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Numerical Investigation of Welding Residual Stress Field and its Behaviour under Multiaxial Loading in Tubular Joints

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Abstract

The lack of clarities in estimating the residual stress threat to the structural integrity has led to conservative assumptions in the current design of welds. The complexities become more in the case of multiaxial loading of welded structure, considering fracture or fatigue. To what extent the residual stresses influence the performance of a welded structure, depends on how stable they are under service loads. Finite element analyses are used here to describe the development of welding residual stresses in tubular joints and their relaxation under multiaxial loading.

It is observed that the effect of the torsion load is more significant than the effect of tension load in releasing of the residual stresses. For pure tensile loading, the relaxation of the residual stresses are negligible as long as the applied load is lower than 50% of the yield strength of the material. For a combined tension-torsion loading of 75% of the yield strength, the residual stresses are almost completely released, and in the weld zone they become compressive.

Introduction

The lack of clarities in estimating the residual stress threat to the structural integrity has led to conservative assumptions in the current fatigue design of welds. In design books [1, 2] and codes [3, 4] the welding residual stresses at the fatigue crack imitation sites are assumed to be of yield strength magnitude. It is also assumed that in general the influences of residual stress and mean stress on fatigue are equal and the distinct differences between these two concerning source, distribution and relaxation under load is not considered. Based on these assumptions a mean stress independency of the fatigue strength is postulated i.e. regardless of the stress ratio, it is recommended to use the S-N curves which are evaluated under pulsating tension loading. The complexities concerning the residual stress influence manifest themselves even more in the case of multiaxial fatigue in which the majority of welded components e.g. power generation and transmission, aircraft and marine engines suffer fatigue failure. In multiaxial fatigue investigations of welds by Siljander [5], Sonsino [6], Maddox [7], it has been almost always avoided to consider the effect of residual stresses by using stress relieved specimens and components in order not to be disturbed by their influence on fatigue. Thus the experimentally determined residual stresses in tubular welds are scarce and not as wide spread as those of the flat welds. A deeper insight into the source and nature of residual stresses in tubular welds based on experimental and numerical works is the first step towards better understanding their threat to the structural safety.

The behavior of the residual stress field under multiaxial loading was studied previously in an experimental work [8]. In this work, the development of welding residual stresses in a tubular joint is studied by using finite element method. The relaxation of the residual stresses due to external loads of type pure tension and combined tension and torsion is investigated numerically.

FEM analysis of welding residual stress

Numerical simulation of residual stresses and distortions due to welding needs to accurately consider the interactions between heat transfer, metallurgical transformations and local temperature dependent mechanical properties. In this study the tubular weld joint is made of S355J2H steel, and its welding is simulated by using finite element method. For this material, the stress-strain curve is extracted from the result of tensile test given in Ref. [8], and for higher temperatures, the stress-strain curves are approximated using a simple approach mentioned in [9]. The stress-strain curves developed in this way are presented in Fig. 1.

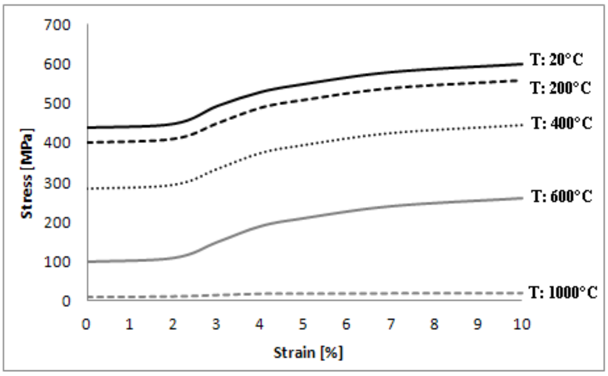


Figure 1: Plastic stress-strain curves of S355J2H evaluated at different temperatures, [8, 9].

For the simulation of the welding and determination of welding residual stresses, the finite element modelling of the welding includes the heat input and the temperature-dependent material properties. Thermal and mechanical analyses are coupled to each other. During heating, the geometry is shifted relatively from its original position. Thus, the final temperature field of the body can be affected by this phenomenon. By neglecting this effect, thermal and mechanical analysis can be treated separately in an uncoupled analysis. The solution of the temperature field is used as the inputs required for mechanical analysis. The thermal and mechanical analyses of the weld to determine the welding residual stresses are briefly described below.

