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Thermo-mechanical FE-analysis of the fabrication of a Cu-Fe canister for spent nuclear fuel

Josefson, B.L.
Chalmers University of Technology, Division of Solid Mechanics, Göteborg, Sweden
Lindgren, L.-E., Häggblad, H.-A., Karlsson, L.
Lulea University of Technology, Division of Computer Aided Design, Lulea, Sweden

ABSTRACT: Two stages in the fabrication of a copper cylinder for a canister for spent nuclear fuel is simulated numerically in a fully three-dimensional thermo-mechanical FE-analysis. First, the residual stress distribution after cold forming of a copper plate to half circular shape is calculated. Second, the residual stress field after joining two such copper half cylinders, containing a forming residual stress field, to one cylinder by longitudinal welding is calculated. These longitudinal welds are made by electron beam welding. After welding one finds axial and hoop residual stresses with maximum tensile magnitudes up to 100 MPa. These stress values are in quantitatively good agreement with preliminary experimental results from a pilot welding study reported in the literature.

INTRODUCTION

In the Swedish nuclear waste program it has been proposed that spent nuclear fuel shall be placed in composite copper-steel canisters. These canisters will be placed in holes in tunnels located some 500 m underground in a rock storage.The canister consists of two cylinders of roughly 5 m length, one inner cylinder made of steel and one outer cylinder mad of copper. The outer diameter of the canister is 0.9 m and the wall thickness for each cylinder is 50 mm. At the storage, the steel cylinder, which contains the spent nuclear fuel, is placed inside the copper cylinder. Thereafter, a copper end is butt welded to the copper cylinder using electron beam welding. Figure 1 shows the lay-out of the proposed canister and one possible design of the copper end. The primary objective in the mechanical design of the canister is to ensure no leakage of radioactive particles to the surroundings. This means, for example, that the risk for creep fracture must be assessed, and that the level of plastic strain in the canister due to the fabrication and to the design loadings must be estimated.

In a previous paper, Josefson et al. (1993), the temperature, strain and stress fields present during and after the final circumferential butt welding of the end were calculated numerically assuming rotational symmetry. To obtain a better estimation of the stress fields present during and after the fabrication of the canister, it has been decided to numerically simulate the fabrication of the copper cylinder.

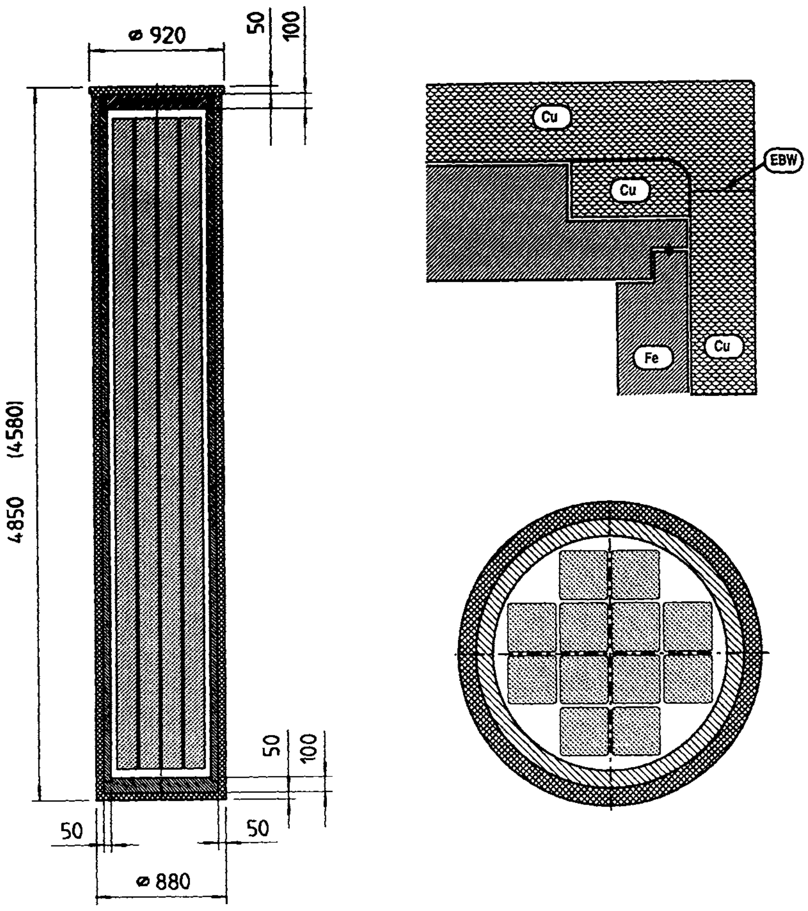

Figure 1. Geometry of canister. Upper right part shows blow-up of region with final circumferential weld. Dimensions in mm. From Josefson et al. (1993)

