

Effect of Residual Stress on the Mechanical Behavior of AISI 304, For TIG Welding

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Abstract- Fatigue is a phenomenon which should be taken into consideration in an engineering design. Residual stress is one of the important factors that affect fatigue life. Tensile residual stresses are harmful for product life and should convert into compressive residual stresses. Welding is a metal joining process, and amount of residual stress produced in welding is more than other mechanical processes. Two plates of AISI 304 grade of dimension 300X300X3 mm are used in present work. TIG welding is use for joining of plates. Longitudinal and transverse specimens are extracted from this plate. Another two plates are welded at an angle of 45° and same shaped specimen is extracted named as Angular weld specimen. These specimens are tested on UTM by using tensile test. Using Labeas and Diamantikos formula calculated residual stress is assigned as an initial stress in finite element software Ansys Workbench. Transient thermal and transient structural analysis is carried out, in order to investigate effect of residual stress on fatigue strength of a component. Stress vs. strain curves for virgin, longitudinal, transverse and angular specimens are compared and analyzed. Structural strength is also examined through this research work.

Index Terms- Angular TIG weld, FEA, AISI 304, Residual Stress

1. INTRODUCTION

Fatigue is the ability of a material to withstand stress without getting failed. Materials are subjected to various fluctuating stresses under different loading condition, when strength of the material is more than the fluctuating stress, then also material fails, this type of failure is called as fatigue failure. There are various factors which affects fatigue life such as cyclic stress state, geometry, surface quality, residual stress, size and distribution of internal defects, direction of loading. Residual stress is one of the most important factor that should be taken into consideration while design of a component. Residual stress is self stress or internal stress that produced in a material when it gets subjected to various manufacturing processes such as welding, casting, forging, machining. The amount of residual stress induced in welding is more as compared to other manufacturing processes. When the magnitude of residual stress increases beyond the elastic limit, material gets plastically deformed and distortion has taken placed. The magnitude of residual stress may be beneficial or harmful for a material, which also depends upon application and working condition. There are two types of residual stress tensile and compressive. Tensile residual stress plays important role in the performance of material. Mostly 90% of components get failed by tensile stresses.

Welding is metal joining process, which has been used in variety of application in a world. As welding process carries heat input, material gets subjected to differential non uniform volumetric changes. Due to heat, expansion and contraction of the material takes place. This expansion and contraction of the material depends upon welding parameters, type of welding process, geometry etc. First compressive residual stresses are produced in the weld treated region, and then these stresses gradually get converted into tensile stresses, during cooling of a material. Solidification of a material depends upon chemical composition, filler material used, cooling temperature, working condition. The amount of tensile residual stress induced; largely affects performance of the material. Weld region and heat affected zone experiences transformation of the grain structure. During welding, heat affected zone and welded zone experiences transformation of austenite into other phases like pearlite, bainite and martensitic. All these transformation occur with increase in specific volume at microscopic level. The transformation of austenite to pearlite and bainite occurring at high temperature are easily accommodated with increase in specific volume. Therefore, this transformation does not contribute much towards the development of residual stress. However transformation of austenite to martensitic occurs at low temperature contributes much toward the development of residual stresses. These stresses may be tensile or compressive, depending upon the location of a material. Tensile residual stresses significantly affect the performance of the weld joint. So, it is always desirable to have compressive residual stress to increase fatigue life of a weld component. Many post weld treatments are available to increase fatigue life such as shot peening, surface rolling, polishing, etc.

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ultrasonic impact treatment or ultrasonic peening is the most effective method to increase fatigue life of a component.

Material selection is a key task in any engineering project. It is obvious that application does decide a material, but quality of results definitely depends upon quality of material. Since welding is a metal joining process, it finds wide application in a world. In this work, residual stress analysis is carried out, so behaviour of the material from yield point to fracture point is very important part of the investigation. Ductile material would be a good choice to examine the material in the plastic region, since yielding is occurred in ductile material. Stainless steel is one of the most widely used ductile materials which find application in different industries. Stainless steels are classified by their crystalline structure into three types as austenitic, ferritic, and martensitic. 300 series austenitic stainless steels are alloys of chromium and nickel. Most common grade of these steels is 304. These steels do have maximum carbon of 0.08 percent. Low carbon grade or L grade steels contain maximum carbon of 0.03 percent. These steels have good weld ability, excellent toughness, durability and corrosion resistant. Austenitic steels are costlier than ferritic stainless steel. 304 finds application in tanks, storage vessel, and pipe, cutlery, Architecture, sinks. Following table shows chemical composition for the AISI 304 grade which is used in this project work.

