SOLID STATE JOINING OF OXIDE DISPERSION STRENGTHENED ALLOY TUBES

Bimal K. Kad[1], Ian Wright[2], and Rod Judkins[2]
[1]University of California - San Diego, La Jolla, CA 92093
[2]Oak Ridge National Laboratory, Oak Ridge, TN 37830

ABSTRACT

Oxide dispersion strengthened (ODS) Fe_3Al and Fe-Cr-Al based (MA956) alloys are currently being developed for heat-exchanger tubes for eventual use at operating temperatures of up to 1100°C in the power generation industry. The development challenge is to produce thin walled tubes, employing powder extrusion methodologies, with a) adequate strength for service at operating temperatures to b) mitigate hoop creep failures. The latter is attempted by enhancing the as-processed grain size via secondary recrystallization. While these mechanical property challenges are being steadily achieved, there is now a forward looking effort to explore joining methods essential to fabricating component systems and assemblies. The challenge is to preserve the dispersion microstructure, responsible for the high temperature strength, during subsequent joining operations which precludes all melting driven welding techniques. We report here on parametric studies of non-fusion based inertia welding of MA956 tubes in butt-joint configurations. Detailed examinations of the weld microstructure, observations of the grain size, micro-hardness and the nature of the solid state interface between the mating surfaces suggest that high quality welds are feasible for a variety of welding conditions. The desired high temperature performance is explored via creep testing. The results obtained are discussed in terms of the process variables employed, the resulting heat affected zone (HAZ) width and the joint microstructures obtained. A high performance joint is facilitated at high weld pressures resulting in a narrow HAZ width.

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INTRODUCTION

Oxide dispersion strengthened (ODS) ferritic FeCrAl (MA956, PM2000, ODM751) and the intermetallic Fe_3Al-based alloys are promising materials for high temperature, high pressure, tubing applications, due to their superior corrosion resistance in oxidizing, oxidizing/ sulphidizing, sulphidizing, and oxidizing/chlorinating environments[1-4]. Such high temperature corroding environments are nominally present in the coal or gas fired boilers and turbines in use in the power generation industry. The target applications for ODS alloys in the power generation industry are thin walled (0.1" thick) tubes, about 1 to 3 inches in diameter, intended to sustain internal pressures (P) of up to 1000psi at temperatures of 1000-1100°C. Within the framework of this intended target application, the candidate dispersion strengthened alloys must strive to deliver a combination of high mechanical strength at temperature, as well as prolonged creep-life (hoop creep in particular) in service.

This material migration to ODS alloys for high temperature service poses significant fabrication challenges. These materials are not readily welded via conventional means or the welds perform poorly. Early work on Fe_3Al, FeCrAl family of ODS alloys provides the outlook that they cannot be subjected to a fusion based joining process. The density disparity between the matrix and the dispersoid precludes any melt based joining, as the lighter oxide dispersion so critical to the high temperature creep performance will simply float away. Thus, solid-state joining methodologies that preserve the dispersion microstructure are inherently more suitable and attractive. Thus, process design and validation of appropriate solid-state joining methodologies represent a critical developmental and design challenge that must be overcome in order to exploit and deploy ODS alloys. Solid-state welding procedures like a) Inertia welding b) Magnetic Pulse welding c) Flash welding and d) Braze/Diffusion welding are the norm in this developmental regime. Recent work has addressed inertia and friction welding of ODS Fe_3Al & MA956 alloys[5-9] with significant promise of developing meaningful joining solutions for component fabrication. While recent in-house work has focused on a) Inertia, b) Magnetic Pulse and c) Flash welding techniques, Figure 1, this current report details parametric studies on inertia welding on account of being deemed a commercially viable and mature technique for eventual fabrication tasks. Processing details of joints and ensuing creep performance are evaluated.