The present paper focuses on the fabrication of the outer copper cylinder. One of the alternative fabrication schemes for the outer copper cylinder consists of cold forming (rolling) and subsequent longitudinal seam welding of two copper half cylinders. This fabrication scheme is here studied in detail in a fully three-dimensonal thermo-mechanical FE-analysis using the in-house code SIMPLE (Lindgren, 1994). The theory for large strains and contact algorithm used in SIMPLE are based on the coding in NIKE-2D (Engelmann, 1991). Details of the solution of the resulting non-linear system of equations can be found in Engelmann (1991). Stresses are evaluated using the effective stress function algorithm.

FINITE ELEMENT MODEL

Cold forming

With the primary objective to calculate the stress fields present after longitudinal seam welding only a qualitative estimation of the forming residual stress field is believed to be needed. Hence, a plane strain model of the copper plates is sufficient. This means that the complex stress field at the edges of the copper plates are not modelled. Moreover, the effect of the initial setting (pre-bending) of two edges of the copper plates, see Punshon (1994) Fig. 11, is also neglected. The FE-model consists of some 400 four-node plane elements with reduced integration of the volumetric strain. The load is applied at four different sections of the plate. This type of loading resembles the actual loading during the cold forming operation, were the half cylindrical shape is obtained by pressing a cylindrical tool (upper support roll) against the plate which in turn is placed on two cylindrical tools (lower support rolls). This is repeated some four or five times, with new positions for the copper plate, until the plate has the desired cylindrical shape.

Longitudinal seam welding

In a pilot study (Punshon, 1994) a particular longitudinal seam welding sequence was employed in order to minimize the risk for opening of the joints during the welding. The copper half shells were first placed horizontally on top of each other using a special fixture. Four tack welds along each of the 5m lengths were then deposited. Thereafter followed a continuous axial tack weld on both sides and finally a continuous full current axial weld was deposited. Electron beam welding, penetrating the half cylinders from the outside, was used in all operations. The first tack welding was not included in the numerical simulations since the local stresses created in this operation will be released by the subsequent welding. Moreover, based on stress measurements on the welded cylinder (Leggatt, 1994) the longitudinal (axial) welds (tack weld and full current weld) along the 5m length were assumed be performed at the same time on both sides of the copper half shells.

This results in a FE-model of one half of a copper half cylinder consisting of some 1440 eight-node solid elements with totally 6100 degrees of freedom (in the mechanical analysis). The FE-model extends 500 mm in the longitudinal (axial) direction and includes the rear end where the longitudinal weld operation finishes. The copper half-cylinder is axially restrained at the front end, while the rear end is free. The grading of the FE-mesh is obtained by use of elements described in McDill et al. (1987). The welding parameters used were taken from Punshon (1994) and adjusted for the unknown heat efficiency to give a HAZ (Heat Affected Zone) width in accordance with experiments. Hence, for the continuous tack weld the net heat power was $P = 8$ kW and the welding speed $v = 300$ mm/min. The corresponding figures for the full current weld was $P = 11$ kW and $v = 150$ mm/min. The total welding operation, including both welds and cooling to room temperature, is performed in 760 load steps. The thermal analysis starts with the heat source entering the front end (taken as thermally insulated) of the FE-model with constant velocity and ends when the heat source has reached the rear end of the FE-model and the cylinder has cooled to room temperature. The thermal load caused by the heat source is applied by defining a moving box along the cylinder. In each loading-step the nodes in the box and those passed by the box is subjected to a uniform input of energy.

In the FE-analysis the development of the thermal and mechanical fields with time are solved simultaneously using a "staggered approach". The cold forming residual stress field is used as initial stress field. The possible thermal and mechanical influence of the fixture was neglected. For example, the experiments in Punshon (1994) indicated that the mechanical restraint provided by the fixture would have a minor influence on the welding residual stress field.

