ELSEVIER

Materials Science and Engineering A 437 (2006) 38–45

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

A comparison of inertia friction welds in three nickel base superalloys

M. Preuss [a,*], P.J. Withers [a], G.J. Baxter [b]

[a] *School of Materials, University of Manchester, Grosvenor St., Manchester M1 7HS, UK*
[b] *Rolls-Royce plc. Derby, UK*

Received 2 July 2005; accepted 15 April 2006

Abstract

In this paper the microstructure, mechanical properties and residual stresses are compared for three inertia friction welded nickel-base superalloys. In contrast to alloy 720Li and RR1000, for Inconel 718 welding produces a precipitation free region leading to significantly reduced strength near the weld line. As a result, for alloy 720Li the hoop stresses are 1.5 times, and in RR1000 two times, higher than the tensile hoop stresses for Inconel 718. The maximum tensile weld stresses in Inconel 718 and RR1000 are yield stress limited in the weld region. That stresses significantly below the yield stress are found near the weld for alloy 720Li may be because the inferior creep properties of alloy 720Li compared to RR1000 result in stress relief during cooling after welding.

Post weld heat treatment at the standard maximum aging temperature for Inconel 718 (732 °C), relieved residual hoop stresses to below 400 MPa. To achieve a similar level of residual hoop stress, Alloy 720Li must be stress relieved at least 30 °C and RR1000 about 80 °C hotter.

Keywords: Neutron diffraction; Residual stresses; Inertia friction welding; Post weld heat treatment; Ni superalloys

1. Introduction

Inertia friction welding is a solid state welding process able to join the new generation of high volume fraction γ' nickel-base superalloys. These alloys are very difficult to fusion weld and are prone to micro-cracking as solidification takes place during welding [1,2]. Furthermore, it is recognised that inertia friction welding is better suited to mass production than electron beam welding since it does not require a vacuum during the joining process [3]. In inertia friction welding, an axis-symmetric work-piece is rotated to a specified speed and then a second, stationary, work-piece is forced into frictional engagement with the first. If the correct welding parameters are chosen, the frictional heat is sufficient to soften the two components in the weld region without introducing melting [4]. It has been shown that the heat affected zone (HAZ) can be very narrow if tubular shaped components with a wall thickness of 10–11 mm are joined together [5,6]. Due to the extreme thermo-mechanical history, the microstructure is heavily modified in the HAZ of a joint. Various studies of inertia friction welded nickel-based superalloys in the as-welded condition have shown two different types of hardness profiles in the HAZ. Alloys such as Waspaloy (25% γ') and Inconel 718 (25% γ'/γ'') generally exhibit a pronounced hardness drop, which is attributed to the absence of γ' in this region after welding [7,8]. However, alloys like N18, Astroloy, Alloy 720Li and RR1000, which contain about 50% γ', show a hardness peak in the HAZ [5,6,9]. The hardness peak is due to the large driving force for precipitation even at extremely high cooling rates. The different reprecipitation behaviours can be expected to have consequences for residual stress levels generated during joining. For example, a soft (low yield point) near weld line region in Inconel 718 will limit residual stress generation since this is where one would expect the highest tensile hoop stresses [10]. Until now, there have been no data comparing residual stress measurements of inertia friction welds from different nickel base superalloys formed under similar conditions. Some of the residual stress work reported in the open literature has been either limited to the axial direction [11,12] or failed to include the issue of stress-free lattice parameter variation across the weld line [13,14] which has been shown to be important for inertia friction welded RR1000 [10].

This paper focuses on the interplay between across-weld microstructural/mechanical property variations and residual stress generation during inertia friction welding Inconel 718, Alloy 720Li and RR1000. In view of the drive to form dissimilar welds combining these three different types of nickel-base

---

[*] Corresponding author. Tel.: +44 161 306 3601; fax: +44 161 3063586.
E-mail address: michael.preuss@manchester.ac.uk (M. Preuss).

0921-5093/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2006.04.058

Table 1
Chemical composition (wt.% of main alloying elements, balance nickel) of Inconel 718, Alloy 720Li and RR1000

Alloy	Cr	Co	Fe	Mo	Nb	W	Al	Ti	Ta	Hf
Inconel 718	19	–	17	3.1	5.2		0.5	0.9	–	–
U720 LI	16	15	–	3.0	–	1.25	2.5	5.0	–	–
RR1000	14.35–15.15	14.0–19.0	–	4.25–5.25	–	–	2.85–3.15	3.45–4.15	1.35–2.15	0.0–1.0

superalloy it is necessary to understand the metallurgical and residual stress issues associated with each alloy. Another important aspect, given that the three alloys studied have different high temperature mechanical properties, is effective post weld stress relief. For this reason, Inconel 718, Alloy 720 and RR1000 inertia friction welds have been residual stress mapped after post weld heat treatment (PWHT) at temperatures applied typically during the aging of each alloy. The results of the residual stress measurements are presented in this paper.

