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"Finite Element Analysis of Residual Stress and Heat Distribution in Plasma-Transferred Arc Hard Facing of SS304"

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Abstract: Plasma-transferred arc (PTA) welding is an advanced thermal process for applying wear and corrosion-resistant layers to metallic surfaces. This research explores the modeling and simulation of PTA hardfacing process using Finite Element Analysis (FEA). The study focuses on the development of an autogenous heat source model and its impact on residual stress, observed through atomic displacement due to heat distribution. Various generations of weld heat source models are reviewed, culminating in the use of a double ellipsoidal power density distribution for accurate representation. The thermal transient simulation employs temperature-dependent properties of SS304, with results informing structural analysis to determine residual stress and displacement. Experimental validation through bending displacement and dye-penetration tests confirms the model's accuracy, highlighting the critical influence of heat input parameters on residual stress and crack formation. This research underscores FEA's pivotal role in optimizing PTA welding processes for enhanced product quality and reliability.

Keywords: enhanced, optimizing, formation, representation

Introduction

Plasma-transferred arc welding (PTA welding) is a thermal process for applying wear and corrosion resistant layers on surfaces of metallic materials. The highly energetic plasma arc melts the surface of the base material. At the same time, the powdery filler material is inserted into the arc. During solidification, a substance-to-substance bond between the filler material and the base material is created. The advantages of this process are a low dilution rate, a small heat-affected zone and a high deposition rate. Thus, many surface properties needed for special applications can be economically produced. There are many technological advancements has been taken place in last many years in the field of Plasma hardfacing [1].

Finite Element Analysis (FEA) holds significant importance in the modeling of plasma transfer arc hardfacing processes [2]. With its capability to simulate complex thermal dynamics, FEA provides invaluable insights into heat generation, conduction, convection, and radiation, essential for optimizing process parameters and minimizing defects [3]. Moreover, FEA enables the prediction of material behavior under extreme conditions encountered during hard facing, facilitating the assessment of various hard facing materials and deposition strategies. Through the identification of defect mechanisms such as residual stresses and metallurgical defects, FEA aids in implementing preventive measures to enhance product quality and reliability. Additionally, FEA enables comprehensive design validation by integrating multiple physics phenomena, ensuring compliance with industry standards and safety requirements [4].

In conclusion, FEA plays a critical role in advancing the modeling and simulation of plasma transferred arc hard facing processes by providing insights into thermal dynamics, predicting material behavior, optimizing process parameters, and validating component designs [5]. By leveraging FEA, engineers can enhance the efficiency, reliability, and quality of PTAH operations across various industrial applications, leading to improved performance and longevity of engineered components [6].

In this article, simulation of the autogenous heat source was used and studied to study the change in the residual stress by measuring displacement of atoms due to heat distribution during the PTAHF process.

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Weld Heat Source:

Knowledge about a weld heat source either comes from experimental observation or more detailed models of the welding process. Experimentally, it was studied by observing various parameters, optical measurement of cross section, using infrared cameras by measuring heat distribution, and distribution of power density etc. Modeling of heat source was greatly influenced by the factors like the accuracy of the data available to model of the heat source such as thermal conductivity, specific heat, latent heats, Young's modulus and Poisson's ratio, etc [7]. The purpose of the modeling and the information available are the other factors influencing the modeling the weld heat source.

Modeling a Weld Heat Source

Most welding processes use a heat source such as an arc, plasma torch, laser or electron beam. The temperature field due to heat from the heat source melts the base metal creating a weld pool. The temperature field driven by the weld heat source is the dominant driving force of the welding process [8]. It causes phase transformations, thermal strain and thermal stress, distortion and residual stress [9]. To analyse or predict the behaviour of a weld in a structure, this transient temperature field must be computed with useful accuracy [10]. The transient temperature outside of the weld pool depends primarily on the distribution of energy from the heat source and the conduction of heat away from the weld pool by conduction in the solid. Stress and strain usually have little effect on the transient temperature field.

Weld heat source models has been classified into categories of First Generation to Fifth Generation. First Generation weld heat source models are the point, line and plane heat source models of Rosenthal and Rykalin [11]. These models act on very simple geometric domains such as infinite sheets or plates. They only determine steady state solutions of the temperature field.

