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Analysis of Stray Grain Formation in Single-Crystal Nickel-Based Superalloy Welds[1]

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Weld repair and refurbishment of single-crystal nickel-based superalloys is a desirable technology that needs to be advanced to allow for more efficient and economical use of expensive turbine components. Currently, technologies exist in which only minimally-stressed sections of single crystal components can be weld-repaired since the resultant weld regions are polycrystalline and the property advantages of using single crystals are lost. One of the primary hurdles to successful weld repair is the abundant formation of new grains, known as stray grains, during solidification. Often, since the high angle grain boundaries associated with these stray grains are weak points, hot cracking is found in weldments and the cracks propagate along the stray grain boundaries.

This paper describes results from recent work in which the formation of stray grains has been studied and the underlying mechanism for stray grain formation has been identified. The study examined autogenous welds made on single crystal Rene N5 using laser, electron beam, and arc welding processes. Welds were made under various conditions of speed and power. The weld microstructures were analyzed by optical microscopy and Orientation Imaging Microscopy (OIM). In addition, extensive modeling was used to model the weld pool shape and the thermal conditions as a function of location along the weld pool interface.

It was found that the formation of stray grains was affected by the welding conditions. Low speed, high heat input welds showed fewer stray grains than high speed, low heat input welds. Furthermore, the low speed welds showed no sign of transverse cracking while the high speed welds showed transverse cracks on the top surface of the weld. Interestingly, the tendency to form stray grains and cracks was noticeably asymmetric with respect to the wed centerline. Stray grains and cracks formed much more frequently on one side of the weld (same side). Figure 1 illustrates the asymmetric formation of cracks in the welds and Figure 2 shows the asymmetric distribution of stray grains in the weld cross section. Figure 2 also shows that cracks (indicated by arrow in figure) follow along the stray grain boundaries.

A previously developed geometric model that identifies the active dendritic growth directions in single crystal welds as a function of the orientation of the weld pool surface normal was used to interpret the microstructures. The results from the heat and fluid flow model were combined with the geometric analysis to determine the growth velocities and thermal gradients resolved along the dendrite growth directions. This analysis allowed for an evaluation of the parameter G^n/V which has been associated with the degree of constitutional supercooling ahead of the advancing dendritic growth front. This analysis showed that (a) the thermal and growth

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conditions were asymmetrical with respect to the weld centerline, (b) the parameter G^n/V was smallest on the side of the weld where stray grains formed, in agreement with theoretical predictions, and (c) the parameter G^n/V decreased with increasing weld speed or decreasing heat input, again leading to a prediction of increased stray grain formation which is in agreement with experimental results. Thus, the combined geometric and thermal model indicates that stray grain formation varies inversely with the parameter G^n/V, as predicted by theory for stray grain formation based on the degree of constitutional supercooling ahead of the advancing dendritic growth front. In contrast, the results do not agree with expectations based on a mechanism of dendrite fragmentation due to fluid flow. The results provide the basic understanding that will be necessary to modify process conditions and alloy compositions so as to minimize the tendency to form stray grains and yield successful stray-grain free microstructures in single-crystal welds.

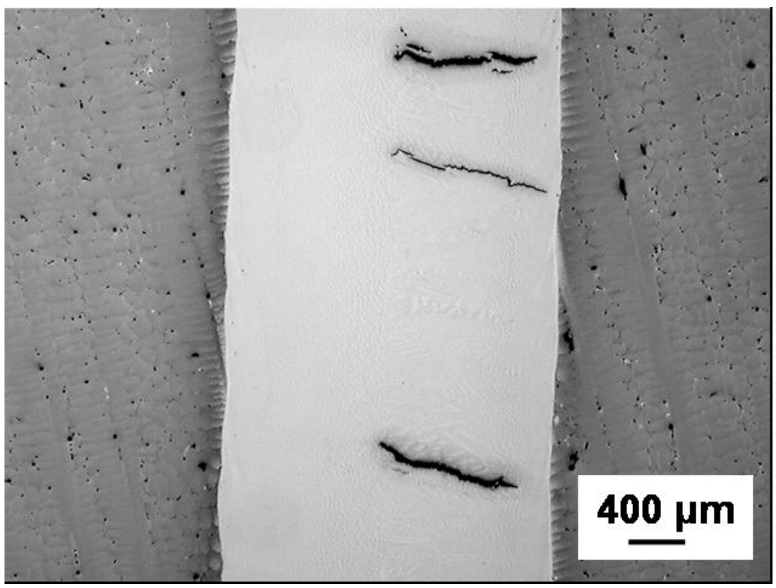

Figure 1: Top surface view of autogenous laser welded Rene N5 showing asymmetric crack formation.

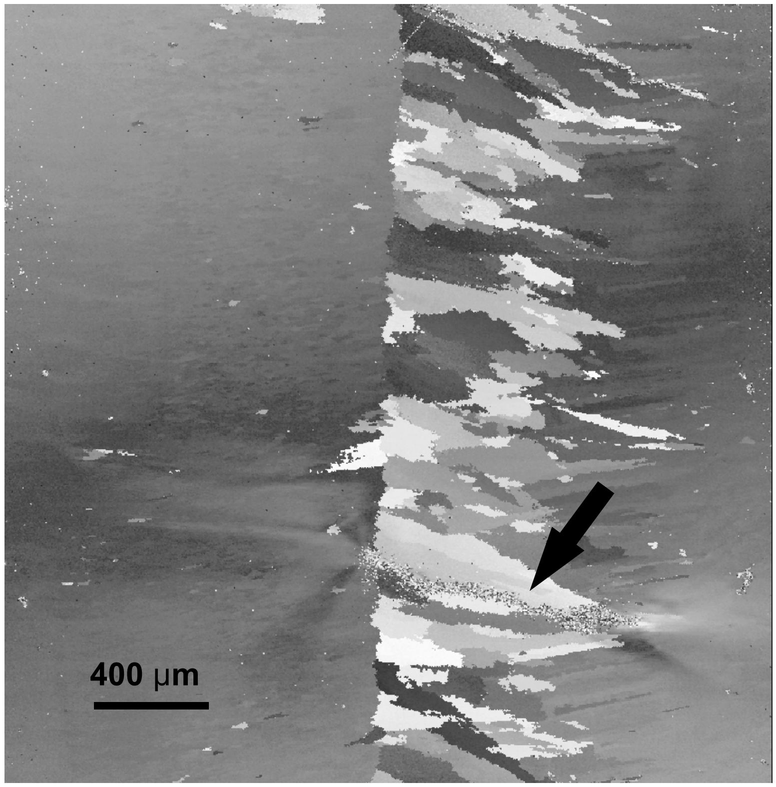

Figure 2: OIM image of same laser weld as in Figure 1 showing enhanced stray grain formation on right side of weld, which is the same side that showed cracking.