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Analysis of Mechanical Behaviour of Welded Joint under Residual Stresses

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ABSTRACT

Tungsten inert gas welding is one of the most reliable and efficient method of permanent metal joining process in industry. When two plates are joined by welding, a complex thermal cycle is applied to the weldment as a result residual stresses are developed in the weld. In this paper, the investigation of effect of residual stresses on mechanical behaviour of austenitic 304 and 316L stainless steel under bending loading has been carried out. Residual Stresses are determined by Labeas-Diamantakos model method. Variation of residual stresses at heat affected zone (HAZ) of plate is also studied. Residual stresses are calculated numerically and values are assigned as an initial stress in finite element model of weld joint. The weldment specimen model is subjected to static bending loading and effect of residual stress on local yielding using deformation theory of plasticity is investigated by MSC Marc software. Residual stresses have significant effect on stress strain behaviour of weld joint. The numerical results are compared with experimental data have good agreement with the experimental results obtained in plastic region. It is well established fact that structural integrity of components is substantially affected by the residual stresses when subjected to thermal and structural loads.

Keywords— **Bending Test, FEA, Residual stresses Stainless Steel, Welding.**

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I. INTRODUCTION

Stainless steel has best properties like high ductility, forming and drawing and excellent high corrosion resistance so it is used in various applications. In the modern day to day applications like in industries, chemical equipment, coal hopper, marine equipment, pressure vessels and other structural components welded plates and shells play a major role. Welding is widely used to join metallic parts, the Gas Tungsten Arc Welding commonly referred to as Tungsten Inert Gas (TIG) – process uses the heat generated by an electric arc between a non-consumable electrode and the work piece to fuse metal in the joint area and produce a molten weld pool but due to introduction of residual stresses during welding it is very essential to understand the behaviour and nature of the joint. Residual stresses are defined as the stresses that exist inside the structure without the application of external loads and are suppose to be self balancing within the bulk.

Residual stress distribution and distortion in weld joints and structures are affected by structural parameters, mechanical and physical properties, and welding process parameters. Thermal energy applied results in irreversible elastic-plastic deformation and consequently gives rise to the residual stresses in and around heat affected zone (HAZ). Particularly, tensile residual stresses near the weld area generally have adverse effects, causing stress rising, fatigue failure, and brittle fracture; Therefore for application of new welding process to structure, it is required to clarify the mechanical behaviour of welded joint in advance in the design stage. The objective of the present work is to simulate the effect of residual stresses on bending strength of welded specimen under static loading and experimentally validate the simulation model. Full range stress strain curve of weld joint at different position of HAZ deviates from virgin alloy stress strain curve. Deviation of stress strain curve is significant in post yield region. George Labeas and Ioannis Diamantakos [4] in his paper have illustrated Numerical investigation of through crack behavior under welding residual stresses. In the case that the residual stress field has both longitudinal and transversal components varying through-the-thickness, the effect of transversal residual stresses on cracks parallel to the weld line is limited due to the small stress field magnitude and longitudinal variation. Nataraj[7] and Gurinder Singh Brar [2] calculated residual stresses and distortion in AISI 304 stainless steel by Fea Software. MatoPerić et al [3] have studied out Comparison between result of Residual Stresses in Butt-Welded Plates Using Abaqus and Ansys. Bending capacity of girth-welded circular steel tubes have analyzed by Chin-Hyung Lee, and Jeong-Hoon Baek[9].In this paper, the flexural responses of girth-welded circular steel tubes were examined by a nonlinear FE analysis. Results showed that the flexural behaviour of girth-welded circular steel tubes always involves local buckling near the girth weld on the compression side, which significantly affects the moment versus end-rotation response. T. Wanga et.al [6] have simulated welded joint under Four point bending. Welded and un-welded I-sections under four-point bending have been assessed using shell element to predict the structural behavior of welded joint. Stress – strain curves of duplex stainless steel alloy which are useful for the design and numerical modeling mechanical behaviour of structural members are developed by Rasmussen [11]. Hyoung et. al. [12] has investigated post necking behaviour and the tensile deformation using elastic-plastic finite element method.

