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Influence of friction stir welding residual stresses on the compressive strength of aluminium alloy plates

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ABSTRACT

The mechanical behaviour of welded structures can be significantly affected by the effects of the employed joining process. The main goal of this work is to assess the influence of the longitudinal residual stresses on the overall compressive performance of aluminium friction stir welded plates. Longitudinal residual stress distribution was measured by means of the contour method and introduced as initial condition into a finite element model of the compressed assembly. Also, the sensitivity of the plates to the magnitude of the initial geometrical imperfections was analysed. It can be inferred that both factors influence the plate's mechanical behaviour.

1. Introduction

Aluminium alloy thin-walled structures are common in aeronautical and naval parts due to particular requirements in terms of weight saving. The design of such structures is often based on the compression strength. Therefore, an exhaustive understanding of the buckling behaviour of the structure is highly desired. This behaviour can be affected by several factors such as: material properties, residual stresses and geometrical distortions [1]. In most cases the aforementioned structures are constituted by several plates or integrally stiffened panels joined together by welding [2–4]. The adopted joining processes can strongly affect all those factors, and, therefore, the mechanical behaviour of the structures when subjected to compression. As a consequence, the choice of a specific joining process, *i.e.* with reduced effects on the assembly performance, and the accurate prediction of its behaviour, is imperative. The impact of process effects on the performance of the welded structure has been object of previous research consisting in the development and application of simulation models based on the finite element method (FEM). Some of these works assess the effect of initial imperfections [5–11] and material properties [5–7,11,12] on the strength of stiffened structures, and also on single plates [13]. However, the effect of residual stress fields is most often not considered, with some literature on the subject accounting for simplified assumptions on the stress distributions [3,6,7].

In recent years a great deal of attention has been focused on the Friction Stir Welding (FSW) process as a valid alternative to conventional fusion welding processes. Indeed, the solid-state nature of FSW allows one to eliminate, or at least significantly reduce, some defects frequently derived from material melting and re-solidification, such as porosity, oxidation, high residual stresses and excessive distortions. During the FSW process, a non-consumable rotating tool, constituted by a shoulder and a pin, is plunged between the adjoining edges of the parts to be welded and moved along the desired weld line. The heat generated by frictional effects and plastic deformation locally increases the temperature. The induced softening allows the processing material to flow around the pin, from the front (leading edge) to the rear (trailing edge) according to complex patterns, resulting in the solid state weld [14]. The temperature increase and high strain rate deformation lead to the formation of micro-structurally distinct zones: the nugget zone (NZ) in the centre of the weld, surrounded by the thermo-mechanically affected zone (TMAZ) and the heat affected zone (HAZ).

Nowadays, a deeper understanding of static strength as well as of fatigue behaviour of FSW assemblies is highly desired for a wider implementation of the technique in safety-critical components. It is generally accepted that the aforementioned properties mainly depend on the microstructure, the micro-hardness and, on a wider extent, on residual stresses induced by the process. Even if FSW residual stresses are often lower than those resulting from conventional welding processes, an accurate knowledge of

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their distribution is crucial to numerically investigate the buckling and fatigue [15] behaviour of welded structures.

In the present work, the characterisation of longitudinal residual stress fields induced by a FSW process was performed by means of the contour method. The collected data were introduced in FEM models of plates with different lengths and subjected to compressive solicitations within the elastic–plastic range. The impact of residual stresses on the collapse load level was studied in detail. The sensitivity of the models to distinct geometrical imperfections was also assessed.

This article is structured as follows: in Section 2 some details regarding the used material, the performed welding process, and the procedure employed for longitudinal residual stress analysis are provided, while in Section 3 the finite element model of the compression test is described and the obtained results are exposed and discussed. Relevant conclusions are finally emphasised in Section 4.

2. Characterisation of the FSW longitudinal residual stress fields

The contour method is a compliance method for residual stress measurement, proposed by Prime [16] in 2001. From a theoretical point of view, the contour method is a derivation of Bueckner's elastic superposition principle which states that: “if a cracked body subjected to external loading or prescribed displacements at the boundary has forces applied to the crack surfaces to close the crack together, these forces must be equivalent to the stress distribution in an uncracked body of the same geometry subjected to the same external loading” [17]. The most interesting capability of the method, when compared to other destructive techniques, is that it allows to completely map the normal component of residual stresses on a cut surface, following a relatively simple and cheap procedure. Moreover, the experimental steps can be performed using devices and machines currently available in most industrial (as well as academic) research laboratories. The application of the conventional contour method is based on four consecutive steps: (i) the cutting of the welded specimen, (ii) the shape acquisition on the relaxed surface, (iii) the data processing and (iv) the stress computation.