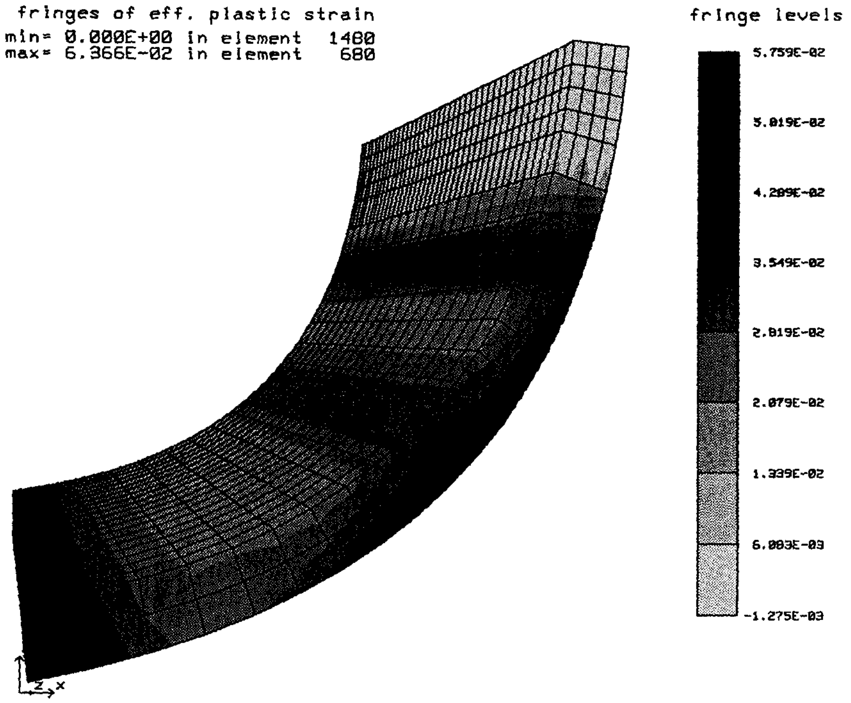

Figure 2. Calculated residual plastic strain field after cold forming to half-cylindrical shape

Moreover, the beam current absorber bars placed outside the copper half cylinders during the welding operation were not included in the FE-analysis.

The thermal material data for the (Cu-P) copper alloy used was taken from handbooks, see Josefson et al. (1993). In the mechanical analysis the material is taken to be thermo-elasto-plastic using von Mises yield criterion and associated flow rule with linear isotropic hardening. Values for entering material parameters were determined from uni-axial tensile tests performed on the actual copper alloy at different temperatures. At room temperature, the Young's modulus 130 GPa, the yield stress 65 MPa (assuming annealed material in the copper plates) and the hardening modulus 1100 MPa.

CALCULATED RESULTS

Figure 2 shows the calculated effective plastic strains in the copper half cylinder after the cold forming. Some equilibrium iterations were needed to transfer the plane residual stress and plastic strain fields to the three-dimensional FE-model and adjust to the boundary conditions at the free end where the welding finishes.

The maximum residual effective plastic strain was found to be roughly 6 % and the maximum von Mises effective stress at maximum bending load 100 MPa. Note, that the surfaces displayed in Figs 2 and 3 are based on one average value for each element. The calculations showed that the FE-model is sufficiently long for a stationary state to develop before the heat source reaches the rear end. During welding one finds, for example, that tensile axial stresses are built up along the weld line on the outer surface.