The effect of residual stresses may either be beneficial or harmful, depending on magnitude, sign (tension or compression) and the distribution of the stresses with respect to the load-induced stresses. Reasons for this can be attributed to significantly different mechanical behavior of weld joint under static loading. Hence, the resulting residual stresses have a strong influence on mechanical behavior and strength of welded joints. The objective of the present study is to carry out an investigation of effect of residual stresses on welded joint compared to virgin plate under three-point bending. Residual stresses are calculated using the formula proposed by Labeas and Diamantakos and these stresses are assigned as initial stresses in MSC Marc FE model of bending test specimen. The specimen model is then subjected to bending loading using theory of plasticity and the results are verified with experimental findings.

II. CALCULATION OF RESIDUAL STRESS

The residual stresses increase the total energy of the structure. The presence of dislocations increases the total internal energy of the structure. For example, high compressive residual stresses may if a Tensile stress is applied to a material that already contains tensile residual stresses; the total stress acting on the part is the sum of the applied and residual stresses. Compressive stresses are stored at the surface of a metal part, because of applied tensile stress, compressive residual stresses are balanced.

Residual stresses and distortions are two of the major concerns which are detrimental to the welded structures. Because of welding residual stresses creates distortion and affect on the service characteristics of welded joints. Particularly, tensile residual stresses near the weld area generally have adverse effects, causing stress rising, fatigue failure, and brittle fracture Therefore, for application of new welding process to structure, it is required to find out the mechanical behaviour of welded joint in advance in the design stage. As it is well known, the residual stresses have a strong influence on weld deformation, fatigue strength, fracture toughness and buckling strength. Thus, it is important to evaluate the residual stresses due to welding. However evaluating residual stresses associated to a welded joint is extremely complicated. Difficulty in determining these stresses is emphasized by the thermal transient, by the variation of the thermal and mechanical properties of the material with the temperature and by the nonlinear heat loses. Residual stresses are calculated using the formula proposed by Labeas and Diamantakos .These stresses are assigned to the weldment model in MSC marc software as like initial boundary condition. The longitudinal residual stresses in the weld region is estimated using equation 1

$$\sigma_y = \sigma_{oy}\left(0.5+\frac{z}{t}\right)\frac{1-\left(\frac{x}{C_0}\right)^2}{1+\left(\frac{x}{C_0}\right)^4}$$

1 σ_{ox} is 205MPa, the maximum value of the tensile residual stress which corresponds to yield stress, Co is 25 mm, the distance from y-axis at which the residual stress value changes from positive to negative Longitudinal stress distribution along in the joint for the weld joint SS304 is shown in the figure 1 and plot of longitudinal stress for joint from the weld line of plate.

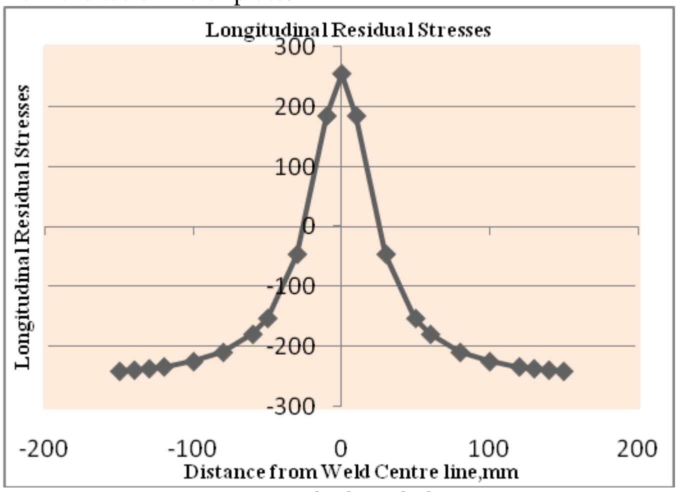


Figure 1.Longitudinal Residual Stress

The transverse residual stress is estimated using equation 2

$$\sigma_x = \sigma_{ox}\left(0.5+\frac{z}{t}\right)e^{-(x/d)^2}\left[1-12\left(\frac{y}{L}\right)^2\right] \qquad 2$$

σoy is 68MPa, the maximum value of the transverse tensile residual stress which corresponds to 0.33 times σox. The value of characteristic parameter is d is 30mm and plate length L is 300 mm. Figure 2 shows the transverse residual stress distribution along the weld line.

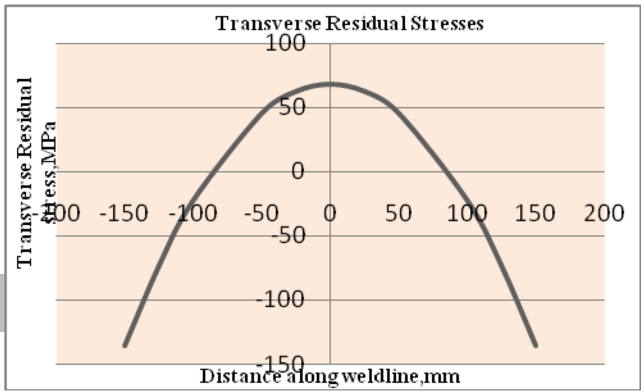


Figure 2.Transverse Residual Stress

III. EXPERIMENTAL BENDING TEST

Gas tungsten arc welding (GTAW), also called tungsten inert gas welding (TIG) which is a widely used method for stainless steel. TIG welding involves a number of variables; each variable has its effect on the weld and there is an interrelationship among variables that affects the weld characteristics. It is used for joining the SS304 and SS316L work pieces. During welding the work piece is subjected to considerable local heating. The objective of the present study is to carry out an investigation of effect of residual stresses on welded joint compared to virgin alloy plate under three-point bending. A bending test produces tensile stress in the convex side of the specimen and compression stress in the concave side. This creates an area of shear stress along the midline. The flexure test method measures behavior of materials subjected to simple loading. The materials 304SS and 316 SS of 3mm thickness are selected for the work. Three plates of each type with 300mm X 150mm dimensions are used for weld joint with square butt joint. The gap is filled by TIG butt welding in two passes. The dimensions of specimen of weldments for bending tests are selected from previous study and bend test parameter. In this study, 200X40X 3 mm (L* W *T) Specimens dimensions are selected .Specimens for tests are taken as perpendicular to weld direction. Three specimen are selected which having weld line of these specification at distance of 0,25mm,40mm apart from the center of specimen.

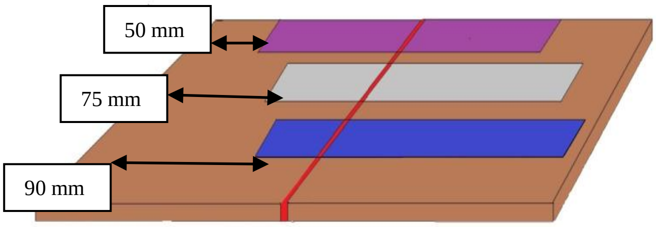
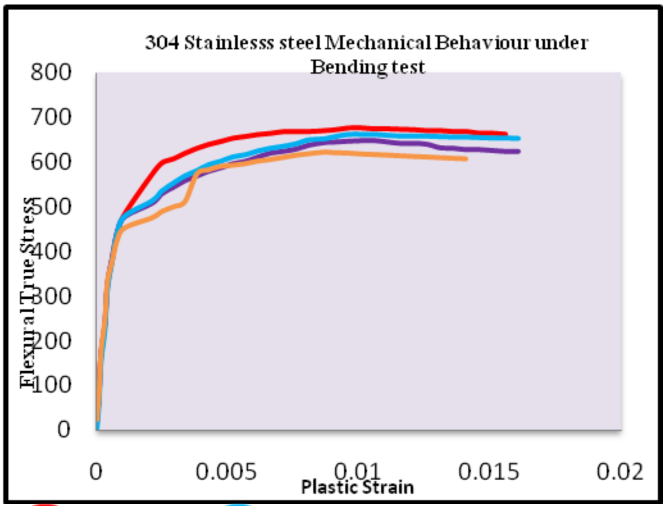


Fig .3 Weldment test specimen extraction from welded plate

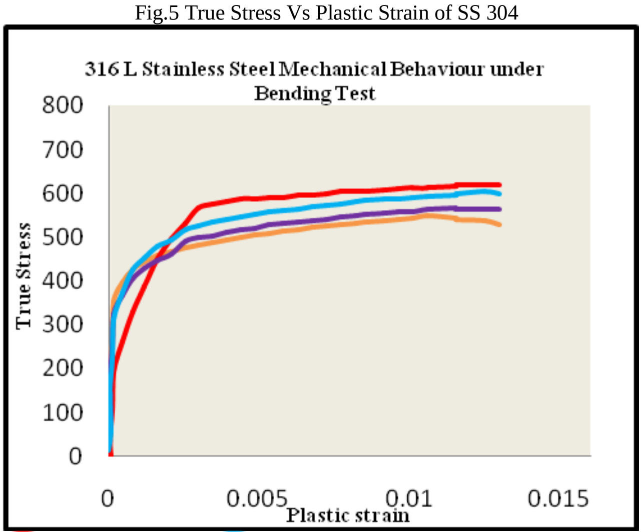
Fig.4 Experimental Setup

Results are plotted in a stress-strain diagram. Flexural strength is defined as the maximum stress in the outermost fiber. This is calculated at the surface of the specimen on the convex or tension side. Flexural stress σ_F is given by $\sigma_f = 3FL / 2bd^2$. It is also called as bending stress and strain is given $\varepsilon f = 6D\ d/L^2$.



=Center weld, = Weld at 40 mm from Centerline, =Weld at 25 mm from Centerline, =Unwelded Specimen

Fig.5 True Stress Vs Plastic Strain of SS 304



=Center weld, = Weld at 40 mm from Centerline, = Weld at 25 mm from Centerline, = Unwelded Specimen

Fig.6 True Stress Vs Plastic Strain of SS 316l

The values of maximum true stress and the transverse weld distance from center of specimen along x axis of SS 304 plate given in tabulated form as below.

Weld distance from center of plate (mm)	40	25	0	-25	-40	Virgin alloy
Values of maximum bending true stress along Y-axis (MPa)	667	652	670	648	660	622

Table.1 Maximum True stress of 304 SS Specimen

The values of maximum true stress and the transverse weld distance from center of specimen along x axis of SS 316L plate given in tabulated form as below.

Weld distance from center of plate (mm)	40	25	0	-25	-40	Virgin alloy

Values of maximum bending true stress along Y-axis (MPa)	585	565	635	562	590	547

Table.2 Maximum True stress of 316 SS Specimen

Graph of maximum flexural true stress and distance from specimen centerline to weld is plotted bellow

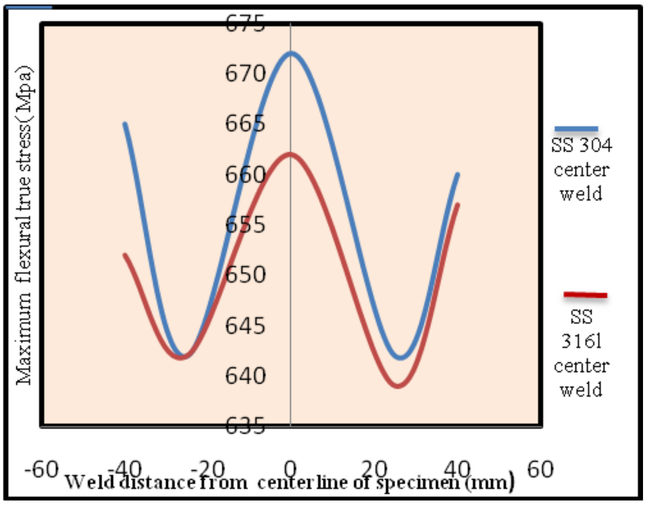


Fig. 7 Maximum flexural true stress at various weld distance

Conclusion of the bending test conducted on the respective specimen is as follows-

The bending load bearing capacity of 304 stainless steel welded specimens is more than 316L stainless steel welded specimen. Mismatch ratio for bending test specimen with respect to virgin alloy of SS 304 and SS 316L which indicates slightly overmatched weld joint along with high strain hardening effect in initial region due to use of high strength filler rod. Mechanical behavior of welded joint is affected by Residual stresses. These experimental results concluded that the effect of residual stresses on bending strength and behavior of welded joint

IV. ANALYSIS OF MECHANICAL BEHAVIOUR WELD JOINT

Finite element analysis (FEA) forms one of the most versatile classes of such methods and were originally developed in the field of structural analysis; but now it has been extended as a general method of solution to many complex engineering and physical science problems. Finite element analysis is a computer based analysis technique for calculating the strength and behavior of structures. In the FEM the structure is represented as finite elements. These elements are joined at particular points which are called as nodes. The FEA is used to calculate the deflection, stresses, strains temperature, buckling behavior of the member. In this paper FEA is carried out by using the MSC MARC. Finite element model is generated using MSC MARC software. A 3D solid 84 brick element with 8 nodes is used to mesh the geometry of the specimen. The Length of specimen is 200mm and the width of specimen is 40mm.Solid 84 elements have 3 dofs. A refined mesh is obtained with 960 elements and 1476 nodes. The shape of the elements is hexahedral type. Now part exists, define a library of the necessary materials that compose the object (or project) being modeled. This includes thermal and mechanical properties. The material used throughout this study is 304 and 316 L stainless steel.

Residual stresses are estimated numerically and values are assigned as an initial stress in finite element model of weld joint. Material is modeled by assigning respective residual stresses on each element. This work presents a method to model mechanical behavior 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 software MSC Marc is used for this purpose. To define plasticity in MSC Marc true stress and strain data is needed which can be obtained from nominal stress and strain using equation 3 and 4 respectively.

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

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

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 the equation

$$\varepsilon pl=\varepsilon t-\varepsilon el=\varepsilon t-\sigma E \quad (5)$$

The computer simulations of flexural test are performed by choosing the ultimate loads recorded in the test. This load is 1000N.The deformation obtained by computer simulation of flexural test is 4.48 mm as shown in Fig. It appears to be very close to the experimental value of 5.8 mm. The maximum flexural strength obtained by computer analysis for specimen is 672 MPa where as its experimental value is 670 MPa.

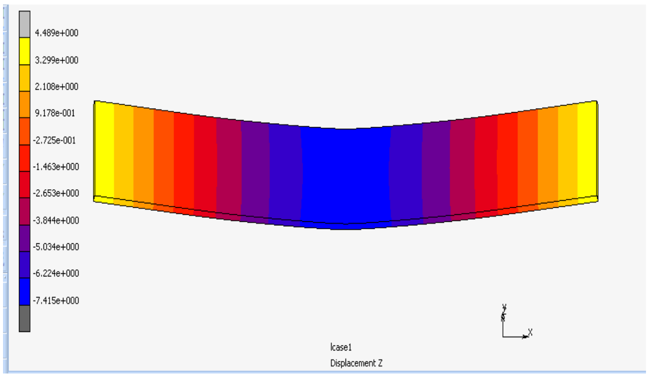


Fig.8 Deformation of welded plate

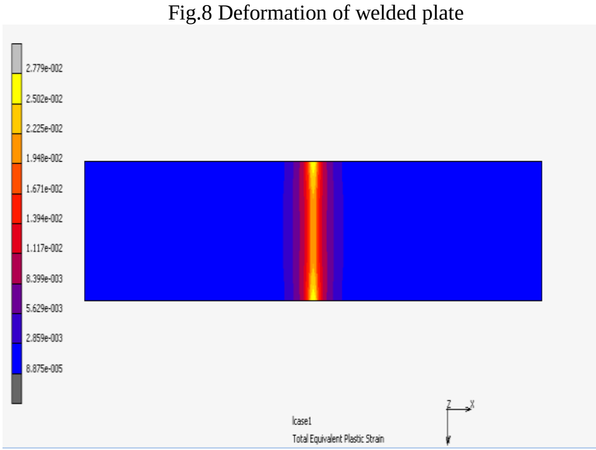


Fig.9 Total Plastic Strain

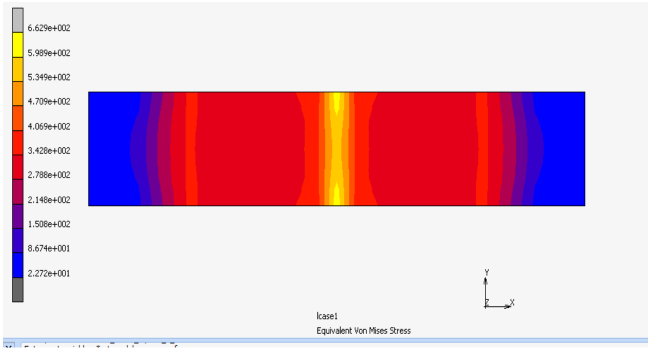


Fig.10. Von mises Stress

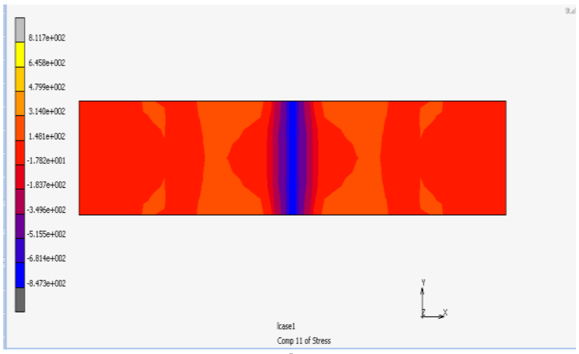


Fig .11 Bending Stresses

The values of maximum von mises true stress and the transverse weld distance from center of specimen along x axis of SS 304 plate given in tabulated form as below

