Evaluation of preheating impact on weld residual stresses in AH-36 steel using Finite Element Analysis

Evaluación del impacto del precalentamiento sobre las tensiones residuales de soldadura en acero AH-36 mediante análisis de elementos finitos

Avaliação do impacto do pré-aquecimento nas tensões residuais de solda no aço AH-36 utilizando Análise de Elementos Finitos

Atif Shazad [1(*)], Muhammad Asif [2], Najam Siddiqui[3], Muhammad Uzair[4], Asad A Zaidi[5]

Recibido: 18/03/2024 Aceptado: 20/05/2024

Summary. - Shipbuilding industry is a valuable and profit earning industry which plays a vital role in country's economic development. Ships have crucial impact on country's trade due to necessary support for maritime transportation. Moreover, ships can be utilized for protecting coastal area. Steel chiefly utilized for ships construction due to its good strength and durability. This study emphasizes on residual stress analysis of AH-36 shipbuilding steel. Abaqus software is utilized for finite element analysis to evaluate residual stresses. Mitigation of these residual stresses is very essential; hence preheating technique is discussed in this study. Preheating was conducted at three temperatures i.e., 100ºC,150ºC and 200ºC. Results indicate that Von Mises stresses were decreased effectively due to preheating. 12.6%, 21% and 45.6% reduction were observed at preheating temperatures 100ºC, 150ºC and 200ºC respectively. Further evaluation of stresses revealed that due to preheating of base plate, longitudinal stresses reduced to 21.3%, 44% and 52.4% by increasing preheating temperature from 100ºC,150ºC and 200ºC, respectively. Mitigation of thermal gradient between weld zone and base plate resulted in reduction in overall stresses of base plate.

Keywords: Mitigation; AH-36; Abaqus; residual stresses; finite element analysis.

(*) Corresponding Author
[1] PhD Scholar, Department of Mechanical Engineering, NED University of Engineering and Technology (Pakistan), atifshahzad2717@gmail.com, ORCID iD: https://orcid.org/0000-0002-3277-7901
[2] Assistant Professor, Department of Engineering Sciences, PN Engineering College, National University of Sciences and Technology, Karachi, Pakistan, muhammadasif@pnec.nust.edu.pk, ORCID iD: https://orcid.org/0000-0003-4318-8253
[3] Engineer, Department of Engineering Sciences, PN Engineering College, National University of Sciences and Technology, Karachi, Pakistan, najam.siddiqui@gmail.com, ORCID iD: https://orcid.org/0009-0004-3086-5715
[4] Associate Professor, Department of Mechanical Engineering, NED University of Engineering and Technology (Pakistan), uzair@neduet.edu.pk, ORCID iD: https://orcid.org/0000-0002-2033-6244
[5] Associate Professor, Department of Mechanical Engineering, Islamic University of Madinah (KSA), sali@iu.edu.sa, ORCID iD: https://orcid.org/0000-0001-5457-5684

Memoria Investigaciones en Ingeniería, núm. 26 (2024). pp. 225-243
https://doi.org/10.36561/ING.26.14
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

Resumen. - *La industria de la construcción naval es una industria valiosa y rentable que desempeña un papel vital en el desarrollo económico del país. Los barcos tienen un impacto crucial en el comercio del país debido al apoyo necesario para el transporte marítimo. Además, los barcos pueden utilizarse para proteger la zona costera. Acero utilizado principalmente para la construcción de barcos debido a su buena resistencia y durabilidad. Este estudio hace hincapié en el análisis de tensiones residuales del acero de construcción naval AH-36. El software Abaqus se utiliza para el análisis de elementos finitos para evaluar tensiones residuales. La mitigación de estas tensiones residuales es muy esencial; por lo tanto, en este estudio se analiza la técnica de precalentamiento. El precalentamiento se realizó a tres temperaturas, es decir, 100 ºC, 150 ºC y 200 ºC. Los resultados indican que las tensiones de Von Mises disminuyeron efectivamente debido al precalentamiento. Se observaron reducciones del 12,6%, 21% y 45,6% a temperaturas de precalentamiento de 100ºC, 150ºC y 200ºC respectivamente. Una evaluación adicional de las tensiones reveló que, debido al precalentamiento de la placa base, las tensiones longitudinales se redujeron al 21,3%, 44% y 52,4% al aumentar la temperatura de precalentamiento de 100ºC, 150ºC y 200ºC, respectivamente. La mitigación del gradiente térmico entre la zona de soldadura y la placa base dio como resultado una reducción de las tensiones generales de la placa base.*

Palabras clave: *Mitigación; AH-36; Ábaco; tensiones residuales; análisis de elementos finitos.*

***Resumo*. -** *A indústria da construção naval é uma indústria valiosa e lucrativa que desempenha um papel vital no desenvolvimento económico do país. Os navios têm um impacto crucial no comércio do país devido ao apoio necessário ao transporte marítimo. Além disso, os navios podem ser utilizados para proteger a área costeira. Aço utilizado principalmente na construção de navios devido à sua boa resistência e durabilidade. Este estudo enfatiza a análise de tensões residuais do aço para construção naval AH-36. O software Abaqus é utilizado para análise de elementos finitos para avaliar tensões residuais. A mitigação destas tensões residuais é muito essencial; portanto, a técnica de pré-aquecimento é discutida neste estudo. O pré-aquecimento foi realizado em três temperaturas, ou seja, 100ºC, 150ºC e 200ºC. Os resultados indicam que as tensões de Von Mises diminuíram efetivamente devido ao pré-aquecimento. Foram observadas reduções de 12,6%, 21% e 45,6% nas temperaturas de pré-aquecimento 100ºC, 150ºC e 200ºC respectivamente. Uma avaliação mais aprofundada das tensões revelou que, devido ao pré-aquecimento da placa de base, as tensões longitudinais foram reduzidas para 21,3%, 44% e 52,4% aumentando a temperatura de pré-aquecimento de 100ºC, 150ºC e 200ºC, respectivamente. A mitigação do gradiente térmico entre a zona de solda e a placa de base resultou na redução das tensões globais da placa de base.*

Palavras-chave: *Mitigação; AH-36; Abaqus; tensões residuais; análise de elementos finitos.*

1. Introduction. –

1.1 Residual Stresses Generation. - Residual stresses are internal stresses that remain in a material even after external forces are removed. These stresses often occur due to uneven heating, especially in welding processes. In welding, localized heating leads to non-uniform temperature distribution, causing structural and metallurgical changes. The base metal and the heat-affected zone usually have higher temperatures compared to the weld metal [3, 22]. As the weld cools, the stress in the weld area increases, potentially reaching the base metal's yield point. Sequential welding creates additional complexities [18]. The solidified parts of the weld resist shrinkage of subsequent beads, causing longitudinal stress in earlier welded sections. In butt joints, the preparation limits transverse movement, leading to transverse residual stress. Similarly, in fillet welds, tensile stress develops along the length of the weld [7].

