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Strengthening mechanisms in an inertia friction welded nickel-base superalloy

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ABSTRACT

This research investigated the strengthening mechanisms associated with the as-welded microstructure developed during inertia friction welding of dissimilar superalloys LHSR and Mar-M247. The weld interface and heat affected regions of the sample were analyzed using hardness indentation techniques and subsequently characterized using SEM, TEM and advanced atom probe tomography. The yield strength of the welded joint was modeled to determine the impact of the gradients in the as-welded microstructure on strengthening mechanisms within the LSHR material. Characterization centered on formation of γ', γ grain size and chemical segregation within the heat affected regions. Results indicate an increased hardness in the vicinity of the weld interface, resulting from the refined dispersion of γ' and γ grains.

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1. Introduction

Nickel base superalloys are important materials for high temperature propulsion disk applications because of their unique creep and strength properties [1–3]. In these materials, the mechanical properties are strongly influenced by the formation of $L1_2$ precipitates (γ') within the FCC γ matrix. Many studies have demonstrated the influence of material processing parameters on size, distribution, and volume fraction of the γ' [4–6], and their related impact on mechanical properties. Considerable research into elemental segregation between γ and γ' has also identified the importance of kinetic influences on the resulting phase chemistries and sizes [7,8]. Fortunately, numerous modeling efforts have linked many of these features and chemistries to the resulting mechanical properties, including the work by Kozar et al. [9], and Parthasarathy et al. [10]. Their work has identified the influence of chemistries, precipitate sizes, and phase volume fractions on dislocation bowing and cutting mechanisms. Additional work by Rao et al. [11,12] augmented the relationships by modeling the strong influence of tertiary γ' volume fraction and particle spacing on the critical resolved shear stresses required for slip in nickel-based superalloys. These previous efforts involved modeling the effects of various microstructure features on strengthening in "near-equilibrium" conditions within the material, versus the non-equilibrium conditions found in as-welded couples.

Given the need for increased creep resistance in the rim region and improved strength properties in the bore region of propulsion disks, it is not surprising that researchers have studied the benefits of joining multiple materials to optimize mechanical response [13,14]. Successful development of this processing capability would provide increased operational temperatures and improve the overall efficiencies of the engine. Researchers have successfully joined different nickel base alloys using Inertia Friction Welding (IFW) techniques [15–19]. IFW is a solid state joining process that has been used to join axisymmetric components in propulsion applications. In the IFW process, a sample is attached to a flywheel of known mass, rotated to a specific velocity and then a second sample is brought into contact with the rotating sample under an applied axial load. The kinetic energy of the flywheel is then converted through friction at the weld interface to heat in the adjoining samples. This produces a rapid temperature transient in a relatively narrow region at the weld interface that can approach the solidus temperature of the sample materials. This rapid temperature transient drops the effective yield strength of the material, and the near weld line material begins to plasticize and flow radially outward into the flash. This radial flow of material removes any oxides, particulate or contaminants on the weld surface, bringing nascent material surfaces together and produces a

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metallurgical bond [15].

Researchers have recently reported IFW of dissimilar superalloys, including a cast Mar-M247 to a PM/wrought LSHR (Low Solvus High Refractory alloy) [19,20]. Their work showed a decrease in the size of γ′ within 100 μm of the weld interface, and alterations in the hardness of both materials within the heat effected zone of the weld. As expected, the IFW process parameters strongly impacted the resulting microstructures and amount of reduction in length of the weld samples. The resulting hardness value increased over 25% within the heat affected region. Although a number of microstructure parameters were connected to the IFW parameters, the relative influence of the parameters were not connected to the strengthening mechanisms. The research also identified a region of refined γ grains within the Mar-M247 side of the weld, and a region of mixed elements from both materials. The LSHR alloy is of particular interest due to its introduction as a new γ′ strengthened superalloy for potential use in high temperature turbine applications. The Mar-M247 alloy is an older nickel material that has been studied more extensively [21,22].

In addition, both Daus et al. [23] and Huang et al. [24] characterized IFW of RR1000 material. In the first study, researchers investigated the influence of IFW process parameters on crack growth rates in joined RR1000 and IN718 alloys. They reported higher crack growth rates caused by intergranular cracking due to oxidation damage along grain boundaries. Huang et al. reported the strong influence of the IFW welding process on γ grain morphology and γ′ evolution within the weld interface region. In particular, they estimated an initial cooling rate of 80–130 °C/s near the weld, producing γ′ with a diameter less than 20 nm. They also showed the enrichment of borides and carbides at the γ grain boundaries within this region, and a smoother morphology to the γ grains compared to the bulk material. The change in γ morphology was attributed to the high cooling rates that suppressed formation of grain boundary γ′.

