# WELDING AND WELD REPAIR OF SINGLE CRYSTAL GAS TURBINE ALLOYS

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## INTRODUCTION

The cost-effective commercial use of single crystal nickel-based superalloys for land-based turbine engine components such as blades and vanes requires that they can be repair welded to improve as-cast yields or to refurbish worn or failed components after intermediate service intervals. This program addresses this vital need by determining the welding behavior and weldability of single crystal nickel-based superalloys in order to develop an understanding and methodology for weld repair of critical components in advanced gas turbine systems. A two-pronged approach is being undertaken. First, the problem of stray grain formation in single crystal welds is being examined in detail. Their formation must be avoided in order to achieve optimum properties in single crystal welds. Thermodynamic, thermal, and solidification modeling as well as examination of model alloys and filler metal composition modifications are being carried out in order to identify the necessary conditions for the elimination of stray crystal formation in weldments. Second, a variety of fusion welding techniques, including electron and laser beam welding, and transient liquid phase bonding, are being utilized on commercial alloys in order to identify process conditions that are amenable to producing crack-free welds. Complementary thermo-mechanical modeling and simulation testing are used to identify weld cracking behavior. The welds are being evaluated by advanced characterization techniques in order to understand the microstructural development and cracking behavior, and to tailor the weld procedures to yield sound welds that meet microstructure and anticipated property requirements prior to, and after, long-term service. The program is being coordinated with an industry-university consortium that provides in-kind support and direction to the program.

## BACKGROUND

In order to achieve performance goals for gas turbine engines, high-temperature operation is required. At such high temperatures, creep must be kept to a minimum and for many metallic components, adequate creep properties can only be achieved with the use of single crystals. Such single crystals are routinely used in aircraft turbine engines. However, due to the increase in size of land-based turbine engines compared to comparable aircraft turbine engines, component cost will be increased dramatically and component quality will be a major manufacturing concern. Consequently, current casting yields need to be improved to make the costs manageable. The problem of improving casting yields is exacerbated by the fact that the larger component size increases the likelihood of having defects. One solution is to develop a reliable repair process that can be used to refurbish defective castings and thereby improve the net yield. Similarly, a technology for repairing parts is essential since replacement costs will be prohibitive. Such a repair technology will be needed for worn parts as well as failed components.

Earlier work at ORNL has shown that it is possible to weld polycrystalline nickel-based superalloys under limited conditions using electron or laser beam welding (1). However, routine commercial welding of single crystal nickel-based superalloys has three major hurdles that need to be surmounted in order to make refurbishment and repair feasible. First, the single crystal nature of the nickel-based superalloys is easily lost during welding due to stray grain formation (2). Second, nickel-based superalloys are very prone to cracking during welding. Finally, non-equilibrium solidification, elemental partitioning, and subsequent solid state transformation can yield microstructures that are not ideal and will not produce material with the needed properties (3,4). In addition to fusion welding, there is a need for the surface buildup of worn components through arc, electron-beam, or laser-beam deposition processes. For such surface deposition, published work by Gaumann et al (5) has shown that the conditions that favor epitaxial growth versus nucleation and growth are related to the temperature gradients, solidification velocities and heat-treatment processes (5).

The three major hurdles for welding of single-crystal nickel superalloys (stray grain formation, cracking, and non-equilibrium microstructure formation) are interdependent. It is the objective of this proposal to investigate the potential for weld refurbishment and repair of components by concentrating on these three effects and to determine processes, process conditions, and alloy compositions that will make such weld processing possible.

## RESULTS AND DISCUSSION

### MATERIALS

Commercial nickel-based superalloys were generously provided by several members of the industry-university consortium that was established for this project. In particular, a single-crystal slab of commercial alloy Rene N5 was provided by GE Power Systems and single-crystal slabs of PWA 1483 and CMSX4 were provided by Siemens-Westinghouse Corporation. Single crystal rods of model alloys based on an Fe-15Cr-15Ni composition were provided by PCC Airfoils Corporation. These materials were used in the studies described below.