Weld distance from center of plate (mm)	-40	-25	0	-25	-40	virgin alloy speci-men
Values of maximum von mises true stress along Y-axis (MPa)	665	642	672	642	665	626

Table.3 Maximum True stress of 304 SS Specimen

The values of maximum von mises true stress and the transverse weld distance from center of specimen along x axis of SS 316L plate given in tabulated form as below

Weld distance from center of plate (mm)	-40	-25	0	25	40	virgin alloy speci-men
Values of maximum von misses true stress along Y-axis (MPa)	630	625	642	627	632	610

Table.4 Maximum True stress of 316 SS Specimen

Graph of maximum flexural true stress and distance from specimen centerline to weld is plotted bellow

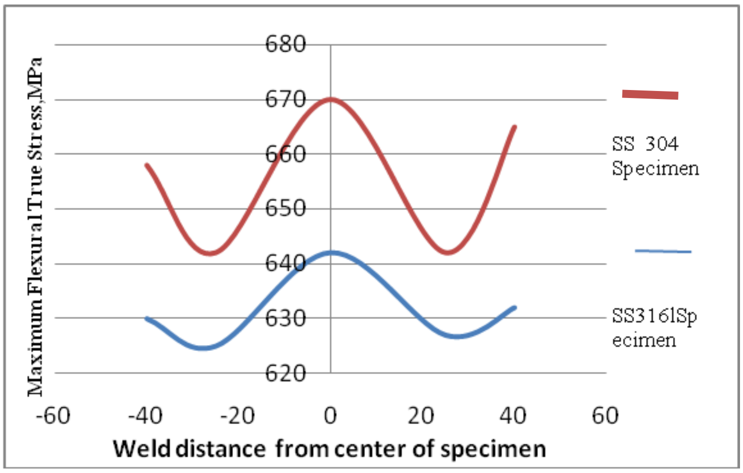


Fig.12 Maximum flexural true stress at various weld distance

V. Tensile Testing and Analysis

Tensile tests are used to determine the mechanical behavior of material under statics, stretch loading. The tensile testing is carried out on six samples of SS 304 and SS 316l grade steels welded by TIG process. The tensile specimens are prepared as per ASTM E8. Tensile tests are conducted using 100KN computer controlled universal testing machine. Before testing, cross- sectional area and gauge length is measured for each sample. The specimen is then loaded into a machine set up for tensile loads as per the ASME specification and placed in the proper grippers so that the tensile specimens undergo deformation. Once loaded, the machine can then be used to apply a steady, continues tensile load .With application of tensile load, specimens undergoes deformation and ductile fracture takes place at particular load and this value is recorded to calculate ultimate tensile strength of component.

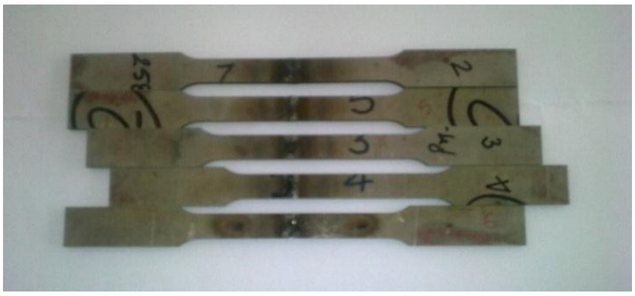


Fig .13 Tensile Specimens for testing

In FEA simulation, Residual stresses are calculated numerically for each element by using Labeas-Diamantakos model method and assigned as initial stress to the material model. This model is simulated by applying boundary condition and monotonically increasing loading condition. Finite element model of the specimen is shown in figure

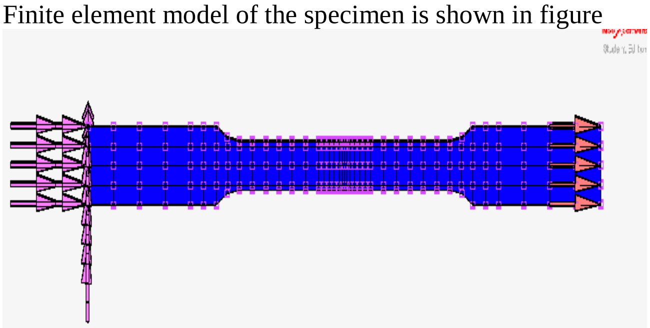


Fig.14.Finite element model of weldment specimen

In this analysis, simulation and experimental results of stress strain curve are compared. Figure shows the comparison of stress Vs strain curve of weldment specimen and virgin stainless steel alloy of SS 304.

