Failure of closure lid welds for the nuclear materials waste packages

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The long-term structural integrity of waste packages is required to assure the safe storage of spent nuclear fuel and high level waste. Due to the potential for high residual stresses caused by welding and the possibility of water contacting of the outer weld surfaces, stress corrosion cracking could occur. Consequently, the magnitude and through wall distribution of weld residual stress in the final un-annealed closure welds is an important factor to be considered in this work. The proposed waste-package design comprises concentric inner and outer cylindrical shells, each with a closure lid welded to its respective shell. The inner and outer shells are fabricated from AISI Type 316 Stainless Steel and Nickel Base Alloy 276 (ASTM B-575) respectively and expected to be assembled using a thermally enhanced fit-up process. The finite element method is used to evaluate the effect of a shrink fit, the proximity of the two welds, and the residual stress distribution due to the weld configuration. The results reflected that heat treatment should be done to eliminate the tensile residual stresses on the closure lid outside surface to reduce the possibility of crack generation possibilities such as stress corrosion cracking Results of this study can be used to optimize the design of the waste package and associated welds and increase their long-term reliability by minimizing the potential for material failures including stress corrosion cracking.

أن السلامه الهيكلية الطويلة المدى لمستودعات النفايات النووية شديدة الأهمية وذلك للخزن الآمن للوقود النووى المستهلك والنفايات النووية ذات المستويات الأشعاعية العالية. يتضمن هذا العمل إقتراح تصميمى خاص بأحد هذه المستودعات وهو مكون من وعائان أسطوانيان متداخلان عن طريق تسخين الوعاء الخارجي ليسمح بالتمدد ثم يضغط على الوعاء الداخلى لينزلق فى مكانه . (Thermal Fit-Up Process) الوعاء الداخلى مصنوع من سبيكة الصلب ٣١٦ (AISI – 316) والخارجى من سبيكة النيكل (ASTM B-575) . بعد وضع النفايات بالداخل يتم لحام الغطاء الخارجي لإحكام الأغلاق ولكن بسبب وجود إجهاد عالى متراكم من عمليات التصنيع المختلفة وكذا من اللحام (Residual Stress) وأمكانية تعرض الاجزاء الخارجية الملحوم للرطوبة والماء مما يتكون معه اجاد تآكل قد يؤدى إلى تصدع فى الاجزاء الملحومة من الغطاء وخروج المواد المشعة من المستوع . وتعتبر حسابات الأجهاد المنتقى من الموضوعات ذات الصعوبة وذلك للآتى:الطبيعة اللاخطية للمشكلة، إعتماد خواص المعادن على الحرارة أثناء وبعد اللحام، التغير السريع فى درجة الحرارة متضمنة التغير فى الطور الخاص بالسبائك. وقد استخدمت الطرق التحليلية ثنائية الأبعاد (Axi-symmetric) لدراسة السلوك الدن للمواد فى درجات الحرارة العالية وذلك لحساب الأجهاد المتراكم لتحديد مدى أمكانية تكون صدوع فى اللحام واستخلص البحث ضرورة تعريض المستودع بعد التصنيع لعملية معالجة حرارية للتخلص من الجهادات الزائدة ويمكن أستخدام نتائج هذا البحث لتحسين تصميم مستودعات النفايات النووية.

Keywords: Nuclear waste package, Residual stress, Welding, Finite element method

1. Introduction

This work presents an evaluation of the residual stress for the closure welds of a waste-package design proposed for the long-term storage of spent nuclear fuel. The determination of weld residual stress is inherently complicated due to the highly non-linear nature of the problem generated from:

1. Rapid temperature change, including micro-structural and phase changes, in and near, the weld.
2. Temperature-dependent material properties.
3. Stress reversals during unloading.

The problem involves the non-linear, elastic-plastic behavior of materials at high temperatures. Although predicting weld residual stress is complicated, the use of a simplified two-dimensional axisymmetric analyses approaches provide a conservative estimate of the weld residual stress and a good representation of the maximum tensile stress.

2. Waste package proposed design

The waste-package proposed design consists of an inner shell and an outer shell, as shown in fig. 1. The inner shell is Type 316 N stainless steel with an outside diameter of 1400 mm and a wall thickness of 50 mm. The outer shell is made from Nickel Base Alloy 276 (ASTM B-575) material with an outside diameter of 1540 mm and a wall thickness of 20 mm. The inner lid is 80 mm thick and the outer lid is 25 mm thick. The inner and outer shells are thermally shrunk fit together with maximum shrink fit stress not to exceed one third of material yield stress [1] .The material properties for both outer and inner shell are presented in table 1.