2. LITERATURE REVIEW

Stainless steel alloy has been widely used in the different sectors, such as pressure vessel, nuclear plant, refineries etc. Welding is the metal joining process which widely used in these applications. However welding process includes application of heat, due to which metal gets joined. Residual stresses are produce in this process. These stresses affect the performance of the weld joint subjected to tensile loading.

In this paper [2], Duplex stainless steel is welded having different behavior under tensile loading. Author has estimated residual stress numerically by using Labeas and Diamantakos formula and value of these stresses put as a initially stress in finite element model of welded joint. The weldment specimen model is subjected to tensile loading in order to investigate effect of residual stress on local yielding. Longitudinal and transverse weldment is subjected to tensile loading. True stress and strain graph for longitudinal, transverse and virgin alloy are compared and analyzed.

Residual stresses in butt welded steel plates are evaluated in this work [4]. Thermo mechanical finite element analysis has been performed to analyze effect of residual stress in butt joint of ASTM 36 steel plate. 2D plane stress analysis results are found to be in good agreement with 3D model and experimental results. 2D simulation of welding not only reduces the complexity of the problem but also providing the nature of residual stress in

weldments.

In this work [10], Author has investigate welding residual stress effect on fatigue crack growth behavior of aluminum alloy 2024-T3 plate. The interaction between residual stress and fatigue crack growth rate has been investigated by variable polarity plasma arc welded aluminum. Crack was continuously monitored using eddy current transducer and residual stresses were measured by neutron diffraction method. The effect of residual stress on fatigue crack behavior was modeled by using a crack closure and residual stress approach. Experimental result found that fatigue crack growth rate in the middle tension specimen is accelerated where as they de accelerated in compact tension sample.

Residual stress for aluminum plate under different butt joint parameters are analyzed by using finite element analysis [9]. A thermal elasto plastic method was used to simulate the process of variable polarity plasma arc welding. The welding temperature and stress field with different butt joint parameters at the intervals of D 0.3mm, 2mm: L 0.3mm, 2mm were calculated. The simulated and experimental results were compared and they are consistent with each other.

In this paper [5], Author has used Taguchi technique for AISI 304 and 316. Experimental investigation has been done for the process of TIG and MIG welding. Mechanical properties of austenitic stainless steel for the process of TIG and MIG welding are discussed.

The voltage is taken constant and different characteristics such as hardness, strength, modulus of elasticity, ductility, grain structure; tensile strength, breaking point, and heat affected zone are observed in both processes and finally concluded.

In this paper, Residual stress analysis of austenitic stainless steel has been carried out by using finite element method [12]. Residual stress is one of the major concerns in different manufacturing industries. In welding these stresses develop due to the non uniform cooling of the welded zone. Tensile stresses are mainly responsible for the failure of the product. There are various methods are available to measure residual stress, some of them are x-ray diffraction, hole drilling method. Author has carried our numerical simulation by creating 2D model of austenitic stainless steel weldment by using ANSYS 15.0 software. Results are studied and analyzed by author for further research purpose.

In this paper [3], Author has investigated residual stress and welding deformation in butt weld joint for different clamped positions on a plate. Thermal elastic-plastic analysis using FEM has been carried out to study thermo-mechanical behavior and evaluate the residual stress and welding deformation for butt joint plate, at different clamped position on plate. The temperature variation, fusion, heat affected zone, residual stress and deflection for different cases has been studied and compared with experimental results. Welding deformation and residual stress are depending on the different restrained position of butt welded joint.

Different engineering structures works under effect of residual stresses resulting from welding or other manufacturing processes. In the present work, Author has studied variation of residual stress fields on stress intensity factor and crack propagation angle. Numerical values of residual stresses are found out by formula proposed by author.

