Microstructure Development in Single Crystal Welds

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Keywords: welding, single crystals, nickel superalloys, stray grains, constitutional supercooling

Abstract. Welding of single crystal nickel-based superalloys leads to excessive stray grain formation as well as cracking associated with stray grain boundaries. This paper examines the microstructure development in both model alloys and commercial alloys and progress in terms of modeling the dendritic growth pattern produced in these alloys. The tendency to form stray grains is also studied, and recent experimental work that supports the principal of constitutional supercooling as the underlying mechanism for stray grain formation is presented.

Introduction

High temperature demands on turbine engines have led to the extensive use of single crystal nickel-based superalloys over the last 20 years. The absence of grain boundaries in single crystal components results in improved creep properties which, in turn, allows for engine operation at higher temperatures, thereby achieving improved engine efficiencies. Due to the intrinsic high cost of such single-crystal engine components, especially for larger land-based turbine applications, there is a need to be able to weld these components for salvaging imperfect as-cast components as well as for refurbishing and repairing worn or damaged parts. Welding of single crystal nickel-based superalloys is problematic due to the formation of new grains during weld solidification (known as stray grains), leading to a loss of the single-crystal nature of the components and an associated loss in creep properties. Furthermore, the formation of stray grains is often associated with increased cracking susceptibility as well. This paper will review earlier work as well as describe new results on the welding of single crystals aimed at developing technologies that can lead to effective welding of complex nickel superalloy single crystals.

Earlier Work on Welding of Model Alloys

Extensive work was done approximately 10 years ago on identifying the controlling factors of microstructure development in single crystal welds [1-3]. In that work, a pure, model Fe-15Cr-15Ni (wt %) alloy was investigated. Electron beam welds were made on disk samples with specific weld surface orientations and welding directions. It was found that the resultant welds consisted of zones of differently oriented dendrites. In spite of the presence of these very distinct zones, the overall single crystal nature of the alloy was maintained. An example is shown in Figure 1. Zones of differently oriented dendrites develop because growth occurs along the preferred <100> growth directions, and the choice of which growth direction among the six possible variants will prevail is based on the relation between weld pool shape and dendrite orientation. The dendrite growth direction that is most closely aligned with the solidification front normal (whose orientation changes with location along the fusion line) is the one that survives. A geometric model, based on an evaluation of growth velocities that are needed to maintain the overall solidification front velocity for different dendrite orientations, was developed and it explained the dendritic growth zones perfectly [1-3]. Those dendrite orientations with better alignment with the solidification growth front direction require slower growth velocities and hence less undercooling at the dendrite tip. Thus, the dendrite tips for these orientations lie ahead of dendrites with other orientations that have higher growth velocities and require higher undercoolings.

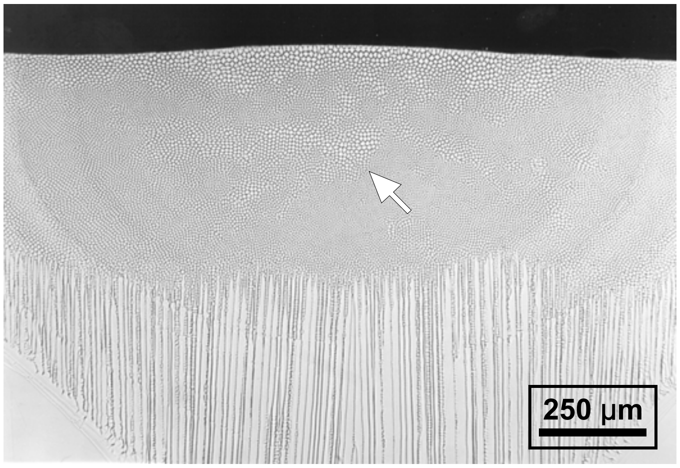

Fig. 1: Fe-15Cr-15Ni single crystal electron beam weld made along [100] on (001) plane.

