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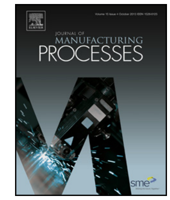

Technical Paper

Finite element modelling of the inertia friction welding of a CrMoV alloy steel including the effects of solid-state phase transformations

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ABSTRACT

Finite element (FE) process modelling of the inertia friction welding (IFW) between two tubular CrMoV components has been carried out using the DEFORM-2D (v10.2) software. This model has been validated against experimental test welds of the material; this included process data such as upset and rotational velocity as well as thermal data collected during the process using embedded thermocouples. The as-welded residual stress from the FE model has been compared to experimental measurements taken on the welded component using the hole drilling technique. The effects of the solid-state phase transformations which occur in the steel are considered and the trends in the residual stress measurements were well replicated when compared to the experimental data.

1. Introduction

Inertia friction welding (IFW) is a quick and repeatable solid state joining technique which can be used to join a wide range of materials in both similar or dissimilar joints [1] avoiding bulk melting of material. Due to the high energy input rates in the process, IFW produces welds with steep thermal gradients around the interface which results in a narrow heat affected zone (HAZ). The HAZ is generally defined as the region of material which has undergone significant structural changes due to the welding process [2] and in IFW can encompass the bond line, the thermo-mechanically affected zone (TMAZ), where large deformations occur, and the region purely thermally affected next to the base material. There are three controllable parameters in inertia friction welding; these are rotational velocity, flywheel inertia and the axial pressure applied to the weld. The weld duration, energy input rate and deformation levels during the welding process can be controlled by varying the parameters [3]. Due to the high temperatures, deformations and subsequent thermal contraction of the weld during cooling, residual stress is induced in the material in and around the weld region.

The modelling of manufacturing processes can allow a greater degree of understanding and insight to be gained than solely through the inspection of completed parts due to the information that can be extracted from the model such as full field residual stress, strain and temperature results and the variation in these fields with changing parameters. All of this can be achieved using a process model without the expense and lead time associated with producing actual components and performing post manufacturing analysis.

Process modelling is particularly useful for IFW as it is a rapid, complex, coupled thermo-mechanical process that is highly dependent on the input parameters. The welds of interest in this study were like-to-like welds of a high strength chromium, molybdenum, vanadium (CrMoV) alloy steel (0.4C, 3.35Cr, 0.4Ni, 1.15Mo, 0.26Mn, 0.15Si, 0.17V).

The modelling of IFW has been addressed by a number of authors using a variety of different approaches; initial models created in the 1970s were purely thermal models using the finite difference method [4,5]. A heat flux which was a function of rotating speed and distance from the centre was applied at the interface and their models highlighted the presence of high heating rates and steep thermal gradients near the interface.

Analytical modelling of the thermal effects of the process was carried out by Davé et al. [6] in 2001 to provide guidance in the selection of weld parameters for the welding of dissimilar materials (Nb to 316SS in this case). The energy used to expel the flash was estimated in this case and then the resulting thermal profile was calculated. The thermal input was derived directly from the angular speed curve obtained from an experimental weld. Two models were proposed and the results were compared to the thermal data obtained from welds. The difference between the two models and measured experimental temperature data was a maximum of 100 and 350 °C for the two techniques.

Later developed fully-coupled thermo-mechanical models of the IFW process mainly use two approaches to the treatment of the interface, the first of these being to use existing experimental

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data which is then converted to a heat flux at the interface [7,8], this allows existing welds for which data is available to be recreated in a model to obtain an accurate representation of deformations and thermal fields during the process. The second approach is the inclusion of a friction law [9–11] based on the current conditions at the interface, which removes the requirement for existing weld data and leads to the development of a predictive capability.

A fully coupled thermo-mechanical finite element model of the IFW process was developed by Moal and Massoni [9]. The code (INWELD) included adaptive re-meshing and although axi-symmetric included the circumferential velocity component which lead to a 2.5D model capable of predicting the slowdown of the flywheel. This work considered a nickel-based alloy, NK17CDAT and the results of the model were compared with actual industrial welds where the rotational speed values compared well but the axial shortening of the welds were overestimated by 20%. This work did not consider the development of residual stresses during the post-weld cooling phase. The DEFORM-2D code was extended in 2001 by Lee et al. [12] in a similar way to include torsional effects and a special axi-symmetric element (again 2.5D) was developed with three velocity components but no velocity gradients in the circumferential direction.

