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THERMO-MECHANICAL FE-ANALYSIS OF BUTT-WELDING OF A Cu-Fe CANISTER FOR SPENT NUCLEAR FUEL

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ABSTRACT

The transient and residual stress and plastic strain field present during electron beam welding of a plane copper end to a canister for spent nuclear fuel is calculated by use of FEM. The canister consists of two concentric cylinders, an inner steel cylinder, containing the waste, and an outer copper cylinder. It is desireable to have a large gap between the two cylinders to ensure a proper assembly. For the case of a large gap, no contact between the cylinders is found and sufficiently low residual stresses and plastic strains are calculated.

INTRODUCTION

The highly radioactive spent nuclear fuel produced in Swedish nuclear power reactors shall be placed in an underground storage. Canisters containing the waste will be placed in vertical holes in the floor of horizontal tunnels located in granite rock several hundred meters below earth's surface. Each cylinder will be surrounded by a 40 cm thick clay barrier which is supposed to reduce the outward flow of radioactive particles from a possibly leaking corroded canister.

The canister proposed consists of two concentric cylinders, an inner steel cylinder containing the spent nuclear fuel, and an outer copper cylinder. The canister has the total length 4850 mm and the outer diameter 880 mm. The wall thickness of each of the two cylinders is 50 mm. After placing the steel cylinder inside the copper cylinder, the canister is sealed by butt-welding a copper end to the copper cylinder by use of Electron Beam Welding (EBW) employing one weld pass only. To ensure full penetration of a weld through the thickness of the copper cylinder a 50 mm thick backing ring made of copper is placed inside the copper cylinder. Half the distance of this backing ring is penetrated by the electron beam. Figure 1 shows the geometry of the canister and a blow-up of the weld geometry.

In the present investigation the transient and residual temperature, stress and strain fields present in the canister during welding and after cooling to ambient temperature are calculated numerically by use of the commercial FE-codes TOPAZ2D [1] and NIKE2D [2]. Two values for the gap distance between the outer and inner cylinder are considered here, 0.2 mm and 2.0 mm. Note that these gaps are measured for a heated inner cylinder, hence the gap distances will change when the copper cylinder is heated and thereafter cooled during the welding.

FE-MODEL

For the present dimensions of the canister, Fig. 1, it is estimated that it is sufficient to study 1 m of the canister in the axial direction. A cross sectional area of this part of the canister is divided into 1250 bilinear 4-node elements assuming rotational symmetry, see [3] for details. Although the transient stress field present in a butt welded pipe is strongly non-rotationally symmetric, the residual stress is often found to be reasonably rotationally symmetric [4,5].

