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The effect of welding conditions on stray grain formation in single crystal welds – theoretical analysis

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Abstract

Stray grain formation during solidification of nickel-based single crystal superalloy welds leads to a degradation of mechanical properties and cracking. Based on the mechanism of constitutional supercooling ahead of the advancing dendritic growth front, the effect of welding conditions (weld speed and power) on the tendency to form stray grains during solidification was evaluated. A simple 3D thermal model was combined with a geometric model to determine the extent of stray grain formation as a function of welding conditions and position in the weld pool, taking into account the influence of dendrite growth orientation. A parameter describing the degree of stray grain formation, averaged over the entire solidification front, was calculated. Processing maps that show the severity of stray grain formation as a function of weld speed, power and orientation were developed. It was found that low power and high weld speed were optimal for minimizing the stray grain formation potential. The effect of crystallographic orientation of the weld on the overall tendency to form stray grains was minimal, although local variations based on orientation were quantified. The theoretical analysis was compared to earlier experimental work on laser welded nickel-based single crystals and all of the experimental observations could be reproduced in the calculations.
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Keywords: Laser welding; Nickel alloys; Single crystal growth; Solidification; Stray grains

1. Introduction

In order to achieve higher efficiency and performance in turbine engines, alloy development for engine components has concentrated on microstructural control. The most modern land and aero turbines use single crystal nickel-based superalloys for many components in order to maximize operation temperatures and high temperature creep strength. Such components are extremely costly and therefore it is desirable to develop a technology that can repair imperfect castings as well as repair damaged, worn, or cracked in-service components. While some weld repair technologies exist, these procedures do not achieve properties in the repaired part that are comparable to those in the original components. Current repair technologies compromise the weld repaired zone properties because the repair weld is polycrystalline and often has a significantly different composition, leading to a change in the microstructure (reduced fraction of strengthening γ' phase) and associated strength. The primary reason desirable properties cannot be obtained in repaired single crystal components is that during weld solidification, the alloys undergo nucleation and growth of equiaxed grains. These new grains are referred to as stray grains. The formation of stray grains removes the desirable single-crystal microstructure and, furthermore, the resultant grain boundaries act as easy paths for crack propagation [1–3]. This paper examines the solidification conditions during welding as a function of the welding conditions in an effort to identify the optimum weld conditions for avoiding stray grain formation.

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Nomenclature

List of symbols

a	material constant used in the calculation of Φ
A_k	area of each ring section, used in calculating $\bar{\bar{\Phi}}$
$\vec{G}$	thermal gradient at any given location on solidification front
G_d	component of thermal gradient along dendrite growth direction
G_x, G_y, G_z	components of thermal gradient along x, y, z axes
G_{y0}	component of thermal gradient in y direction on the weld pool surface($z = 0$, $y > 0$), which corresponds to the locations, where $\varphi = 0$
G_r	component of thermal gradient along radial direction
K	thermal conductivity
n	material constant used in the calculation of Φ
$\vec{\mathbf{n}}$	unit vector normal to solidification front at any given location
N_0	nucleation density in the liquid
Q	heat source power
r	radial direction in Y–Z plane
T_0	ambient temperature
V_n	growth velocity normal to solidification growth front
V_b	weld beam velocity
V_d	dendrite growth velocity along one of six $<100>$ preferred dendrite growth directions
x, y, z	coordinate axes, see Fig. 1 for orientation of axes
α	thermal diffusivity
θ	angle between $\vec{\mathbf{n}}$ and negative x direction (see Fig. 1)
φ	angle between projection of $\vec{\mathbf{n}}$ on Y–Z plane and negative y direction (see Fig. 1)
ψ	angle between $\vec{\mathbf{n}}$ and dendrite growth direction at any given location on solidification front (see Fig. 1)
Φ	areal fraction of stray grains ahead of the advancing solidification front
$\bar{\Phi}$	Φ averaged over all φ for a given ring section (i.e., fixed x)
$\bar{\bar{\Phi}}$	Φ averaged over entire solidification front, i.e., over all φ and x
$\bar{\bar{\Phi}}_j$	$\bar{\bar{\Phi}}$ averaged with crystallographic dendrite orientations taken into account ($j = c$) or not taken into account ($j = nc$)

In the last decade or so, there have been numerous studies of the dendritic solidification behavior in single crystals under welding conditions [1–9]. Some of these studies have shown that the crystallographic orientation of the dendrites can be determined with a geometric model that identifies the dendrite growth orientation that is best-aligned with the solidification front normal as a function of the weld orientation and location on the solidification front [4,5]. Additional studies have examined the mechanism of stray grain formation during welding [7–9]. These studies have shown that constitutional supercooling just ahead of the solidification front can lead to the nucleation and growth of equiaxed grains and, if this is extensive enough, the single crystal solidification microstructure will be replaced by a polycrystalline microstructure with numerous stray grains [8,9].

In this study, the weld pool shape will be examined as a function of welding conditions. The models developed earlier to describe the extent of constitutional supercooling and stray grain formation as a function of the solidification conditions (growth velocity and thermal gradient) [7,9,10] will be combined with the geometric models describing the dendritic growth directions as a function of weld pool surface orientation [4,5] to determine the dependence of stray grain formation on welding conditions. The analysis leads to specific conclusions regarding the optimum welding conditions and weld orientations needed to minimize the extent of stray grains in single crystal welds.

2. Numerical analysis procedure

2.1. Calculation of weld pool shape

Over the years, many numerical models have been developed to describe the weld pool shape as a function of the welding conditions. As the models have improved, they have included many more phenomena that affect the final weld pool shape. However, concurrent with these advances, the models have also become more computationally demanding. In this study, the accuracy of the advanced models has been sacrificed in order to allow for a more thorough and tractable evaluation of the details of dendritic growth, and how they are affected by welding conditions. Consequently, the mathematically simple 3D Rosenthal solution [11] has been used to define the weld pool shape and the thermal conditions at the solidification front as a function of welding conditions. The temperature is given by the following expression: