INVESTIGATIONS INTO EFFECT OF RESIDUAL STRESSES ON MECHANICAL BEHAVIOUR OF DUPLEX STAINLESS STEEL WELD JOINT

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ABSTRACT
Duplex stainless steel alloy is widely used in the manufacture of pressure vessels, nuclear plant, chemical refineries and paper mill. Welding is the most preferred fabrication method in these structural applications; however during welding the work piece is subjected to thermal cycle as a result residual stresses are developed in the weld. Residual stresses have significant effect on performance of the weld joint subjected to tensile loading. In addition to this duplex stainless steel is welded using strength over matched filler material. Thus the weld joint consist of two different materials having different behaviour under tensile loading. This paper presents a method to model mechanical behaviour of weld joint in the presence of residual stresses using deformation theory of plasticity. Residual stresses are estimated numerically and values are assigned as an initial stress in finite element model of weld joint. The weldment specimen model is subjected to static loading and effect of residual stress on local yielding is investigated. Commercially available finite element analysis code ABAQUS is used for this purpose. The response of weld joint to monotonically increasing tensile load is determined experimentally by conducting transverse and longitudinal tension tests to validate simulation model particularly in plastic region. The results show that deformation theory of plasticity can be used to model post yield behavior of a weld joint. As expected stress-strain behavior of the weld joint differ marginally from virgin duplex stainless steel alloy. The work presented in this paper will help designer to ensure structural integrity.

KEYWORDS: *Duplex Stainless Steel, Welding, Residual Stresses, Tension Test*

I. INTRODUCTION

Welding is an indispensable joining process used in fabrication of structures. However, weld joint in any structure consist of zones with different mechanical characteristics which makes it a vulnerable location for fracture [1]. Residual stresses, imperfections etc. present in a weld joint contribute to its ultimate fracture. A weld joint fracture may lead to catastrophic consequences in terms of risk to human life. During the welding process, the weld area is heated sharply compared to the surrounding area and fuses locally [2]. Plastic deformation takes place due to the unevenness of the temperature fields, restraining effects of the structure, and variations in the material properties that occur during the heating and cooling cycle. Plastic deformation remains after welding is completed to form residual stresses. High longitudinal residual stresses are developed at central section of the plate. As the distance from the weld centre increases, the longitudinal residual stress gradually decreases. Along the transverse direction, the longitudinal residual stress changes to compressive, whereas along the longitudinal direction it reduces to zero, as dictated by the equilibrium condition of residual stresses. Similar distribution is observed in case of transverse residual stress with minor difference in magnitude. Residual stresses generated during welding are detrimental for performance of weld joint even under static loading. Reasons for this can be attributed to significantly different mechanical behaviour of weld joint under static loading. Full range stress strain curve of duplex stainless steel (DSS) weld joint deviates from virgin alloy stress strain curve. Deviation of stress strain curve is significant in post yield region. The objective of the present work is to simulate the effect of residual stresses and strength mismatch of filler wire on local yielding of duplex stainless steel weldment specimen under static loading and experimentally validate the simulation model. Mansoo et.al. [3] have proposed modifications in true stress strain curve to precisely predict onset of necking using finite element analysis and test using iterative method. Eduardo and Diego [4] have proposed experimental-numerical methodology to derive the elastic and hardening parameters for characterization of the sheet specimens. Mechanical and fracture properties of steel weld joints were studied by G. Cam, et. al. [5] to find mismatch ratio. Flat micro tensile specimens were used for determining the mechanical properties of similar and dissimilar weld joints. Hyoung et. al. [6] have investigated the tensile deformation and post necking behavior using elasto-plastic finite element method. It was demonstrated that the necking initiation and post necking could be simulated well by the use of the radial direction constraint. Carlous et. al. [7] have presented a methodology to simulate behaviour of aluminium specimen in simple tension test using finite element method. Rasmussen [8] has developed an expression for the stress – strain curves of duplex stainless steel alloy which are useful for the design and numerical modeling mechanical behaviour of structural members. Bacha et. al. [9] has proposed a methodology to calculate local values of stress in tension test specimen considering the effect of triaxiality. The test was simulated numerically by a damage mechanics cell model based on the finite element method. Ehlers and Varsta [10] emphasized that the true stress should be obtained independently of the strain as a function of the cross-sectional area at any given instant. The strain until fracture is calculated from the measured surface displacements and the stress is derived from the measured force and the cross- sectional area in the necking region. In the present work authors have estimated residual stresses and same are assigned as initial stresses in Abaqus FE model of tension test specimen. The specimen model is then subjected to tension loading using deformation theory of plasticity and the results are verified with experimental findings.

II. ESTIMATION OF RESIDUAL STRESS

Fabricated structure responds differently to the in service loading than expected from design calculations because of the welding induced residual stresses. Thus knowledge of welding induced residual stresses is necessary in order to predict behavior of welded structure under applied loading. Attempts have been made by many researchers to understand weld residual stresses and distortion using predictive methodology, parametric experiments or empirical formulations. In the present work residual stresses are estimated using the formula proposed by Labeas and Diamantakos [11] and the values are modeled as initial stresses in FEA software Abaqus. The longitudinal residual stresses in the weld region is estimated using equation 1

$$\sigma_x = \sigma_{ox}\left(0.5 + \frac{z}{t}\right)\frac{1-\left(\frac{y}{c_o}\right)^2}{1+\left(\frac{y}{c_o}\right)^4} \quad . (1)$$

σ_{ox} is 210 MPa, the maximum value of the tensile residual stress which corresponds to stress at 0.1 % strain on nominal stress strain curve. C_o is 29 mm, the distance from y-axis at which the residual stress value changes from positive to negative, i.e. from tension to compression. This variation along *y* axis at specimen mid plane is shown in figure 1.

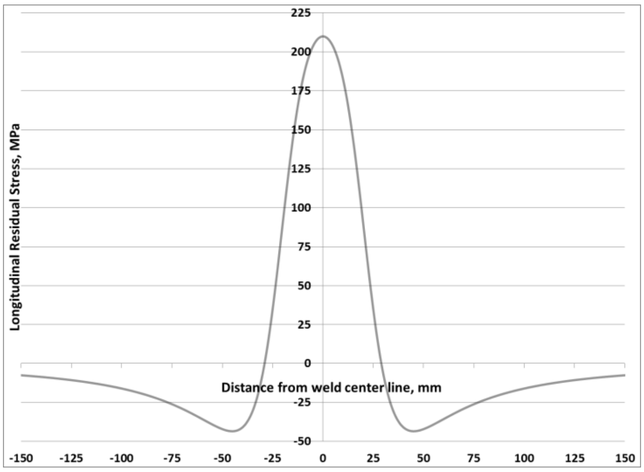

Figure 1. Variation of Longitudinal Residual Stress

The transverse residual stress is estimated using equation 2

$$\sigma_y = \sigma_{oy}\left(0.5+\frac{z}{t}\right)e^{-\left(\frac{y}{d}\right)^2}\left[1-12\left(\frac{x}{L}\right)^2\right] \quad . (2)$$

σ_{oy} is 70 MPa, the maximum value of the transverse tensile residual stress which corresponds to 0.33 times σ_{ox}. The value of characteristic parameter is d is 25 mm and plate length L is 250 mm. Figure 2 shows the simulated transverse residual stresses along weld line, *x* axis.

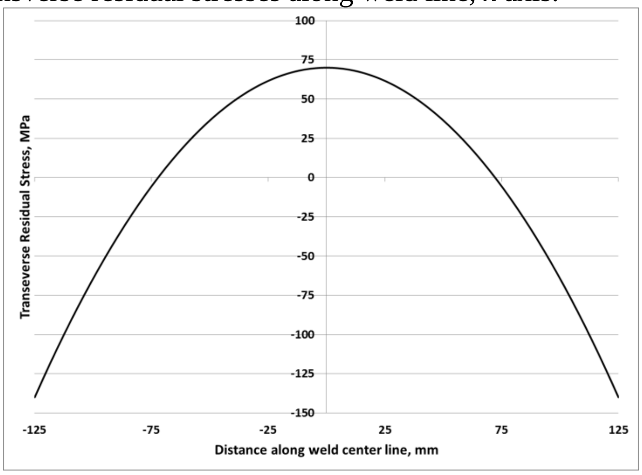

Figure 2. Variation of Transverse Residual Stress

III. ANALYSIS OF WELD JOINT MECHANICAL BEHAVIOUR

As the stress in the alloy exceeds the yield point stress, permanent (plastic) deformation begins to occur and associated strains are called as plastic strains. Duplex stainless steel follows von Mises yield criterion with isotropic strain hardening its corresponding flow rule [12]. Any deviation from elastic to plastic behavior of a material is marked by a yield point and post-yield hardening on a material's stress-strain curve. Both elastic and plastic strains accumulate as the alloy deforms in the post-yield region. Slope of the stress-strain curve during post-yield loading decreases and is characterized by a tangent drawn at a point on it, called as tangent modulus. The plastic deformation of the material increases its yield stress for subsequent loadings: this behavior is called work hardening. The plastic deformation is associated with nearly incompressible material behavior and finite element modeling of this effect is very complex in elastic-plastic simulations. A mathematical model describing the response of the alloy independent of the structure's geometry in plastic region under tensile loading is needed. This goal can be accomplished if instead of nominal stress measures true stress and strain is used that account for the change in area during the finite deformations. To define plasticity in Abaqus true stress and strain data is needed which can be obtained from nominal stress and strain using equation 3 and 4 respectively.