Residual stress in welded structures can result in two primary outcomes: premature failure or distortion, or a combination of both. Distortion occurs when the area around a heated weld cools and contracts unevenly, causing one part of the weld to shrink and placing uneven stress across the weld's cross-section [24]. This leads to elastic contraction in the weldment. Such non-uniform contraction manifests as visible distortions. Therefore, predicting the post-welding behavior of materials and adjusting design and construction methods accordingly is crucial. This approach is essential to mitigate distortions and residual stresses, which commonly affect the dimensional precision of structures [19].

1.2 Variations in Residual Stresses. - The impact of residual stresses varies based on their application; they can be either beneficial or detrimental. In some designs, residual stresses are deliberately employed for advantageous purposes. For example, through a process known as laser peening, compressive residual stresses are introduced on the surface of an object. This method is used to strengthen brittle surfaces or enhance the durability of thin sections [23]. However, more often, residual stresses have negative consequences. They can compromise the structural integrity of a product, and manufacturers may not become aware of them until they have already caused considerable deformation [14].

Finite element analysis was implemented to model the welding process and to anticipate stresses in butt welding of two similar carbon steel plates. Research findings indicate that the axial residual stress calculated using this finite element approach aligns closely with the results obtained from experimental observations [12]. [11] conducted a study focusing on FEA of welded structures. Their objective was to develop a reliable method for optimizing the strength of weld joints and predicting their thermal behavior. The study's results highlighted that the critical metallurgical area is the cooling metal adjacent to the weld pool.

[1] conducted a study to evaluate the effectiveness of weld-bonded connections, study also examined joints formed through adhesive bonding by utilizing the finite element method. This involved creating models for spot welding, adhesive bonding, and weld bonding, each complete with specific constraints, stress scenarios, and appropriate material characteristics.
Principal stresses generated due to spot welding were found greater than major principal stresses produced in adhesive bonded joint, and weld bonded joint [2, 16] employed the finite element method for replication of a fusion welded joint. Their developed model incorporated dynamic heat transfer, elastoplastic behavior, a shifting heat source, and

temperature-sensitive thermophysical properties. Fatigue properties of welded joints were evaluated by [13], finite element method was used to assess the fatigue strength. Fracture locations and forecast about lifespan before failure of welded joint were main attributes of this research.

Detail modelling of welded joint was performed by [6] in FEA, digital recreation of physical dynamics of welding process was main objective of this research. Model’s accuracy against computational time was required to be balanced, the results of this study revealed comprehensive insight into the mechanical properties of joints. The sequence of welding process significantly impacted the peaks of longitudinal stress. [9] studied impact of multi-pass welded joint in pipes, a three-dimensional thermo-mechanical model was developed to investigate the effect of welding procedures on the residual stress field in a multi-pass welded pipe.

Mitigation of residual stresses and distortions, [4] investigated post welding method for degradation of residual stresses. Different clamping situations studied by [20] positively influenced the residual stress distribution in T-Joint. [8] performed multi-beam preheating process to abate structural deformations. Reduction in compressive stresses in weld area was observed after implanting this method. [25] performed study to assess the influence on cold spraying on Friction stir welded AA 2219 alloy residual stresses. Impact of shot peening due to cold spray enhanced mechanical properties and degraded residual stress.

Manufacturing induced residual stresses were studied by [10] to figure out number of residual stresses in specific areas of T joint weld configuration. High peaks of residual stresses adjacent to the weld areas indicated greater quantity of residual stresses. Cruciform fillet joints were examined by [17] to evaluate distortions and residual stresses by utilizing Simufact welding software. Numerical methods and experimental work were compared to evaluate behavior of joints and validation of results.

[26] conducted research regarding influence of residual stress on bending resistance of welding joints. It was observed that residual stresses influenced negatively on bending resistance by degrading its stiffness more than 10%. Residual stress generation in double welded rib to deck joints were investigated by [8], research aim was focused on enhancement of fatigue strength of streel bridges. Ultrasonic impact treatment was utilized to mitigate deleterious effects of residual stresses and advantageous compressive stresses were induced for improvement in fatigue strength.

2. Motivation. - After an extensive review of existing literature, it has been noted that a substantial amount of research has been dedicated to Finite Element Method (FEM) simulations of welding processes, especially in relation to the formation of residual stresses. Despite this, there remains a noticeable gap in the literature regarding the stress analysis of materials used in the maritime industry a sector vital to global trade and the economic stability of nations. This study seeks to address this gap by focusing on AH-36, a material commonly used in shipbuilding, to investigate the residual stresses that develop during its welding process. Although FEM is providing good results but with certain limitations like constant material properties, Point heat source, Transient thermal behavior, Simplified geometries and Phase transformations etc.

3. Methodology. - The methodology of this research was focused on simulations performed in ABAQUS software. Two types of simulations were performed on welding joint, thermal analysis of the joint and structural analysis of the joint to evaluate influence of residual stresses. Welding analysis in other software's is time consuming and model settings are difficult, however ABAQUS/CAE plug is recently created in Abaqus Welding Interface (AWI) to eliminate this deficiency. Graphical user interface was provided by this software for setting cross-sectional simulation of welding in ABAQUS. Model tree as shown in Figure I illustrate details like weld passes and controls etc.

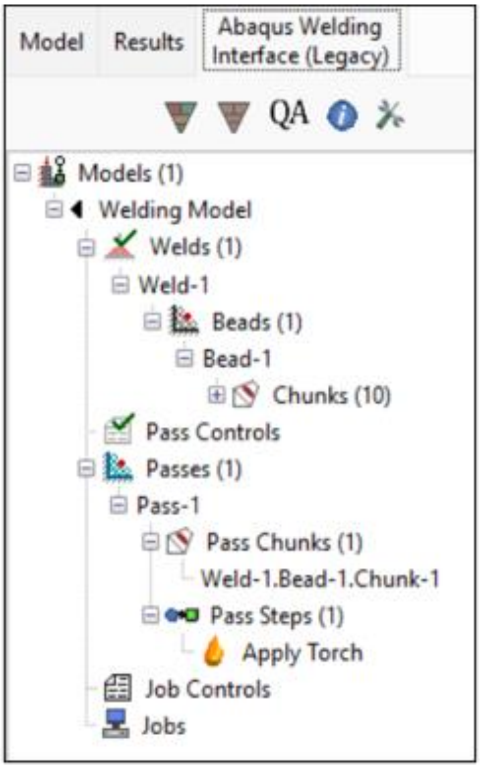


Figure I. Model Tree in Abaqus.

