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Numerical Investigation on the Effect of Residual Stress and Deformation in Multi-pass TIG welding using Finite Element Analysis

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Abstract: *Welding is an unavoidable technique that receives a lot of attention because of its greater number of industrial practices. When plate thicknesses exceed the limitations of two pass procedures, multi-pass welding can be employed. Further it also allows for the welding of a wide range of weld joints viz., different plate thicknesses and materials to use the same procedures. To help with the elimination of slag and minimize weld cracking, each weld pass should be slightly convex.. In other hand, the results of finite element analysis can be used to determine operating conditions, reduce defects, and control residual stress and deformation. The experimental method necessitates a large number of experiments, which takes a lot of time, money, and raw materials. As a result, a complete understanding of all physical events that occur throughout the welding process is required for the numerically based investigation. The primary reason for the study is to determine the mechanical impacts of welding, residual stress and distortions during multi-pass welding of two plates held in a V-joint configuration. Numerically simulated TIG welding process can help to detect operating and influential multi-pass parameters of the weld. Hence, the results obtained was provided a promised process variables with efficient welding and it can be employed in future welding applications.*

Keywords: *Multi-pass, TIG welding, Residual stress, Weld distortion, Welding simulation, FEA*

1. Introduction

An essential segment in the production / fabrication process is welding. It is usually the best way to join two or more pieces of metal to form a single component. Unlike any other method of joining metals, welding creates joints that are both permanent and significantly stronger. The primary benefit of welding as a joining process include permanent metal joining and high joint efficiency at low cost [1],[2]. Further, it is has been used widely in the fabrication of metal joining viz. pipeline production, boiler fabrications, ship building, structural engineering applications and etc., [3]. Other than metal joining, dissimilar materials also have been utilized to minimize the material cost incurred in fabrication of a specific applications. Tungsten Inert Gas (TIG) welding is an arc welding which working under non-consumable electrode, thereby the demand in usage of TIG welding is continuously increasing with various industrial applications viz. welding of pressure vessels, chemical cylinders, propellant tanks, structure of automobiles and aero-vehicles. The thin metal section or plates can be used to join with most common engineering materials as ferrous and non-ferrous, particularly, stainless steel, copper alloys, magnesium alloys and aluminum alloys [4].

In comparison to alternative techniques including shielded metal arc welding and gas welding, the process gives the operator more control over the weld, resulting in stronger, and better-quality welds. However, conducting better welding in a gas tungsten arc welding (GTAW) or TIG process by using multiple pass arc feeds as shown in Fig.1 in welding exceeds the limits of two pass techniques. Residual stresses are constituted stresses that exist in engineering components, even though there is no external force. These stresses are usually brought on by non-uniform volumetric change in metallic components, regardless of the manufacturing operations employed, such as casting, machining, forming, joining, heat treatment, coating, etc. [5].

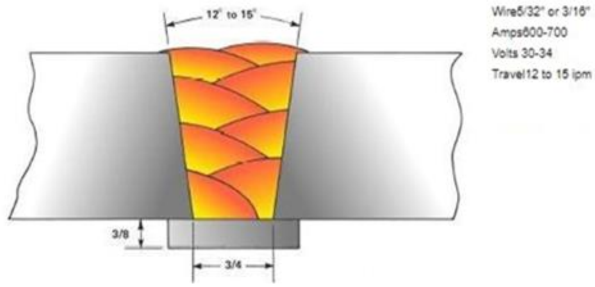


Fig.1 Multi-Passes uniformly distributed

However, the maximum value of residual stresses does not surpass the metal's elastic limit since stresses over this limit generate plastic deformation, and residual stresses above this limit are therefore accommodated in the form of component distortion. The residual stresses can be tensile or compressive with respect to location and type of non-uniform volumetric change occurring due to differential heating and cooling, as in welding and heat treatment. The differential welding thermal cycle that occurs between the weld metal and the region encompassed by the fusion boundary. This heat influenced zone during welding is the main cause of residual stresses in welded joints. It is well known that the residual stresses developed around the welding zones as a result of localized heating and quick cooling, which results in post-weld deformations of the structure [3],[6].

Weldments experience residual stresses as a result of uneven and non-uniform distributions of the plastic and thermal stresses. The yield strength and thermal stress simultaneously drop as the base metal's temperature rises.