$$\sigma = \sigma_{nom}(1 + \varepsilon_{nom}) \quad . (3)$$

$$\varepsilon = \ln(1 + \varepsilon_{nom}) \quad . (4)$$

However these relationships are valid only prior to necking. Smooth stress-strain behaviour of the alloy after yielding is approximated by defining a series of straight lines joining the data points of true stress and true strain. The true yield stress of the material is defined as a function of true plastic strain. Total strain values are converted into the elastic and plastic strain components as per equation 5

$$\varepsilon^{pl} = \varepsilon^{t} - \varepsilon^{el} = \varepsilon^{t} - \sigma/E \quad . (5)$$

Full range nominal stress-strain curve of virgin duplex stainless steel alloy (2205) as defined by Rasmussen [8] is used to define the plastic behavior as per equation 5. Plastic behavior of filler duplex stainless steel alloy 2209 is also defined in similar manner using properties supplied by manufacturer. Longitudinal and transverse weldment tension test specimen is extracted from the welded plate as shown in figure 3.

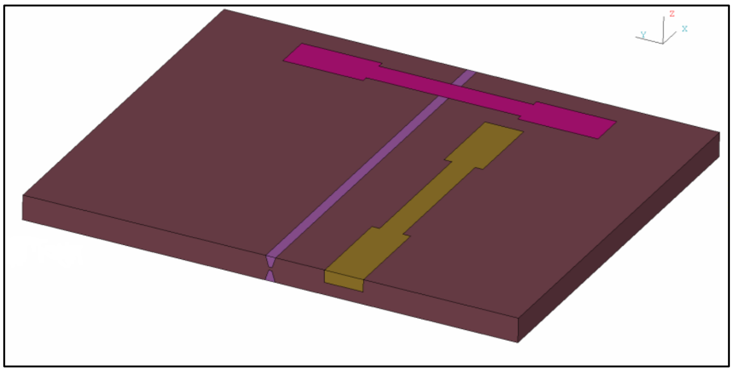

Figure 3. Weldment tension test specimen extraction scheme

Material is modeled by assigning respective residual stresses as initial stress. Response of this finite element model is simulated by applying monotonically increasing load iteratively with a time step of 0.001. Specimen geometry is modeled using 8-node biquadratic, reduced integration plane stress CPS8R element recommended for problems involving large strains. Finite element model of the specimen is shown in figure 4.

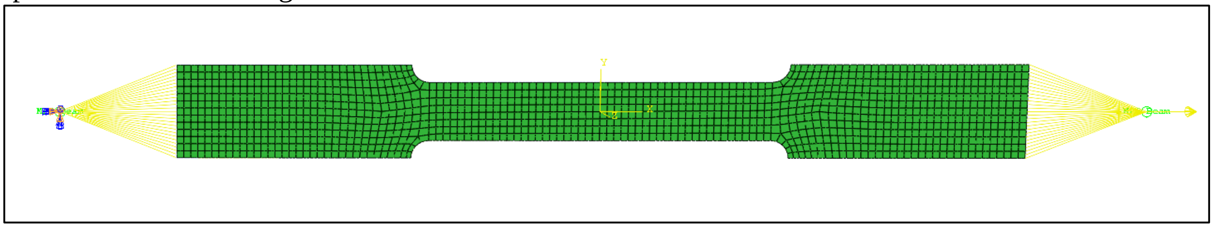

Figure 4. Finite element mesh model of weldment tension test specimen

IV. RESULTS

Simulation and experimental results of tension test specimen of duplex stainless steel alloy is presented in this section. The specimen is modeled and analysed using finite element software Abaqus and experimentally tested as per ASTM E8M standard for longitudinal and transverse tension loading. Test specimen drawing is shown in figure 5.

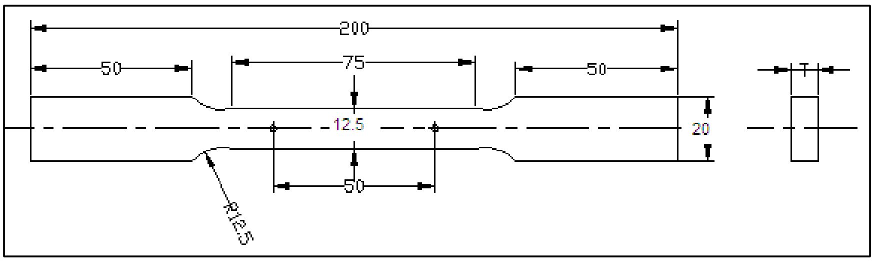

Figure 5. Specimen drawing for tension test as per ASTM E8M

Tension tests were carried out on Universal Testing Machine (UTM) as shown in figure 6. Deformations were recorded using high precision mechanical dial gauge extensometer.