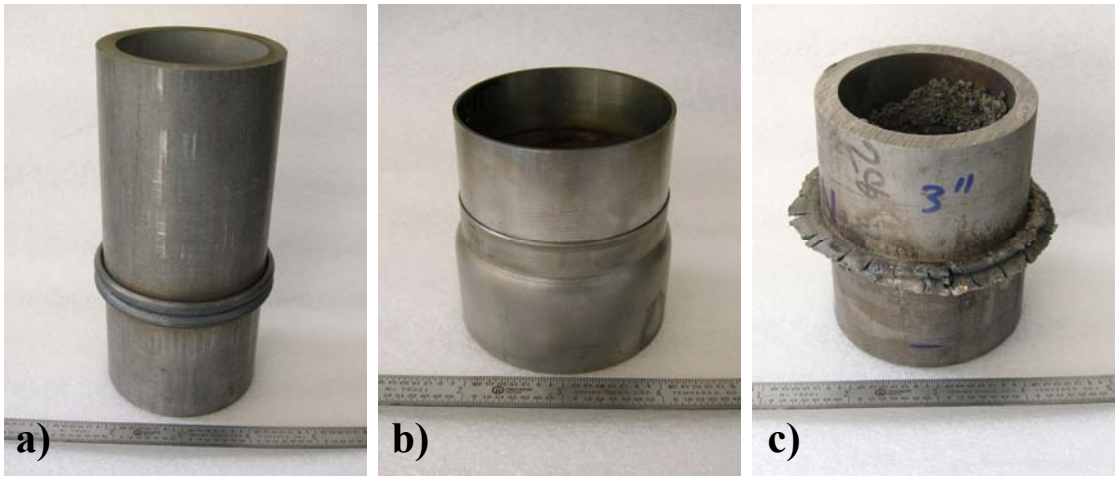

Figure 1a) Inertia welded butt joint (UCSD), b) pulse welded lap joint (UCSD) c) flash-upset butt joint (EWI) in 2"ID ODS-MA956 alloy tubes. The joints are robust but exhibit process dependent creep performance variances.

EXPERIMENTAL DETAILS

Materials: All materials for this study were provided by Special Metals Corporation in the form of nominal 2-1'2"OD, ¼" wall thick MA956 tubing in the un-recrystallized fine-grained state. Short sections were cut for inertia welding trials and the joints were recrystallized for 1-hour at 1375°C to produce the coarse grained microstructure necessary for maximum creep performance.

Welding Equipment: Figure 2 shows the sequence of welding operation to produce robust joints in MA956 tubing. All joints were fabricated using either the Caterpillar model 150B, 180B inertia welding machines. Initial trials were attempted on model 150B followed by a production style configuration adopted for the 180B model which provide for better joint concentricity. The intended mating pieces are suitably clamped in the head chuck (spinning piece) and the tailstock (stationery) piece. The head stock moves to the starting position (separated by 1/8" from the tail stock piece) and rotates to the desired RPM. Upon achieving the prescribed flywheel RPM (fixed kinetic energy), the drive mechanism disengages and a fixed weld force is applied which brings the parts in contact. Frictional heat causes mating surfaces to soften and plastically deform to form a full circumferential through wall-thickness joint. When rotation stops, the parts are held for a few seconds during which the weld cools while still held firmly in the collets. The entire weld process takes up to 60 seconds. Process variables such as friction force, rotational speed and upset displacement are monitored for evaluation of overall joint performance.