Thermal analysis

The heat transfer in the materials is governed through the following equations:

$$\rho \frac{dH}{dt} - \mathrm{div}\left(\lambda \,\mathrm{grad}\, T\right) - Q = 0, \tag{1}$$

$$\lambda \,\mathrm{grad}\, T_n = q\left(T,t\right) \quad \text{on} \quad \delta\,\Omega_q, \tag{2}$$

$$T = T_p\left(t\right) \quad \text{on} \quad \delta\,\Omega_q. \tag{3}$$

Where ρ is density, H is enthalpy, t is time, λ is thermal conductivity, T is current material temperature, n is outward normal vector of domain $\delta\Omega$, Tp is prescribed temperature, Q is input energy and q is heat flux density. The parameter q depends on time and temperature to consider heat loss due to convection and emission from the surfaces. This parameter is governed by Equation (4).

$$q = h_{con}\left(T - T_a\right) + \varepsilon_{em}\sigma_{bol}\left(T^4 - T_a^{\ 4}\right) \tag{4}$$

Where T_a is temperature of the surrounding, h_{con} is surface convection film coefficient, ε_{em} is materials emissivity coefficient and σ_{bol} is the Stephan-Boltzmann constant.

Radiation is dominant for higher temperatures, while convection accounts for the majority of heat loss in lower temperatures.

Mechanical analysis

Elastic-plastic mechanical analysis is assessed according to static equilibrium and constitutive equations as follow:

$$\sigma_{ij,j} + \rho b_i = 0 \quad (5)$$

$$\sigma_{ij} = \sigma_{ji} \quad (6)$$

Where σ_{ij} is the stress tensor and b_i is the body force. According to Equation (6), it is assumed that the stress tensor is symmetrical. In constitutive equations, the thermal elasto-plastic material model is considered based on the von Misses yield criterion and the isotropic strain hardening rule. Stress strain relations are expressed as follow:

$$[d\sigma] = [D^{ep}][d\varepsilon] - [C^{th}]dT \quad (8)$$

$$[D^{ep}] = [D^{e}] + [D^{p}] \quad (9)$$

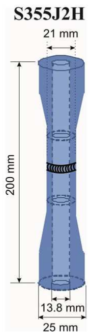
Where $[D^e]$ is the elastic stiffness matrix, $[D^p]$ is the plastic stiffness matrix, $[C^{th}]$ is the thermal stiffness matrix, $d\sigma$ is the stress increment, $d\varepsilon$ is the strain increment and dT is the temperature increment.

Welding simulation

The thermo-mechanical modeling was conducted using ABAQUS software. The body under study is a tubular body with external diameter of 21 mm and length of 200 mm and a thickness of 3.6 mm (figure 2). After modeling of the body in finite element software, the mesh sensitivity analysis was performed to obtain a suitable mesh for the analyses. The 3D solid model consists of 21720 eight-noded brick elements. Fig. 2 shows the mesh used for modeling of the tubular body. The elements used to model the butt weld section are also shown in Fig. 2. The body is constrained in one end and free in the other end.

The problem is formulated as an uncoupled thermal mechanical analysis. First, a non-linear thermal analysis is performed. Then the temperature history of the whole model is used as an input to the mechanical analysis. Both the thermal and mechanical models are the same except for the element types, which has temperature or displacement degree of freedom, respectively.

The deposited weld was modeled using the element birth and death technique. This method is based on deactivation of weld-line elements by assigning them a very low stiffness and specific heat and then reactivation of them sequentially during the welding process. The convection coefficient of steel in contact with free flow of air was set to 12 $W/m^{2o}K$ uniformly, with respect to time and temperature. The emissivity coefficient was considered as a constant value of 0.1. Fig. 3 shows the temperature distribution during welding of the tubular body.



