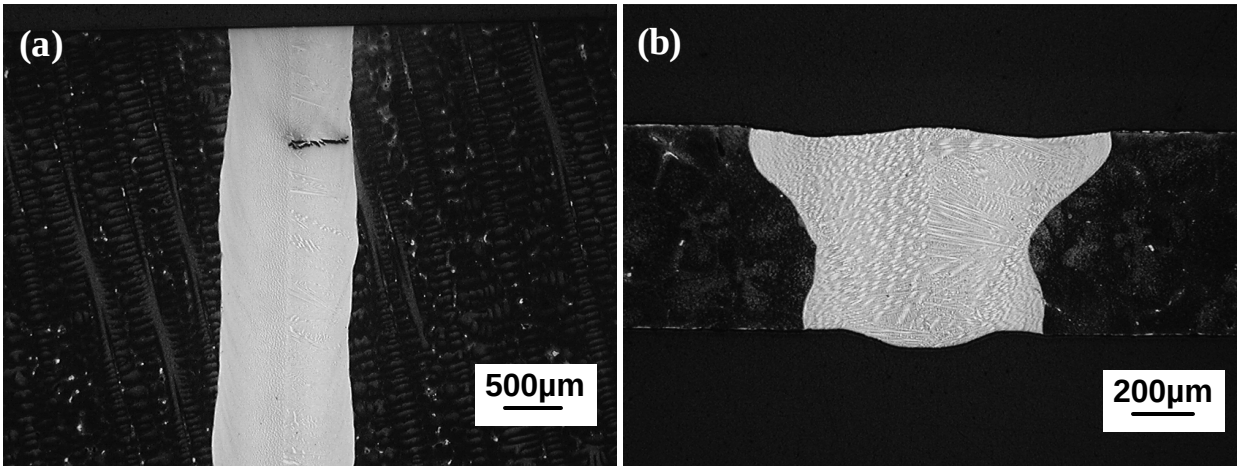


Figure 4: Optical micrographs of electron-beam welded Rene N5: (a) top-view and (b) transverse view.

variant is active, the changing weld pool solidification front orientation also changes the resolved velocities and gradients for the same growth direction.

The theories of Kurz and co-workers provide the framework for understanding the solidification behavior of single crystal welds In these experiments and in earlier ones, the condition for selection of the active dendrite growth variant among the six possible <100> base metal orientations is a minimum dendrite tip undercooling condition. The prediction of which zones are active at different locations across the weld pool solidification front fits perfectly with the minimum dendrite growth velocity condition, which is equivalent to the minimum tip undercooling criterion according to the analysis of Kurz, Giovanola and Trivedi [5]. The occurrence of stray grains was addressed in other work by Kurz and co-workers [6,7] and was based on an evaluation of the constitutional supercooling ahead of the growing dendritic front. The theory indicates that the parameter G^n/V will control the extent to which stray grains will