Although previous research has experimentally linked material hardness to phase morphology, the exact impact of non-equilibrium microstructure and chemistry associated with IFW has not been modeled using strengthening mechanisms. The objective of this research is to investigate the relative influence of various deformation mechanisms on the yield strength of an as-welded LSHR sample processed by IFW.

2. Materials and methods

Due to the interest in joining dissimilar Ni-base superalloys, the commercial alloys Mar-M247 and Low Solvus High Refractory (LSHR) were chosen. The chemistries of the as-received materials are provided in Table 1. Because we were interested in the evolution of γ′ within LSHR material under IFW conditions, we used the stronger (at high temperatures) Mar-M247 as the joining material, forcing the majority of IFW deformation and strain to accumulate on the LSHR side.

The LSHR and Mar-M247 alloys were the same materials used in previous IFW studies [19,20]. The LSHR cylindrical samples were cut from a 330.2 mm diameter iso-forged billet and Mar-M247 samples were extracted from a directionally solidified plate. Optical and scanning electron microscopy were used to image the microstructures. Quantitative analysis of the size and area fraction of primary and secondary γ′ particles were conducted using Fovea Pro [25] and Photoshop image analysis software [26]. Fovea Pro was used to provide image filtering and segmentation capability as a plug-in software module within Photoshop. γ′ particles were additionally identified using backscatter and secondary electron images by their morphology and location. As reported [19,20], prior to welding LSHR had a fine-grained duplex microstructure consisting of equiaxed γ grains, primary γ′ particles, and carbide particles. The average feature diameters were approximately 3.5, 1.3, and 0.7 μm, respectively. Nanometer sized secondary and tertiary γ′ were dispersed within the γ grains, but were difficult to quantify because of their size. The total volume fraction and primary volume fraction of γ′ were approximately 55%, and 35%, respectively. The carbide volume fraction was approximately 1%. The material was evaluated using a Vickers' microhardness tester under 500 g load, exposed for 20 s (19). The room temperature yield strength was measured as 1165 MPa, with a hardness value of 465 HVN. The as-cast Mar-M247 material consisted of coarse-grained, dendritic γ grains larger than 1 mm in diameter and coarse carbide particles (maximum size is ~20 μm) homogenously dispersed within the alloy. The alloy contained cuboidal shaped primary γ′ precipitates, approximately 1.25 μm in diameter, and a volume fraction of 64%. The room temperature yield strength was 703 MPa, with a hardness value of approximately 400 HVN.

The two materials were successfully joined at the Edison Welding Institute using an MTI model 120 IFW machine with the following parameters: 0.379 kg m ^{2} moment of inertia, 346 rad/s initial angular speed, 55.2 kN axial force, resulting in an initial kinetic energy of 22.6 kJ. Further details were published elsewhere [19]. Welded samples were prepared using standard metallographic techniques, and imaged using a FEI Nova 200 NanoLab Dual Beam FIB operating at 20 Kv. Both secondary (SE) and back scattered electron (BSE) images were obtained to distinguish the γ grains and γ′ precipitates, and to determine the welding interface between the two materials. Electron back scatter diffraction (EBSD) techniques were also employed to determine the γ grain size and identify potential twins using Photoshop software. Data was collected using a DigiView 3 camera on a FEI NanoSEM 230 SEM operating at 20 kV with an operating current of 6.1 nA. The EBSD step size was 50 nm for locations within 250 μm from the weld interface, and a value of 100 nm for locations greater than 250 μm. This provided the necessary spatial resolution for the smaller refined γ grains closer to the interface while allowing large area scans for the regions with larger γ grains.

Microstructure features for the 1 mm position were determined using scanning electron microscope (SEM) SE, BSE, and EBSD techniques using Photoshop software. The morphology, z contrast, size, and location of smaller γ′ particles provided sufficient detail to allow their segregation from the parent γ phase. Although Kuhr et al. successfully identified primary γ′ precipitates in IN100 using etched samples and SEI techniques [27], it is difficult to determine which of the precipitates are at γ boundaries, and which are fully within the grain. The distinction is critical to the proposed strength model since grain boundary γ′ are expected to contribute to Hall-Petch mechanisms while interior grain precipitates impact dislocation cutting mechanisms [20]. The

Table 1
Chemical composition (at%) for LSHR and Mar-M247 [19].

Element	Al	Ti	Cr	Co	Ni	Nb	Mo	Hf	Ta	W	Zr	C	B
Mar-247	12.1	1.1	10.2	10.6	61.3	0.0	0.5	0.3	0.7	3.2	0.05	0.16	0.015
LSHR	7.2	4.3	14.2	21.2	48.6	0.9	1.7	0.0	0.5	1.4	0.05	0.03	0.03