Second Generation weld heat source models replace the point, line and plane models that mathematically are delta functions, with distribution functions. The first of these was a distributed flux model by Pavelic and by Rykalin. However, it could not model deep penetration welds such as electron beam, laser or plasma welds and most high-power arc welds such as those with a nail head cross-section. Goldak et al proposed a distributed power density model that could model deep penetration welds with somewhat more complex weld pool shapes [12].

The next advance in weld heat source models, Third Generation models, predicted the liquid weld pool shape. Sudnik has developed these weld heat source models to the current state of the art. Weiss extended Sudnik's ideas to include some effects of the arc interaction with the weld pool shape. Weiss was able to predict effects of vertical, horizontal welding on weld pool shape in addition to flat welding. The Third Generation Models ignore the Lorenz force, the Marangoni force and the force due to the momentum flux from any droplets added to the weld pool from a consumable electrode.

Fourth Generation models are distinguished by adding the equations of fluid dynamics to the modeling of the weld heat source. Recall that the First, Second and Third Generation models have no fluid velocity. The most general equations for macroscopic fluid dynamics are the Navier-Stokes equations. They can include buoyancy and Lorentz forces acting on the interior of the liquid phase. Marangoni effect forces, pressure and shear forces from the arc act on the surface of the weld pool.

Fifth Generation models make a serious effort to include a model of the arc in the heat source model. This adds the equations of magneto- hydrodynamics to the equations in the previous models. Although these Fifth-Generation models are very general, they face even more serious mathematical difficulties than the Fourth Generation Weld Heat Source Models.

FEA Simulation Model

The thermal transient simulation was carried out first using the temperature dependent properties of the base plate as given in the Table-1. Then, the out put in terms of temperature distribution was captured at each node and supplied to carryout the structural analysis of the modelled base plate. By structural analysis simulation residual stress and the displacement at each node was calculated.

Table-1: Temperature dependent properties of SS304

Temperature	**Degree Kelvin**	**293**	**373**	**473**	**573**	**673**	**773**
Elastic modulus	GPa (ksi x 1,000)	193	193	193	187	183	179
Coeff. of thermal expansion	/°C x 10-6	16.27	16.6	17.02	17.43	17.84	18.26
Thermal conductivity	W/m °C	15.56	16.2	17.5	18.8	20.1	21.4
Specific heat	J/kg°K	475	505	527	548	561	577
Density	Kg/m3	7900	7900	7900	7900	7900	7900
Poison ratio	--	0.28	0.28	0.28	0.30	0.32	0.28

Initially, FEA model of the plate was generated for 2-D transient thermal analysis using an element type PLANE55 and 3-D thermal analysis using SOLID70 type of element. The meshed model of the plate is shown in Figure-1.

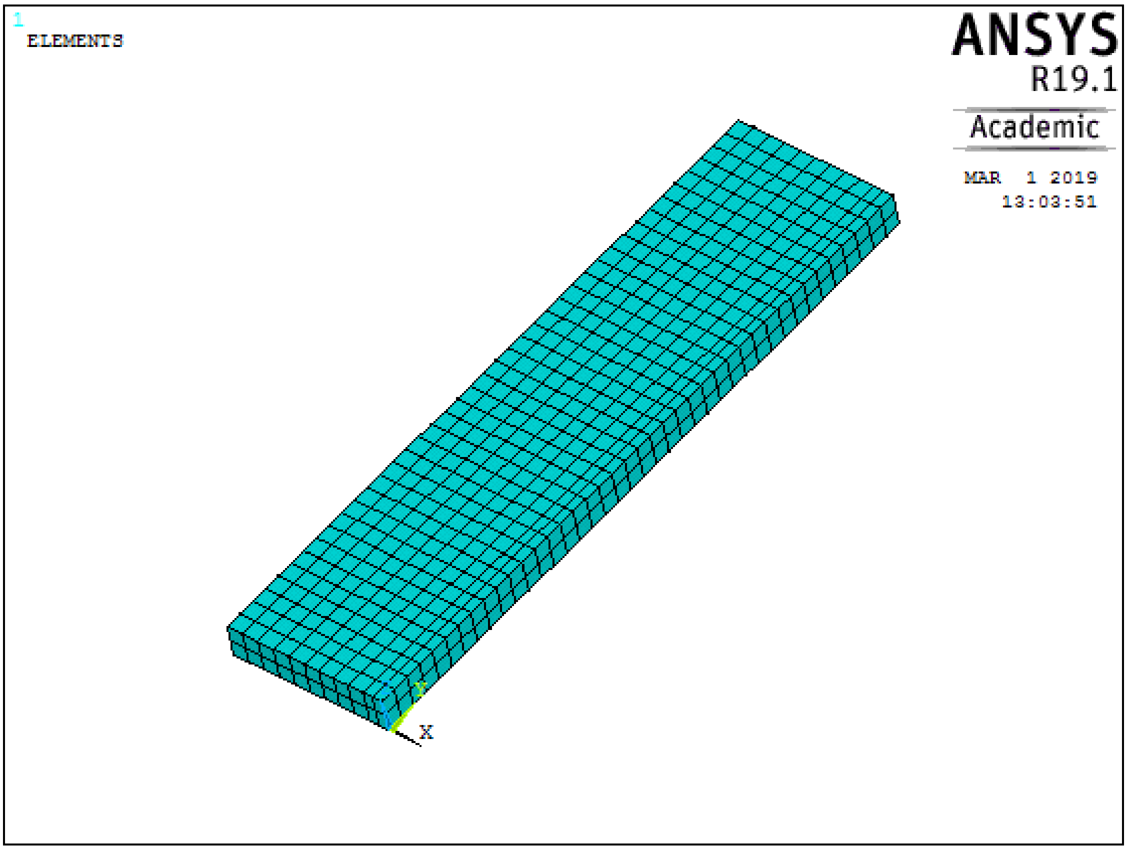

Figure 1 Mesh model of the SS304 plate

Selection of Heat Source

The heat source model in this study adopted was the autogenous welding simulation of 304SS (UNS S30400) plate with double ellipsoidal power density distribution.

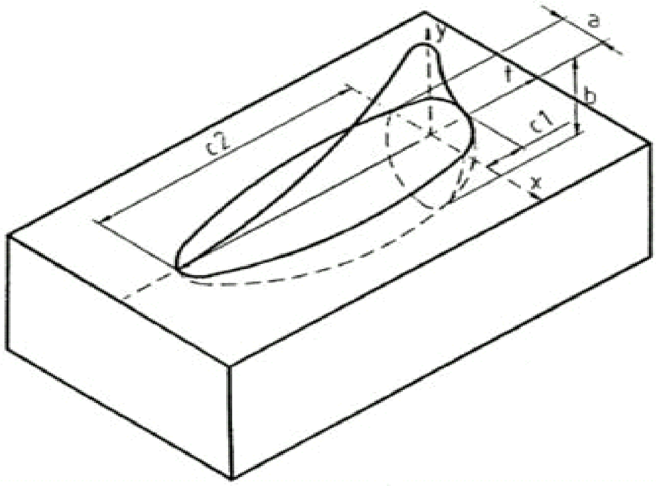

Figure 2 Double ellipsoidal power density distribution model

In this model, the fractions f_f and f_r of the heat deposited in the front and rear quadrants are needed, where $f_f + f_r = 2$. The power density distribution inside the front quadrant and for the rear quadrant of the source the power density distribution inside the ellipsoid becomes:

$$q(x,y,z,t) = \left(\frac{6\sqrt{3}f_f Q}{abc_1\pi\sqrt{\pi}}\right) e^{-3(x^2/a^2)} e^{-3(y^2/b^2)} e^{-3(z^2/c_1{}^2)}$$

$$q(x,y,z,t) = \left(\frac{6\sqrt{3}f_r Q(r)}{abc_2\pi\sqrt{\pi}}\right) e^{-3(x^2/a^2)} e^{-3(y^2/b^2)} e^{-3(z^2/c_2{}^2)}$$

Where,

$Q(r) = \text{energy input rate (W)}$

The parameters a, b, c can have different values in the front and rear quadrants since they are independent. Indeed, in welding dissimilar metals, it may be necessary to use four octants, each with independent values of a, b and c. In cases where the fusion zone differs from an ellipsoidal shape, other models should be used for the flux and power density distribution. For ellipsoid quadrants can be superimposed to more accurately mode.