## STRAY GRAIN FORMATION IN MODEL ALLOYS

Previous work has shown that commercial nickel-based superalloys are extremely prone to stray grain formation (2). In contrast, stray grain formation in a model, high purity stainless steel alloy (Fe-15Cr-15Ni) was rare (6). It has been proposed that stray grain formation is related to the extent of constitutional supercooling ahead of the advancing solidification front (2,7). Detailed examination of stray grain formation as a function of welding conditions was not possible in commercial alloys or the high-purity model alloys. This is because in the former, excessive stray grain formation was found regardless of the welding conditions while in the latter, no stray grains were found under any conditions. Since the extent of constitutional supercooling, and hence the tendency to form stray grains during welding, is proportional to the solidification temperature range, model alloy compositions with larger solidification temperature ranges were identified by ORNL and prepared by PCC Airfoils. The alloy compositions and the calculated solidification temperature ranges are shown in Table 1, along with calculated values for the high-purity model alloy and typical nickel-based superalloys.

**Table 1: Model alloy compositions and corresponding (calculated) solidification temperature ranges.**

| Alloy Composition (wt %) | Calculated Solidification Temperature Range (°C) |
|---|---|
| Fe-15Cr-15Ni (high purity alloy) | 7.9 |
| Fe-15Cr-15Ni-1Al | 11.9 |
| Fe-15Cr-15Ni-3Al | 29.4 |
| Fe-15Cr-15Ni-1Si | 27.9 |
| Fe-15Cr-15Ni-1Ti | 33.6 |
| Typical Ni-based single crystal superalloys | 40–50 |

Electron beam welds were made on the experimental alloys at two different speeds to assess the sensitivity of stray grain formation in these model alloys to welding conditions. A comparison of the grain structure in the high-purity alloy and one of the new model alloys is shown in Fig. 1. The results show that the new alloys are indeed vulnerable to stray grain formation. Furthermore, results showed that the extent of stray grain formation was affected by the welding conditions. These promising results will be followed by more extensive weld runs in order to identify the relationship between welding conditions and stray grain formation.

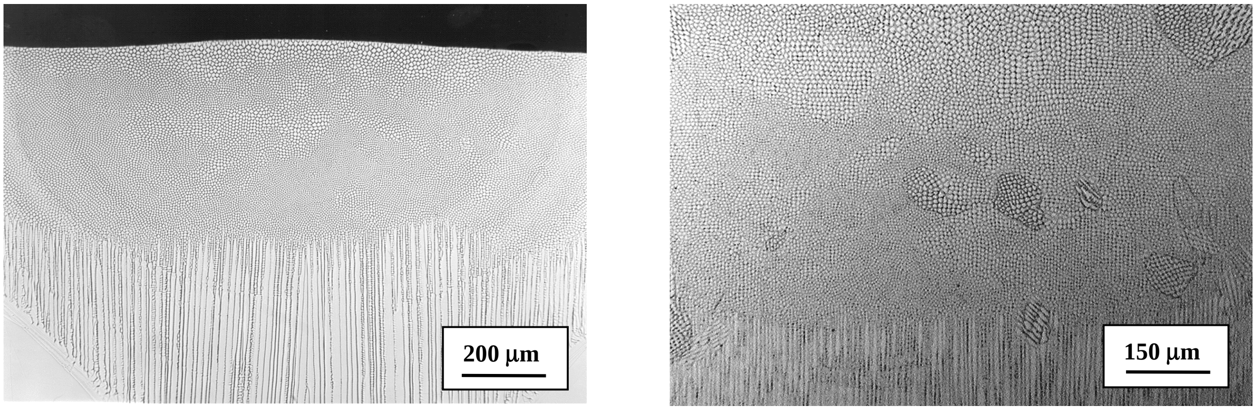


**Fig. 1. Transverse view micrographs of electron-beam welded single crystals welded along [100] direction and on (001) plane at same speed of 4.2 mm/s.** The alloy on the left is high-purity Fe-15Cr-15Ni and shows a complete absence of stray grains. The alloy on the right is Fe-15Cr-15Ni-1Si and shows numerous stray grains.