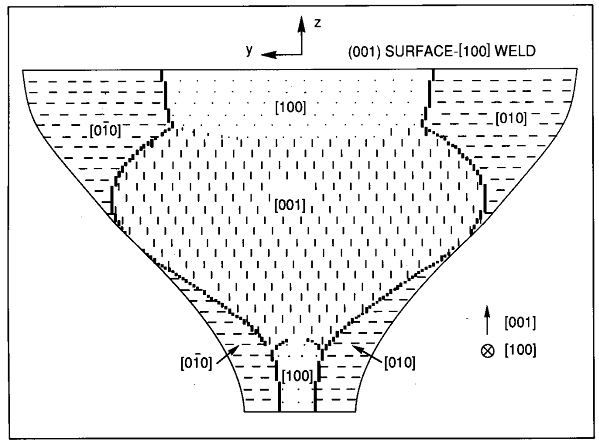

Fig. 2: Calculated dendritic growth pattern for weld with orientation in Fig. 1.

A plot of predicted dendrite orientations for the same weld orientation shown in Figure 1 is pictured in Figure 2. The overall dendritic zone pattern is reproduced. Any discrepancy between the predicted and observed dendrite zone patterns can be traced to the assumptions regarding the weld pool shape, which determines the solidification front orientation, and such discrepancies do not represent a failure of the basic geometrical model. In fact, the predictions of the geometric model were also confirmed by experiments on bi-crystal welds in which competition among dendrites at the centerline between two differently oriented crystals took place [4].

One of the key observations in the earlier work on the model Fe-15Cr-15Ni alloy was the nearly complete absence of stray grains, i.e., newly nucleated grains with crystallographic orientations different from the base material. Numerous weld orientations and conditions were studied in the Fe-15Cr-15Ni model alloys and, in all cases, stray grain formation was extremely rare. In the worst cases, only one or two stray grains were found in the entire sample. The absence of stray grains and perfect retention of the single crystal nature is noteworthy and is in stark contrast to the behavior of nickel superalloys, described below. The use of model alloys sheds light on the underlying mechanism of stray grain formation and possible means of avoiding the same in nickel-base superalloys, as detailed later.

Earlier Work on Welding of Nickel Superalloys

In contrast to the observations described above for the model Fe-15Cr-15Ni single crystals, nickel-based superalloys are extremely vulnerable to stray grain formation. An example is shown in Figure 3. In addition to the loss of the single crystal nature of the alloy in the weldment, the formation of stray grains can lead to preferential cracking along the stray grain boundaries [5,6]. This is not surprising since commercial single-crystal nickel-based superalloys do not have grain boundary strengthener additions that are common in polycrystalline and directionally-solidified nickel alloys. The formation of stray grains in nickel-based superalloy single crystals is common over a wide range of alloy compositions [5-8].

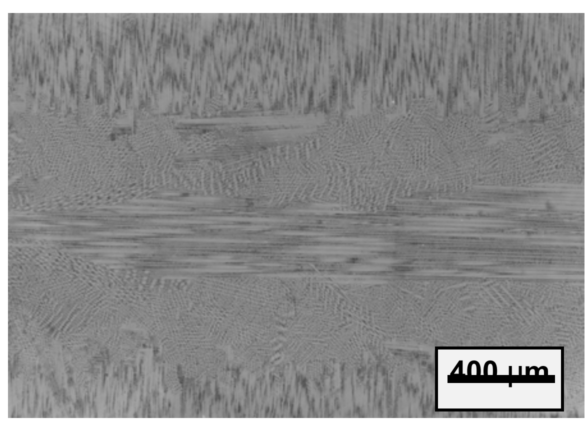

Fig. 3: Top view of laser welded PWA1480.

Theory of Stray Grain Formation

One explanation for the susceptibility of nickel superalloys to stray grain formation is based on fluid flow considerations, and the development of powerful convective flows that may lead to dendrite fragmentation and formation of new grains ahead of the solidification front [9]. An alternative explanation is based on the concept of constitutional supercooling (CS) and the potential for nucleation of new grains ahead of the solidification front [5,10]. In this latter mechanism, solute build-up ahead of the solidification front combined with a relatively shallow temperature gradient ahead of the front can lead to undercooling of the liquid and nucleation of new grains. This mechanism, as applied to nickel superalloys, has been studied theoretically [10]. The basic criterion for avoiding constitutional supercooling (and stray grain formation) is given by:

$$G/R > \Delta T/D \qquad (1)$$

where G is the thermal gradient in the liquid at the solidification front, R is the dendrite growth velocity, ΔT is the solidification temperature range, and D is the liquid diffusivity.