In case of Plasma Transferred Arc Welding other condition of molten pool is not spherically symmetrical. This lifting function also has ascertained degree of unitary property. To improve this model a double ellipsoidal heat source model has been proposed. Energy input rate in double ellipsoidal heat source model can be expressed as following [13]:

$$Q(r) = q_m \exp\left(-3\left((X^2) + (\frac{(Y^2) - U * (TIME)^2}{R^2}\right)\right)$$

$$q_m = \frac{3}{\pi R^2} Q$$

Where,

$Q = \eta VI$

$\eta = heat\ source\ efficiency, V = Voltage, I = Current$

$U = Welding\ Speed$

$R = Radius\ of\ arc\ generated\ from\ torch$

Thermal Transient analysis

The welding process simulated in the software is for the autogenous model. The initial temperature of plate is taken as 303°K. The arc radius of plasma torch(R) is 3 mm for the heat flux equation, which is selected from the data of plasma torch manual. The welding is done on the edge of the plate from which NL node line passing and heat source mathematical model used is combine heat source of Gaussian and Double Ellipsoidal. The convection is applied on the all the surface except the bottom surface of the plate, the convection type is natural air convection the convection heat transfer coefficient of air was taken as 10 $W/m^2\,°K$. The welding time was 80 second for the variable voltage and variable current process parameter and it is changing for the variable speed process parameter. The cooling period of 3 hours was applied for all different process parameter to get back the value of plate temperature to the initial temperature. The temperature distribution over the entire time is shown in the figure 3 to 5.