## STRAY GRAIN FORMATION IN COMMERCIAL ALLOYS

A series of autogenous laser welds were made on the Rene N5 single crystal alloy at different weld speeds and weld powers. The weld direction was along the axis of the slab from which the specimens were machined, and the surface normal was the same as that of the slab. X-ray analysis indicated that the weld direction was 15° from [100] and the surface normal was 22° from [001]. It was found that the extent of stray grain formation in these welds was influenced by the welding conditions. Low speed welds tended to maintain the single crystal nature of the base material while high speed welds resulted in more extensive stray grain formation. Furthermore, since the weld direction and sample surface normal were not along symmetric crystallographic orientations, there was a marked difference in the grain structure on either side of the weld centerline. Orientation Imaging Microscopy (OIM) was used to reveal the extent of stray grain formation.

Thermal modeling was used to identify the weld pool shape in these welds as a function of welding conditions. The modeled weld pool shape was combined with the crystallographic orientation data and the weld conditions to determine the dendritic growth velocities as a function of position in the weld pool, using a geometrical model developed earlier (8). The thermal modeling also allowed for a determination of the thermal gradient as a function of position along the solid-liquid interface. These results were used to evaluate the extent of constitutional supercooling as a function of weld conditions and weld position. The results showed that the conditions leading to the greatest constitutional supercooling corresponded very well with the experimental results on stray grain formation. Further details may be found in a publication that is presently being prepared (9).

## WELD CRACKING BEHAVIOR IN COMMERCIAL ALLOYS

Nickel-based superalloys are extremely prone to weld cracking (1). Experiments were conducted to determine the influence of welding conditions on cracking behavior. Two types of experiments were conducted. Autogenous gas tungsten arc (GTA) and laser welds were made on Rene N5 sheet samples for different welding conditions. All GTA welds showed cracking, although the extent of cracking was less for lower speed welds. Low speed laser welds did not show any cracking, but as the speed was increased, cracking became more prevalent. The cracking behavior was closely related to the extent of stray grain formation. Cracks tended to follow along stray grain boundaries. This is shown in Fig. 3.