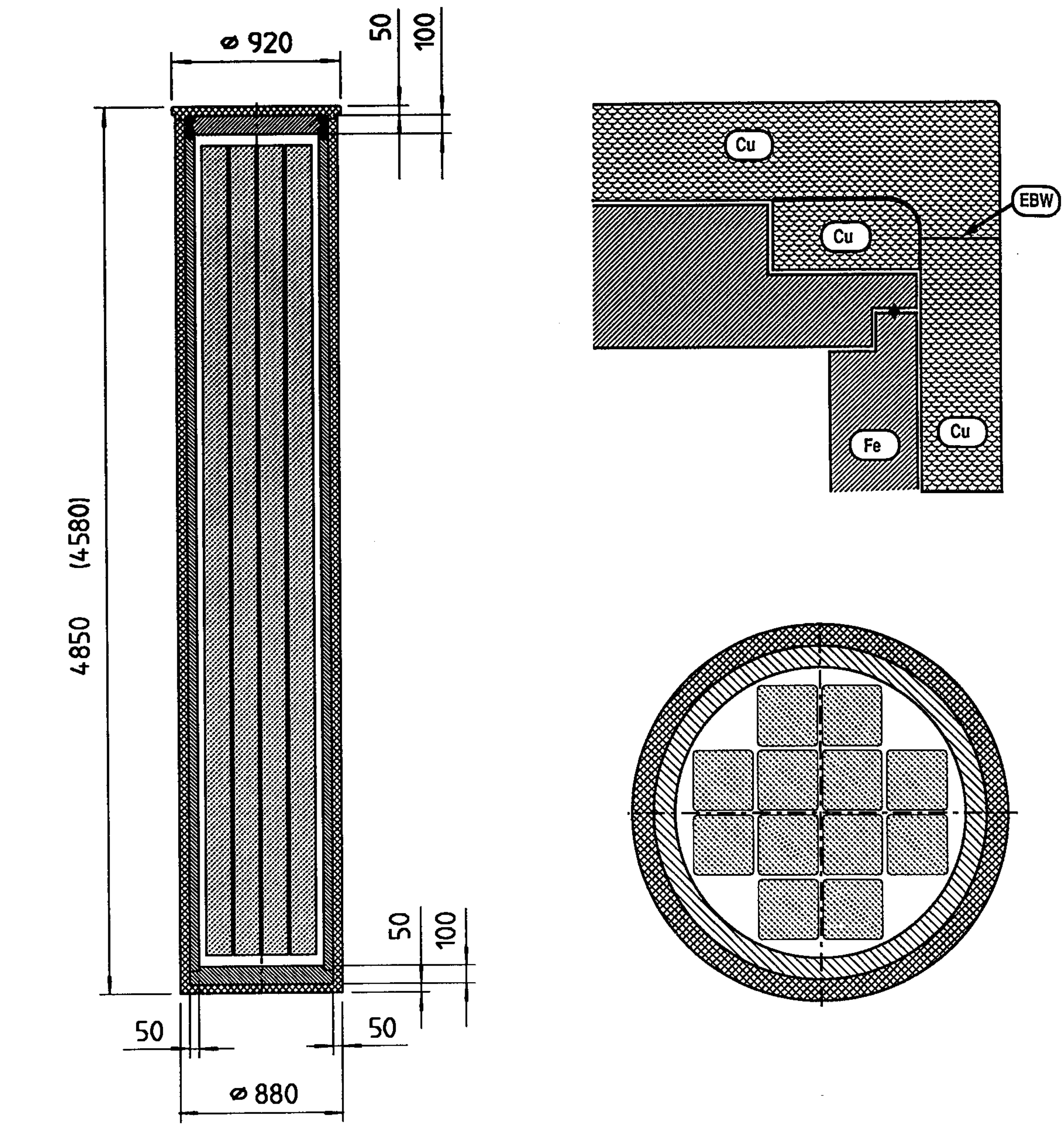

Fig 1 Geometry of canister. Upper right part shows blow-up of weld region. Dimensions in mm.

The welding speed is normally high in electron beam welding, but the high thermal conductivity in copper will lead to a high heat flux also in the direction parallel to the heat source. This will reduce the validity of the assumption of rotational symmetry. However, the main reasons for adopting a rotationally symmetric FE-model in the present study are to reduce (considerably) the size of the model and to limit the CPU-time needed. The same FE-mesh has been used for both the thermal and mechanical analyses. In each element the temperature is taken as constant, that is the average temperature value from the four corner nodes is assigned to the center of the element, to give the same spatial variation for the mechanical and thermal strains. To model contact conditions, slidelines have been applied between the inner steel cylinder and the outer copper cylinder and between the inner steel end and the outer copper end.

FE-CALCULATIONS

Preliminaries The coupling between the thermal and mechanical field through the strain rate term in the thermal analysis (heat conduction equation) is considered as very weak for welding problems, it has therefore been neglected here. The mechanical field is then coupled to the temperature field through the temperature dependent constitutive parameters, the thermal strain and the contact resistance (gap) discussed below.

Dividing the analysis in two parts, the temperature field due to the heat input is first calculated and secondly the mechanical analysis is performed with the previuosly calculated history of the temperature field as load. The possible contact between the inner steel and outer copper cylinder will also, formally, couple the thermal and mechanical analysis. The gap between the cylinders, which may be zero at some points, is calculated in the mechanical analysis. However, it also enters in the thermal analysis as a part of the contact resistance between the two cylinders. This coupling is here accounted for only approximately. Thus, the contact resistance in the thermal analysis is taken as constant in time and the zones in contact were estimated from initial mechanical calculations. Note also that the theory for large strains available in NIKE2D [2] is employed.