This involved first looking at temperature changes, then examining the stress caused by these changes. The heat source was identified based on how temperature spread and the material's ability to expand when heated. In stress analysis, the same mesh was used for both heat and stress analysis. This demonstrates a very fine mesh in the heat-affected zone and weld region, while larger mesh sizes are used farther from the heat-affected zone as shown in Figure 2. The plates can move freely. The temperature data from the heat analysis is used as input for the stress model, which is created using the AWI plugin. Since the heat model uses temperatures higher than the melting point, stress analysis limits temperatures to below the melting point using a simple subroutine. Material AH-36 was used for this analysis due to its significant importance in shipbuilding industry. Mechanical and thermophysical properties of AH-36 represent in Figure 3. These values were briefly explained by Dragi et al in his research about FEA of butt joint [5]. In this study, the parent metal was preheated to temperatures 100ºC, 150ºC and 200ºC to investigate impact on residual stresses.

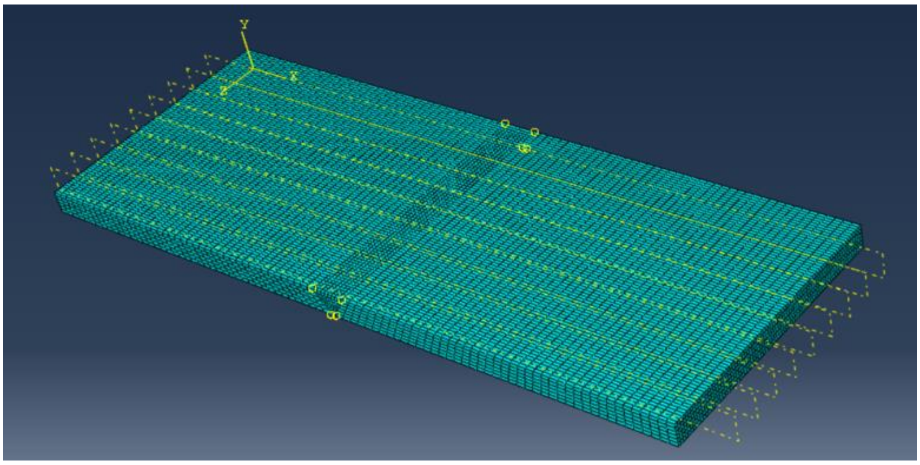


Figure II. Meshing.

A welding torch was utilized, set to a very high temperature of 1500ºC, which is slightly above the liquidus temperature of 1482ºC. This precise temperature setting is crucial as it ensures the material reaches a molten state, necessary for effective welding. The torch was moved at a controlled speed, taking 15 seconds for each section, highlighting the importance of torch speed in achieving uniform heat distribution and consistent weld quality. During the process, the temperature was elevated to the required level for most of the time the torch was operational, ensuring thorough heating of the material. For the final part of the process, the temperature was maintained at this level to stabilize the weld and prevent any potential defects.

Temperature (°C)	Specific heat (J/kg°C)	Conductivity (W/m°C)	Density (kgm-3)	Yield stress (MPa)	Thermal expansion coefficient (10-5/°C)	Young´s modulus (GPa)	Poisson´s ratio
0	480	60	7880	380	1.15	210	0.3
100	500	50	7880	340	1.2	200	0.3
200	520	45	7800	315	1.3	200	0.3
400	650	38	7760	230	1.42	170	0.3
600	750	30	7600	110	1.45	80	0.3
800	1000	25	7520	30	1.45	35	0.3
1000	1200	26	7390	25	1.45	20	0.3
1200	1400	28	7300	20	1.45	15	0.3
1400	1600	37	7250	18	1.45	10	0.3
1550	1700	37	7180	15	1.45	10	0.3

Figure III. Mechanical and Thermophysical properties of AH-36 steel.

4. Validation study. - In validation process, analysis results were compared with the experimental data from [15] as shown in Figure 5. The geometry of the weld joint, illustrated in Figure 4, was modelled after the referenced study to ensure accurate validation. Thermal histories were recorded using thermocouples placed at specific locations on both the left and right plates during welding. Thermocouples were located at 125mm along the weld line. For this thermal analysis, we used Stainless Steel 304 as the material. We accounted for latent heat effects, with a melting range between

2600°F (solidus) and 2700°F (liquidus), and a latent heat value of 118 BTU/lb. Throughout the analysis, we maintained a constant material density of 0.283 lb/in³.

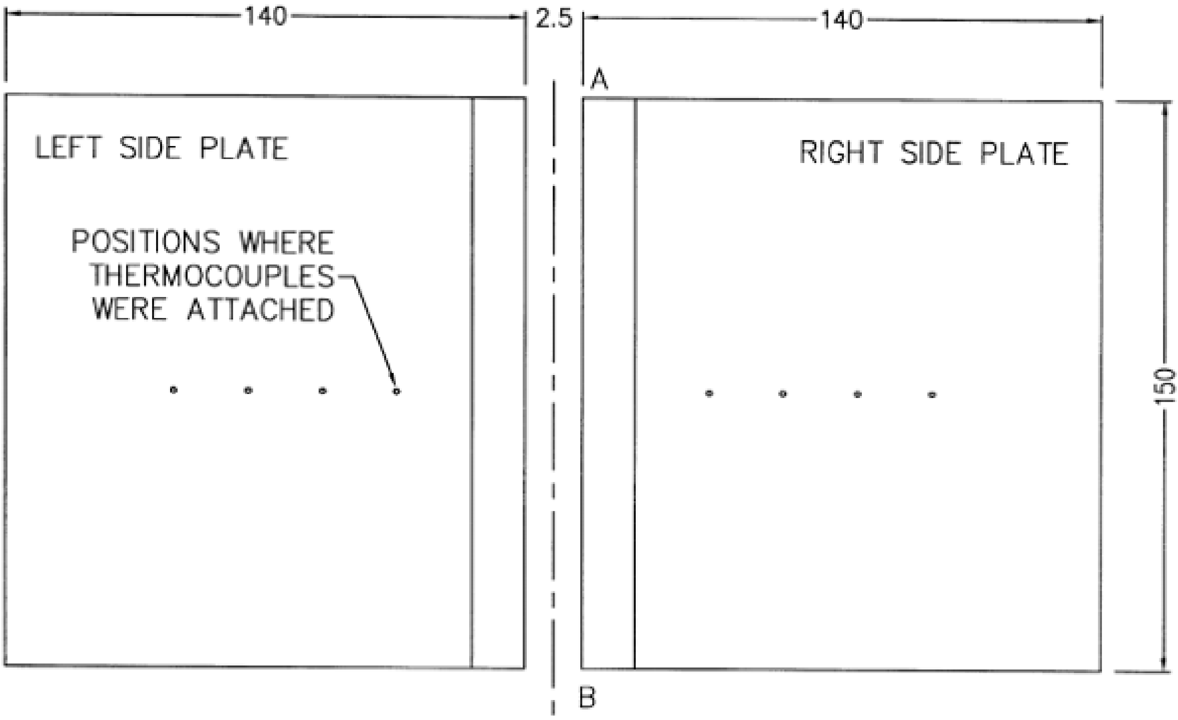


Figure IV. Geometry for validation.