3. ESTIMATION OF RESIDUAL STRESS

In the present work, First residual stresses are determined by using software Ansys Workbench. Figure shows simulated distribution of longitudinal and transverse residual stress.

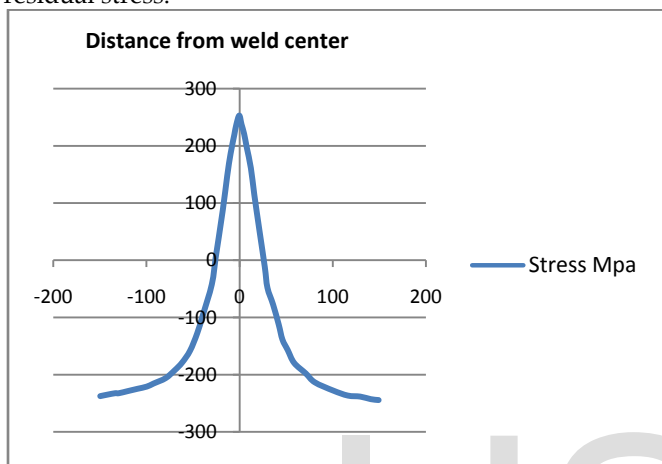


Fig. 1 longitudinal residual stress distribution of welded plate

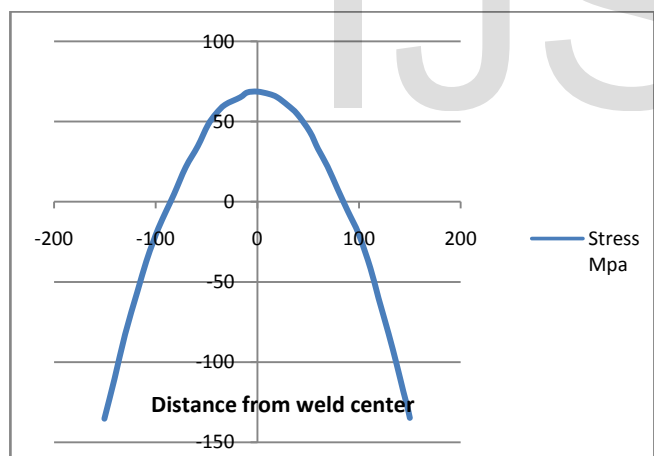


Fig. 2 Transverse residual stress distribution of welded plate

However following are the formulas proposed by Labeas and Diamantakos to find out magnitude of residual stress. The longitudinal residual stress in the weld region is found out by following equation,

$$\sigma_x = \sigma_{ox} \left(0.5 + \frac{z}{t} \right) \frac{1 - \left(\frac{y}{c_0} \right)^2}{1 - \left(\frac{y}{c_0} \right)^4} \quad (1)$$

σ_{ox} is a parameter defining the maximum value of the tensile residual stress and c_0 is the distance from y-axis at

which stress value changes from positive to negative that is from tension to compression. The function σ_x produces symmetric stress field with respect to y-axis, which has maximum value at $x = 0$. The effect of the residual stress vanishes far from the weld line. Where z is the through the thickness coordinate with $z = 0$ located at the bottom of the plate and t is the plate thickness. The residual stresses are self-equilibrated and the function σ_x decreases monotonically, until it reaches its minimum negative value and then increases again to zero without fluctuating with increasing x .

The Transverse residual stress in the weld region is found out by following equation,

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

σ_{oy} is a parameter defining the maximum value of the tensile transverse residual stress, d is a characteristic parameter of the σ_y distribution along the x-axis and L is the length of the plate. In the studied case $\sigma_{oy} = 70$ MPa, $d = 30$ mm, and $L = 300$ mm.