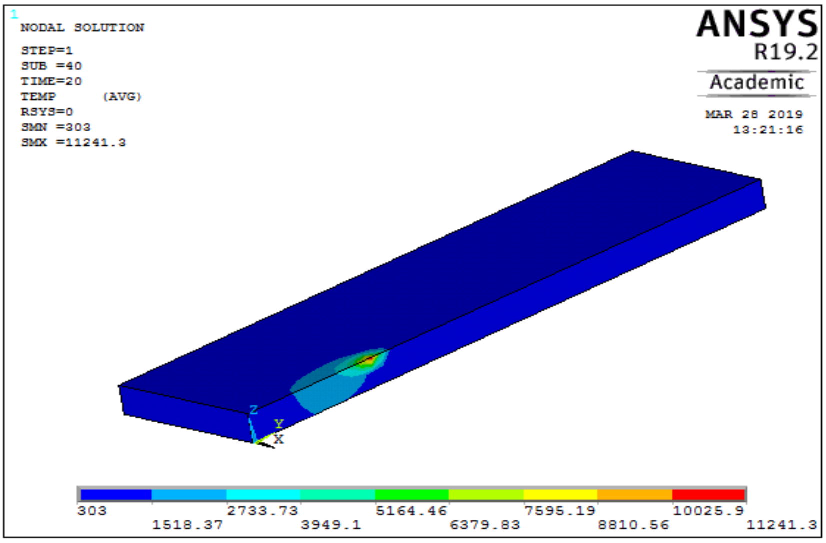

Figure 3 Temperature distribution at starting of simulation

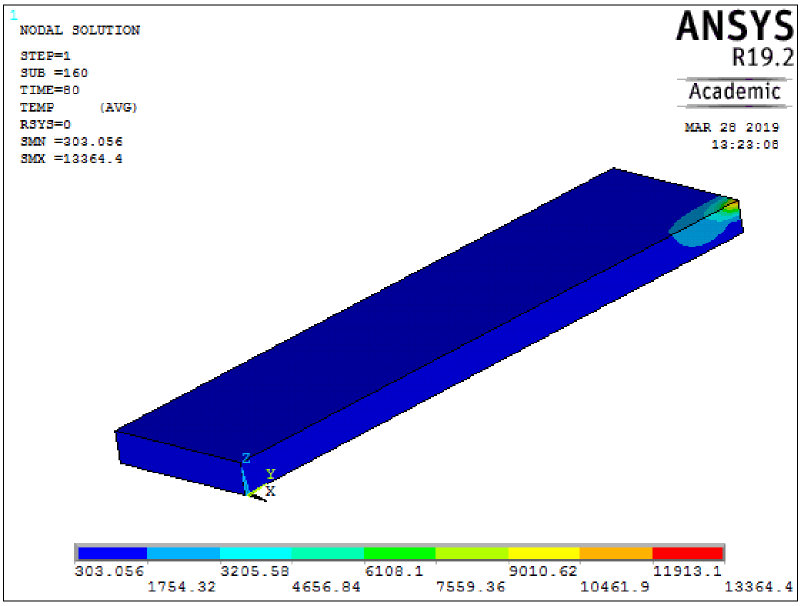

Figure 4 Temperature distribution at intermediate stage

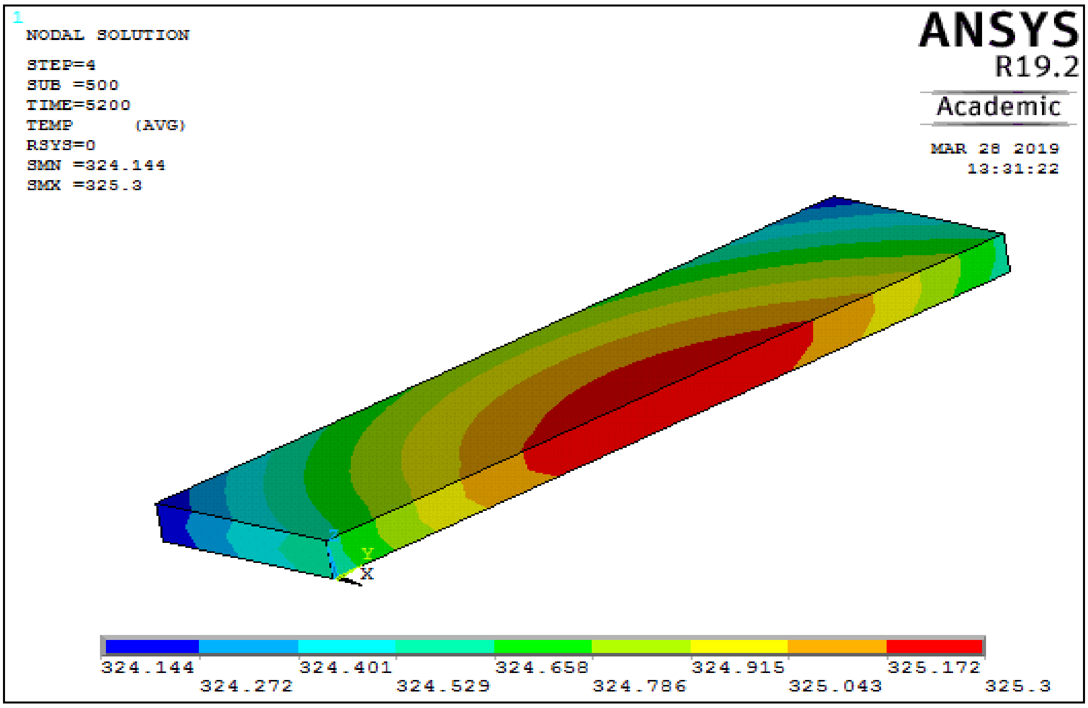

Figure 5 Temperature distribution at end of simulation

Structural analysis

To find the value of residual stress and displacements in the plate due to welding, the thermal analysis result was used into the structural analysis in the software. The zero degree of freedom boundary constraint is applied on the bottom of surface. Von mises stress is obtained to get the value of residual stress acting in the plate as shown in figure 6. Z – direction of component was considered for the finding out displacement value because, residual stress causes bending in the Z-direction and the same is shown in figure 7.