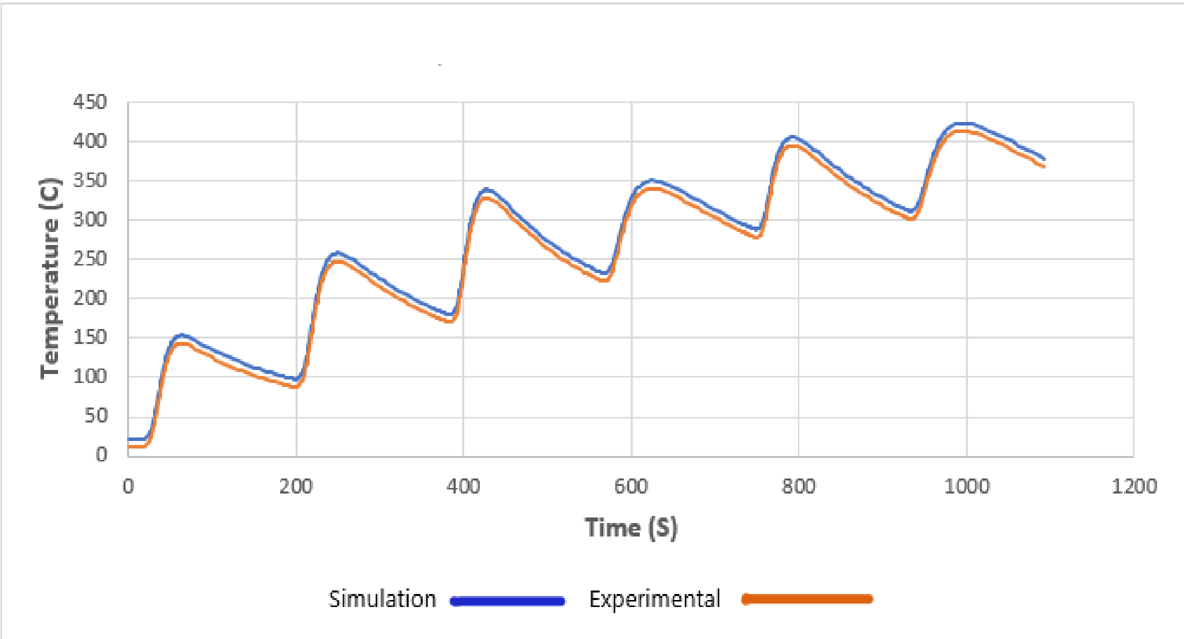


Figure V. Temperature distributions Curves for Validation.

In ABAQUS, setting the right boundary conditions is key for getting accurate results. For this problem, two main boundary conditions were used: the surrounding air temperature and thermal convection. The thermal convection was set at 0.025mW/mm^{2}K. The air around the model was kept at 21ºC. The analysis didn't consider any phase change.

The Automated Welding Interface sets the weld bead's temperature to 1500ºC during the welding process. Figure 6 shows the boundary condition of the weld bead has been created during pass.

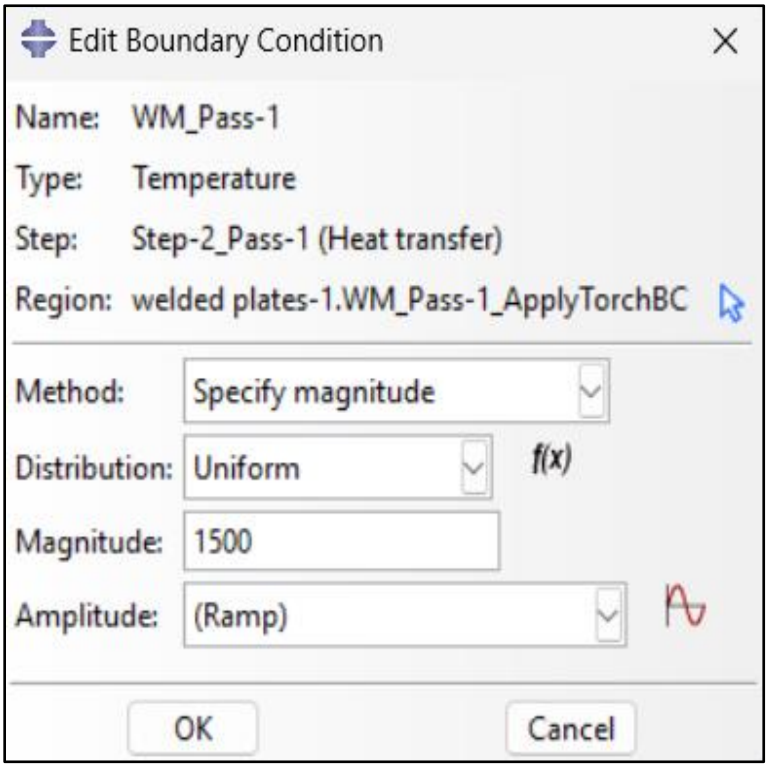


Figure VI. Boundary Conditions during pass creation.

5. Results and Discussions. -

5.1 Results of Parent Model Analysis. - The AH-36 material was chosen for this study. Comparative study of temperature distributions and residual stresses before and after preheating was performed to investigate impact on properties. The results were presented in the form of graphs and contour maps. To determine the residual stresses caused by welding, we assessed the results of thermal and structural analyses using the contour plots from both studies.

5.1.1 Temperature distributions for Parent Model. - Figure VII illustrates the temperature distribution on the welded plates after thermal analysis. The initial temperature of parent material and surrounding atmosphere both set to 21ºC with the coefficient of heat convection 0.025mW/mm^{2}K while value of emissivity maintained at 0.9. The maximum temperature can be seen as 1500ºC which is greater than the liquidus temperature (1482ºC) of the AH-36 steel.