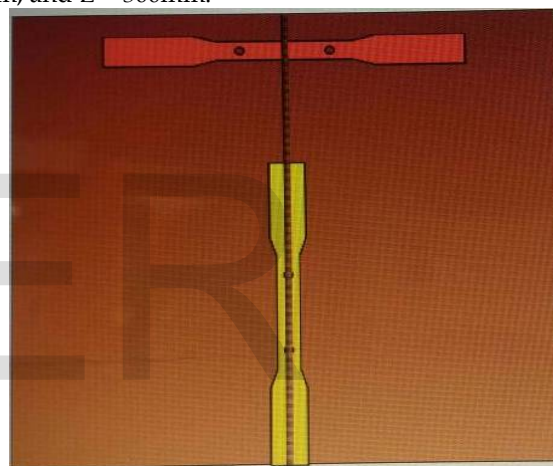


Fig. 3 Test specimen extraction scheme

4. ANALYSIS OF RESIDUAL STRESS

Finite Element Analysis has been carried out by using Ansys Workbench. For the weld deposition of material, Ansys mechanical APDL is used. Sequential transient thermal and transient structural analysis has been carried out to determine residual stresses. Macro birth and death element technique is used for the filler deposition on a metal. In this technique, first all elements are killed by using EKILL, ALL command. Heat flux is then applied on top face of the element and this active the first element and first load step is solved. One by one all the elements are solved by using same process. Whole analysis is solved in 62 steps, for that cooling time is kept as 2000 seconds. Following images shows fringe pattern of residual stress and from which Distance from weld centre vs. Stress curve is plotted. Curve is made smoother to get proper distribution of residual stress. Material non-linearity is defined by using bilinear kinematic hardening rule. Bauschinger's effect is observed in kinematic hardening

rule. The lowering of yield stress is observed, when deformation in one direction is followed by deformation in other direction known as Bauschinger effect, this is observed because of residual stresses left in the material during previous plastic deformation. In simple words, yield stress for compression is less than yield stress for tension. In bilinear curve we have to define value of tangent modulus, yield stress and modulus of elasticity. For defining material behaviour, values of specific heat, thermal conductivity, bulk modulus, Poisson's ratio, co-efficient of thermal expansion are defined based on temperature.

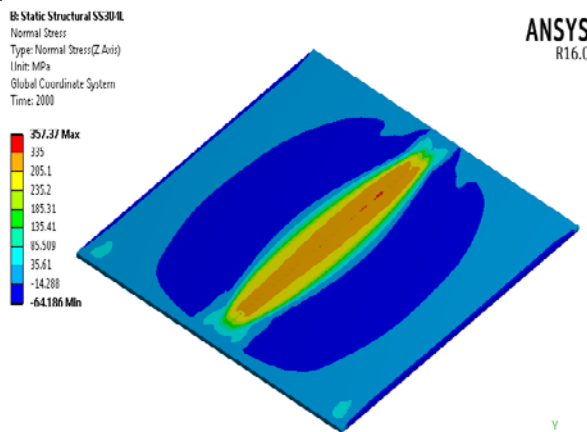


Fig. 4 Longitudinal residual stresses

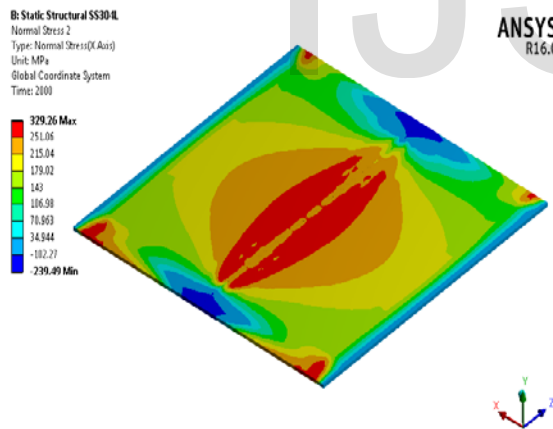


Fig. 5 Transverse residual stresses

5. EXPERIMENTAL WORK

In the present work, Austenitic Stainless Steel of grade AISI 304 has been used. The steel plate of dimension 300X150X3 mm is selected. Two plates of specified dimension are welded by using Tungsten inert gas welding process. Argon is used as an inert shielding gas. Plates are welded by using butt joint. Present work is carried out in three stages as shown below.

Stage 1 - Test specimen of specified dimension has been cut by using WEDM operation. This stage does not involve

welding process.