Fig.2 Failure due to residual stress

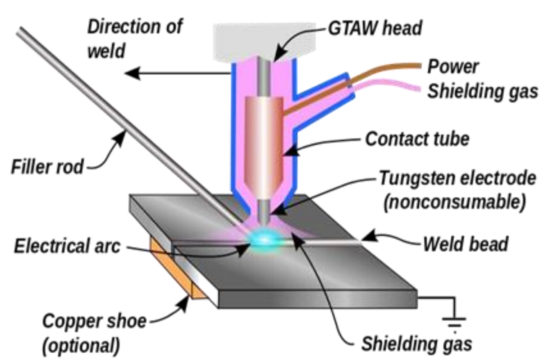


Fig. 3 Schematic of TIG welding

Residual stress may shorten thermal and mechanical fatigue lifetime. Fig.2 depicted that, increase the risk of stress corrosion cracking near the heat affected zone. Further, high residual stresses in the surroundings of the weld can stimulate the stress corrosion / fatigue cracking and brittle fractures. Additionally, the buckling strength of structures can be lowered by residual stresses in the base plate [7].

As shown in Fig. 3, it is clear that residual stresses that are below the temperature zone have an impact on how the TIG welding process functions. Thus the major issues with the welded structures can be brought on by residual stresses and distortions. In this paper, the multi-pass welding with uniform distribution was chosen and computationally used to determine the appropriate parameters in order to handle the aforementioned welding residual stress related issues.

2. Methodology

This numerical investigation focuses on the mechanical and thermal responses of the welding plate during welding process by using thermo-mechanical model of V-joint GTAW of Al5059 plate with a welding fixture. Primarily the induced residual stresses and temperature distributions were forecasted and the influences of the welding fixture of the plate were evaluated. In this study, it is identified that the residual stress and distortion are most dominant problems in welding process and all the welding-related factors were examined by using the numerical analysis. A heat source model is needed to do the required investigation. Here, the Gaussian heat source model has been used to predict the residual stresses from the welding process. At the initial stage, model has been developed for single pass welding after that it was built to multi-pass welding process for further analyses. Three-dimensional (3D) model was proposed for accurate post-weld deformation and residual stress distribution prediction. The model was developed in the CATIA software and then loaded into the ANSYS software for the purpose of thermal analysis. In thermal analysis, the temperature field is computed for each integration point as a function of time.

The thermal stress analysis uses this temperature time-history as an input. Here, the mechanical solution of the structure and the thermal solution can be fully or sequentially connected. Because it is possible to ignore the rate of heat genera on caused by mechanical dissipation energy in the heat transfer analysis. The modelling of a welding process frequently uses a sequentially coupled thermal stress analysis, in which a thermal analysis is followed by a stress analysis. The model results are compared with experimental data, such as weld pool geometry and residual stress variations, to validate the results.

3. Simulation and Analysis

Basically, either manual or torch GTAW requires the best coordination of the welder, and most applications experienced a limited efficiency as a result of manual performance. Since most applications demand for the welder to manually feed filler metal into the weld area with one hand while operating the welding flame with the other, GTAW typically necessitates the use of two hands. Further, it’s crucial to keep the arc length short and avoid making contact between the electrode and the work item. An electric spark produced by a high frequency generator, which is similar to a Tesla coil, is being used to commence the welding arc. This spark enables the welding current to pass through the shielding gas while the electrode and work piece are still separated, typically 1.5 mm to 3 mm apart. The size of the welding pool is determined by the size of the electrode and the intensity of current, and it is created by the welder by moving the torch in a small circle after the arc is struck. The operator then moves the torch back slightly and tilts it rearward by roughly 10º to 15º from vertical while keeping a constant distance between the electrode and the work item. The front end of the weld pool's filler metal is manually added as needed. This procedure was executed while adopting a few assumptions for the simulation analysis [7].

The appropriate process variables must be used to achieve a weld of acceptable standard. Adjusting one process variable typically requires changing one or more others in order to achieve a high-quality weld since the process variables are not entirely independent of one another. The process variables that have to be taken into consideration in the simulation analysis include the electrode position, electrode size, electrode extension, the arc length, arc travel speed, inductance, and electric current rate [8].