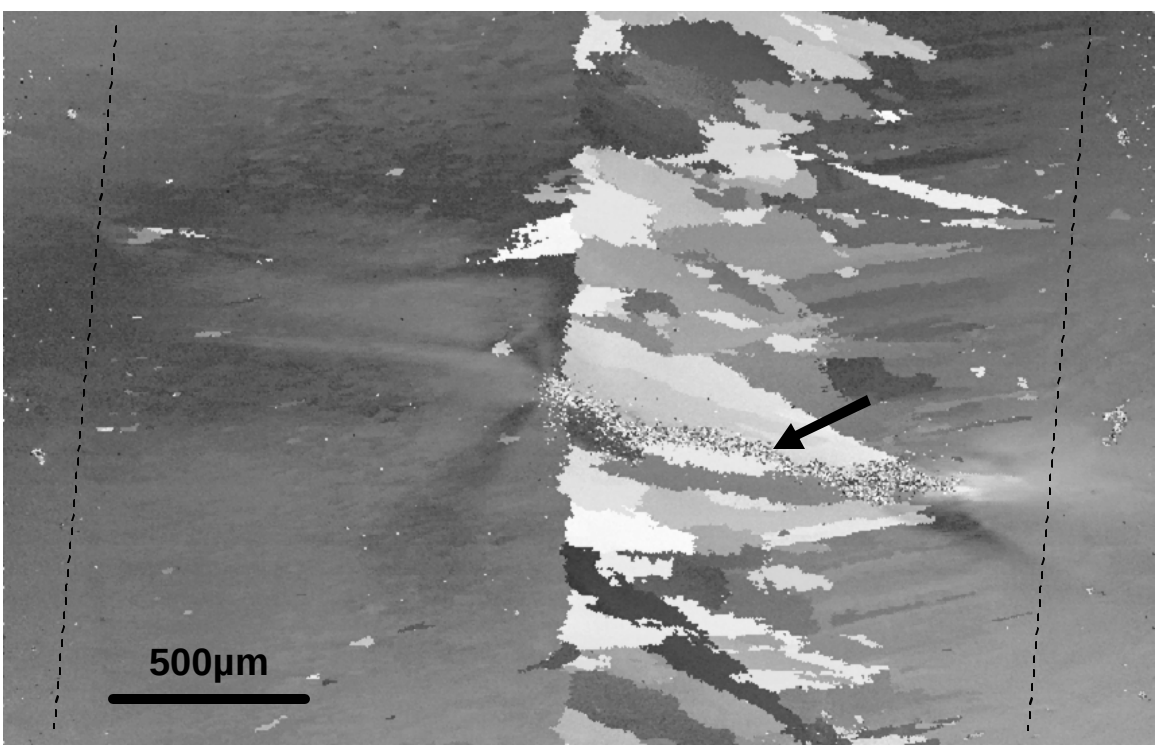


Figure 5: OIM map revealing grains and grain boundaries in laser weld (Figure 3). The dashed lines are approximate weld boundaries and the arrow points to a transverse crack.

form, and as the value of G^n/V increases, the tendency to form stray grains will diminish. The thorough heat and fluid flow analysis of the laser and electron beam welds, presented elsewhere [12], showed that the experimental results were in good agreement with the theoretical analysis. Thus, the theories of dendritic growth advanced by Kurz and his co-workers have been instrumental in providing the necessary background for interpreting and understanding the solidification behavior in single crystals. It is hoped that these same theories can be exploited to identify the optimum welding conditions that will lead to successful stray-grain free and crack-free welds of single crystal nickel-based superalloys in the future.

Acknowledgements

This research was sponsored by the Office of Fossil Energy, DOE National Energy Technology Laboratory, and the Division of Materials Sciences and Engineering, U. S. Department of Energy, under contract DE-AC05-00OR22725 with UT-Battelle, LLC. The authors would like to thank General Electric Corporation for supplying the Rene N5 material and R. W. Reed, Jr. for preparing the welds.

References

1. M. Rappaz, S. A. David, J. M. Vitek and L. A. Boatner, "Development of Microstructures in Fe-15Ni-15Cr Single Crystal Electron Beam Welds," *Metall Trans A*, 20A (1989), 1125-1138.
2. M. Rappaz, S. A. David, J. M. Vitek and L. A. Boatner, "Analysis of Solidification Microstructures in Fe-Ni-Cr Single-Crystal Welds," *Metall Trans A*, 21A (1990), 1767-1782.
3. S. A. David, J. M. Vitek, M. Rappaz and L. A. Boatner, "Microstructure of Stainless Steel Single-Crystal Electron Beam Welds," *Metall Trans A*, 21A (1990), 1753-1766.
4. M. Rappaz, J. M. Vitek, S. A. David and L. A. Boatner, "Microstructural Formation in Longitudinal Bicrystal Welds," *Metall Trans A*, 24A (1993), 1433-1446.
5. W. Kurz, B. Giovanola, and R Trivedi, "Theory of Microstructural Development During Rapid Solidification," *Acta metal*, 34 (1986), 823-830.
6. M. Gaümann, R. Trivedi, and W. Kurz, "Nucleation Ahead of the Advancing Interface in Directional Solidification," *Mater Sci Eng A*, A226-228 (1997), 763-769.
7. M. Gaümann, C. Bezençon, P. Canalis and W. Kurz, "Single-Crystal Laser Deposition of Superalloys: Processing-Microstructure Maps," *Acta mater*, 49 (2001), 1051-1062.
8. M. Gaümann, S. Henry, F. Cléton, J.-D. Wagnière and W. Kurz, "Epitaxial Laser Metal Forming: Analysis of Microstructure Formation," *Mater Sci Eng A*, A271 (1999), 232-241.
9. J. M. Vitek, S. S. Babu, S. A. David, and J-W. Park, "Microstructure Development in Single Crystal Welds," *Mater Sci Forum*, 426-4 (2003), 4123-4128.
10. Sysweld, ver. 2002, ESI, Detroit, MI.
11. D. Dye, O. Hunziker, S. M. Roberts and R. C. Reed, "Modeling of the Mechanical Effects Induced by the Tungsten Inert-Gas Welding of the IN718 Superalloy," *Metall Mater. Trans A*, 32A (2001), 1713-1725.
12. J-W. Park, S. S. Babu, J. M. Vitek, E.A. Kenik and S. A. David, "Stray Grain Formation in Single Crystal Ni-Base Superalloy Welds," *J Appl Phys*, 94 (2003), 4203-4209.
13. J. M. Vitek, S. A. David and L. A. Boatner, "Microstructural Development in Single Crystal Nickel Base Superalloy Welds', *Sci. Technol. Welding Joining*, 2(3) (1997), 109-118.