WELDING AND WELD REPAIR OF SINGLE-CRYSTAL GAS TURBINE ALLOYS

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Abstract

Oak Ridge National Laboratory has initiated a new, DOE-sponsored program on the welding and weld repair of single-crystal nickel-based superalloys. The program has several objectives: to identify the mechanism for stray grain formation in welds; to determine the weldability and crack-resistance of several commercial alloys; and to evaluate the effects of welding process and conditions on the weld microstructure. Extensive use of computational thermodynamics, simulation testing, and advanced microstructural characterization techniques will be used in the course of the program. The final goal is to identify new filler metal compositions that will be suitable for welding of single crystal alloys by resisting stray grain formation and cracking while maintaining optimal properties.

Introduction

As the demand for higher efficiency gas turbine engines increases, there is an increasing need to use single-crystal nickel-based superalloys for critical components. These materials offer benefits in terms of high-temperature strength, particularly with regard to long-term creep behavior. For use in land-based turbines, these components may be large and expensive, and therefore repair of worn components is a vital need. Oak Ridge National Laboratory (ORNL) has embarked on a new program, funded by the U. S. Department of Energy, to investigate the welding and weldability of single-crystal nickel-based superalloys and to evaluate the potential for weld repair of components made from these materials.

The program is divided into two parts that will be undertaken in parallel, as shown in the chart in Figure 1. The first part will investigate the grain structure after solidification. Nickel-based superalloys are prone to stray grain formation during welding, where new grains with orientations different from that of the base material are
produced (1). As a result, the single crystal nature of the material is lost and the mechanical properties are compromised. This portion of the program will attempt to identify the mechanisms that control stray grain formation and to find possible filler metal alloy compositions in which the stray grain formation tendencies are minimized or even eliminated.

The second part of the program will examine the weldability of single-crystal nickel-based superalloys. In addition to their susceptibility to stray grain formation, these alloys are prone to cracking during welding (2). Often, the cracks are associated with stray grain boundaries. This program will evaluate the weldability of several single-crystal nickel-based superalloys in order to identify the effects of weld process and process conditions on the propensity for cracking during welding. In addition, the program will examine the as-welded microstructures to determine the effect of the weld process and process conditions on the scale and distribution of the two-phase gamma + gamma prime microstructure.

The findings from the two parts of the program will be combined in the final stage of the program in an effort to identify potential weld metals that retain the single crystal nature of the base metal after welding while resisting cracking, and producing microstructures that are compatible with desired mechanical properties. This paper describes in greater detail the program plans, which are based on earlier work performed at ORNL.

**Stray Grain Formation During Welding**

During welding, initial weld metal solidification proceeds epitaxially from the base metal. Thus, if the base material is a single crystal, the first material to solidify during welding will retain the single crystal nature of the base material. However, as weld metal solidification proceeds, new grains, called stray grains, may nucleate and grow. In the case of nickel-based superalloys, this is an undesirable consequence of welding because the single-crystal microstructure is preferred in order to retain the optimum elevated temperature creep properties of these materials.

ORNL has studied extensively the weld solidification of a model single crystal Fe-15Cr-15Ni alloy (3-6). It was found that retaining the single crystal nature of the base material was possible in this alloy, as shown in Figure 2. In the figure, different zones are recognized, corresponding to dendritic growth along variants of the preferred <100> growth directions. However, the overall crystallographic orientation of the fusion zone is fixed and is the same as the crystallographic orientation of the base material. This early work led to the development of a geometric model that identified the dendritic growth microstructure in the fusion zone as a function of the orientation of the weld surface, the weld direction, and the solidification front (3, 5). Further work showed that the retention of the single crystal nature of the weldment was strongly
dependant upon the weld composition (1). Thus, if sulfur additions were made to the Fe-15Cr-15Ni alloy, abundant stray grain formation was found along the weld centerline, as shown in Figure 3.

In contrast to the model Fe-15Cr-15Ni alloy, nickel-based single-crystal superalloys are significantly more prone to stray grain formation. This is shown in Figure 4, which shows an electron beam weld of alloy PWA 1480 (Ni-10Cr-5Co-12Ta-4W-5Al-1.5Ti). The schematic diagram on the right indicates the presence of large regions where stray grains were found (marked “S” in the figure).