The common solution methodology existing for welding simulation analysis are (a) Rosenthal’s Solution deal with the semi-infinite body subjected to instant point, line or surface heat source, can satisfactorily predict the temperature at a distance far enough from the heat source, but fail to do so at its vicinity, (b) Eagar and Tsai modified Rosenthal's theory to include a two-dimensional surface Gaussian distributed heat source with a uniform distribution parameter and found an analytical solution for the temperature of a semi-infinite body subjected to this moving heat source. Their solution was a significant step forward for temperature prediction at near heat source regions. Even though this 2-D solution using the Gaussian heat sources could predict the temperature at regions closer to the heat source, they are still limited by the shortcoming of the 2-D heat source itself with no effect of penetration, and (c) Goldak first introduced the three dimensional, Double Ellipsoidal moving heat source and used FEM to calculate temperature field of a bead on-plate. They showed that their 3-D heat source could overcome the shortcoming of the previous 2-D Gaussian model to predict the temperature of the welded joints with much deeper penetration [7-9].

In this work, the Gaussian heat source model presented in equation (1) was employed. The heat conduction equation, which is governs the thermal field throughout the welding process as follows [10], [11];

$$\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)+Q_v = \rho(T)\,C_p(T)\frac{\partial T}{\partial t} \tag{1}$$

where, k, Q_v, ρ, C_p, and T are thermal conductivity, volumetric heat flux, specific mass, specific heat and temperature presented respectively. Thermodynamic boundary conditions for heat transfer include convection and radiation at the outer surfaces of solids. The heat flow density of convection (q_c) in the liquid / gas is given in (2) by Newton's heat transfer law as [10], [12];

$$q_c = \rho(T)\,h_c(T - T_0) \tag{2}$$

where, T, T_o and h_c are represents the temperature of the external surface, temperature of liquid/gas and is the coefficient of convective heat transfer respectively. In addition to the characteristics of the surface and environment, this coefficient is dependent on the convection conditions on the solid surfaces. Sorensen (1999), Teng et al. (2001) and Gery et.al (2005), have proposed the values of coefficient of convective heat transfer from 15 to 25 W/m^2K . The Stefan-Boltzmann equation (3) governs the heat flow density for radiation, qr as follows,

$$q_r = \epsilon_r \sigma_r (T^4 - T_0^4) \tag{3}$$

where, ϵ_r , σ_r, and T are represents the emissivity of the material surface, the Stefan-Boltzmann constant and the temperature respectively. The temperature of the welding process influences the degree of emissivity. Emissivity increases with temperature, where the temperature ranges between ambient and around 1450 ºC [13].

In this numerical investigation, the welding heat source was described using a combination of volume heat generation and surface heat flow models. The proportions that were used were 20% surface heat flow and 80% volume heat generation. In this, the volume heat generation provides 80% of the total energy, while the surface heat flow contributes 20% of the total energy. Each nodes of elements along the weld centerline acquires an equal distribution of the volume heat generation. Nodes under the welding flame were equally divided by the 80 % volume heat generation with irrespective of welding speed. From the tip of electrode, the surface heat flow is distributed as a Gaussian distribution is given in the equation (4). The formulation of the Gaussian heat-source distribution is [14],

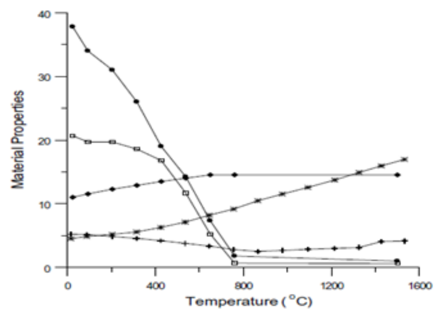
$$q(x,z,t) = \frac{3Q}{\pi r_b^2}\exp\left(-\frac{3}{r_b^2}\left[(x-vt)^2+z^2\right]\right) \tag{4}$$

where, Q is the heat input, v is welding speed and r_b is the distribution radius.

4. Result and discussion

4.1. Residual Stress Developed during Multi-Pass Welding of Stainless-Steel Plates

The material was selected and used for this investigation is ASTM A36. It is a ferritic-pearlitic based construction grade steel, which is frequently used for vehicles manufacturing and structures and is easily welded without special heat treatment. ASTM A36 structural steel was used to fabricate all the specimen that was butt-welded. Further, arc welding with tungsten inert gas was used for the weld. The dimensions of two similar plates are 110 mm x 30 mm x 4.5 mm, joined together by a single V-groove for a finished weldment that measures 80 mm x 30 mm x 4.5 mm. Before being welded, the two plates were tack-welded to one another at both ends, leaving a consistent 2 mm space between them. The mechanical and thermal properties of materials used were presented in the Fig.4 with respect to varying temperature.