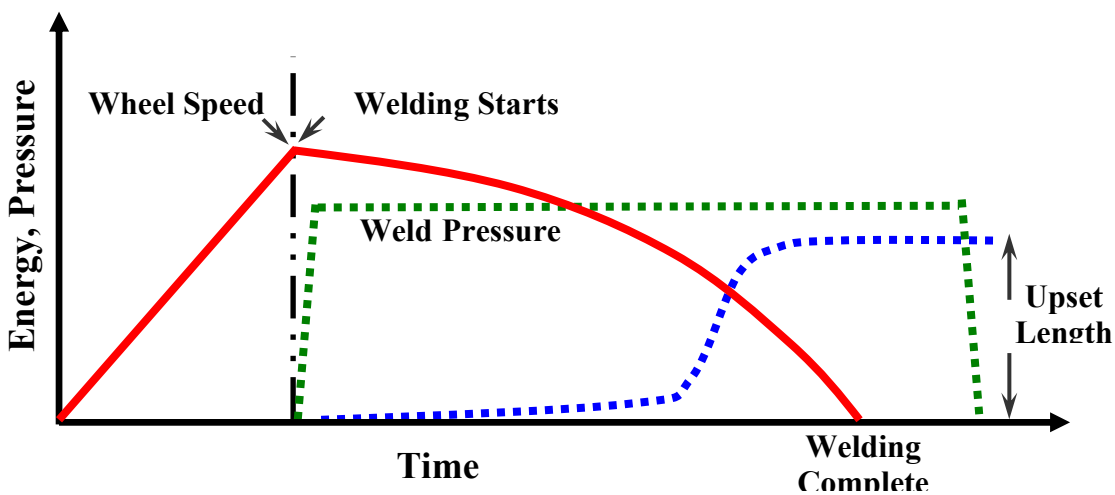

Figure 2. Schematic sequence of events in Single Stage Inertia Welding used for MA956 Joints.

Mechanical Testing: Creep test coupons are spark machined from the joint sections, Figure 3. Creep tests coupons are flat dog-bone shaped samples 0.125" wide and 0.040" nominal thickness where the width and the thickness correspond respectively to the tube circumference and the wall thickness. For a tube wall thickness of 0.25" versus the actual test specimen thickness of 0.04" multiple samples can be sliced from a single spark cut slug thereby providing ample test efficiencies.

Figure 3. Creep specimens cut from the MA956 joints.

MATERIALS CHARACTERIZATION

Figure 4(b) shows the optical micrograph of polished and etched longitudinal section microstructure of a typical inertia welded joint. The initial tubes have their grains elongation along the tube axis. However in the as-welded configuration the macroscopic grain flow rotates the grain elongation from being parallel to the tube axis to perpendicular near the bond line, Figure 4(c). Heat localization at the mating surfaces results in dynamic recrystallization in a narrow region of the bond line where the grains can be resolved at the resolution of an optical microscope, Figure 4(a). The joints were subsequently recrytsallized as this is the default treatment for high creep performance. TEM images of the recrystallized HAZ region present a slightly different picture, Figure 4(d). The most significant difference is that the bent grains are fragmented and reorganized into small grains with only a slight aspect ratio parallel to the bond line. Any grain shape anisotropy is mitigated and the microstructure can be approximated as isotropic across the bond line in the Heat Affected Zone.

Considerable effort has been expended to control the HAZ width and the grain microstructure in the joints produced. As a consequence joints have been produced with HAZ widths in the rage of 0.1mm – 3.0mm principally altering the weld pressure during fabrication, see Figure 2. Creep testing of this entire array of samples continues till date. Looking ahead to the next section, we note that the general trend of reducing the HAZ width produces impressive gains in the over all creep performance