3. Weld residual stress analysis methodology

In recent years, considerable progress has been achieved in modeling the heat transfer in the weld pool [2-4]. An extensive 3-D finite difference analysis of fluid flow and heat transfer conditions in the case of Gas Tungstun Arc Welding (GTAW) or Gas Metal Arc Welding (GMAW) including the effect of moving heat source, the imposed magnetic field and surface tension effects have been studied [5-7]. In fact weld pool convection, which causes more heat transferred from the heat source to the weld root, plays an important role in the formation of the finger penetration geometry. Heat input of 5700 W of arc welding electrode with traveling speed of

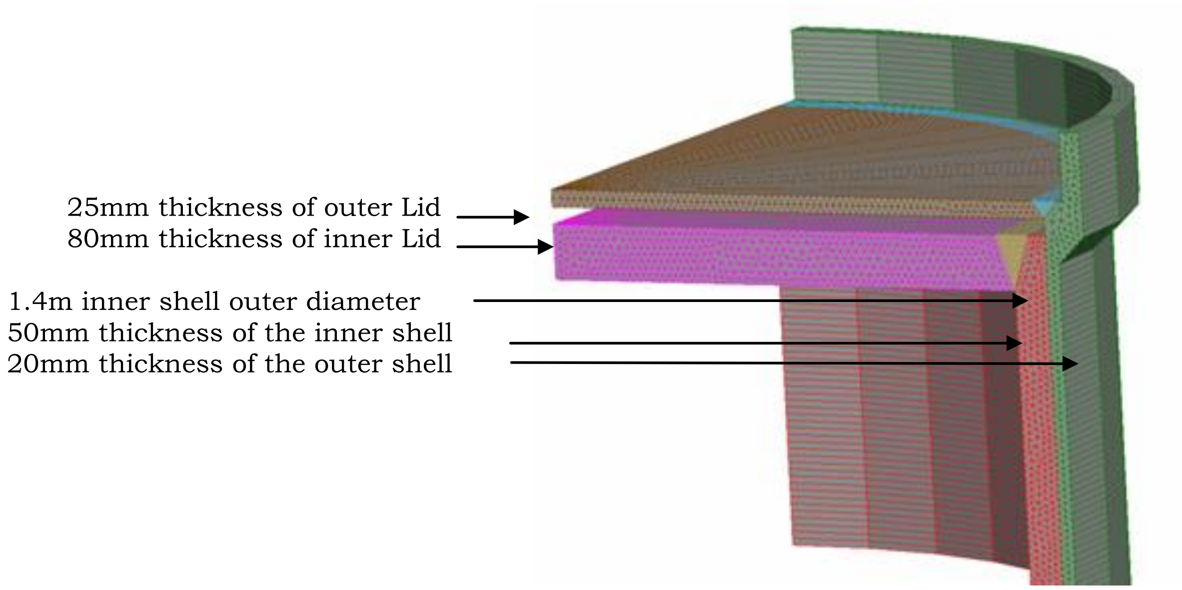

Fig.1. Waste package dimension and 3-D FE model.

Table 1
Mechanical and thermal properties of the used materials

Mechanical and thermal properties	AISI-type316	AL - 276
Density (Kg/m^3)	7.92 x10^3	8.9 x10^3
Yield Strength (N/m^2)	330x10^6	285x10^6
Modulus of Elasticity (N/m^2)	196x10^9	205x10^9
Thermal Conductivity (W/m.^{o}C)	16	10.2

10 mm/sec is assumed [4]. The surface temperature value of the pool is simply the liquidus value of the alloys used which is approximately about 1400 °C for both Ni-base and steel alloys. The governing equation describing the transient heat transfer mechanism could be represented over a volume *V* by the following integral equation [8] :

$$\int_V \left(\rho C \frac{\partial T}{\partial t} - \nabla.(K \nabla T) - Q \right) dV = 0 . \qquad (1)$$

Where K, T, ρ, C_P , t and Q are the conduction heat transfer coeficient, temperature, density, specific heat, time and volumetric heat generation per unit time respectively. As long as the welding process is accompained by a change of material phase, the heat transfer parameters used in the calculations are functions of temperature as shown in fig. 2 [4]. This situation leads to the rise of nonlinear system of equations associated with complexity in the solution so that iterative technique must be used.