In many of the earlier welding trials on nickel alloy single crystals, distinguishing between these two mechanism has been impossible because stray grain formation has been extensive and identifying conditions that promote or inhibit stray grain formation has not been possible. However, recent results suggest that the CS condition may, indeed, be the controlling mechanism for stray grain formation, at least in welds (versus castings) where the molten pool is relatively small and the growth velocities and thermal gradients are relatively high. In a studies of weld cladding and laser deposition, where the thermal flow conditions are simplified and primarily uni-directional, the potential for epitaxial growth of a weld layer that maintains the base material single crystal orientation has been demonstrated [8,11-12]. Furthermore, an evaluation of the solidification conditions has shown that the CS criterion describes the potential for avoiding stray grain formation quite well.

New Results on Model Alloys

As noted above, earlier work on a model, "pure" Fe-15Cr-15Ni alloy showed that this material is resistant to stray grain formation. Upon examination of the CS criterion given by Equation (1), this resistance can be readily explained by the low value of ΔT (solidification temperature range) for this alloy[1]. The equilibrium solidification temperature range can be calculated using computational thermodynamics. A comparison of ΔT for the "pure" model Fe-15Cr-15Ni alloy with commercial nickel superalloys and other alloys is shown in Table 1. The value for ΔT for the model alloy is considerably less than that for any of the commercial nickel superalloys. Hence, for the same thermal and growth conditions during welding, it should be much easier to satisfy the condition in Equation (1) for Fe-15Cr-15Ni and hence avoid stray grain formation in this model alloy, as was the case. Recently, new Fe-15Cr-15Ni alloys were made in which the starting materials were not as pure as in the earlier alloys. In addition, limited but purposeful alloying additions were made to the base Fe-15Cr-15Ni composition. These will be referred to as "alloyed" Fe-15Cr-15Ni. Both the reduced purity of the starting material and the additional alloying result in a larger ΔT, as shown in Table 1; approximately a three-fold increase in ΔT is found. Electron beam welds were made on these alloys, as before, and representative results are shown in Figure 4. The micrographs should be compared to Figure 1, which is a weld on the "pure" Fe-15Cr-15Ni weld, made in the same orientation and at the same speed. In the "pure" alloy, there are a few small zones with larger dendrite arm spacings (arrow) but these areas do not represent stray grains since their crystallographic orientation is identical to the rest of the weld and the base material. It is clear that stray grain formation is more prevalent in the "alloyed" samples. The increase in stray grain formation can be readily explained by the increase in the solidification

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[1]The equilibrium solidification temperature range is considered here. Although the true solidification temperature range may be larger, due to non-equilibrium solidification and partitioning during welding, it is assumed that the trends found for the equilibrium solidification range parallel similar trends for non-equilibrium solidification conditions.

Alloy, Composition [wt %]	ΔT [°C] (database ref. in [])
Fe-15Cr-15Ni	7.9 [14]
PWA-1480, Ni-12Ta-10.4Cr-5.3Co-4.8Al-4.1W-1.3Ti	49.4 [15]
CMSX-4, Ni-9Co-6.5Cr-6.5Ta-6W-5.6Al-1Ti-0.6Mo	38.1 [15]
Rene N5, Ni-7.5Co-7Cr-6.5Ta-6.2Al-5W-3Re-1.5Mo-.15Hf-.05C	40.3 [15]
Fe-14Cr-15Ni-1Si-.04Cu-.01Al	26.4 [14]
Fe-14Cr-14.9Ni-.65Si-.05Cu-.01Al-.01Ti	20.1 [14]

Table 1: Calculated equilibrium solidification temperature range for various alloys and compositions using ThermoCalc [13] and the SSOL [14] and Ni-DATA [15] databases.