Stage 2- Two Austenitic plates of specified dimensions are welded by using TIG welding process. From welded plate test specimen of specified dimension is cut by using WEDM operation.

Stage 3- In this, two angular plates (45°) has been welded by using TIG welding process. From this plate, tensile test specimen at 45° angle has been extracted by using WEDM process in order to determine effect of residual stress on local yielding.

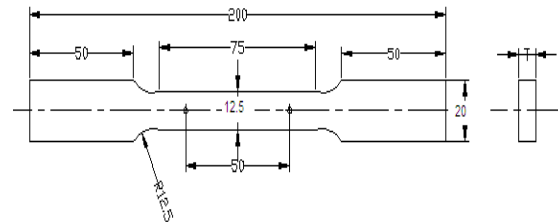


Fig. 6 Specimen drawing as per ASTM E8M

After welding of plates, test specimen of specified dimension is extracted by Wire Cut Electro Discharge Machining (WEDM) process. Superior surface finishing is achieved by using WEDM process. This process is very expensive as compared to other machining processes. Material removal mainly occurs due to thermal evaporation and melting. This thermal process is carried out in absence of oxygen, so dielectric fluid should be used for an oxygen free machining environment. There are various dielectric fluids are available such as Paraffin, Transfer oil, Kerosene, Deionised water. This process uses a small diameter copper or brass wire as a travelling electrode for removal of a material.



Fig. 7 Setup for Wire Cut Electro Discharge Machine

Figure shows a setup of WEDM process. Electro discharge machining or spark erosion machining is an electro-thermal machining process, where electrical energy is used to generate electric spark and material removal mainly occurs due to thermal energy of the spark. The electrode wire of diameter 0.2 to 0.3 mm diameter made of copper is used in this work. During this process, the wire is continuously fed through the top supply reel and wound

by bottom collecting reel. This continuous supply of a wire is essential because it gets eroded during the process and eroded wire is collected at back side of the machine. The spark is struck between moving electrode and the work piece thereby removing the material. The dielectric medium used is deionised water. Following image shows the specimens photograph after WEDM process.



Fig. 8 Test Specimen extracted using WEDM

6. EXPERIMENTAL TESTING

Tensile testing is uniaxial testing method used to determine mechanical properties of the material such as yield stress, tensile strength, percentage elongation, percentage reduction. This test is carried out on Universal Tensile Machine. For this test standard shape specimens have to be prepared. These standards are made by American Society for Testing and Materials. In this work, we have used standard specimen of ASTM E8. By doing this test stress vs. strain, force vs. displacement graph can be obtained. UTM is attached with the computer. One rotating knob is provided to increase the load; this load knob is attached with one of the linkage of the machine called as cross head displacement (CHD). Anvils are attached with this bar and specimens are clamped in anvils. As the knob gets rotated, uniform pull force is transmitted to specimen through the CHD member and output results are plotted on computer screen. This is static analysis test in which load is increased uniformly with respect to time, until a specimen gets fractured. After testing is finished, graphs can be obtained and analyzed for further research. This test is very important in engineering, to study the material behavior which is used to design a product in various applications.

In this test, four standard specimens are prepared as virgin, longitudinal, transverse and angular. These specimens are tested on UTM, in order to investigate effect of residual stress on the performance of a material. Residual stress is one of the important factors that affect the fatigue life, so by doing this test, behaviour of the material in plastic region is observed and analyzed for all four specimens. This test gives the output in the form of

engineering stress vs. engineering strain. It means that the stresses and strains are calculated by considering the original cross-section area. These values are converted into true stress and strains by using formulas.

It is very important to observe the behaviour of true stress strain curve, as it considers instantaneous cross-section area of the specimen. Engineering and true stress strain curve are different in shape, as true stress strain curve stands above in XY plot than engineering. Result of this test is depends upon gauge length. Reading of this gauge length is taken before and after test, in order to calculate elongation and reduction of a material. Fracture is the final point on the stress strain curve, where zero displacement is observed and crack gets initiated. This point is also called as Ultimate Tensile Strength (UTS) point. These yield and ultimate stress values are very important to design a product, although application does decides whether to design for yield or ultimate stress.