Analysis of the weld residual stress involves two key steps:

- Determining the temperature response due to the application of the weld beads and performing the elastic-plastic stress analyses. The application of the weld beads results in a rapid increase in temperature of the deposited weld bead and neighboring base metal. As the weld torch approaches, the temperature increases to that of the melting temperature of the weld material. Once the weld torch passes, the heat source decreases and the weld bead cools due to convection and conduction. The thermal analysis of the weld bead application is important to obtain an appropriate time-dependent description of the temperature response through the entire thermal transient.
- Once the thermal history is known for the welding process, the elastic-plastic stress analysis is performed. The stress analysis comprises a series of analyses using the thermal history of the weld.

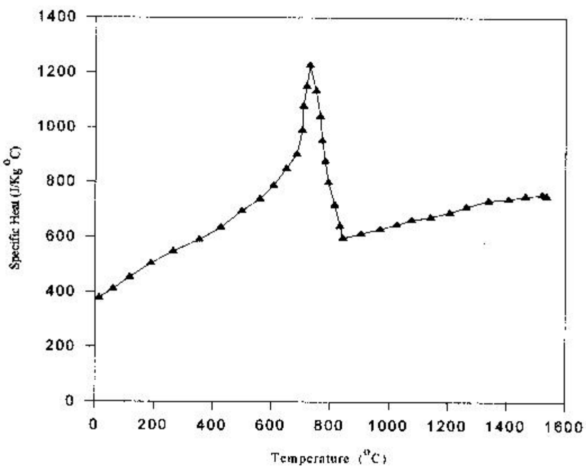

Fig. 2. Temperature - specific heat material curve used in the calculation.

Although the determination of weld residual stress is a three dimensional problem, it has been found that simplifications of this complex process still reasonably estimates on the residual stress in the weld [9-10]. These simplifications include modeling point source as a line heat source to reduce a three dimensional problem to a more simple two-dimensional axisymmetric problem.

In actual practice, the weld is applied in a series of sequentially ordered weld beads. The application of every individual weld bead becomes cumbersome if there are several weld beads. However, studies have demonstrated that grouping weld beads to form larger passes or grouping into layers are in reasonably good agreement with the resulting residual stress behavior [1].

3.1. Finite element model

The FE package COSMOS/M version 2.6 [11] is used in the analysis.The finite-element model used for thermal and residual stress calculations is shown in fig. 3.. To simulate the stresses due to thermal shrink fit, the two cylinders are modeled separately, each based on its unstressed geometry, using triangle axisymmetric elements. The interface is modeled with contact (Gap) elements. Nodes are selected on the outer boundary of the inner cylinder, while a line is used to define the inner surface of the outer cylinder. A one step solution is performed; no external forces are defined. Friction effect is taken into consideration through friction coefficient of 0.7 (steel on steel clean surfaces) [11]. The radial interference was 0.45 mm. This interfer

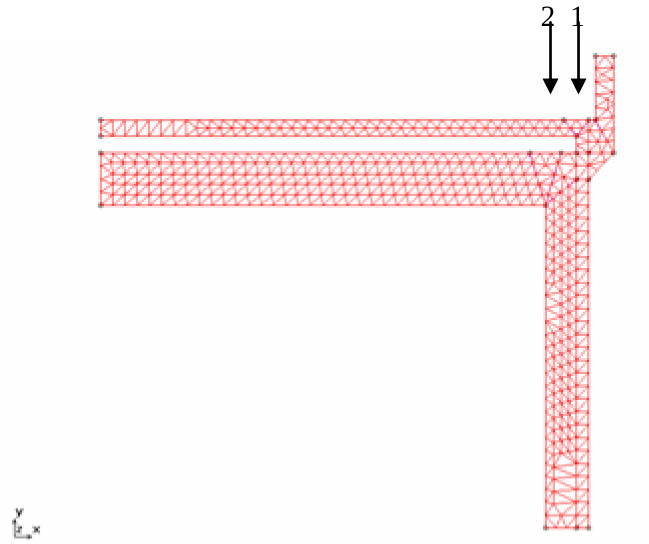

Fig. 3. Finite Element model for heat transfer and residual stress calculations.