temperature range for these "alloyed" materials, which leads to a more severe requirement on G/R, as given by Equation (1), in order to avoid CS and stray grain formation. It is also noteworthy that the stray grains were most prevalent near the centerline of the weld, where G/R is the smallest [16]. There was a small difference in the weld power when welding the "pure"samples versus the "alloyed" material (450 W versus 550 W, respectively). Calculations of the thermal gradient along the centerline at the liquidus temperature were made for both conditions using the analytical Rosenthal equations for the 2D case [17] (all welds were full penetration). They showed that the gradients were nearly the same: 4×10^5 K/m for the "pure" samples and 2.6×10^5 K/m for the alloyed material. Thus the change in G is small in relation to the approximate 3-fold increase in ΔT, and therefore, the increased susceptibility to stray grain formation can be attributed to the increase in solidification temperature range. Further experiments are underway to examine in detail the effect of welding conditions (power, speed) on the tendency to form stray grains in these model alloys.

Preliminary Results on Commercial Alloy Rene N5

A detailed study into the stray grain formation tendencies of single crystal nickel superalloys has recently been initiated at ORNL. The aim is to identify the mechanism of stray grain formation in these materials, and to evaluate the potential for forming stray-grain-free welds. The investigation of

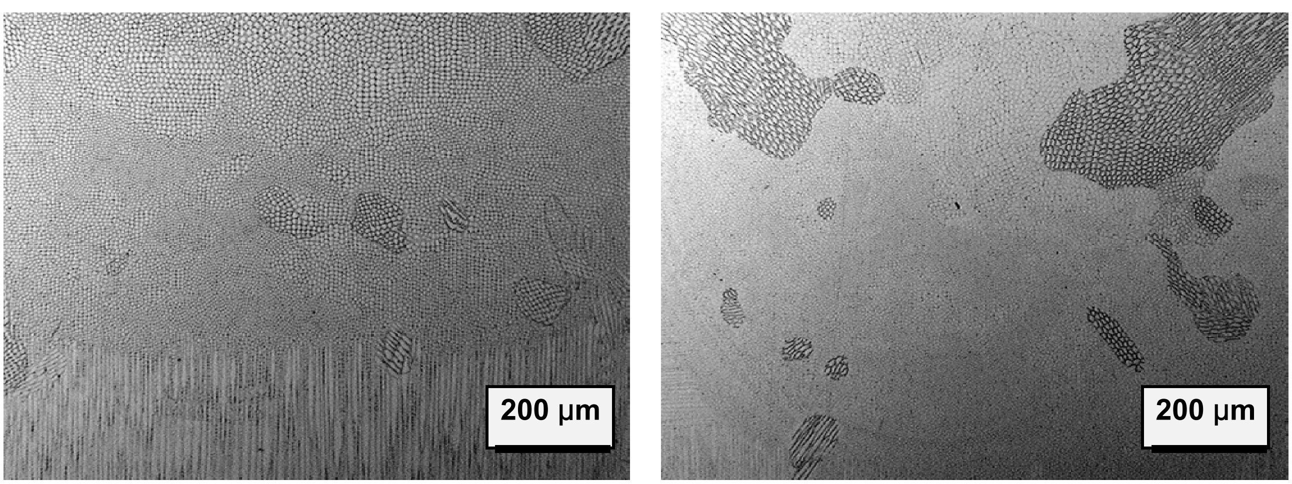

Fig. 4: Transverse view of electron beam welds made in [100] direction on (001) plane for "alloyed" model alloys (a) Fe-14Cr-15Ni-X and (b) Fe-14Cr-14.9Ni-X (see Table 1 for exact alloy compositions) showing more abundant stray grain formation compared to "pure" Fe-15Cr-15Ni alloy (Fig. 1).

commercial alloys is being complemented by studies on model alloys, as described above. Some preliminary results will be presented here. The results are very interesting and exciting because they show the potential for producing perfect, defect-free welds.