Fig. 9 Test setup for tensile test

Figure shows a test setup of a Universal Testing Machine (UTM). Tensile test is done on fixed length called as gauge length.

- Analysis of tensile test

Tensile test is simulated in Ansys workbench; Standard shaped specimen is modeled in UG software and imports it in Ansys Workbench. Non linear analysis has been carried out by putting values of elastic modulus, poisson ratio and tangent modulus. Model is meshed by keeping element size as 2. Load step is applied to the model, by giving axial pull force. Load vs. displacement values are noted down and stress vs. strain curve is plotted.

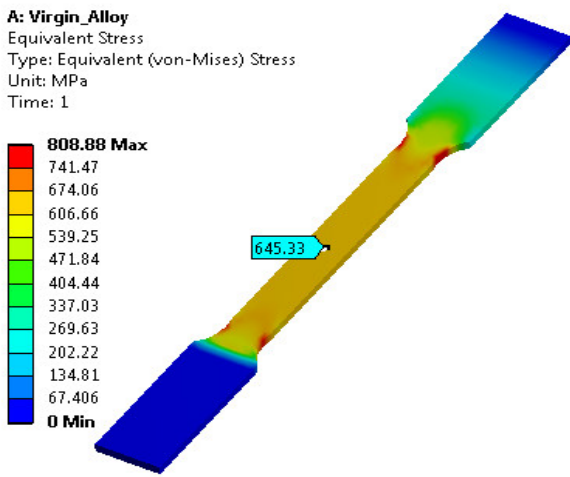


Fig. 10 stress values of Virgin alloy

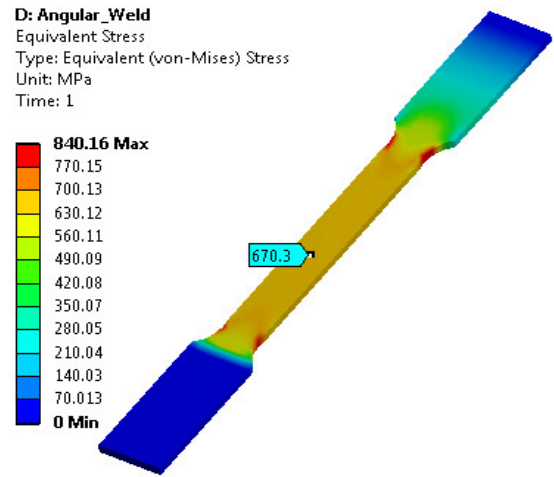


Fig. 13 Stress values of Angular Weld

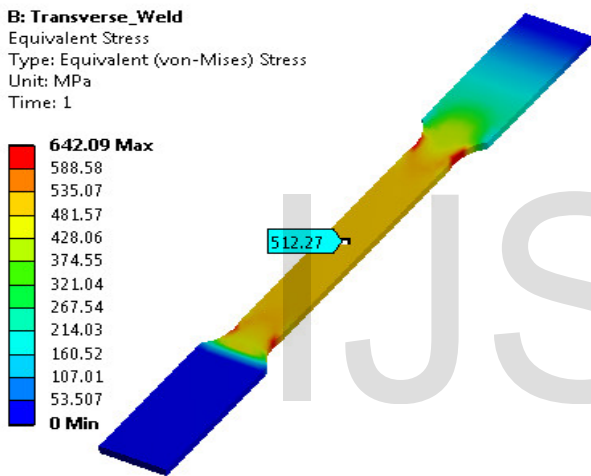


Fig. 11 Stress values of Transverse weld

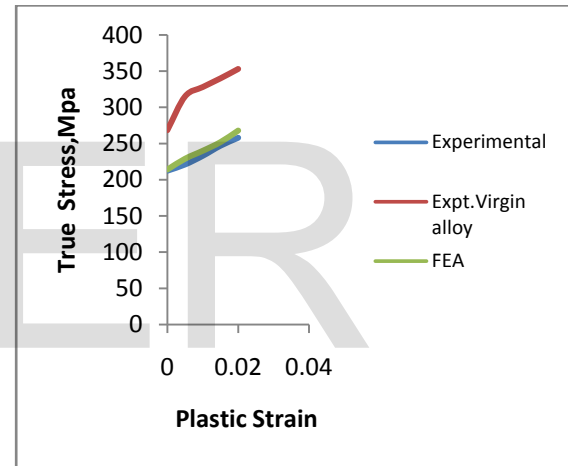


Fig. 14 Plot for Transverse Weld specimen

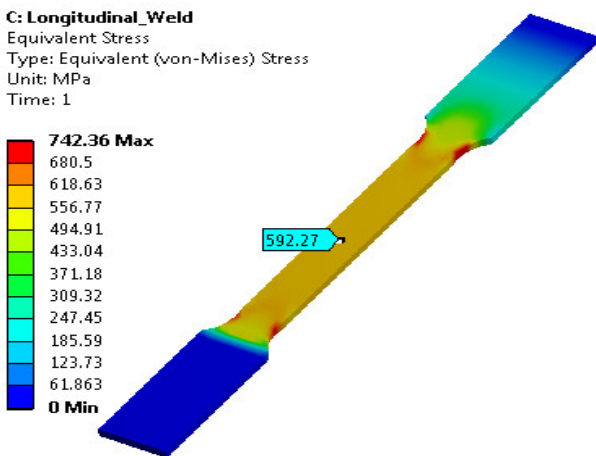


Fig. 12 Stress values of Longitudinal weld

Figure 14 shows comparison of true stress vs. plastic strain for transverse weld specimen. However, there is marginal difference between the stress values of virgin alloy specimen and transverse specimen.

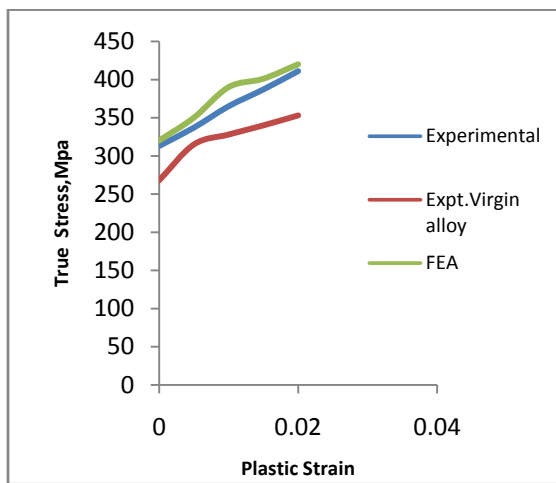


Fig. 15 Plot for Angular weld specimen

This graph has been plotted by converting the values of engineering stress vs. engineering strain graph from tensile test. For conversion following formula has been used.