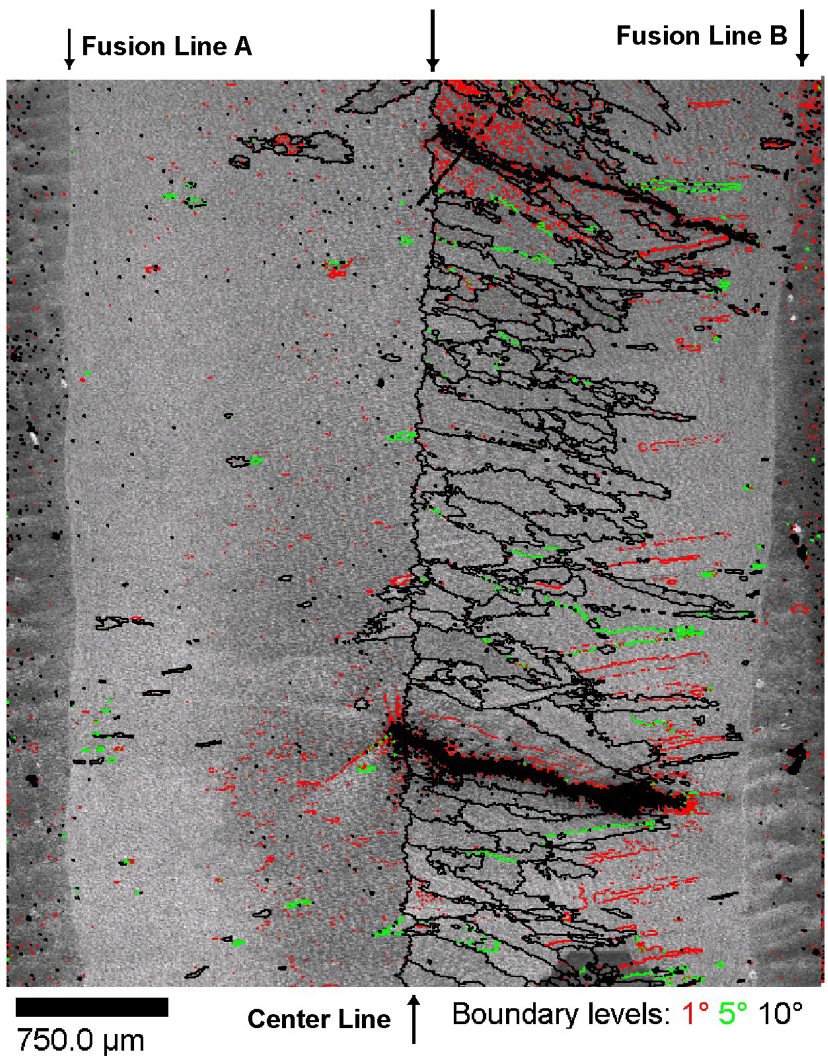


**Fig. 2. Optical micrograph of the top surface of laser welded Rene N5 with grain boundaries (as determined by OIM) super-imposed.** The results show the formation of high-angle grain boundaries (>10° misorientation) near the center of the weld on only one side of the weld.

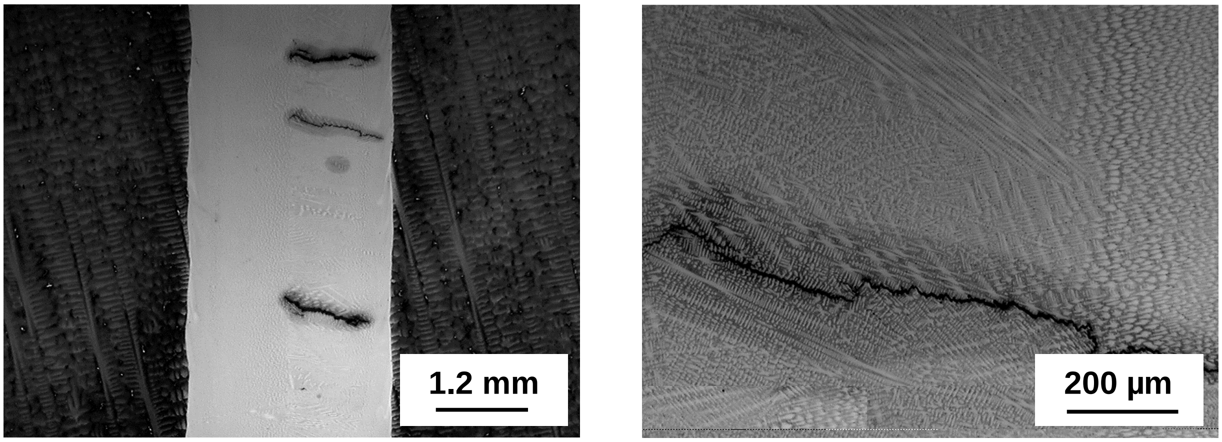


**Fig. 3. Top view of laser welded Rene N5 showing cracking behavior (left) on only one side, where stray grains were found (see Fig. 2) and higher magnification view (right) showing cracks follow along stray grain boundaries.**

Additional welds were made on Rene N5 by Honeywell Aerospace Services (a consortium member in this project) using their powder laser deposition process. Welds were made for two different geometries (groove and clad) with different filler metals. The results showed extensive cracking for the groove geometry. Cracking was most severe when the filler metal was a high-strength, high gamma prime content alloy, which is comparable to the single crystal alloys. The clad geometry was less susceptible to cracking.

Extensive modeling studies have been initiated to model the development of stresses during welding. These modeling results will be used to determine the effect of welding conditions on the magnitude of the stresses encountered during welding and to interpret the experimental results. The calculations will also be used to identify preferred welding conditions that minimize stresses and reduce the extent of cracking.

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