Linear autogenous laser welds were made on thin sheet of a Rene N5 alloy. The welds were made along the longitudinal direction of the cast plate from which the thin sheet material was cut; this direction was roughly parallel to the [100] direction, and the sheet normal was approximately (013). A micrograph of a weld is shown in Figure 5. The photo clearly shows a disparity in behavior from one side of the weld to the other. On the left side, no cracking was found while transverse cracks are present on the other side of the centerline. A higher magnification view, also shown in Figure 5, shows that the cracks tend to follow stray grain boundaries. The results of an Orientational Imaging Microscopy analysis on the same sample are shown in Figure 6. High angle (10°) boundaries are outlined and it is clear that the stray grains are abundant on one side of the weld but nearly completely absent on the other side. Although these results are only preliminary, they show some outstanding features. First, the susceptibility of a weld with stray grains to cracking is clearly demonstrated. Second, the results show that producing stray-grain-free welds for conditions other than uni-directional cladding is possible. Finally, the results infer that stray grain formation is not controlled by dendrite fragmentation, at least in these welds, since one could presume that convective flows and the tendency to fragment dendrites would be the same on both sides of the centerline. The fact that the behavior is very different on opposite sides of the weld centerline is presumably due to the crystallographic asymmetry of the weld centerline. Further experiments and calculations are currently underway to determine what the exact dendrite orientations and solidification conditions are on either side of the weld to ascertain whether the asymmetric behavior can be explained by different degrees of CS on each side of the weld.

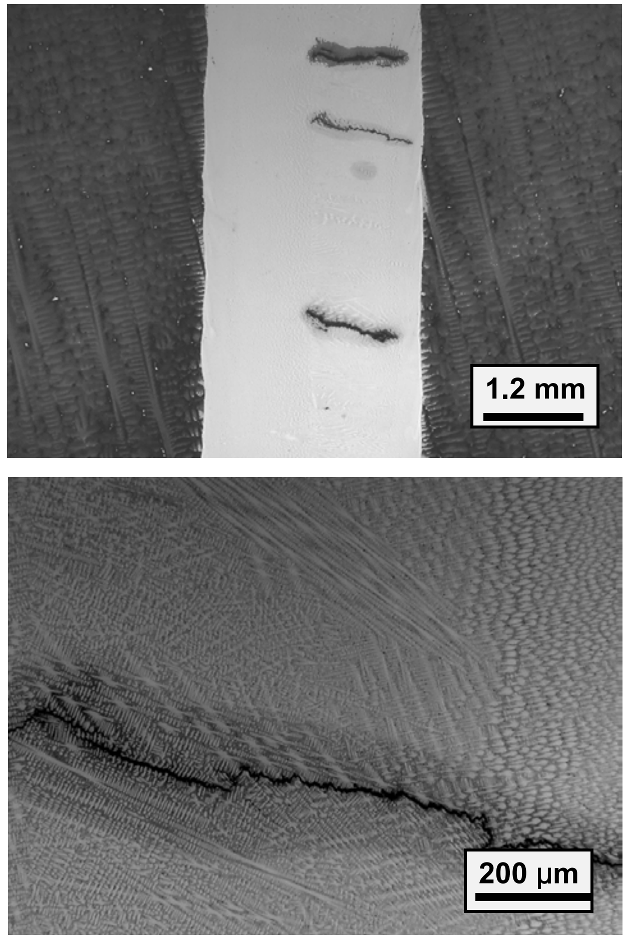

Fig. 5: Laser weld on Rene N5. (a) top viewing showing cracks on one side of centerline and (b) higher magnification of (a) showing cracks are associated with stray grains.

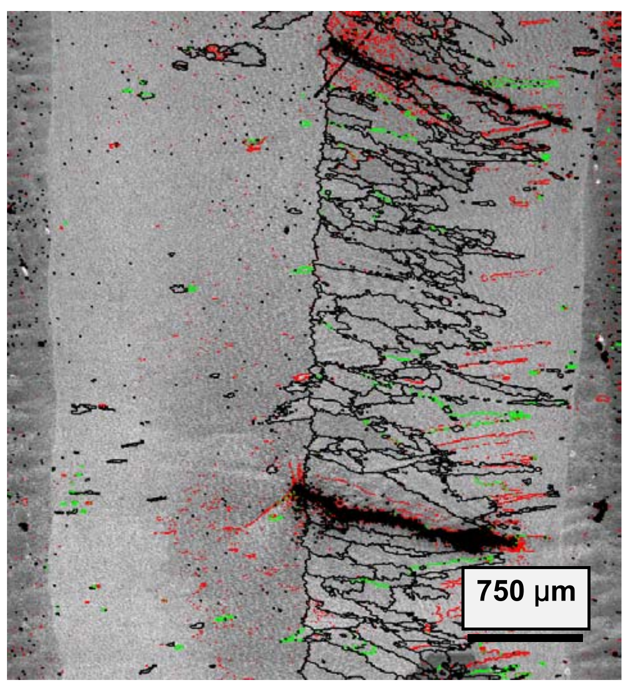

Fig. 6: OIM image of weld in Fig. 5(a) showing stray gray boundaries (outlined) on one side.