Thermal analysis The inner steel cylinder was assumed to have a constant temperature of 180°C and the outer copper cylinder and the copper end were at room temperature, 20°C, when the heat input was applied. In the calculations the heat was applied in a small volume at the interface between the copper end and the upper end of the copper cylinder, see Fig. 1. The net line energy input was 24 MJ/m and the corresponding welding speed was 100 mm/min. The strength of the heat input was constant across the thickness of the cylinder and backing ring. The convection and radiation between the outer surface of the steel cylinder and the inner surface of the copper cylinder is modelled with a thermal contact resistance. Hence, the heat transmission coefficient h is obtained from:

$$\frac{1}{h}=\frac{1}{h_0}+\frac{d}{k_g} \tag{1}$$

Here $1/h_0$ is a small contact resistance representing non-perfect contact, k_g the thermal conductivity of the gas in the gap and d is the gap. The values chosen in the analyses were k_g= 0.10 W/m°C and h_0= 1000 W/m^2°C. Perfect contact was assumed between the copper cylinder and the upper and right boundary surfaces of the backing ring. For the small gap, 0.2 mm, initial calculations revealed that the inner vertical surface of the backing ring will come in contact with the steel cylinder during the welding. This surface remained in contact during the cooling phase. Contact was also detected at the lower horizontal surface of the backing ring. To simulate the contact at the inner vertical and lower horizontal surfaces the distance $d = 0$ in Eqn (1) for these surfaces of the backing ring.

Material data The steel material is an ordinary C-Mn steel which is taken as thermo-elastic. The copper material is an OFHC alloy which is assumed to be thermo-elasto plastic. Isotropic linear hardening and an associated flow rule is adopted. The temperature variation of thermal properties for the ordinary steel and for the copper alloy used is supplied by the manufacturer or obtained from handbooks in Physics. Figure 2 shows the temperature variation of the Young's modulus, yield stress and hardening modulus respectively for the copper alloy used here.

Parts of the material located in the HAZ will accumulate compressive plastic strains as it is rapidly heated when the heat source is applied. For Gaussian points in this region that melts, plastic strains accumulated before (and during) melting are defined as inelastic strains and they are not used for the calculation of hardening during the subsequent cooling phase. With this approach, hardening in one phase does not depend on plastic deformation experienced in a previous phase.

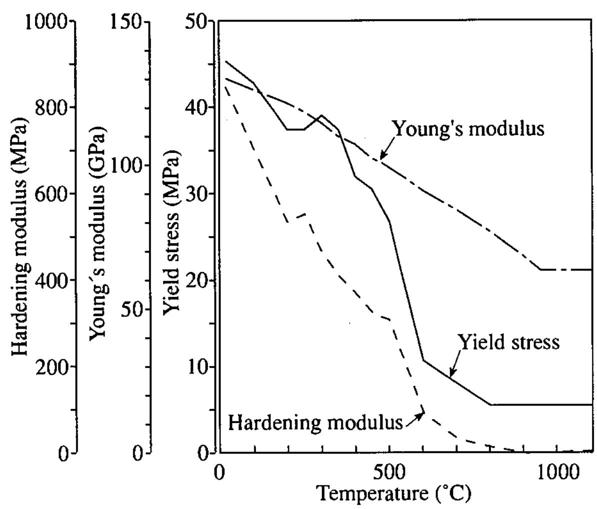

Fig 2 Temperature variation of mechanical material parameters for copper alloy.