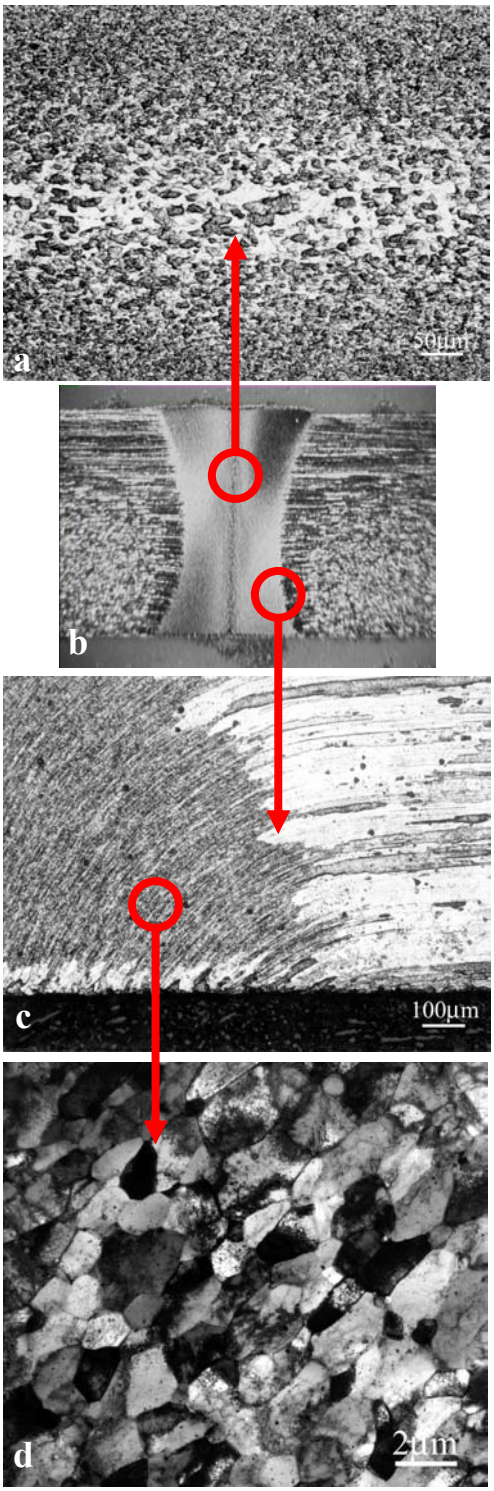

Figure 4. Weld HAZ microstructure (b) with coarse grains at the bond centerline (a). Macroscopic flow in welding causes grain rotation parallel to bond centerline (c) with (d) grain fragmenting upon recrystallization.

Creep Properties: The geometrical considerations for creep testing of joints are an important issue as illustrated here. The baseline hoop creep data is extracted from 2-1/2"OD tubes that were subsequently flattened and samples cut in the transverse orientation. However, for the joint sections, transverse samples are not feasible as the processed joint width is considerably narrower than the 0.125" specimen width and any sample cross-section will contain the base material as well. The issue is further exacerbated as the tube joint will need to be flattened to extract the transverse specimen. Thus an alternate strategy of extracting

longitudinal specimens ensures the joint section comprises the entire gage cross-section. We like to point out that sample orientation is a particular issue in MA956 tubes on account of the grain shape anisotropy where grains are extended along the longitudinal direction. However, the joint microstructure reveals that the recrystallized grain microstructure in the joint is fairly isotropic, see Figure 4(d), and the particular orientation of the volume of material comprising the joint region during testing is not critical. Thus, the joint creep performance can be evaluated in the longitudinal sample geometry where the base material in the gage length is loaded elastically and the bulk of the creep, as surmised from the tensile tests, occurs in the small volume of the joint region in the gage length.

Table 1 lists the creep test results for several series (IW#7-9) of inertia welds produced using variations in energy input and weld pressure conditions. Sample IW#8 with the largest HAZ yields poor LMP performance when compared to the as-received and recrystallized base material. This performance is incrementally improved as the HAZ is reduced to 1-1.5mm (as in IW#7), However, significant creep enhancements are achieved for joints where the HAZ is as narrow as 100-200μm, see Figure 5. This joint feature is fully reproducible in subsequent joints.