D'Alvise et al. [10] extended the work of Moal and Massoni [9] by including a new mathematical formulation and subsequently an extension to account for dissimilar material weld combinations by developing a specific coupled thermo-mechanical finite element module implemented in the FORGE2 commercial code in 2002 to perform analysis of the IFW process. Mechanical equations taking into account the inertia, forces and friction were included in the model. A friction law based on pressure, rotational speed and temperature was proposed to represent the interface contact during the weld period. Similar and dissimilar nickel-based alloy materials and geometry welds were investigated and weld time, upset and thermal results from the model were compared with experimental measurements taken during the welding process. In all cases the model over predicted the values when compared to those from the welds. However the variation in the results across seven different welds, with different parameters, compared well.

Modelling of the IFW of the nickel-based superalloy RR1000 was carried out using a fully coupled thermo-mechanical model developed in DEFORM-2D by Wang et al. [7] and Grant et al. [8]. These works considered the build-up of residual stresses in the components by modelling the post-weld cooling phase using an elastic–plastic material model. The approach used in both of these pieces of work for the welding modelling was to determine the energy input rate from experimental data and covert this to a thermal boundary at the interface. The residual stress in the model of Wang et al. [7] were over predicted by around 35% in the as-welded and cooled state; however no machining was performed on the model before the comparison was made with experimental results, where some machining of the weld had occurred. An improved material database was used by Grant et al. [8] and an improved match to the experimental residual stress results was achieved. Microstructural analyses were carried out on welds and a good match in peak temperatures inferred from the presence of gamma prime phases (approximately 20 °C difference) was seen. Comparison of the γ' precipitation variation across the weld line and the microstructure produced by fast heating and cooling experiments following predicted temperature profiles also showed good agreement.

An analysis of the microstructure evolution of the FGH96 superalloy, with a particular focus on dynamic recrystallisation (DRX) and grain size prediction was carried out by Nie et al. [13] using the MSc.Marc software. Microstructure predictions were made using a basic DRX model fitted to data generated using a Gleeble 1500 thermo-mechanical simulator and were qualitatively compared with the results of experimental welds and showed reasonable agreement.

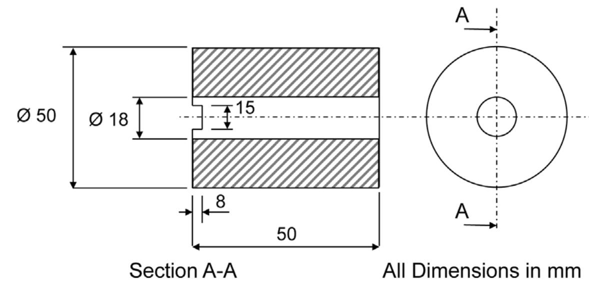

Fig. 1. Weld specimen geometry.

The importance of solid-state phase transformations on the residual stresses generated in inertia friction welds between a high strength steel (AerMet 100) and a nickel-based superalloy (Inconel 718) has been discussed previously [11], however no comparisons were made with any experimental residual stress values.

The current work uses the additional capability added to the DEFORM-2D software by Lee et al. [12] to perform fully coupled thermo-mechanical finite element analyses of the IFW process for CrMoV steel including both workpieces. As well as the welding phase, the post-weld cooling phase is also modelled in order to evaluate the residual stresses generated during the welding of the component by use of the thermal profile which exists at the end of the welding process. The effect of solid-state phase transformations is included in the model as these have been shown to have an important effect on the residual stresses generated during cooling of steel welds and the residual stress profiles from this model are compared with experimental hole drilling investigations on actual welds of the material. Weld data is used to create models with improved accuracy in terms of temperatures, phase volume distribution and deformations when compared to existing modelling techniques which usually result in a good match of a limited number of outputs and while the implementation is not a fully predictive approach, this strategy allows a wide variety of information to be gained from the models, including variations of temperature, residual stress and phase information throughout the entire welded components. Accurate predictions of these quantities is important in industrial applications due to their implications on the performance and life of components in service.

2. Experimental procedures

2.1. Test welds

Two test welds between two identical CrMoV steel components were carried out in order to provide information for and to validate the process model being developed. These welds were instrumented with thermocouples during welding and were also subject to residual stress characterization using the hole drilling technique [14] in the as-welded state to compare directly with the model outputs.

2.1.1. Geometry

The parts welded for this study were cylindrical components with weld interface geometries with an outer diameter (OD) of 50 mm and a wall thickness of 16 mm. An overview of the weld specimen geometry is given in Fig. 1

2.1.2. Weld parameters

Weld parameters for the welds considered in this work are presented in Table 1.