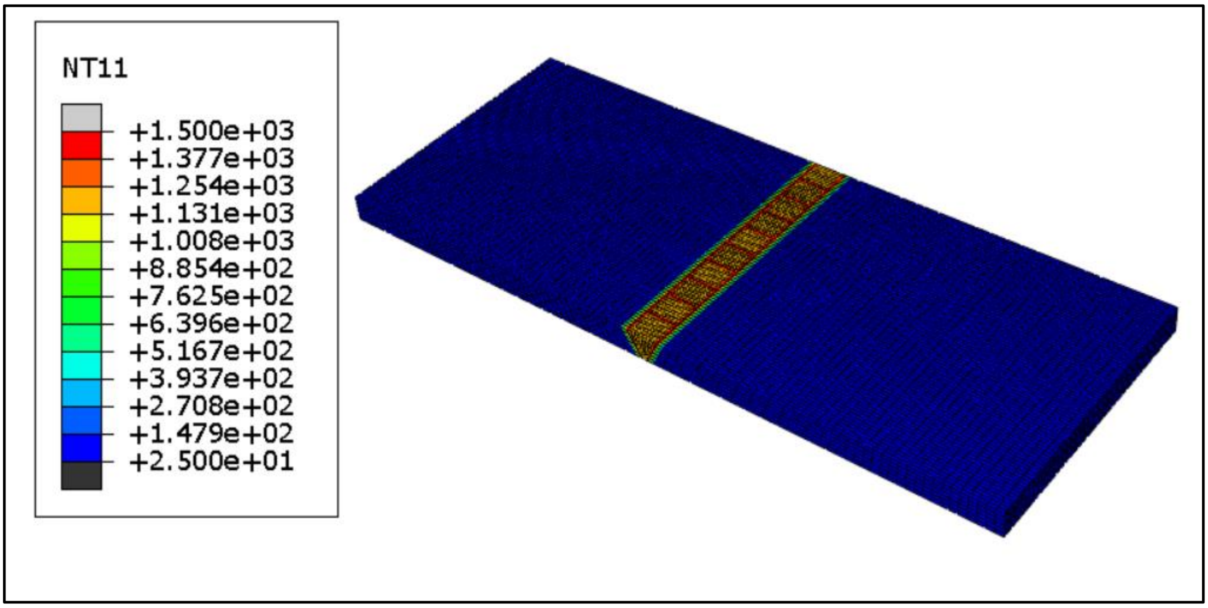


Figure VII. Temperature Distributions for Parent Model.

5.1.2 Von Mises Stress Distributions before Preheating. - Figure VIII represents Von Mises stress intensity map which demonstrates that stresses were building up in the heat affected zone (HAZ) area around the weld zone (WZ). Due to concentration of stresses in HAZ, failure of joint inclined to this particular region. Any microcrack amplify the stress concentration and results in deterioration as well as enlargement of crack. Therefore, additional safety measures like heat treatment might be used in that region to lessen the degree of stress concentration. It was observed that the maximum stress generated in the middle of the weld along its path as shown in Figure 9, so this was location of interest. The region parallel to that mid plane were faced large compressive stresses due to the expansion of weld region, hence inclined to high residual stresses. HAZ was susceptible to failure due to large residual stresses.

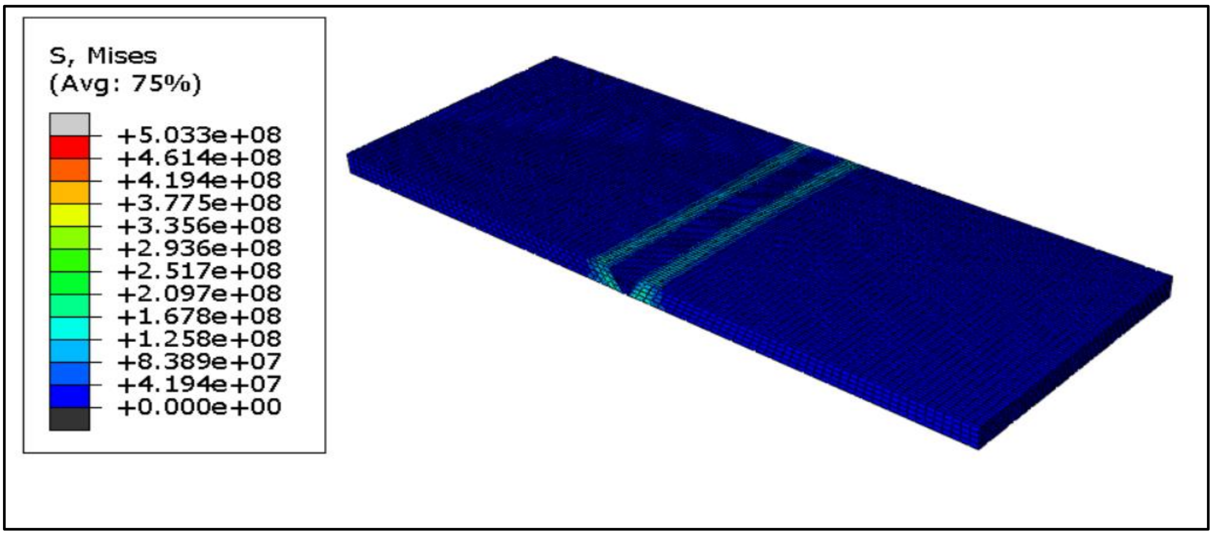


Figure VIII. Von Mises stress distribution.

https://doi.org/10.36561/ING.26.14
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

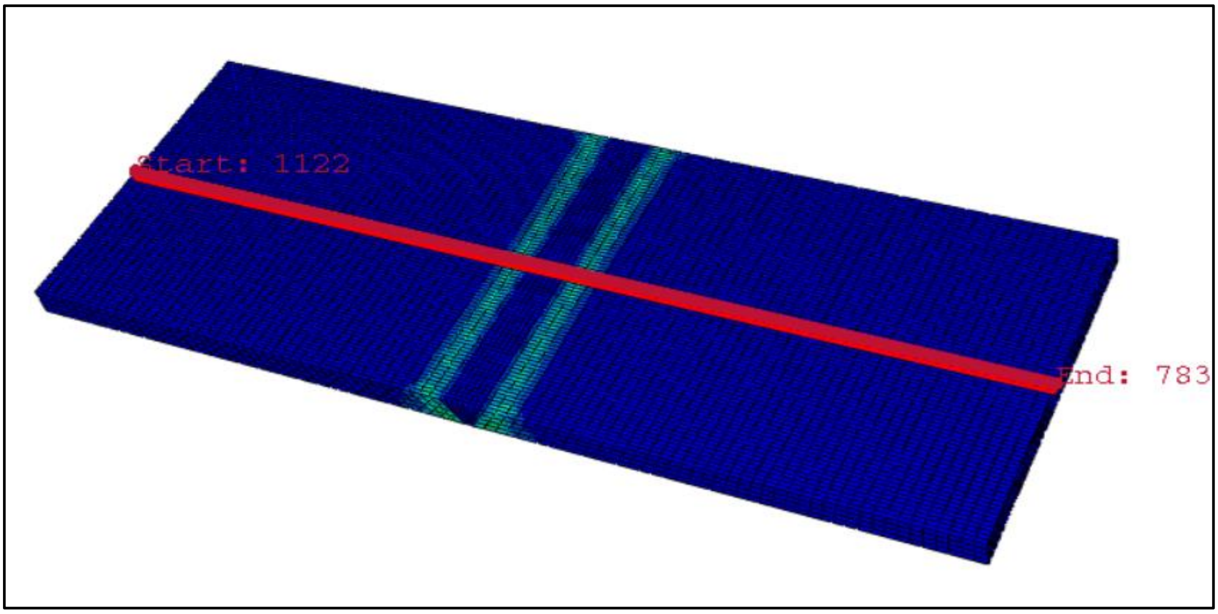


Figure IX. Mid Plane for Maximum Stress.

Stress distribution was found out in the welded plates along the path as shown in Figure 10. The maximum value of the stress distribution came out to be 103 MPa at the root of the weld at the distance of 122mm and 140mm from the start of the path, the value drops to 0.28MPa at the end of the welded plates.