One mechanism for the formation of stray grains is based on the principle of constitutional supercooling in the liquid ahead of the growing dendritic front (1, 7, 8). The principles behind this mechanism are shown schematically in Figure 5, where the composition profile and corresponding temperature profiles along the growth direction are shown. The solute build-up ahead of the growing dendrite can be associated with a varying equilibrium liquidus temperature. The actual thermal gradient in front of the solidifying phase can be superimposed over this liquidus profile. If the actual thermal profile lies beneath the equilibrium liquidus profile over an appreciable distance, as shown in the figure, then there will be a tendency to nucleate new grains ahead of the solidification front, resulting in stray grain formation. The criterion for avoiding constitutional supercooling is given by: $G/R > \Delta T_s / D_L$ where $G$ is the thermal gradient, $R$ is the rate of advancement of the solidification front, $\Delta T_s$ is the solidification temperature range, and $D_L$ is the diffusion coefficient of the segregated solute in the liquid.

This program will investigate the extent to which constitutional supercooling controls stray grain formation during welding. Work will be carried out on single crystals in the model Fe-15Cr-15Ni system, in which the extent of stray grain formation can be controlled (stray grain formation in current commercial nickel superalloys is too extensive to be studied in a controlled manner). Limited alloying additions that increase $\Delta T_s$ will be made in order to exacerbate the tendency to form stray grains. Different weld processes and process conditions will be used to change the thermal gradient $G$ and the growth rate $R$ so that the extent of constitutional supercooling will be changed. These results will provide a fundamental understanding of stray grain formation and will then be applied to nickel-based superalloys. Weld conditions that minimize the extent of constitutional supercooling will be investigated. Furthermore, computational thermodynamics will be used to identify compositional variations that may alter the solidification temperature range, $\Delta T_s$, and thereby may minimize the constitutional supercooling.

Sample calculations are shown in Table 1, where the influence of several alloying additions on the solidification temperature range in three different base alloys (PWA 1480, CMSX 4, and Rene N6) is shown. The table lists the change in $\Delta T_s$ when the base alloy composition is changed one element at a time by ±1 wt % for Al, Ta, or W. Such
calculations can provide guidelines for optimizing the resistance to forming stray grains by minimizing $\Delta T_S$ and the extent of constitutional supercooling. For example, the table shows that the aluminum level in Rene N6 is far from optimal (in terms of the constitutional supercooling criterion) in that reductions or additions of aluminum will reduce $\Delta T_S$ and therefore will tend to reduce the extent of constitutional supercooling. Similarly, the calculation results in the table indicate that substitution of tungsten for tantalum may be desirable since it would result in a net decrease in $\Delta T_S$. These calculations are possible with computational thermodynamics because the multi-component effects can be readily taken into account. Thus, such model calculations will be used extensively to provide guidance for identifying potential filler metal compositions that will minimize stray grain formation tendencies.

**Weldability Studies**

Single-crystal nickel-based superalloys are extremely susceptible to hot-cracking, as demonstrated in Figure 6, which shows a cross-section of an electron-beam PWA 1480 weld. As mentioned earlier, cracking is also associated with stray grains. Figure 7 shows a pulsed laser weld on PWA 1480 in which many of the cracks developed along the stray grain boundaries. This program will investigate the susceptibility of single-crystal nickel-based superalloys to hot-cracking by examining several different alloys welded by different processes and under different weld conditions. In addition to examination of the as-welded material, extensive measurements of the hot ductility of various alloys will be made. Hot ductility, and the size of the temperature range over which the ductility is low, are directly associated with the propensity for hot-cracking. A minimal nil-ductility temperature range is desired. A sample hot ductility curve for alloy CMSX 4 in the homogenized condition is shown in Figure 8. These measurements are made by heating the sample to the nil strength temperature and then cooling to a pre-determined temperature and testing the sample under tension. The ductility is plotted versus test temperature in Figure 8. It can be seen that CMSX 4 has minimal ductility over an extended temperature range, indicative of a strong susceptibility to hot-cracking. The objective of this portion of the program is to identify the effect of compositional and microstructural changes on the hot-ductility and weldability in an effort to identify optimal alloy compositions and welding conditions to maximize crack resistance.

