Journal of Materials Processing Technology 238 (2016) 409–422

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

# Numerical simulation of resistance upset welding in rod to tube configuration with contact resistance determination

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ARTICLE INFO

*Article history:*
Received 31 March 2016
Received in revised form 18 July 2016
Accepted 24 July 2016
Available online 25 July 2016

*Keywords:*
Resistance upset welding
Numerical simulation
Contact resistance
Nuclear fuel pin cladding
P91

ABSTRACT

A 2-D axisymmetric finite element model of upset resistance welding on tube to rod configuration is developed. It is based on an electrical-thermal-mechanical analysis and developed on commercial software MARC for nuclear fuel pin cladding welding application. It allows to assess local temperature and strain fields during welding. A parameter influence study reveals, among others, the importance of contact resistances between samples and electrodes. Some contact resistance models are proposed and a specific calibration method of those models, which implies experimental tests and numerical simulations, is developed. This calibration method allows to obtain a good agreement between the welding simulation and the relevant instrumented experiment for two different studied geometries.

## 1. Introduction

In the context of development of sodium cooled fast reactors (the so-called fourth generation nuclear reactors), new geometries and new alloys are developed for nuclear fuel pin claddings. Oxide Dispersion Strengthened (ODS) 9%–14% Cr steels are currently in development as potential material candidates. Dubuisson et al. (2012) presented the microstructural and mechanical aspects of those alloys, and showed their good resistance to swelling under irradiation and interesting creep properties. In a recent work, Yvon et al. (2015) showed promising results concerning the stability of the nano-oxide dispersion under irradiation doses up to 150 dpa. Because of their nano-sized oxide particles dispersion, those steel grades do not allow melting during the welding process. A solid state welding process, resistance upset welding is therefore considered to achieve welding of claddings on their end plugs. Nuclear fuel pin claddings weldability studies are ongoing to assess the feasibility of such welds. Numerical simulation of resistance upset welding has been developed to better understand the physical phenomena occurring during the process and to optimise the welding geometry and parameters. Numerical simulations are also used to estimate strains and stresses, and more particularly to assess the local thermo-mechanical cycles (temperature, strain and strain rate) imposed to the material, and responsible for welding microstructures and defects. Reliable numerical simulation is thus of primary importance in order to optimise and control the process.

Relatively few authors have published concerning numerical simulation of upset welding. The literature is mainly dedicated to rod to rod or sheet to sheet configurations, where cross sectional area of the parts to weld are equal and electrodes can be considered far from the weld. Eggert and Dawson (1986) were the first to use finite element method to simulate the process using an electro-thermo-mechanical coupling method. They have discussed the assessment of a viscoplastic model by comparison with the experiment and obtained good agreement between simulated and measured temperatures and voltages. Those results validated the effectiveness of the model as a predictive tool. However, this work focussed on tapered rod geometry where contact resistances at the interface could reasonably be neglected.

Electrical and thermal contact resistances between samples to weld and between samples and electrodes are known to have an influence on resistance welding, especially at the beginning of the process. Their effects have already largely been discussed for resistance welding applications in spot welding configuration. De et al. (2003) studied the influence of both sheet–sheet and electrode-sheet electrical contact resistances. They showed that both have an impact on the weld formation, although an increase of the former over a limit value has no effect on final results. Determination of

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http://dx.doi.org/10.1016/j.jmatprotec.2016.07.042

**Nomenclature**

| | |
|---|---|
| ODS | Oxide dispersion strengthened |
| I | Welding current |
| F | Welding force |
| t | Welding time |
| woc | Without chamfer |
| wc | With chamfer |
| CR | Contact resistance |
| ECR | Electric contact resistance |
| TCR | Thermal contact resistance |
| p-e | Plug-to-electrode |
| t-p | Tube-to-plug |
| t-e | Tube-to-electrode |
| TC | Thermocouple |
| T | Temperature |
| V | Potential |

electrode-sheet contact resistance is presented as a necessary condition in order to simulate the process. Concerning upset welding, Kerstens and Richardson (2009) have investigated the influence of contact conditions and pressure uniformity over the temperature field during upset welding of two similar steel sheets, with an electro-thermal finite element model. They highlighted the great influence of electrode bending, nonuniformity of contact pressure between electrode and sample, and contamination at the interface on the formation of hot spots inside the weld. This study confirm that, in upset welding configuration, interfacial conditions can be of primary importance on the formation of weld defects by inducing electrical or thermal current constriction. Rogeon et al. (2009) compared different approaches to take electrical and thermal constriction at the interface into account in finite element models. Those approaches were: (1) via contact parameters (contact resistances and heat partition coefficient), (2) by applying equivalent conductivities in a thin layer at the interface, (3) by directly taking the geometry of surface asperities into account in the mesh, this last one is presented as the reference method. If simpler and largely less computer time consuming than the reference one, the first approach, which is chosen in the present study, only describes electro-thermal phenomena at macroscopic scale, i.e. it is unable to describe temperature field at the close neighbourhood of the interface, under a distance of the order of magnitude of asperities height (a few micrometres). On the other hand, the difficulty of the second approach is that it implies to fix a priori the interface layer thickness in order to allow a better description of physical phenomena in this close neighbourhood.