2. Experimental

2.1. Material

The chemical compositions of Inconel 718, Alloy 720Li and RR1000 [15–17] are listed in Table 1. RR1000 and Alloy 720Li have a larger wt.% of Al and Ti than Inconel 718 and consequently a significantly higher volume fraction of γ' ((Ni, Co)$_3$ (Al, Ti) [2]). This affects markedly the development of microstructure. The three alloys used for this investigation came from fully heat-treated and annealed forgings. Rings with an outer diameter (OD) of 143 mm, a wall thickness of 10–11 mm and an axial length of 50 mm were machined from the forging and subsequently inertia welded at MTI, South Bend, Indiana, USA. Two welds of each alloy were available in order to study the as-welded and PWHT'd condition. The PWHT were carried out using small chamber furnaces with a temperature accuracy of ±2 °C. For the microstructural studies, samples were machined across the weld line of the joint assembly after the residual stress measurements had been completed. The samples were then sectioned for subsequent investigations.

2.2. Mechanical cross-weld testing

In order to evaluate the mechanical properties of the development inertia friction welds microhardness mapping and tensile testing in conjunction with surface strain field measurements were undertaken on samples in the as-welded condition. Microhardness testing was carried out under a load of 1 kg using a calibrated Vickers hardness indentation machine. The average indentation size was between 60 and 70 μm, giving a high spatial resolution across the weld line. With an average grain size of less than 5 μm in RR1000 [5] (powder-metallurgical alloy), each measurement sampled a sufficient number of grains. Since the base Alloy 720Li and Inconel 718 materials (cast alloys) displayed a relatively large mean grain size (10–20 μm, measured using scanning electron microscopy back scatter images), hardness indents often covered only a small number of grains leading to a significantly higher scatter in the microhardness profiles. The polished and etched samples were aligned with the indented surface perpendicular to the hoop direction. For each sample, measurements were carried out on a grid of five lines parallel to the axial direction and spaced greater than four indentations apart.

Tensile testing was carried out on cylindrical cross-weld specimens electro discharge machined (EDM) from the three welds in the as-welded condition. In order to capture the cross-weld strain variation during tensile loading, in situ surface strain field recording was carried out using a commercial electron speckle pattern interferometry (ESPI) system (Ettemeyer Q300). ESPI offers the possibility of full field and non-contact measurement of displacements and strains [18]. ESPI has sufficient strain resolution to reconstruct local stress–strain curves. This is done by continuously recording strain maps at increasing loads during tensile testing. By identifying the strain at each location as a function of applied load, it is possible to recover many stress–strain curves from a single tensile test corresponding to different positions across the weld line. From the reconstructed stress strain curves the 0.2% proof stress can be determined in a conventional manner. This technique has been recently used to record 0.2% proof stress profiles across friction welds with a spatial resolution better then 50 microns [19,20].

2.3. Microstructural studies

Since the γ' distribution is known to vary dramatically over a few millimeters from the weld line in 11 mm wall thickness inertia friction welded nickel-base Superalloys [5,6], spatial accuracy during microstructural studies is of great importance. High energy X-ray synchrotron diffraction measurements were undertaken on the ID11 beam line at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, in order to quantify the fraction of γ' across the welded region. Diffraction profiles were collected in transmission on cross-sectional slices cut from the inertia friction welded tube (as-welded condition) so as to contain the axial and radial directions and then electropolished to an average thickness of 1 mm. A monochromatic beam of 60 keV energy ($\lambda = 0.208321$ Å) was stopped down by slits to 150 μm in the axial and 3 mm in the radial direction and scanned (axially) across the weld. The high intensity of the synchrotron beam allowed accurate measurements of the (1 0 0) superlattice reflection, arising from the ordered γ' phase (LI$_2$ structure), where the (1 0 0) refection is systematically absent for the disordered γ matrix phase. Since γ and γ' are coherent with a simple cube–cube ([0 0 1]||[0 0 1]) relationship, by normalizing the integrated intensity of the superlattice reflection with the integrated intensity of the (2 0 0) reflection, any influence of the texture on the measurement could be elim-