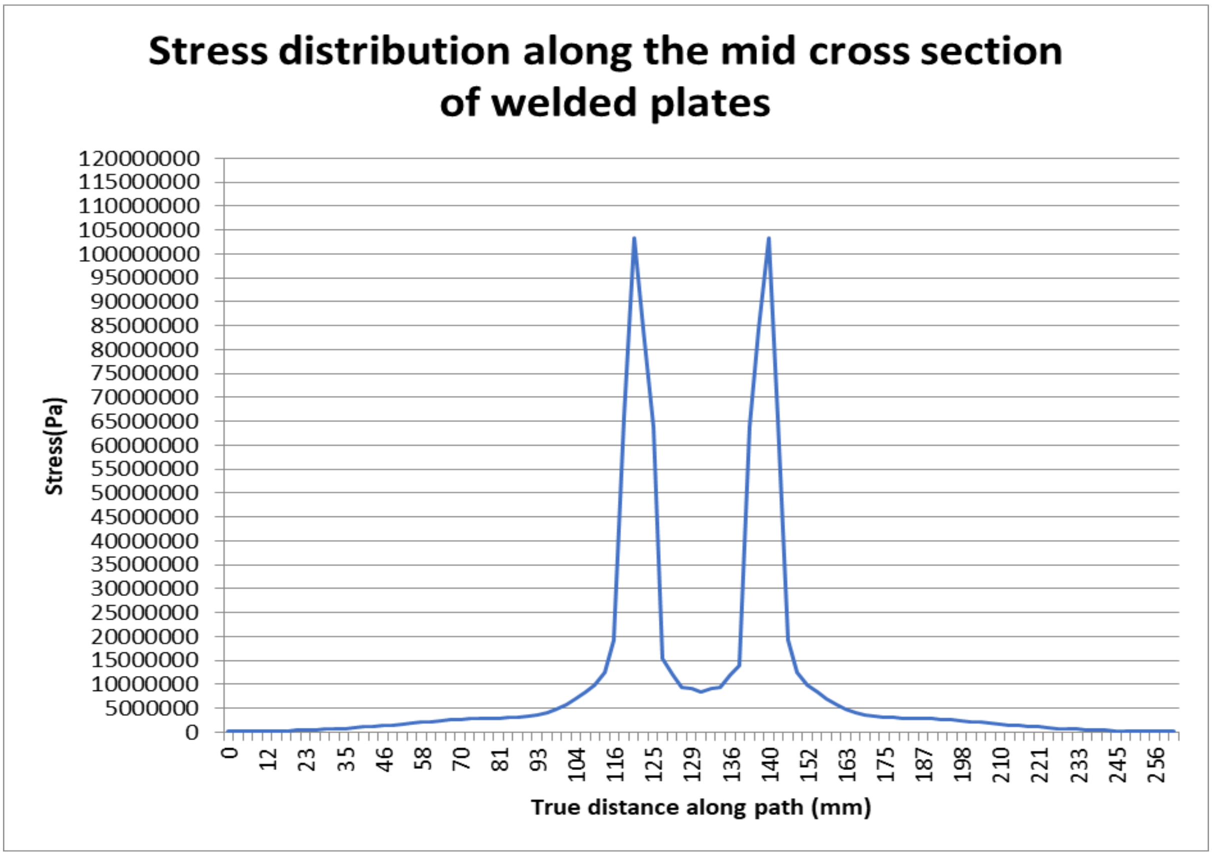


Figure X. Stress distribution along path length.

Figure XI illustrates the axial stresses impacting the plate along the Z axis, originating from the tensile tension of the welding line. A compressive stress peak, quantified at -313 MPa, contrasts with the highest tensile stresses reaching 355 MPa. Exceeding the tensile strength threshold in certain areas can lead to deformation. Notably, the cooling method employed significantly influences the reduction in axial stress values during the plate's cooling phase.

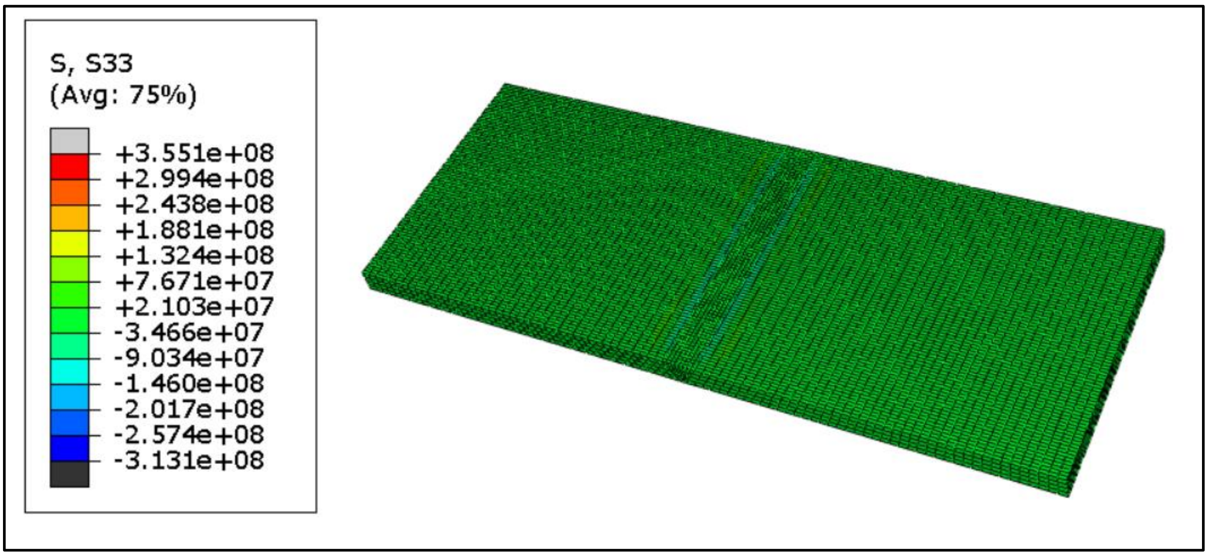


Figure XI. Stresses Parallel to weld direction (S33).

In Figure XII, the illustration of S33 stress distribution, aligned parallel to the weld line, unfolds a nuanced observation. Adjacent to the WZ, the material undergoes a phase of compressive stresses, which gracefully diminish with increased distance from the weld line. Notably, the apex of these stresses is characterized by a compressive nature, reaching a significant magnitude of -54.5 MPa.