Table 1: Creep testing of Inertia Welded Joints in MA956 Tube Materials

Test	HAZ width	Test Temp	Stress	Creep rate/day	LMP
MA956, HT1375^{o}C, 1hr, Air	**NA**	**900°C**	**2Ksi**		**45.00**
IW#8, HT1375^{o}C, 1hr, Air	**2.5–3.0mm**	**800°C**	**2Ksi**	**4.6x10^{-3}**	**42.72**
IW#8, HT1375^{o}C, 1hr, Air	**2.5–3.0mm**	**900°C**	**2Ksi**		**43.04**
IW#7, HT1375^{o}C, 1hr, Air	**1.0–1.5mm**	**800°C**	**2Ksi**		**43.59**
IW#7, HT1375^{o}C, 1hr, Air	**1.0–1.5mm**	**800°C**	**2Ksi**		**43.87**
IW#7, HT1375^{o}C, 1hr, Air	**1.0–1.5mm**	**850°C**	**2Ksi**	**4.0x10^{-4}**	**44.50**
IW#7, HT1375^{o}C, 1hr, Air	**1.0–1.5mm**	**850°C**	**2Ksi**		**44.12**
IW#7, HT1400^{o}C, 1hr, Air	**1.0–1.5mm**	**850°C**	**2Ksi**		**44.22**
IW#7, HT1375^{o}C, 1hr, Air	**1.0–1.5mm**	**900°C**	**2Ksi**		**43.72**
IW#7, HT1375^{o}C, 1hr, Air	**1.0–1.5mm**	**900°C**	**2Ksi**		**44.29**
IW#7, HT1375^{o}C, 1hr, Air	**1.0–1.5mm**	**900°C**	**2Ksi**		**44.52**
IW#9, HT1375^{o}C, 1hr, Air	**0.1–0.2mm**	**850°C**	**2Ksi**	**1.0x10^{-4}**	**47.20**
IW#9, HT1375^{o}C, 1hr, Air	**0.1–0.2mm**	**900°C**	**2Ksi**		**47.71**
IW#9, HT1375^{o}C, 1hr, Air	**0.1–0.2mm**	**900°C**	**2Ksi**	**1.6x10^{-4}**	**48.60**
IW#9, HT1375^{o}C, 1hr, Air	**0.1–0.2mm**	**950°C**	**2Ksi**	**4.0x10^{-4}**	**48.47**

At the outset the results seem to indicate the importance of processing parameters in dictating overall creep response as indicated by observed creep rate and overall Larsen-miller parameter (LMP). For example, Table 1 shows that for reduced HAZ, a lower overall creep strain rate is possible even for testing at higher temperatures. What is clearly promising is that robust quality joints are possible with creep performance approaching and exceeding the base material performance. This suggests that the base material microstucture may not optimum which is perhaps being favorably altered during the high weld pressure processing. We surmise that the dynamic hot working

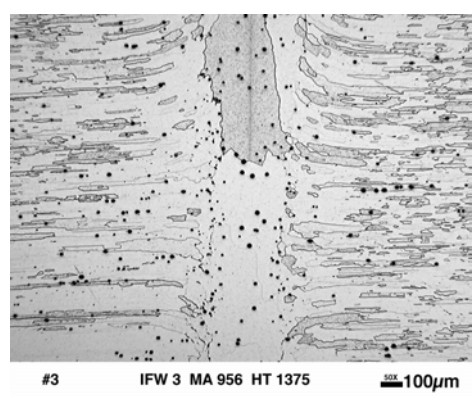

Figure 5. Narrow HAZ width joints produced at large weld pressures.

induced during inertia welding may aid the subsequent secondary recrystallization to produce large grain size in the HAZ. This is consistent with the observed HAZ grain structure of Figure 5, and needs to be confirmed via further TEM study. In keeping with the general trend of reducing the joint HAZ width subsequent joints are produced, via a combination of energy input and weld pressure process parameters to closely mimic the HAZ microstructure of Figure 5. These tests continue till date. Threshold performance has been systematically improved. For equivalent tests at 900°C, the base material LMP is about 45 compared to the IW#9 joint with LMP of 47.71 and 48.60. Thus, the notion of improving joint creep performance via manipulating the factors that dictate HAZ width has significant merit as been demonstrated here.

SUMMARY AND CONCLUSIONS

Inertia welding of ODS MA956 tubes has been successfully attempted. The butt joint configuration is a viable joint intended for heat exchanger fabrication employing MA956 tubes. Results show that robust joints can be produced over a wide range of processing parameters. However, the process needs to be optimized specifically to improve the overall creep performance of the joint and consequently the fabricated component. Significant improvements have been demonstrated via manipulating the process parameters of energy input and weld pressure that dictate the thermal excursion in the heat affected zone as well as the overall deformation history in the vicinity of the bonding interface. Our results till date suggest that the scale of the HAZ region has an effect on the ensuing creep performance and efforts to manipulate process parameters to mitigate HAZ width have significant merit for overall creep enhancement of the fabricated joint. A narrow HAZ is key to improving the joint creep response.

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