Since its development, the contour method has been widely applied for validation purposes as well as for stress analyses in several contexts, including FSW [18–21].

In the present investigation, AA2024-T3 aluminium rolled plates were joined by FSW. The used tool consisted of a 20 mm diameter shoulder with a conical pin, characterised by the following dimensions: height of 3.80 mm, larger diameter of 6.20 mm and cone angle of 30°. The tool was made from AISI1040 quenched steel (56 HRC). The tilt angle and tool shoulder penetration, were defined as 2° and 0.2 mm, respectively, according to preliminary tests. The residual stress scenario used in the present analysis was obtained assuming an angular tool velocity of 1400 rpm and a linear velocity of 70 mm/min. The experimental setup for the welding process, including the clamping system and the used tool, is represented in Fig. 1.

As far as the application of the contour method is regarded, a FSW specimen was sectioned at mid-length and orthogonally to the weld line by a wire electrical discharge machining (WEDM) process. Out of plane displacements of the sectioned surfaces were recorded by means of a coordinate measuring machine (CMM) in a moisture and temperature controlled room. Experimental data were then imported, averaged and fit to a unique smoothing surface in MATLAB. The measured and digitalised out-of-plane displacements were used, with reversed sign, as input nodal boundary conditions in an elastic FE model of the cut sample, initially assuming a block shaped geometry [16]. Additional constraints were imposed in order to prevent rigid body motion. The commercial software ANSYS was used to solve the linear elastic boundary value problem. The contour method stages, after the sample cut, are represented on Fig. 2. Further details on the adopted procedure as well as an analysis of the influence of process parameters on stress distribution can be found in the work of Carlone and Palazzo [18]. The computed longitudinal residual stresses, according to the imposed displacements, are shown in Fig. 3. In the following section, the procedure developed to investigate the influence of welding stress on the buckling behaviour of stiffened panels is described in detail.

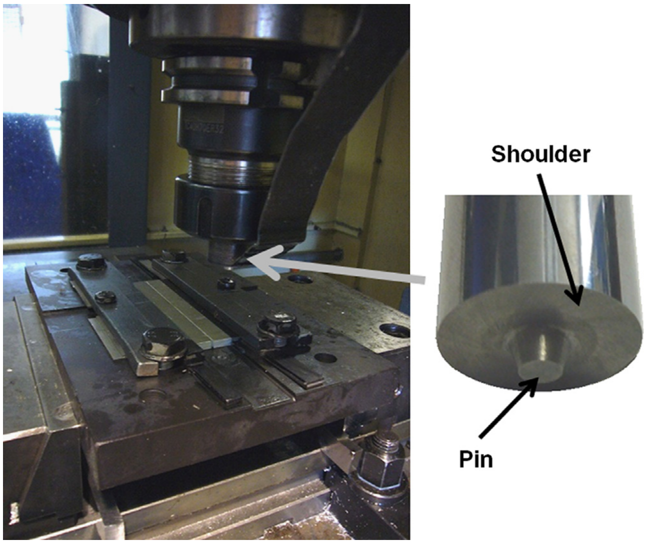

Fig. 1. FSW experimental setup and used tool.

3. Compression analyses

3.1. Numerical model

The effect of the measured residual stresses was tested in FEM models of the welded plates. The dimensions of the cross section were defined equal to the experimentally welded specimen (60 × 4 mm). A set of different panel lengths was tested, with magnitudes (L) ranging from 50 to 550 mm. The boundary conditions used, when the compressive load was applied, are schematically shown in Fig. 4. The non-loaded edges had no restrictions in terms of displacement or rotation. The nodes of the loaded edges (top and bottom in Oz direction) were connected by rigid elements and clamped boundary conditions were considered.

The numerical model was solved using the ABAQUS FEM code [22]. The model was discretised using S4R elements (4 nodes shell elements with reduced integration), considering 9 integration points across thickness. A constant number of 9000 elements were used for different lengths, accounting for 60 elements along the width and 150 elements along the length. In all cases the quality of the mesh, in terms of number of elements, is higher than literature suggestions taking into account the buckling mode [9,23]. Nevertheless a mesh convergence study was performed including residual stresses.

3.2. Material modelling

Different material properties were considered relative to the base material and the welding zones (without further distinction between NZ, TMAZ and HAZ), to account for microstructural