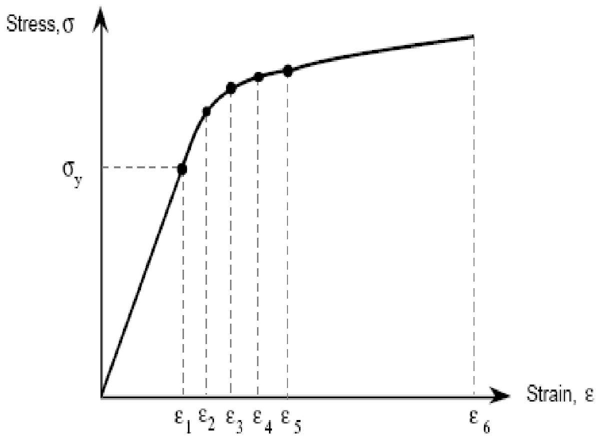

Fig. 4. A multi-linear uniaxial stress-strain curve for plasticity calculation (σ, σ_y, and ε are the stress, yield stress and strain respectively).

ence fit stress was analyzed without the closure lids. Symmetric boundary conditions were applied at the centerline and at the bottom of the model. The stress-strain behavior was modeled as isotropic hardning .The elastic-plastic material deformation mechanism will be represented by the flow rule for isotropic hardning [12] as,

$$d\varepsilon_{ij}^{plastic} = 1.5 \frac{d\sigma_e}{H} \frac{S_{ii}}{\sigma_e} \quad (i = 1,2,3) . \qquad (2)$$

Where

$\sigma_e = \sqrt{1.5 \sum S_{ij} S_{ij}}$ and

$S_{ij} = \sigma_{ij} - (\sigma_{11} + \sigma_{22} + \sigma_{33}).\frac{\delta_{ij}}{3} \, d\varepsilon^{plastic}$ is the incremental plastic strain tensor,

S_{ij} is the stress deviator tensor,
δ_{ij} is the kroncker delta function,
H is the strain hardening parameter, and
σ_e is the effective stress.

Step by step load increment application strategy is used in the numerical solution . The A multi-linear uniaxial stress-strain curve discribing elastic-plastic behavior is shown in fig. 4. The weld heat input is activated for a time intervals each is two seconds (one second for ramp up and one second for ramp down). The heat input is modeled as element heat generation rate. The time between weld pass is assumed to be the time for the weld torch to travel the length of the closure weld. After the inner closure weld is finished, the elements for the outer lid are activated. The same analysis procedures are repeated for the outer closure weld. During thermal analyses, all surfaces are considered insulated. The final residual stress distributions are calculated at temperature of 100 °C which is the expected maximum internal temperature of the waste package.

4. Results

The stress generated due to the shrink fit thermal process is shown in fig. 5 for the radial one and in fig. 6 for the hoop stress.The results agreed very well with the criterion of not exceeding one-third of the material yield stress. Two sections were selected for stress results presentation, in the outer lid closure weld . The sections, were marked 1 and 2 in fig. 3. fig. 7 and fig. 8 displays the hoop and axial residual stress generated in the sections 1 and 2 in the welding heat affected zone(HAZ) area through the outer lid thickness starting from inside to outside respectively.

The analysis showed that the location '1' on the HAZ biased to the outer shell has higher tensile resuidal stress than location '2', which is away from the inner shell. The difference between the tensile stress level in both locations is minimum near the surface and maximum near half of the thickness. The axial stress is compressive on position '2' and tensile type on position '1' near the outer shell. The tensile stress level on position '1' reduces gradually by moving to the outer surface to reach its minimum value on the surface.

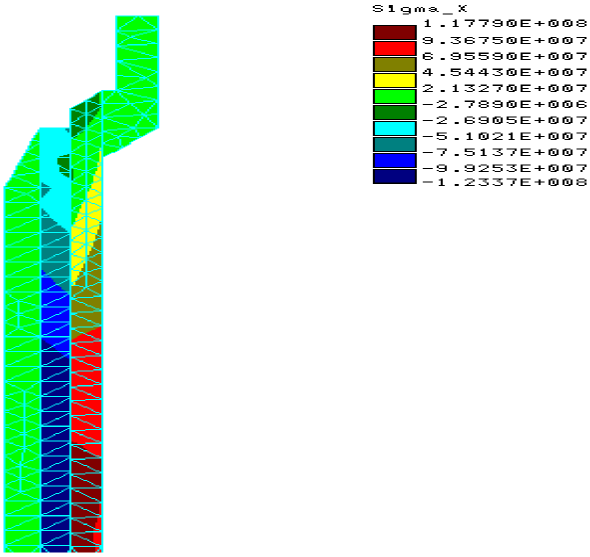

Fig. 5. Radial stress distribution due to thermal shrink fit including the effect of friction.