**Microstructure Studies**

Single-crystal nickel-based superalloys are characterized by a two-phase gamma + gamma prime microstructure. The gamma prime precipitates typically have a cuboidal morphology that becomes somewhat unstable after extended elevated temperature exposure. However, it has been found that the welding conditions, and the associated solidification and cooling conditions in the fusion zone, can lead to quite a variation in
the as-welded microstructure (9). This is demonstrated in Figure 9, where the microstructures in CM 247 are compared after simulated slow-cooling (corresponding to typical arc welding conditions) and rapid-cooling (comparable to high-density processes such as laser welding). Whereas the slowly-cooled microstructure exhibits the typical cuboidal gamma prime morphology, the rapidly-cooled sample contains spherical shaped gamma prime precipitates. In addition, the gamma prime precipitates are significantly smaller than those found in the slowly-cooled material. Further examination of the microstructure as a function of the cooling conditions revealed that the elemental alloy partitioning is also affected (9). These effects may have important consequences. For example, changes in the alloying element partitioning between gamma and gamma prime may affect the lattice mismatch between these two phases, and it is well known that the mismatch plays an important role in determining the creep properties at elevated temperatures. This program will investigate in detail the effect of weld processes and weld conditions on the as-welded microstructure. In addition, the long-term phase stability will be studied by means of computational thermodynamics and kinetics analyses, and the impact of non-equilibrium elemental partitioning on phase stability will be investigated.

**Program Advisory Committee**

A major feature of this program is that an advisory committee has been assembled to provide valuable guidance during the course of the project. The advisory committee consists of component manufacturers, engine manufacturers, and repair companies. In addition, a representative of the academic community is included in the advisory group so that ongoing work in the academic arena can be coordinated with this program. The current members of the advisory group are: EPRI, General Electric Corporation, PCC Airfoils, Hickham Industries, Honeywell Corporation, Siemens-Westinghouse Corporation, and South Carolina Institute for Energy Studies.

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**References**


Figures and Tables

Study nature of stray grain formation

Identify controlling mechanisms

Investigate weldability and microstructure evolution

Identify effect of process, process parameters

Identify potential weld metals that retain single crystal nature, resist cracking, and exhibit microstructures commensurate with desired properties

Figure 1. Chart showing the overall workplan of the new DOE project.
Figure 2. Transverse view of weld on model Fe-15Cr-15Ni alloy showing dendritic microstructure and single crystal nature of weld.
Figure 3. Top view of weld of Fe-15Cr-15Ni alloy with S addition showing stray grain formation along weld centerline.
Figure 4. Stray grain formation and schematic diagram showing stray grain zones in electron beam weld of PWA 1480 single crystal.
Figure 5. Schematic diagram showing the nature of constitutional supercooling ahead of the growing dendrite tip.
Figure 6. Electron beam weld of single crystal PWA 1480 showing extensive hot cracking in fusion zone.
Figure 7. Pulsed laser weld on single crystal PWA 1480 showing tendency to form hot cracks along stray grain boundaries (examples given by arrows).
Figure 8. Plot showing extensive temperature range for low ductility in CMSX 4 nickel-based superalloy.
Figure 9. Microstructures of slowly cooled (left) and rapidly cooled (right) CM247 showing the significant changes in gamma prime precipitate size and morphology.
Table 1: Change In Solidification Temperature Range (°C) With Incremental Composition Changes

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<tr>
<th>Base Alloy</th>
<th>Al -1%</th>
<th>+1%</th>
<th>Ta -1%</th>
<th>+1%</th>
<th>W -1%</th>
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<tr>
<td>PWA1480</td>
<td>-3.6</td>
<td>+2.3</td>
<td>-2.8</td>
<td>+2.9</td>
<td>-1.7</td>
<td>+1.5</td>
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<td>CMSX 4</td>
<td>-4.0</td>
<td>+3.3</td>
<td>-3.5</td>
<td>+3.5</td>
<td>-1.1</td>
<td>+1.1</td>
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<tr>
<td>Rene N6</td>
<td>-5.7</td>
<td>-2.5</td>
<td>-4.3</td>
<td>+0.9</td>
<td>-1.1</td>
<td>+1.2</td>
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