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Residual stress measurements in a thick, dissimilar aluminum alloy friction stir weld

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Abstract

Plates (25.4 mm thick) of aluminum alloys 7050-T7451 and 2024-T351 were joined in a butt joint by friction stir welding (FSW). A 54 mm long test specimen was removed from the parent plate, and cross-sectional maps of residual stresses were measured using neutron diffraction and the contour method. The stresses in the test specimen peaked at only about 32 MPa and had the conventional "M" profile with tensile stress peaks in the heat-affected zone outside the weld. The asymmetric stress distribution is discussed relative to the FSW process and the regions of highest thermal gradients. The general agreement between the two measurement techniques validated the ability of each technique to measure the low-magnitude stresses, less than 0.05% of the elastic modulus. Subtle differences between the two were attributed to spatial variations in the unstressed lattice spacing (d_0) and also intergranular strains affecting the neutron results. The FSW stresses prior to relaxation from removal of the test specimen were estimated to have been about 43 MPa, demonstrating the ability of FSW to produce low-stress welds in even fairly thick sections. To avoid the estimated 25% stress relaxation from removing the test specimen, the specimen would have had to be quite long because the St. Venant's characteristic distance in this case was more related to the transverse dimensions of the specimen than to the plate thickness.

Keywords: Residual stresses; Friction stir welding; Neutron diffraction; Aluminium alloys

1. Introduction

Friction stir welding (FSW) is a revolutionary joining process which has seen remarkable growth in research, development and application in recent years. Conventional structural components for aircraft – beams for floors, spars, with tailored characteristics to meet durability and damage tolerance requirements, and so on – are normally built up using discrete components of different alloys. To reduce the costs associated with conventional alignment and assembly steps of built-up structures, ever more assembled components are being converted to unitized structures via such processes as casting or machining from forged preforms or thick plate stock. FSW offers additional avenues to unitization of structural components. Lap and butt joining of thin-sheet materials provides an alternative to conventional joining/fastening. Another pathway to structural components is the fabrication of "tailored blanks," using FSW to join shaped blocks of plate or forgings, from which unitized parts may be machined. Both of these approaches are in various stages of development and production.

FSW has sufficiently matured such that direct joining of 1 inch thick plates of 2XXX or 7XXX aluminum alloys (AA) is currently within the state of the art, creating starting stock with distributed property characteristics [1]. Static strengths in such joints typically exceed 80% of

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the parent strength of the weaker alloy. Investigations of durability characteristics are underway. A significant potential contributor to the durability behavior of FSW joints and surrounding material, however, will be the magnitude and distribution of residual stress imparted by the FSW process. Crack growth rates in test coupons of FSW in aluminum alloys have been observed to change in the region of friction stir welds. Detailed testing has shown that that the rate changes occur primarily from residual stresses, even at very modest magnitudes, rather than microstructural changes [2–6]. Therefore, knowledge of residual stresses is crucial if accurate property measurements are required. Furthermore, residual stresses in structures would be expected to differ from those in test coupons. Therefore, knowledge of residual stresses in structural components, not just test coupons, is also critical.

The measurements presented in this paper of internal residual stresses in a 25.4 mm thick FSW of dissimilar aluminum alloys provided measurement challenges beyond what has been previously reported in the literature. All previous reports of FSW residual stresses were for thicknesses of 10 mm or less and mostly for monolithic welds. Some surface and near-surface results have been reported using X-ray diffraction [7,8] and hole drilling [4,9]. Through-thickness stresses were measured by hole drilling in a 3 mm thick FSW in various aluminum alloys [10]. Using layer removal, X-ray measurements have been used to reconstruct internal stresses [5]. The vast majority of results for subsurface residual stresses have been reported from neutron diffraction and synchrotron X-ray diffraction measurements. Such measurements generally require an unstressed reference lattice spacing (d_0) in order to determine strains from measured lattice spacings [11]. Unfortunately, the FSW process often results in inhomogeneity and spatial variations of the unstressed lattice spacing, which must then be measured or otherwise addressed. The unstressed spacing in FSW specimens has been measured by sectioning a reference piece to obtain stress relief [12–14], which is tedious and arguably renders the neutron measurement destructive. In thin FSW specimens, the assumption of zero stresses in the direction of the plate normal has been used to overcome the reference issue [15–18], but this assumption becomes less sure as the sample thickness increases and some have reported measuring significant magnitudes for this stress component [14]. Sometimes, the varying reference spacing issue is not accounted for and leads to issues in interpreting the results [19]. For thin samples and when thickness-averaged stresses are acceptable, the d vs. $\sin^2\psi$ technique has been used with synchrotron X-ray diffraction to bypass the reference spacing issue [11]. The only significant exploitation of the non-destructive nature of diffraction measurements involved using synchrotron X-ray diffraction to measure the evolution of residual stresses during fatigue cycling [12]. Destructive measurements using incremental slitting (crack compliance) have provided particularly insightful measurements for examining the effect of residual stress on fatigue crack growth [2,6,8]. Only two works report results in dissimilar friction stir welds, and they were both under 4 mm thick [18,20].

This study compares contour method [21] measurements with neutron diffraction measurements. Each method has its inherent strengths and weaknesses which complement each other in several key areas, thus enabling a thorough investigation of the stress state in a specimen. The contour method is destructive, but it is quite insensitive to inhomogeneities in the specimen as long as they do not significantly affect the elastic constants. The contour method has been demonstrated to be able to measure residual stresses in many applications, such as thick sections, that would be difficult or impossible for other methods. Examples include 107 mm thick aluminum alloy forgings [22], stresses from a ballistic penetration event in a 51 mm thick plate of HSLA-100 steel [23], laser-peening stresses in thick plates of a corrosion-resistant Ni–Cr–Mo alloy [24], and stresses in railroad rails [25].

The measurements in this study fulfill a secondary purpose of validating the contour method for low-magnitude stresses. The contour method has been validated by comparing with neutron diffraction measurements in a TIG-welded steel plate [26] and a 316 L stainless steel plate with an metal-arc weld bead [27] and by comparing with both synchrotron X-ray and neutron diffraction data in an aluminum weldment [28]. In those applications, the peak residual stress magnitudes were 0.35%, 0.17% and 0.25% of the elastic modulus, respectively. In this study, the stress magnitudes ended up being less than 0.05% of the elastic modulus, therefore testing the sensitivity of the method to low stresses.

2. Experimental

2.1. Specimen preparation

Plates (25.4 mm thick) of 7050-T7451 and 2024-T351 were procured from a commercial vender. The temper designations indicated that the plates were stress relieved by uniaxially stretching in the rolling direction to at least 1.5% plastic strain. The Edison Welding Institute (EWI) in Columbus, Ohio, performed friction stir butt welding to produce a 305 mm × 457 mm plate from two 153 mm × 457 mm plates as shown in Fig. 1. A one-pass single-sided joint was formed at a rate of 50.8 mm per minute using a threaded-pin FSW tool. This particular weldment was fabricated by locating the 2024-T351 panel on the advancing side of the weld. X-ray radiography and metallographic cross-sections verified that the joint was sound and free of voids and root surface disbands. After welding, the panel was aged at 121 °C for 24 h to stabilize the weld nugget. A significant portion of the panel was consumed by microstructure and mechanical property characterization. A 54 mm × 162 mm sample was extracted for residual stress determinations.