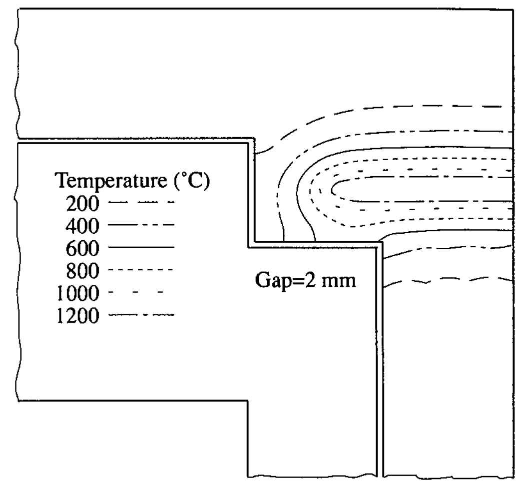

Fig 3 Calculated isotherms during early stage of cooling. Figure is valid for large gap.

CALCULATED RESULTS

Thermal results The gap distance will have a small influence on the temperature field during the early stages of cooling. Figure 3 shows calculated isotherms in the weld region when the maximum temperature is roughly 1400 °C. It is clearly seen that the gap isolates the steel cylinder from the copper cylinder even if there will be contact at the backing ring for small gap distances. During this initial part of the cooling the width of the gap does not influence the temperature field. This is due to the very narrow weld zone. The corresponding highest temperature calculated for the steel canister was 240 °C.

Mechanical results When the welding is completed material in the weld region cools rapidly and contracts, at the same time the temperature in the surrounding material is slowly increasing. ***For a large gap, that is 2.0 mm,*** there will be no contact between the copper and steel cylinders (except initially in some few points). Thus, the copper cylinder will act as a butt welded pipe. The stiff copper end (and upper part of cylinder with backing ring) will restrict the cross sectional rotation and radial decrease during cooling of the weld region of the copper canister. This creates a bending moment that is the resultant of tensile axial stresses at the inner surface and compressive axial stresses at the outer surface of the copper canister.

Figures 4 a,b show isolines for the welding residual axial and hoop stresses in the copper cylinder. The axial stress distribution typical for a butt welded pipe (where a large heat input over wall thickness has been employed) is clearly displayed. It is more difficult to predict the shape and magnitude of the residual hoop stress. However, as seen in Fig. 4b, the stress concentration at the lower right corner of the backing ring seems to increase the hoop stresses as compared to the butt welded pipe case. For ***the small gap, 0.2 mm***, the axial stresses are controlled by the contacts giving large tensile values near the inner surface of the backing ring that are balanced by low stresses in the weld region. Isolines for the welding residual axial and hoop stresses for the small gap are shown in Figs. 5 a,b. The contact surfaces at the backing ring are also clearly displayed in Figs. 5 a,b.

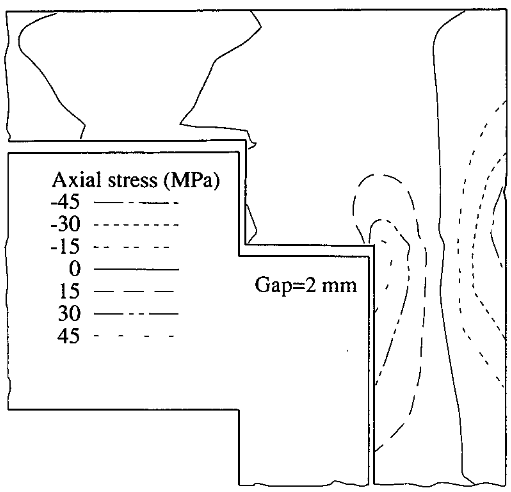

Fig 4a Calculated isolines for welding residual axial stresses for the large gap 2.0 mm.

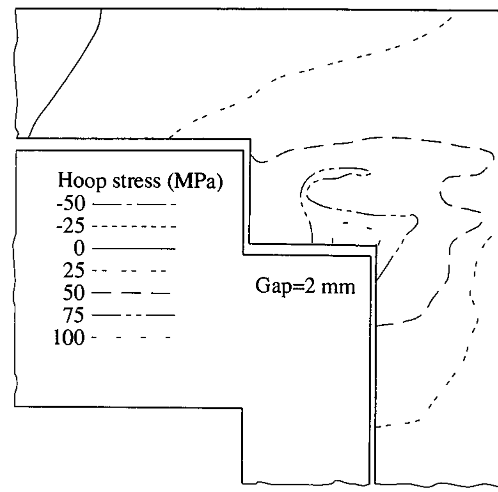

Fig 4b Calculated isolines for welding residual hoop stresses for the large gap 2.0 mm.