Welding parameters	Value, Unit
Voltage	12 V
Current	130 A
Welding speed	30 cm/min

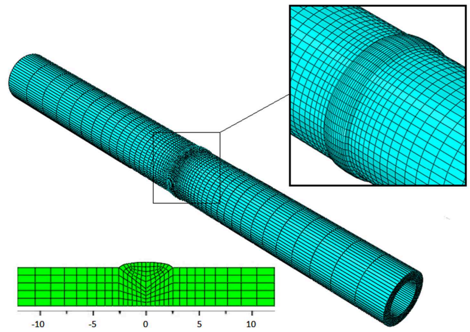


Figure 2: FEM mesh used in the analysis of the tubular body based on the geometry and welding parameters.

Figure 4 shows the axial and hoop residual stresses in the welded tubular joint on the inner and outer surfaces of the joint. The axial residual stress shows a w-profile with the maximum in the weld bead at zero level, being of tension type with a magnitude of 500 MPa at the inner surface and of compressive type with a magnitude of -430 at the outer surface. In the hoop direction, the distribution of residual stresses varies in the circumferential direction. For the position of 180 degrees from the weld start, the hoop stresses are of tension both on the inner surface and the outer surface, as shown in Figure 4.

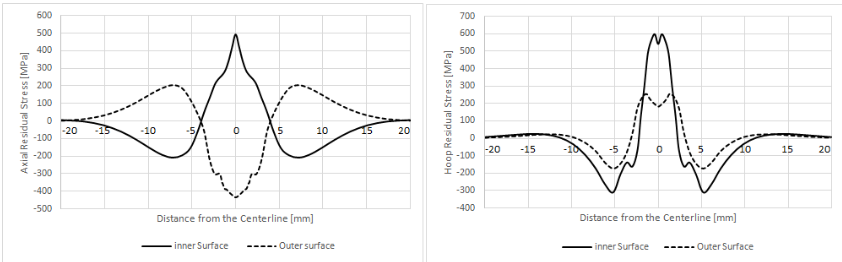


Figure 4: Residual stress profiles in the axial and hoop directions of the pipe.

Relaxation if the residual stresses under mechanical loading

After the calculation of the welding residual stress field, two relaxation studies were performed under pure tension and tension/torsion loading. The modelled sample was subjected first to monotonically increasing loads up to a specific value, and then it was unloaded completely. The redistribution of the residual stresses was determined after reloading.

Effects of the pure tension loading

The sample was numerically subjected to monotonically increasing tensile load of magnitude related to 25%, 50% and 75% of the yield strength of the base material. The load was applied at one end of the tube while the other end was constrained. After loading to the specified tensile load, the sample was unloaded completely and the redistribution of the residual stresses were calculated. Figure 5 shows the axial and hoop residual stresses in the inner surface of the joint after different loading levels. It is observed that the pure tensile loading has minor effects on the residual distribution as long as they are lower than 50% of the yield strength of the material. At a load level of 75% of the yield strength, the residual stresses are relaxed more pronounced as expected.

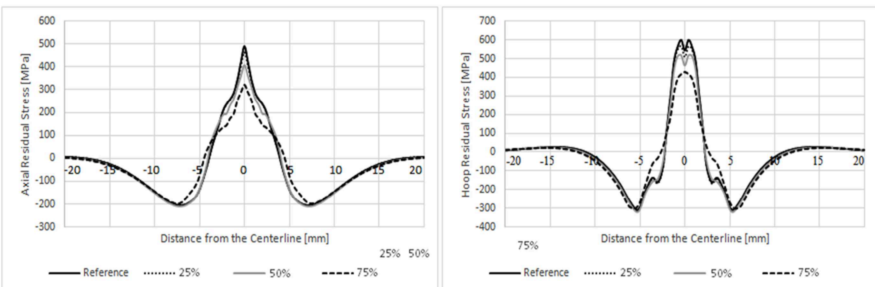


Figure 5: Residual stress relaxation in the axial and hoop directions under monotonic tension loading.

Effects of the combined tension-torsion loading

The sample is subjected to monotonically increasing tension-torsion of magnitude 25%, 50% and 75% of the yield strength of the base metal at the free end of the tube in the finite element modelling. The tensile and torsion loads are applied simultaneously. After loading to the specified tension-torsion load, the sample is unloaded completely and redistribution of the residual stresses is determined. Figure 6 shows the axial and hoop residual stresses in the inner surface of the joint after different loading levels.