$$\sigma_t = \sigma_e (1 + \varepsilon_e), \quad \varepsilon_t = \ln(1 + \varepsilon_e),$$

$$\varepsilon_{pl} = \varepsilon_t - \varepsilon_{el}$$

$$\varepsilon_{pl} = \varepsilon_t - \frac{\sigma_t}{E}$$

Where Modulus, $E = \frac{\sigma_t}{\varepsilon_t}$

7. CONCLUSION

Investigation of residual stress on the mechanical behavior of AISI 304 has been carried out. Tensile testing is done on the specimen, in order to check local yielding of a material. Residual stresses are found out by using formula proposed by Labeas and Diamantakos and values are assigned as an initial stress in the finite element software ANSYS. Longitudinal and transverse residual stress comes out to maximum at the centre of a butt welded plate.

Simulated results of FEA agree with the experiment results from tension test. Engineering stress, strain curve are converted to True stress, plastic strain curve and are compare with the virgin alloy specimen to study the mechanical behavior of a metal. There is a marginal difference between the curves after reaching plastic state. This indicates the effect of residual stress on a metal. However, in case of angular weld, residual stresses get neutralize, as welding has done at 45° angle, so shear stresses get balanced and as a result of which fatigue strength of material increased. True stress vs. plastic strain curves are plotted for virgin, longitudinal, transverse and angular weld and compared.

8. REFERENCES

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