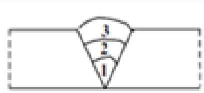


Symbol	Material Properties	Unit
●— σ_y	Yield stress	$\times 10^7$ Pa
□ —E	Young's modulus	$\times 10^{10}$ Pa
◆ — α	Thermal expansion	μ m/m °C
+—k	Conductivity	$\times 10$ W/m °C
*—c	Specific heat	$\times 10^2$ J/Kg °C

Fig.2 Mechanical and thermal Properties of ASTM A36

Table 1 shows the welding process parameters used in a single V-groove joint with multi-passes for effective welding. A three-dimensional parametric model with appropriate geometry was built in CATIA V5-3DX software as shown in Fig.5 for subsequent numerical analysis.

Table I Multi-pass welding process parameters

Pass sequence	Pass no.	Welding parameter		
		Current (A)	Voltage (V)	Speed (mm/s)
	1	85	25	1
	2	85	26	0.75
	3	85	25	0.55

The assumptions and specified dimensions are used to validate the geometry-based parametric model. The numerical simulation is then started while taking into account the CATIA V5-3DX model, and the model was transferred to ANSYS R18.1, Mechanical Finite Element Analysis (FEA) software of simulate weld for advanced analytical procedures using the IGES file format.

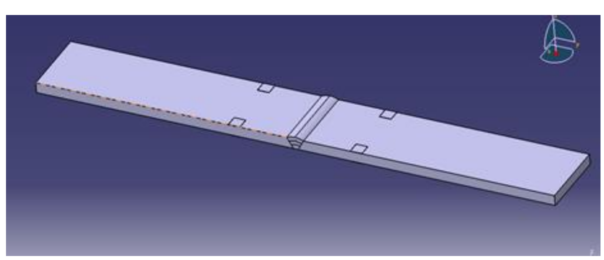


Fig.5 Parametric CATIA model

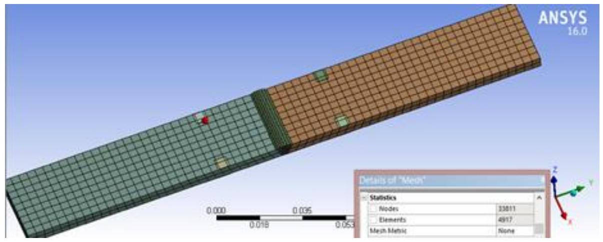


Fig.6 ANSYS mesh model

The hybrid mesh model is used in ANSYS for numerical simulation and is considered to be used to execute computations with a simulate weld platform [15]. Fig.6 represented the mesh model of numerical simulation by using simulate weld.

FEA is a mathematical description of a physical system and can typically be carried out in three stages: pre-process, solution, and post-process. FEA started with CAD model consisting of a part or assembly, material attributes, and appropriate boundary conditions which are referred as pre-processing. Post-processing is the study of the outcomes of resolving that mathematical representation at solution stage.

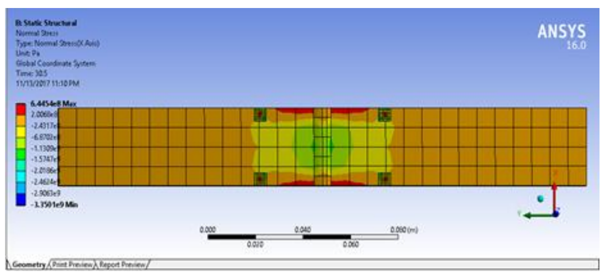


Fig.7 Longitudinal residual stress

When welding stainless steel plates in multiple passes, residual stress was induced which were numerically simulate d and the results presented in the Fig.7 and Fig.8 is clearly depicted the residual stress induced and distributed in both the way of longitudinal and transverse directions.