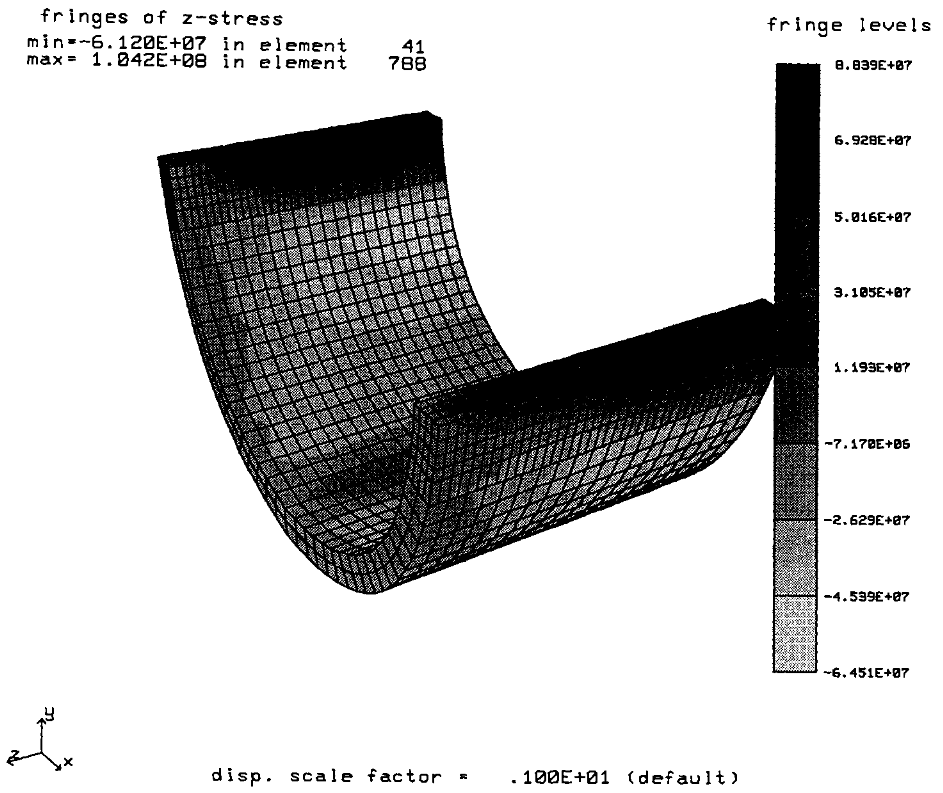

Figure 3. Calculated residual axial stress field (Pa) in copper cylinder after longitudinal welding

The residual axial stress field in the cylinder after completed longitudinal welding is shown in Fig. 3. The corresponding through the thickness variation of the residual axial and hoop stress at the weld line 300 mm from the rear end of the cylinder after the tack weld and after the full current weld is shown in Fig. 4. It is seen that tensile residual axial stresses are calculated through the thickness at the weld lines. These tensile axial stressses are balanced by compressive axial stressses at other circumferential locations.

The residual stress fields shown in Figs. 3 and 4 can be compared with experimental results for a copper cylinder having the same geometry but where minor changes in the welding procedure were made (Legatt, 1994). Residual stresses were measured on the cylinder inner and outer surfaces by use of the centre hole rosette gauge method. One finds quantitatively the same residual stresses at the weld line although the measured hoop stresses at the inner surface is lower (average value -80 MPa) as compared to the calculated value -20 MPa in Fig. 4. The calculated circumferential variation of the axial stress with high tensile values (peak values of roughly 100 MPa) at the weld line balanced by lower values at other circumferential positions is also observed in the experiments. The calculated maximum effective plastic strain in the copper cylinder is found to increase only marginally after the longitudinal welding. Hence a maximum value of some 6-10 % plastic strain is foreseen, which is considerably lower than the ductility for the copper alloy.

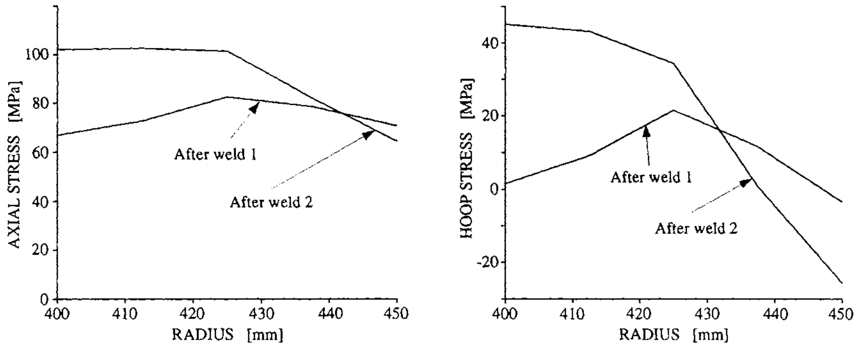

Figure 4. Calculated through the thickness variation of residual axial and hoop stresses at weld line 300 mm from rear end of copper cylinder after tack weld and after full current weld .

Prior to the final circumferential butt welding of the copper end to the copper cylinder it is proposed to perform a stress relief annealing operation, preferrably at 400 C. This operation has not been modelled in the present investigation. Based on experimental relaxation results for the present copper alloy one may anticipate that a furnace stress relief annealing (with the copper cylinder not being subject to mechanical restraints) will reduce the peak stress values to about 20 % of the welding residual stress values.

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