Journal of Manufacturing Processes 26 (2017) 240–251

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

Three-dimensional mapping of the residual stress field in a locally-rolled aluminium alloy specimen

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ARTICLE INFO

Article history:
Received 15 December 2016
Received in revised form 14 February 2017
Accepted 16 February 2017

Keywords:
Residual stress
Neutron diffraction
Finite element analysis
Rolling
Welding

ABSTRACT

Detrimental residual stresses that occur in welded joints can be removed by rolling the weld seam. In this study we show that rolling could be applied to much thicker-section welds than has previously been attempted. A residual stress field introduced by localised rolling of an aluminium alloy specimen was studied to establish whether the plastic deformation caused by rolling would be sufficient to treat thick-section welds. It was modelled using finite element analysis and characterised using detailed neutron diffraction measurements. During rolling, plastic deformation occurs through the entire thickness of the specimen and strongly compressive residual stresses are created in the rolled area. Some features of the three-dimensional residual stress field, such as a region of tensile stress beyond the end of the rolled area, could be detrimental to structural integrity. It is recommended that these should be taken into account in the design of rolling-based weld treatment and surface treatment processes.

1. Introduction

Even in the absence of externally-applied loads, residual stresses can linger inside materials due to internal strain incompatibility. Residual stresses strongly affect a range of material behaviours and failure mechanisms including brittle fracture and fatigue fracture [1]. As a result, accurate residual stress characterisation is often crucial for the design and analysis of high-reliability mechanical components [2,3], and for the development of fabrication processes such as welding [4] and metal additive manufacturing [5]. In general, tensile residual stress normal to the plane of a crack-like defect increases the propensity for propagation of the crack. Therefore the presence of large tensile residual stresses in any part of a structure known to have an increased likelihood of defects, such as a weld seam, is undesirable.

Localised high-pressure rolling of metals can produce non-uniform plastic deformation in the rolled region. As a result, rolling can be used to modify the distribution of residual stress. This the basis for common surface treatments such as roller burnishing and deep rolling. Burnishing and deep rolling treatments involve deforming a region of material at the surface of a component using a small, hard, spherical or cylindrical tool of a few millimetres in diameter. This generates compressive residual stresses at the material's surface [6,7]. The compressive residual stress, and any associated surface hardening and smoothing, can impart improved fatigue resistance [8]. The depth over which the residual stresses resulting from these processes act is small: typically less than 1 mm [9–11].

Recently, it has been shown that localised rolling can be used to mitigate the tensile residual stresses which characteristically arise in welded joints during manufacture [12–16]. Large residual stresses may occur throughout the thickness of a joint, but small-scale burnishing-type treatments are not able to reach the material deep inside in thick-section welds. A process which causes much deeper and more extensive plasticity is required. Experimental studies by Altenkirch et al. [12] and Coules et al. [13,14] have shown that residual stress mitigation in weld seams can be achieved using a large, highly-loaded but freely-rotating roller to cause extensive plastic deformation of the weld region. This extensive plasticity causes weld-induced residual stresses to relax. The roller is applied directly to the weld seam, after welding. For welds in relatively thin structural steel and aluminium alloy (<10 mm thickness), this form of roller treatment can greatly reduce the residual stress present in the weld seam. With a sufficiently large rolling load the residual stress distribution may even be inverted, creating a zone of compressive residual stress along the weld [13]. This form of rolling is also being investigated for application to metal additive manu-

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http://dx.doi.org/10.1016/j.jmapro.2017.02.010
1526-6125/

factured structures, and has been shown to improve the residual stress state [17,18], and microstructure [19,20], and to reduce the incidence of porosity defects [21].

Both the small-scale roller burnishing/deep rolling methods and the larger-scale weld rolling technique rely on the ability of the roller to produce plastic deformation in the workpiece. Although it is well-established that rolling contact can introduce compressive residual stresses at a material's surface [22], little work on the three-dimensional nature of the resulting stress field has been performed. Consequently, it is not clear whether detrimental patterns of residual stress may arise at the edges of the rolled/burnished areas. For deep rolling and roller burnishing, the lack of detailed experimental information can be attributed to the difficulty in measuring residual stress fields over the length scale involved (<1 mm from the surface). Most experimental measurements of residual stress introduced by deep rolling are made using Incremental Centre Hole Drilling (ICHD) or conventional X-ray diffraction, which are the most appropriate and accessible techniques for this length scale [23]. These techniques only provide a limited (typically one-dimensional) characterisation of the residual stress field. The larger-scale residual stress fields which occur after localised rolling of welds allow for more advanced residual stress measurement techniques to be used, including neutron diffraction and synchrotron X-ray diffraction [12,13]. However, the characterisation of rolled welds has so far focussed on sheet/strip metals less than 10 mm thick. There has also been a focus on the distribution of residual stress transverse to the rolling direction, rather than on the through-depth distribution of stress. As a result, it is unclear whether rolling can reduce the residual stresses present deep inside thick-section welds [24].