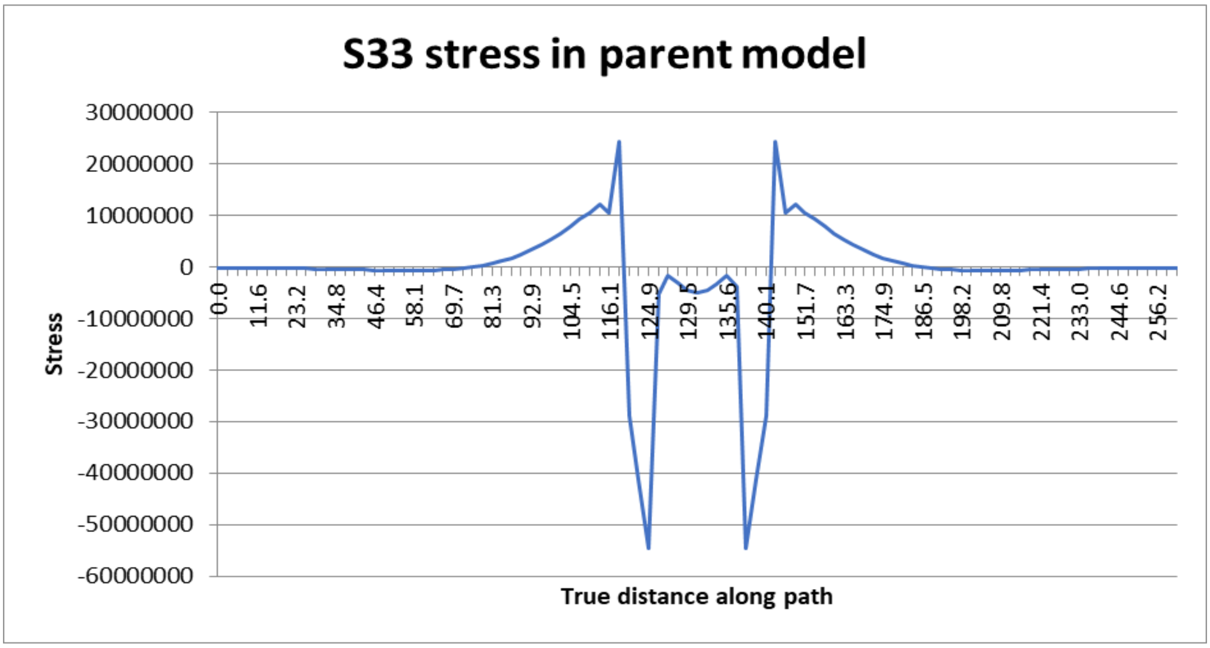


Figure XII. Stresses along weld line.

Figure XIII elegantly captures the stress distribution extending across the plate's length. Within the region of the weld area, the plate is subjected to pronounced tensile stresses, a stark contrast to the surrounding weld metal, where compressive stresses show their dominance. Beyond these zones, the narrative shifts as the rest of the plate exhibits stresses of a markedly lower magnitude.

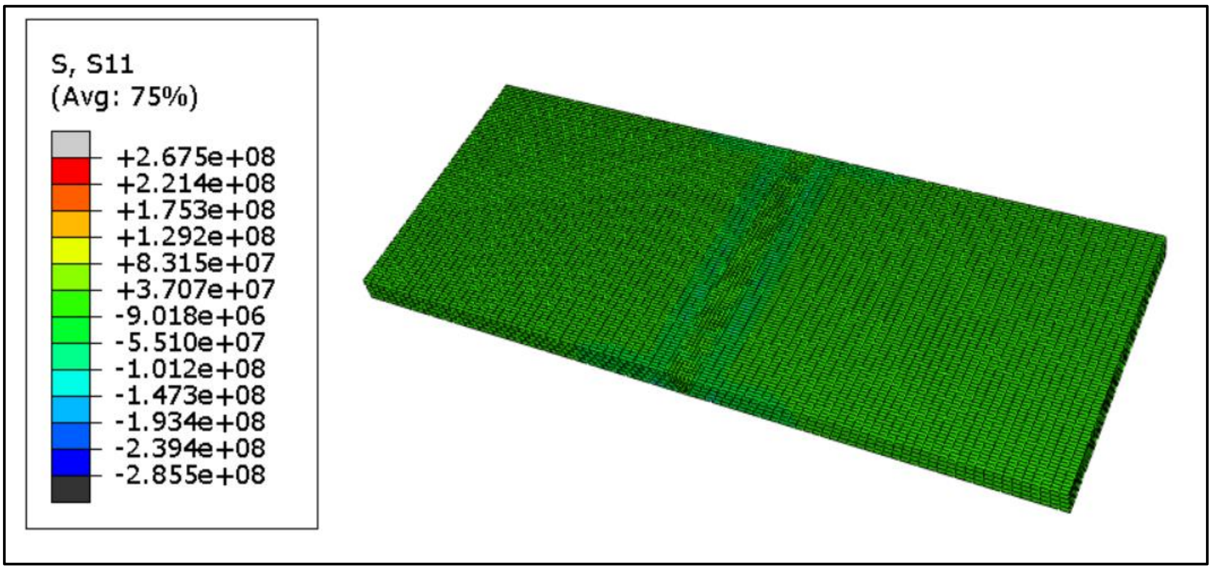
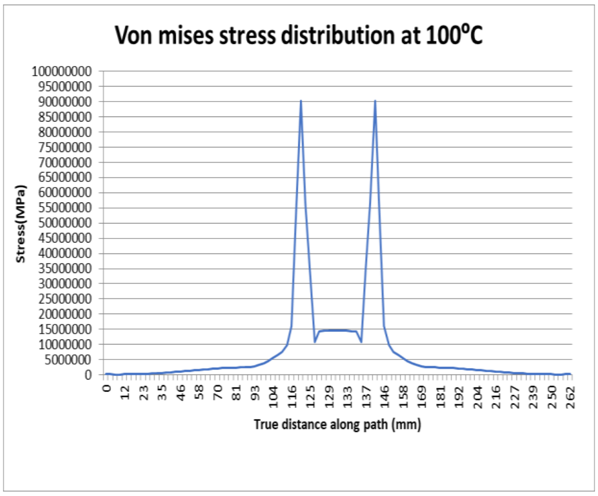


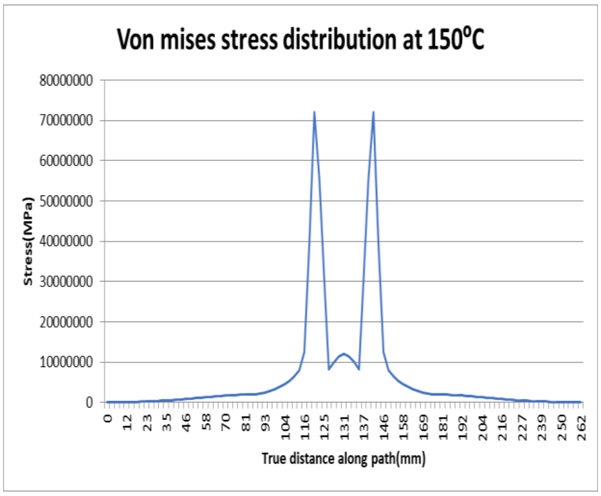
Figure XIII. Stresses along length of Plate (S11).