Figure 6. Tension testing of weldment specimen on UTM

Experimental and simulation results of stress strain curve are compared in this section. Figure 7 shows the comparison of true stress vs plastic strain curve of virgin duplex stainless steel alloy and longitudinal weldment specimen.

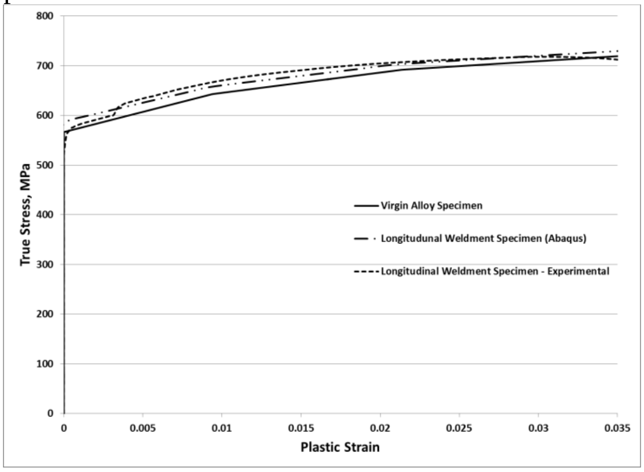

Figure 7. Stress strain curve of longitudinal weldment specimen

Figure 8 shows the comparison of true stress vs plastic strain curve of virgin duplex stainless steel alloy and weldment specimen in transverse tension test.

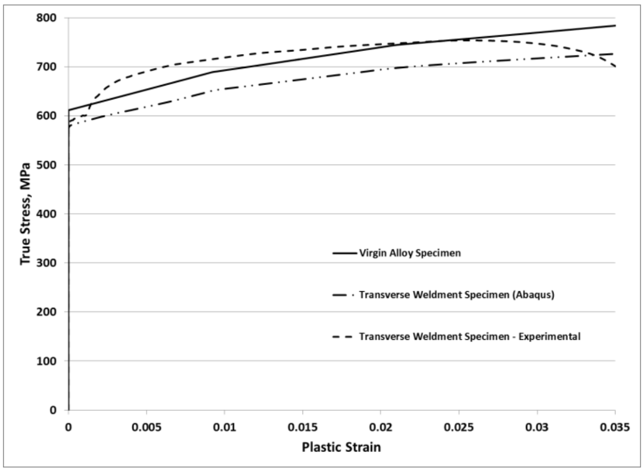

Figure 8. Stress strain curve of transverse weldment specimen

Table 1 show the summary of the results from simulation and test of duplex stainless steel virgin alloy and weldment specimen.

Table 1- Results Summary

Duplex Stainless Steel	**0.1 % Offset Strength, MPa**	
	Longitudinal	*Transverse*
Virgin 2205 Alloy	620	562
Weldment Specimen	598	567
Mismatch ratio	0.97	1.01

V. CONCLUSIONS

Experimental and simulated stress-strain curves of duplex stainless steel longitudinal and transverse weldment specimen were compared with the virgin alloy to quantify the effect of residual stresses. In case of longitudinal weldment specimen stress strain curve matches with that of virgin alloy because of over alloyed filler wire. Marginal deviation between stress strain curve of longitudinal weldment specimen and virgin alloy is observed at the plastic strain 0.03, which clearly indicate the effect of residual stress.

The effect is less pronounced in longitudinal specimen than transverse specimen. Mismatch ratio for longitudinal tension test specimen indicates slightly under matched weld joint due to its closeness to residual stress transition region. Mismatch ratio for transverse tension test specimen indicates slightly overmatched weld joint along with high strain hardening effect in initial region due to use of high strength filler rod. Simulation result of weldment stress strain curves from finite element analysis agrees with experimental results which validates the proposed model of assigning residual stresses as initial stress.

VI. SCOPE FOR THE FUTURE WORK

Scope in the present work is limited to longitudinal and transverse tension test of weldment specimen without considering sheet anisotropy. It is proposed to analyse post yield behaviour of the tension test specimen considering the effect of combined isotropic and kinematic hardening rule. This would give more accurate results for high strain rate application.

Nomenclature

x dimension along weld length

y dimension perpendicular to weld line

z thickness dimension

t thickness of plate

L length of plate

σ_x longitudinal residual stress

σ_y transverse residual stress
σ_{ox} parameter defining the maximum value of the longitudinal tensile residual stress
σ_{oy} parameter defining the maximum value of the transverse tensile residual stress
C_o distance from x-axis at which the residual stress value changes from positive to negative
d characteristic parameter
ε^{pl} true plastic strain,
ε^{t} true total strain,
ε^{el} true elastic strain,
σ true stress, and
E Young's modulus.

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