Summary

There is a critical need to develop procedures for welding of nickel-based single crystal superalloys that yield crack-free welds without abundant stray grain formation. Studies on single crystals of model alloys have shown that the dendritic solidification and the resultant pattern of differently oriented dendritic zones can be explained by a geometrical model that considers the degree to which different dendrite growth directions are aligned with the solidification front growth direction. Results on such model alloys support the proposal that constitutional supercooling ahead of the growing dendrite tips is the controlling mechanism for stray grain formation. Nickel-based single crystal superalloys are more vulnerable to stray grain formation because of the large solidification temperature range that promotes constitutional supercooling ahead of the growing interface. In addition to the loss of the single crystal nature of the alloys, the stray grain boundaries also are as especially vulnerable to cracking during welding. Preliminary results were shown for autogenous laser welds on alloy Rene N5 that showed that these alloys can be welded without stray grain formation and accompanying cracking, but only under limited conditions and specific crystallographic orientations.

Acknowledgments

This research was sponsored by the Division of Materials Sciences and Engineering, and the Advanced Turbine Systems Program, Office of Fossil Energy, U. S. Department of Energy, under contract DE-AC05-00OR22725 with UT-Battelle, LLC. The authors would like to thank L. Graham of PCC Airfoils for providing the Fe-Cr-Ni single crystal alloys and General Electric Corporation for the Rene N5 alloy.

References

[1] M. Rappaz, S.A. David, J.M. Vitek, and L.A. Boatner: Metall. Trans. A Vol. 20A (1989), p.1125
[2] S.A. David, J.M. Vitek, M. Rappaz, and L.A. Boatner: Metall. Trans. A Vol. 21A (1990), p.1753
[3] M. Rappaz, S.A. David, J.M. Vitek, and L.A. Boatner: Metall. Trans. A Vol. 21A (1990), p. 1767
[4] M. Rappaz, J.M. Vitek. S.A. David and L.A. Boatner: Metall. Trans. A Vol. 24A (1993), p. 1433
[5] J.M. Vitek, S.A. David and L.A. Boatner: Sci. Technol. Weld. Joining Vol. 2(3) (1997), p.109
[6] S.A. David, J.M. Vitek, S.S. Babu, L.A. Boatner and R.W. Reed: Sci. Technol. Weld. Joining Vol. 2(2) (1997), p.79
[7] T.M. Pollock: Mater. Sci. Eng'g. Vol. B32 (1995), p. 255
[8] J.M. Vitek and S.A. David: unpublished results, Oak Ridge National Laboratory (1997)
[9] T.M. Pollock and W.H. Murphy: Metall. Mater. Trans. A Vol. 27A (1996), p. 1081
[10] M. Gäumann, R. Trivedi and W. Kurz: Mater. Sci. Eng'g. Vol. A226-228 (1997), p. 763
[11] M. Gäumann, S. Henry, F. Cléton, J-D. Wagnière and W. Kurz: Mater. Sci. Eng'g. Vol. A271 (1999), p. 232
[12] M. Gäumann, C. Bezençon, P. Canalis and W. Kurz: Acta Mater. Vol. 49 (2001), p. 1051
[13] B. Sundman, B. Jansson and J-O. Andersson: CALPHAD Vol. 9 (1985), p. 153
[14] SSOL Database, 1993, ThermoCalc Software, Stockholm, Sweden
[15] Ni-DATA, version 5, N. Saudners, ThermoTech Ltd., Surrey, U.K.
[16] S.A. David and J.M. Vitek: Inter. Mater. Rev. Vol. 34(5) (1989), p. 213
[17] S. Kou: *Welding Metallurgy* (Wiley-Interscience, 2nd edn., Hoboken, NJ, USA 2003) p. 49-50