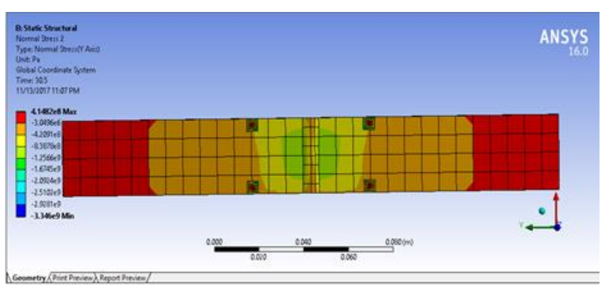


Fig.8 Transverse residual stress

Further, Fig. 9 and Fig.10 indicated the maximum residual stress that was induced in a weldment from the center of weld line for the longitudinal and transverse directions, respectively.

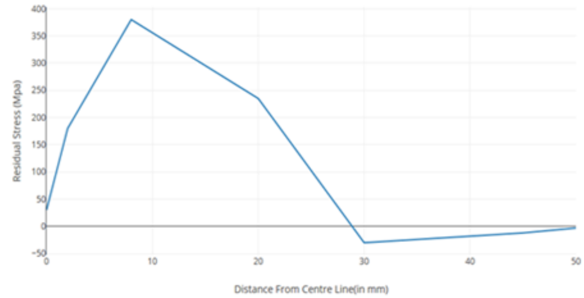


Fig.9 Longitudinal residual stress plot from center of weld line

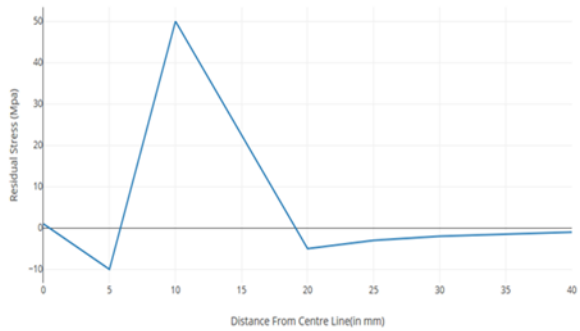


Fig.10 Transverse residual stress plot from center of weld line

The results obtained from the numerical simulations, the tensile residual stresses were generated close to the weld zone, and their magnitude reduces as one moves away from the weld zone. Due to the ability to prevent of parent materials, weld metal from contracting during cooling and the presence of clamps, high tensile stresses have created in the vicinity of the weld. Fig.7 and 8 shows the three-dimensional residual tension that was created during the welding process and is present surrounding the weld zone. Further, it is observed that longitudinal stress is greater than transverse stress, as shown in Fig. 9 and 10. Additionally, it was found that the weld plate's surrounding clamping zone experienced compressive stresses.

4.2. Temperature Distribution during Multi-Pass Welding

TIG welding takes 16 multi-passes to join two plates and Material properties used for simulation in ANSYS are as presented in Table.2

TABLE.II Input parameters for analysis

Parameters	Input values
Density	2670 kg/m^3
Specific heat	875 J/kg.K
Material strength	2.5 MPa
Young’s modulus	2x10^{11} Pa
Poisson’s ratio	0.3
Voltage	18-20 V
Current	180 A
Gas flow rate	18 l/min
Feed rate	3 mm/sec

Initially simulate weld done for single pass for newly activated elements and thermal stresses are calculated using the current load step temperature.

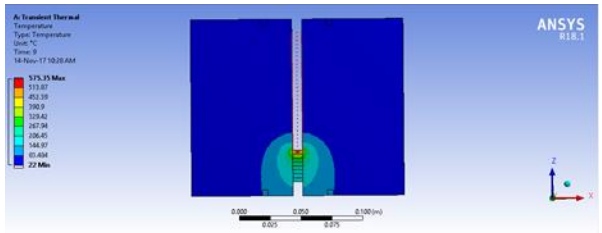


Fig.11 Temperature distribution in welding associated with element birth

The temperature distribution is typical with a slight variation from ambient, as shown in Fig. 11. As seen in Fig. 12, a single pass results in thermal stress distributions as temperature increases.

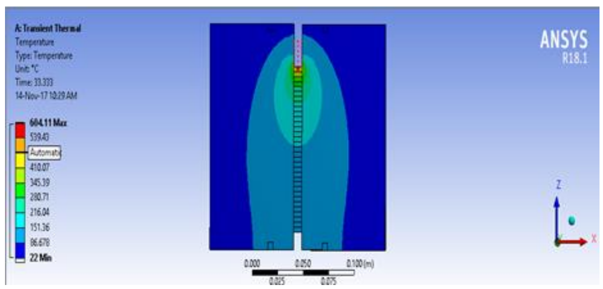


Fig.12 Temperature distribution in full welding

The relationship between specific heat, thermal conductivity and temperature was shown in Fig.13, which clearly indicates that both components increased with temperature rise.