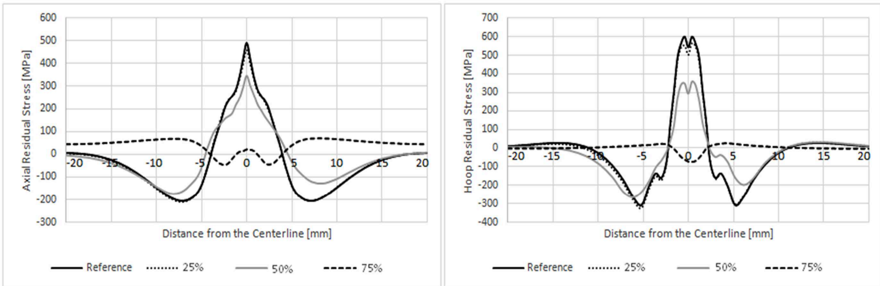


Figure 6: Residual stress relaxation in the axial and hoop directions under monotonic tension-torsion loading.

It is observed that the combined tension-torsion loading has significant effects on the residual stress distribution. At a load level of 50% of the yield strength of the material, the stress in the hoop direction is released to about half of their original values. At a load level of 75% of the yield strength, the residual stresses are almost completely released, and in the weld zone they become compressive. Comparing the results presented in Figures 5 and 6, it can be stated that the effect of the torsion load is more significant that the effect of tension load in releasing of the residual stresses. This is in good agreement with the conclusions given in Ref. [8].

CONCLUSIONS

Development of welding residual stresses in a tubular joint was studied by using finite element method. The relaxation of these stresses due to external loads of type pure tension and combined tension and torsion was investigated numerically. Based on this study, the following conclusions may be made:

- Residual stresses in the axial direction have a w-formed shape.
- Pure tensile loading has minor effects on the relaxation of the residual distribution as long as they are lower than 50% of the yield strength of the material. At a load level of 75% of the yield strength, the residual stresses are released more pronounced.
- Combined tension-torsion loading has significant effects on the residual distribution. At a load level of 75% of the yield strength, the residual stresses are almost completely released, and in the weld zone they become compressive. It is observed that the effect of the tension-torsion load is more significant than the effect of pure tension load in releasing of the residual stresses.

REFRENCES

[1] Radaj D., Ermüdungsfestigkeit, Fatigue Strength, Springer Verlag, 1995 (In German).

[2] Haibach E., Betriebsfestigkeit, Fatigue Strength in Service, 2.Aufl., Springer Verlag, 2002 (In German).

[3] Hobbacher A., Recommendations for Fatigue Design of Welded Joints and Components, IIW-Document, XIII-2151-07 / XV-1254-07, 2007.

[4] EN 1993-1-9 (Eurocode 3): Design of Steel Structures, Part 1.9: Fatigue strength of steel structures, CEN, Brussels, Belgium, 2005.

[5] Siljander. A, Kurath. P, Lawrence. F. V, Non-proportional fatigue of welded structures, Advances in Fatigue Lifetime Predictive Techniques, ASTM STP 1122, Edited by M. R. Mitchell and R. W. Landgraf, Philadelphia,(1992), pp. 319-338.

[6] Sonsino. C. M, Overview of the state of the art on multiaxial fatigue of welds, Multiaxial fatigue and fracture ESIS publication, vol. 25, 1999,pp. 195-218.

[7] Maddox S. J, Sonsino C. M, Multiaxial fatigue of welded structures-problems and present solutions, Manuel de Freitas, Editor, Proceedings of the Sixth International Conference on Biaxial / Multiaxial Fatigue and Fracture, Lisboa, vol. II, 2001, pp. 3-16.

[8] Farajian A , Nitschke-Pagel T, Siegele S, Welding Residual Stresses in Tubular Steel Joints and their Behavior under Multiaxial Loading, HTM Journal of Heat Treatment and Materials, 69, 2014, pp. 6-13.

[9] Michaleris P, Dantzig J, Tortorelli D, Minimization of Welding Residual Stress and Distortion in Large Structures, Welding Journal, pp. 361-366, 1999.