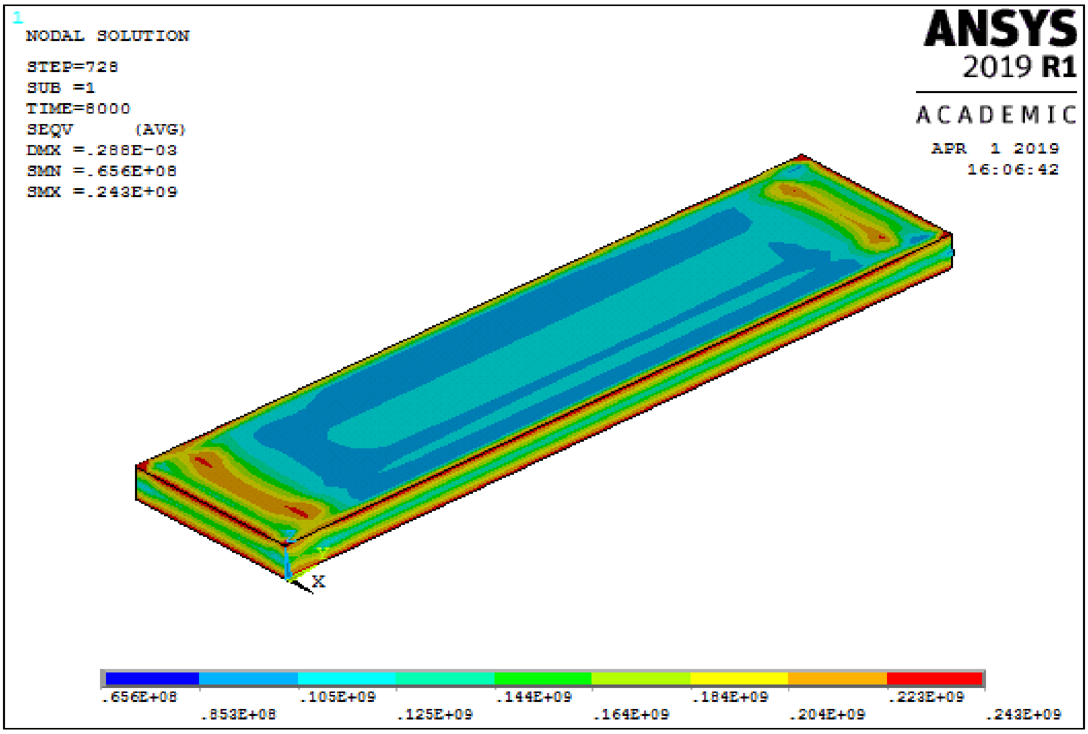

Figure 6 Von mises stress

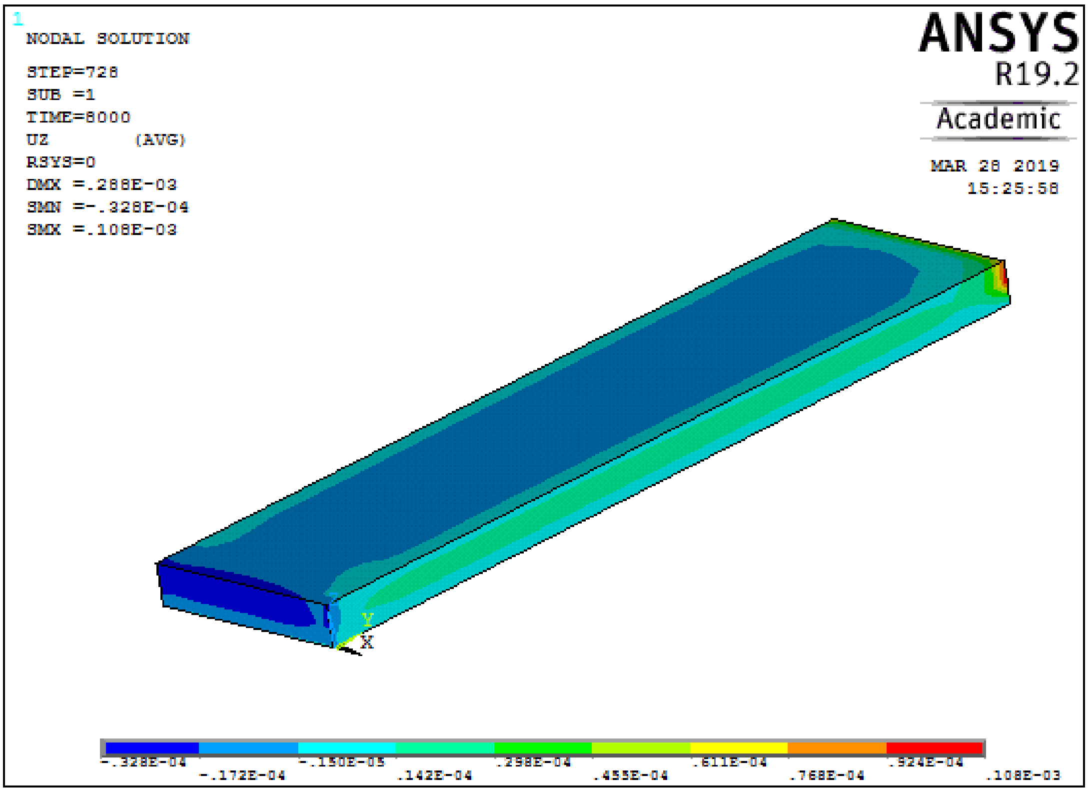

Figure 7 Displacement along the Z-axis

Experimental Validation of the Analysis

To validate the results, obtain from analysis and simulation done in software, two autogenous plasma weld plate for high and low heat input parameter were prepared. Bending displacement and the die-penetration test were carried out for both the plate which is shown in the figure 8 (a) and (b).

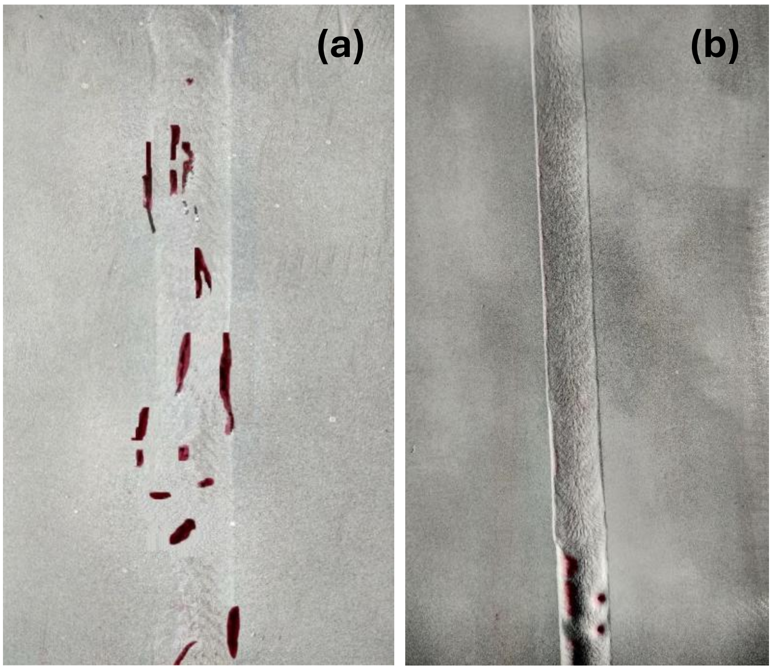

Figure 8Test plate with (a) high heat input (b) low heat input

By the dye penetration test it was founded that in the plate with the higher heat input crack generated in the fusion zone, while for the plate with lower heat input, no crack was observed. Also, the result obtained from the analysis, the plate has maximum value of the residual stress and displacement value in the plate having higher heat input. And the value of residual stress is exceeding the yield stress value in the fusion zone for these set of parameters. This indicates that fracture may be initiated in the fusion zone and there are chances of the crack generation. Similarly, for the other process parameter, minimum value of the residual stress and displacement value was observed in the analysis result.

Conclusions

FEA significantly advances the understanding and optimization of plasma-transferred arc welding processes. The developed indigenous heat source model, based on a double ellipsoidal power density distribution, effectively simulates the thermal and structural behaviour of SS304 during PTA welding. The study confirms that higher heat input parameters lead to increased residual stress and potential crack formation, while lower heat inputs minimize these effects. Experimental validation supports the simulation results, emphasizing the importance of precise heat source modeling for predicting and mitigating defects. FEA proves to be an indispensable tool for enhancing the efficiency, reliability, and quality of PTA welding, contributing to the longevity and performance of engineered components across various industrial applications.

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