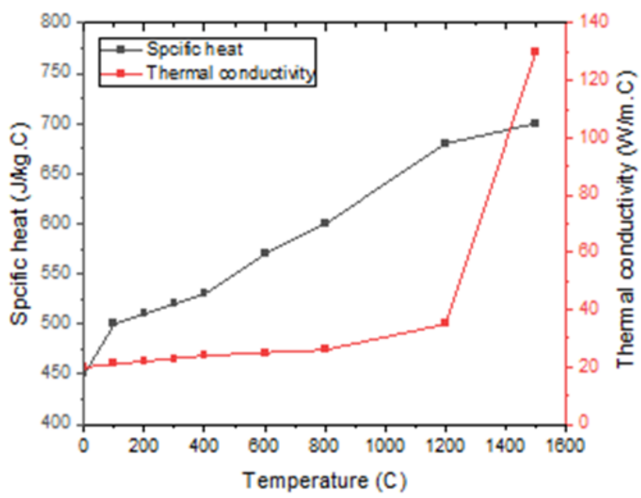
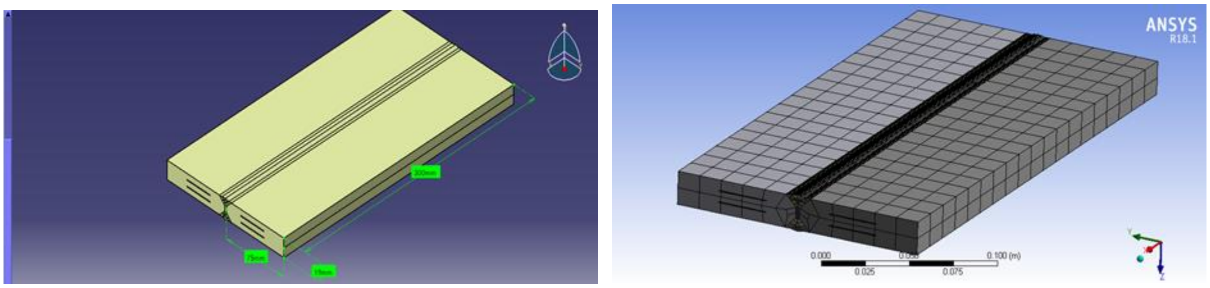


Fig.13 Relationship with thermal properties

K-Type thermocouples placed at various locations were used to extract the transient temperature cycles that occurred in the plates during welding in order to validate the simulation's results. The thermocouples detected high temperatures as the welding torch moved closer. Conduction and convection heat dissipation cause the temperature to begin to drop as the heat source moves forward. However, when latent heat of fusion is released during energy transfer in the solid-melting interface region, the temperature values at the solid-melting interface stay unaltered.

4.3. Temperature distribution and Residual Stress Developed during Multi-Pass with v-groove Welding

The numerical simulation technique for double v-groove multi pass welding was being used in order to show that it is compatible for a variety of applications. A CAD model and ANSYS mesh model is shown in Fig.14 (a-b) respectively, these models developed for further numerical analysis.



(a) (b)

Fig.14 Parametric models for analysis (a) CAD model (b) ANSYS mesh model

The multi-pass welding FEA numerical simulation in ANSYS mesh models carried out in ANSYS environment. The welding passes were shown in Fig. 15 (a–c), which indicated how each step was performed and simulated consistently.