In this study, we examine the applicability of localised rolling for the stress relief of welds in thick-section materials. Specifically, we examine the depth to which plasticity and residual stress can be introduced using rolling, and the nature of the three-dimensional field of residual stress which arises. For welds, it is desirable to produce relaxation of weld-induced residual stresses throughout the thickness of the weld in order to prevent tensile residual stress from promoting the initiation of failure at internal weld defects. Using measurements from a specimen of homogenous, non-welded material subjected to localised rolling, we demonstrate that this process can produce plasticity deep inside the material.

2. Method

2.1. Overview

A rectangular aluminium alloy plate was rolled along its centreline using a large, narrow roller applied with a constant force and rolling velocity. Characterisation of the mechanical properties of the plate material was performed. The rolling process was simulated using the finite element method in order to predict the residual stress field in the rolled specimen. Neutron diffraction was used to measure the complete residual stress tensor at a large number of locations inside the rolled specimen and ICHD measurements were performed at the surface. Using the finite element model and measured results, the applicability of the rolling method for residual stress modification was assessed.

2.2. Rolled plate

The specimen was a 204 × 153 × 25 mm oblong piece of aluminium alloy 6082-T6. It was cut from a larger plate with the grain oriented in the direction of the longest dimension. The machine used for rolling is described by Coules [24] and Coules et al. [13]. The specimen was rolled on one surface using a cylindrical roller

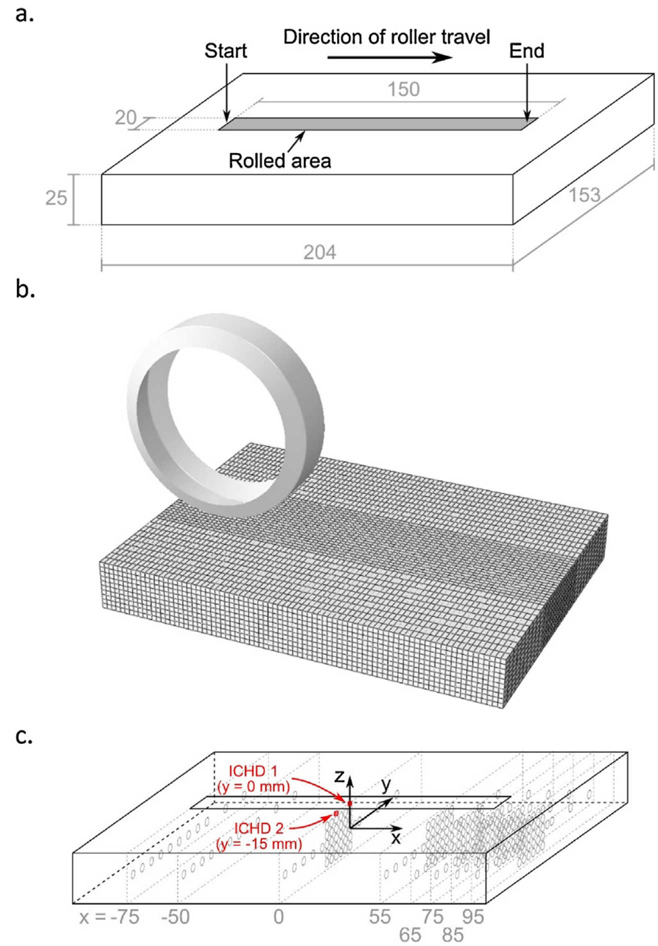

Fig. 1. a.) Geometry of the rolled aluminium alloy specimen showing the rolled region. b.) Finite element model of the rolling process. c.) Neutron diffraction measurement locations (grey circles) and ICHD measurement locations (red markers). Dimensions in mm.

of hardened AISI Type H13 tool steel with a diameter of 100 mm and an axial width of 20 mm. The roller was brought into contact with the upper surface of the specimen (Fig. 1b) and then a vertical force of 150 kN was applied to it. It was translated 150 mm along the specimen's length at a velocity of 8.3 mm s^{-1} while maintaining the constant 150 kN vertical force. Finally the roller was raised, having indented a rectangular region of the specimen's upper surface (Fig. 1a). Throughout this process, the roller was allowed to rotate freely on its axis. During rolling, the specimen was supported on its lower surface by the rigid steel bed of the rolling machine. An end stop bolted to the machine bed was used to prevent the specimen from moving in the rolling direction.

2.3. Material characterisation

Two types of mechanical test were performed to provide the material stress-strain characteristics required for the FE modelling: monotonic uniaxial tests and fully-reversed cyclic uniaxial tests. Both types of test were performed at ambient temperature.

For the monotonic tests, cylindrical specimens of un-deformed plate material were cut from the same batch of material as the rolled plate. The specimens had a parallel length of 28 mm, a diameter of 5 mm, and conformed to BS EN ISO 6892-1:2009 [25]. They were tested in tension to failure at a constant elongation rate of 3.33 μm s^{-1}. Testing was performed using an Instron 1340-series tensile testing machine and an iMetrum video extensometer system. Tensile specimens longitudinal and transverse to the grain of