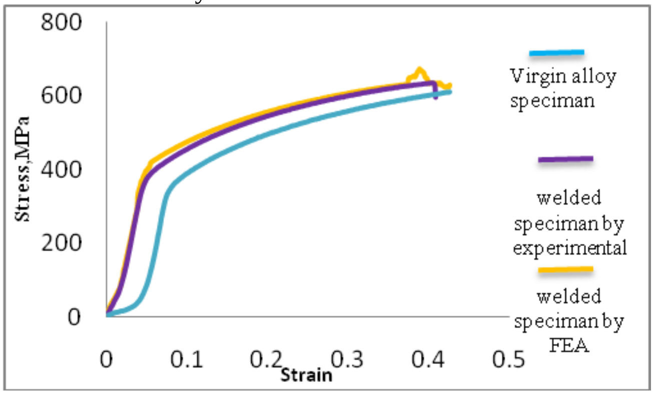


Fig.15.Stress strain Curve

Following table shows summary of the results from tensile testing of 304 and 3016L stainless steel virgin alloy and weldment specimen as bellow.

Sr. No	Sample ID	Ultimate Tensile Strength MPa	Remark
1	SS 304 Centre Weld Plate	636.21	Weld OK. Broken from Plate
2	SS 304 -weld 15mm away from Centre	633.83	Weld OK. Broken from Plate
3	SS 304 -weld 25mm away from Centre	622	Weld OK. Broken from Haz

Table.5 Ultimate tensile strength of SS 304

Sr. No	Sample ID	Ultimate Tensile Strength MPa	Remark
1	SS 316l Centre Weld Plate	561.03	Weld OK. Broken from Plate
2	SS 316l -weld 15mm away from Centre	559.38	Weld OK. Broken from Plate
3	SS 316l-weld 25mm away from Centre	596.43	Weld OK. Broken from Haz

Table.6 Ultimate Tensile Strength of SS 316L

VI.CONCLUSION

Effects of Residual stresses are detrimental or beneficial, depending on its magnitude, sign (tension or compression) and the distribution of the stresses with respect to the load-induced stresses. Due to tensile residual stresses nearer to the HAZ area adverse effects are observed such as causing stress rising and fatigue failure. It is required to clarify the mechanical behavior of welded joint in advance in the design stage.

a) For bending test,

1) To investigate the effect of residual stresses on experimental and FEA simulated stress-strain curves of stainless steel 304 and 316L weldments were compared with the virgin alloy. The bending strength of centre welded specimen is higher than other welded plates which are apart from centre. It shows that internal strength or stresses or energy of material increased by Residual Stresses due to the welding.

From the experimental and FEA result, maximum bending true stress decreases from weld centre line to the end of the plate, while plastic strain increases; this proves that residual stress is affected on heat affected zone(HAZ) of weldments.

2) The bending Strength capacity of 304 stainless steel welded specimens is more than 316L stainless steel welded specimen. Stress strain curves of weldments from finite element analysis agrees with experimental results for validation with proposed model of assigning residual stresses as initial stress.

b) For Tensile test

It is found that in weldment specimen, Ultimate tensile stress reaches their maximum values in heat affected zone from weld center of the plate and is linearly reduced at the plate end. In the present case value of maximum ultimate tensile stress reaches to 636.21 MPa of Stainless steel 304 and 561.03 MPa of 316L stainless steel .It clears that, because of residual stresses induced in welding, stress rising capacity of weld specimens are increased.

Nomenclature

x	dimension along weld length
y	dimension perpendicular to weld line
z	thickness dimension for residual stresses
t	thickness of plate for residual stresses
L	length of plate for residual stresses
Σx	longitudinal residual stress
σy	transverse residual stress
σox	parameter defining the maximum value of the longitudinal tensile residual stress
σoy	parameter defining the maximum value of the transverse tensile residual stress
Co	distance from *x*-axis at which the residual stress value changes from positive to negative
d stresses	characteristic parameter of residual
εpl	True plastic strain,
εt	True total strain,
εel	True elastic strain,
σ	True stress, and
E	Young's modulus

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