Optimisation of upset welding process in tube to rod configuration, where cross section areas of the parts to weld are not equal, where electrodes are close to the weld, and where the weld is submitted to extreme deformation in a short amount of time, have been accomplished using experimental approach by Seki et al. (2004) in order to weld nuclear fuel pin claddings. Defect free welds have been obtained but this approach does not allow to determine thermo-mechanical cycles of welding, and thus provides a limited understanding of the process. For the same application, coupled experimental approach and numerical simulation has been proposed by Corpace (2011) to identify a weldability area without melting. Description of the formation of the weld is performed and discussed. However, uncertainties on temperature field are reported, and explained by uncertainties on contact resistances values, as well as inaccuracy on simulated mechanical cycles induced by the use of a small strain framework without remeshing procedure during calculation.

**Table 1**
Chemical composition of P91 steel grade in wt%.

| Element | C | Mn | Si | Ni | Cr | Mo | Cu |
|---|---|---|---|---|---|---|---|
| wt% | 0.09 | 0.40 | 0.22 | 0.13 | 8.30 | 0.95 | 0.05 |

The main contributions of the present study are (1) to provide a model which is robust and in agreement with the experiment for simulation of upset resistance welding in tube-to-rod configuration for different welding geometries, (2) to identify the most influent parameters on simulation results, including thermal and electrical contact resistances, and (3) to propose an approach for calibrating contact resistance models so as to obtain a good agreement with some experimental observables. A coupled numerical simulation and experiment approach is adopted. In the following sections material and welding process are briefly recalled. Experimental conditions of welding are then described. The perimeter of the numerical model, i.e. governing equations, solving procedure, boundary conditions and main hypothesis are then mentioned. Special attention for contact conditions is paid in the next part. Among others, we highlight the necessity to calibrate independently the electrode-to-plug and electrode-to-tube contact resistance models when their interface geometrical configurations differ. Different contact parameter calibration methods are consequently proposed. Finally, numerical simulation is validated by comparison with welding experiments achieved in good repeatability conditions. The influence of material properties and contact conditions is also discussed.

## 2. Material and welding process

Numerical simulation setup and experiments presented are carried out using a non-ODS model material 9%Cr steel grade P91 (X10CrMoVNb9-1, composition presented in Table 1). It has the advantage to be available off the shelf, while it shows electro-thermal properties close to those of 9–14%Cr ODS grades, and similar behaviour under welding. As delivered material is composed of tempered martensite. Welded microstructures are revealed by Villela's reactive attack to identify quenched martensite. Roux (2007) reported the solidus temperature of this grade to be 1450 °C, liquidus temperature is determined to be 1500 °C.

Samples to weld, schematized in Fig. 1, are composed of a cylindrical end plug of diameter D varying between 10 mm and 10.73 mm, and of a tube of 10.73 mm external diameter $D_{tube}$ and 0.50 mm thickness *e*. Two welding geometries found in the literature are studied: (a) geometry presenting a chamfer with an angle $\alpha$ of 70°, with a same diameter D for plug and tube, and a tube which extends beyond the electrode by a distance $L_t > 0$ mm. This geometry has already been used by De Burbure (1978) and Corpace (2011). (b) Geometry without chamfer, where $D_{tube} > D_{plug}$, and the electrode protrudes from the tube ($L_t < 0$ mm). This geometry was proposed by Babkin et al. (2000). Only results for the two cases ($\alpha = 70°$, $D_{tube} = 10.73$ mm, $D_{plug} = 10.73$ mm, $L_t = 1$ mm) and ($\alpha = 0°$, $D_{tube} = 10.73$ mm, $D_{plug} = 10.2$ mm, $L_t = -1$ mm) are presented, the associated geometries will be called respectively "with chamfer" and "without chamfer". Welding is achieved on a TECHNAX medium frequency resistance welding device integrated in CEA ALTEA experimental platform. During the process, the two samples are clamped into copper alloy (CuCrZr) electrodes, themselves tightened into jaws which allow current supply. The samples are pressed on each other via a pneumatic jack providing a force F chosen in the range 2000 N to 5000 N, applied on the plug end (Fig. 1). The tube side is fixed while the plug side displaces during welding. They are heated by a 1 kHz alternative current I which is rectified and smoothed, like the one used by Corpace (2011). The current is applied during a welding time t, i.e. from 10 ms to 100 ms