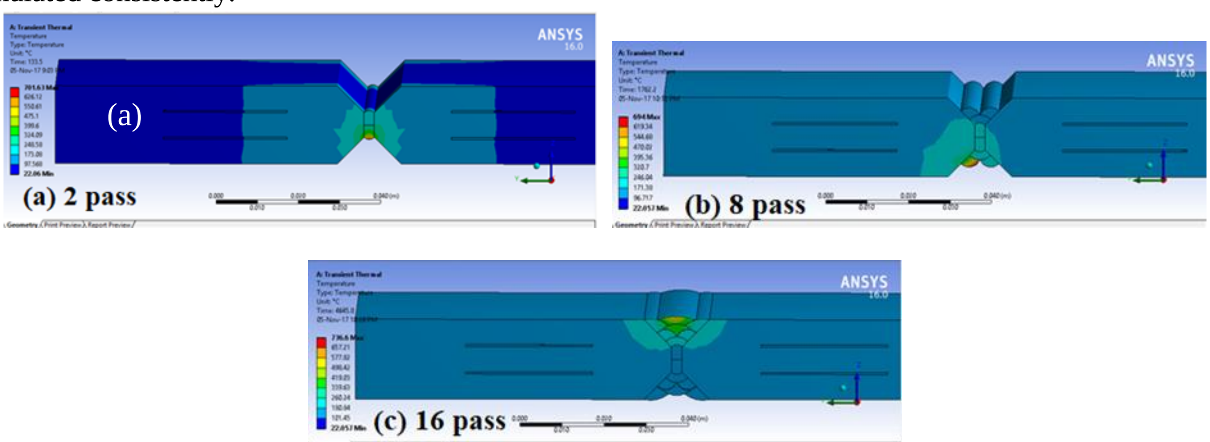


Fig.15 Steps of welding passes in front view (a) 2 pass (b) 8 pass (c) 16 pass

The FEA simulations carried out to determine the residual stress formation and thermal distribution. Fig.16 and Fig.17 indicated the residual stress-related results that were obtained, demonstrating the significant variations in both the longitudinal and transverse stress components.

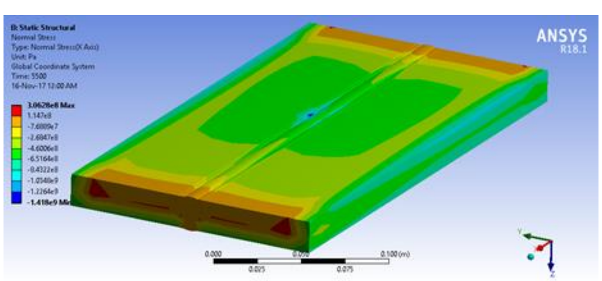


Fig.16 Longitudinal Residual stress from FEA

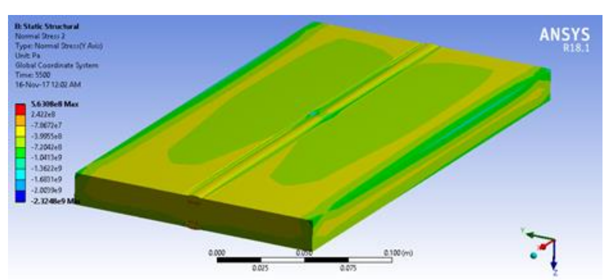


Fig.17 Transverse Residual stress from FEA

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Similar to the simulation results for thermal distribution, the data were presented in Fig. 18, which showed how the multi pass procedure was carried out optimistically and with less power.

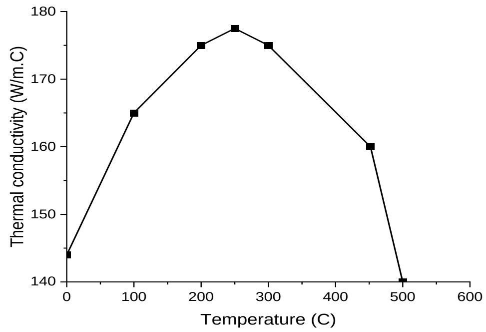

Fig.18 Simulation result of thermal distribution

5. Summary and Conclusion

The multi pass welding was performed by using FEA numerical simulation technique. The assumptions made with respect to butt-welded TIG welding to determine residual stress impact and thermal distribution in the welded region. The obtained simulation results helped to draw some conclusions as follows,

- It was verified that the generalized plane strain assumption produced acceptable stress distributions in both the longitudinal and transverse directions.
- With increasing distance from the heat source's center, the temperature in the region of the weld bead and the heat-affected zone decreases significantly.
- When using multiple passes, a compressive stress appears away from the weld bead and a very large tensile longitudinal residual stress appears near the weld toe.
- Near the weld toe, a significant transverse residual tensile stress is generated. As the distance from the weld toe rises, the stress decreases until it reaches zero.
- The results from multi pass welding were promising process variables with effective welding, and it can be used in future welding applications.

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