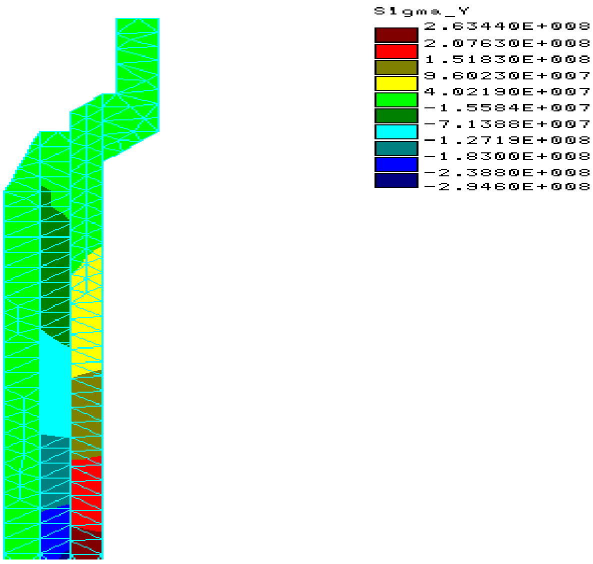

Fig. 6. Hoop stress distribution due to thermal shrink fit including the effect of friction.

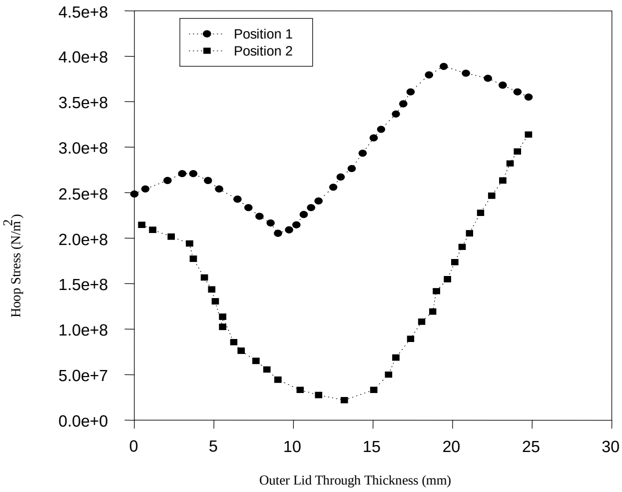

Fig. 7. Hoop residual stress generated in sections 1 and 2 around the welding Heat Affected Zone (HAZ) starting from inside to outside.

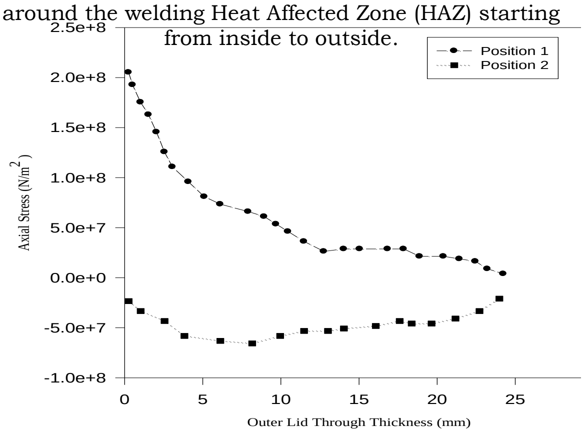

Fig. 8. Axial residual stress generated in sections 1 and 2 around the welding Heat Affected Zone (HAZ) starting from inside to outside.

5. Conclusions

Nonlinear finite element method have been used to evaluate the waste package closure welds regarding to resuidal stresses generated because of the assembling and welding process. The inner lid closure weld has a lower residual stress distribution than the outer lid closure weld. The thicker inner lid is partly responsible for the lower residual stress, in addition to the benefit of compressive shrink fit stress in the inner shell. The outer lid welds have significant tensile radial and hoop stresses at the outside surface. Heat treatment should be done to eliminate the tensile residual stresses on the closure lid outside surface to reduce the possibility of crack generation causes such as stress corrosion cracking. A proposal of coating the outer surface with Aluminum layer for corrosion protection should be evaluated. Further work regarding to fracture mechanics including possible crack propagation is needed.

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