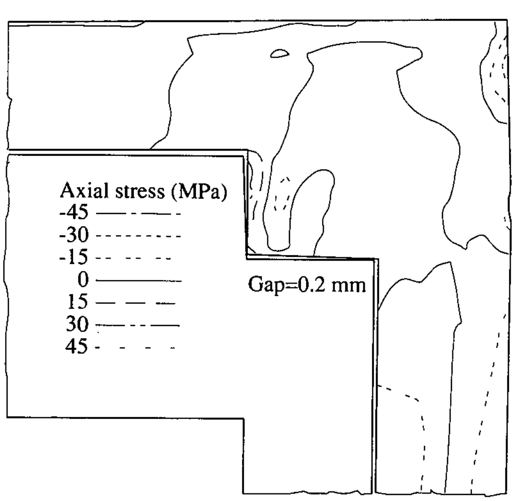

Fig 5a Calculated isolines for welding residual axial stresses for the small gap 0.2 mm.

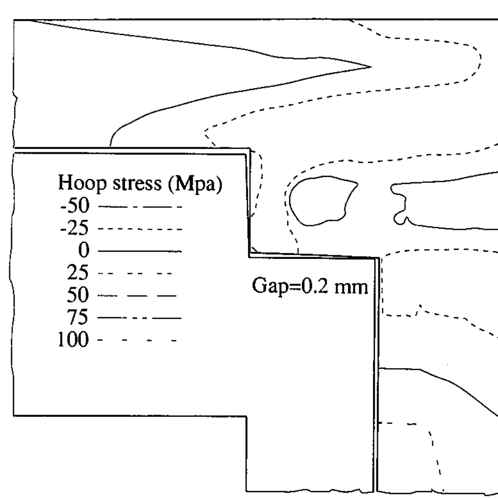

Fig 5b Calculated isolines for welding residual hoop stresses for the small gap 0.2 mm.

The residual stresses in the steel cylinder were found to have roughly the same maximum values as in the copper canister. However, with the higher value for the yield stress in the steel used, σ_Y = 300 MPa, the assumption of elastic conditions in the steel cylinder seems to be justified.

An entity of special interest in the copper cylinder is the accumulated plastic strain. High values for this entity would indicate an increased risk for creep fracture. One finds that plastic strains are concentrated to the stress concentration at the lower right corner of the backing ring and to the HAZ close to the weld. The maximum values are calculated in the backing ring for both gaps and they are 13% and 5% for 2.0 mm and 0.2 mm gap respectively. In the HAZ the maximum value was found to be 5 % for both gaps. Considering the rough geometrical modelling of the stress concentrations at the backing ring one may conclude that the accumulated plastic strains seem to be acceptably low. Note that these plastic strain values do not include plastic strains accumulated prior to and during melting. This means that plastic strains in the weld zone are lower than in the HAZ.

DISCUSSION

The calculations presented here are peformed for a proposed canister configuration only. Welding parameters used in the present calculations were supplied to us as estimates based on a limited number of pilot EBW experiments on a 100 mm thick short copper cylinder that was made at the Welding Institute (TWI), see [6]. The aim with that investigation was to see if electron beam welding was a feasible welding process. Low residual strains were measured in the copper cylinder after the welding.

The knowledge of the material behaviour is also still insufficient. For example, creep relaxation experiments performed at 100 °C on the copper alloy proposed indicate that almost all relaxation takes place in a short time period after initial loading. One might therefore expect some stress redistribution due to creep deformation in the copper to take place already during coooling after welding, see [7]. A further stress redistribution will also take place when the welded canisters are awaiting final underground deposition, see [7].

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