5.2 Preheating of Parent metal. - Preheating technique was utilized to investigate impact of preheating on residual stresses of AH-36 steel. Results achieved after mitigation of residual stresses by preheating were compared with the results of simulation before preheating. Non uniform distribution in welding is a primary source of distortions and residual stresses. Preheating is a process used to raise the parent metal temperature before welding to minimize the temperature differential. The parent metal was warmed in this investigation to temperatures of 100°C, 150°C and 200°C. The residual stresses or distortions were significantly reduced.

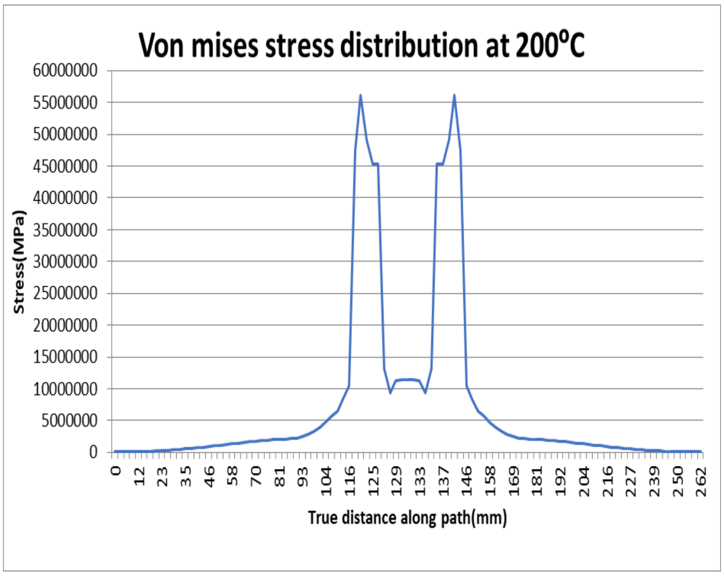
5.2.1 Von mises Stress Distributions. - The base metal was preheated to temperatures of 100ºC,150ºC and 200ºC to reduce the temperature gradient between WZ and parent metal. Figure XIII illustrate the overall von mises stress distribution in the welded plates. It was observed in Figure XIV (a) that maximum stresses at distance of 122mm and 140mm from WZ was reduced from 103MPa to 90MPa due to preheating of base plate at 100ºC. 12.6% reduction was achieved due to preheating which ultimately decrease the thermal gradient. Similarly Figure 14(b) and 14(c) illustrate familiar reduction pattern in Von mises stresses due to preheating of the base plate at 150ºC and 200ºC.



(a)



(b)



(c)

Figure XIV. Von Mises Stresses (a) Preheating at 100ºC (b) Preheating at 150ºC (c) Preheating at 200ºC

Reduction in thermal gradient was obvious due to preheating of base plate, hence stresses were further mitigated from 90MPa to 72MPa at preheating temperature 150ºC. Further increment in preheating temperature to 200ºC, Von mises stresses reduced from 72MPa to 56MPa. Reductions observed due to 150ºC and 200ºC temperature were 21% and 45.6% respectively.

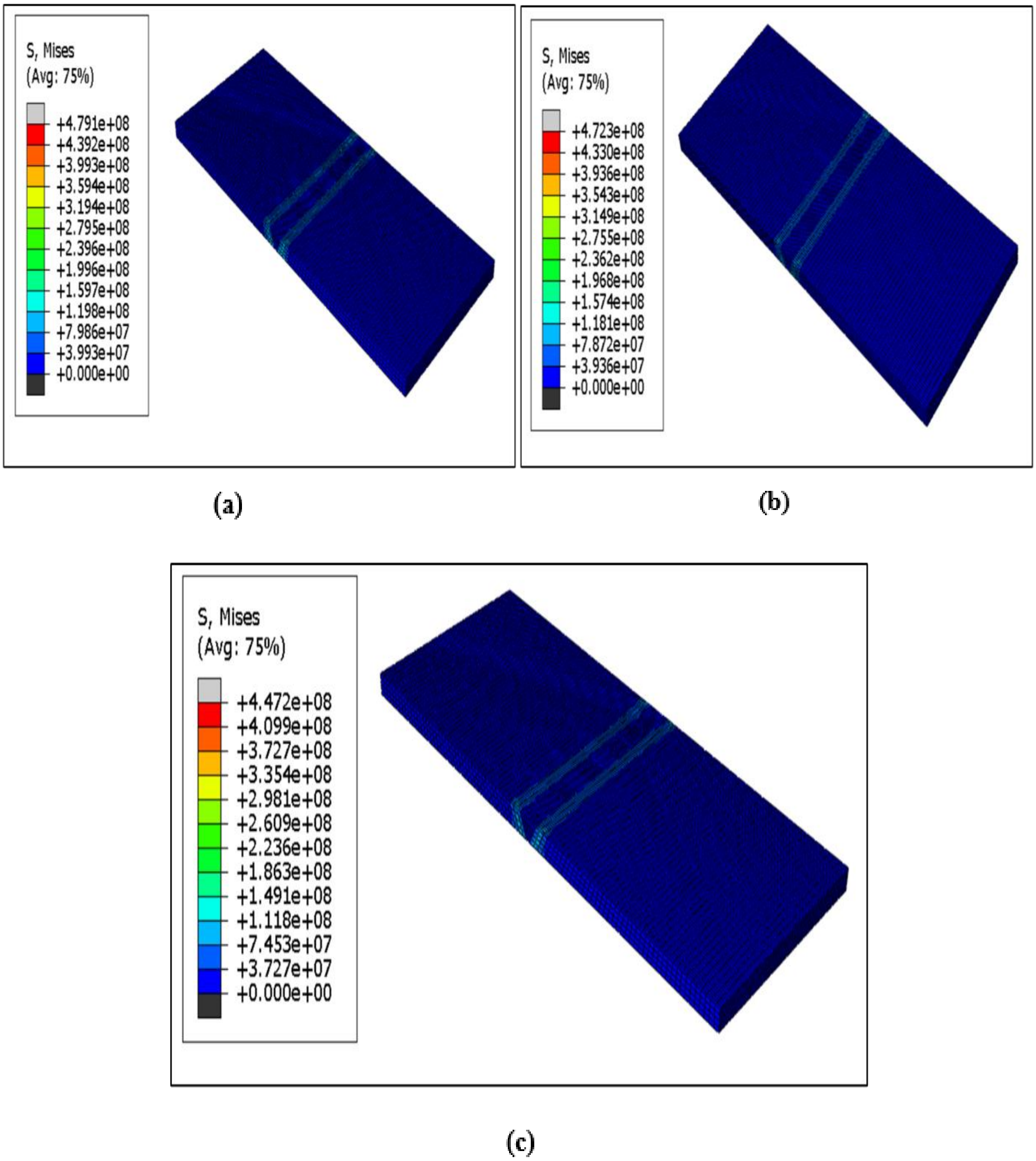


Figure XV. Simulations of Von Mises stress distributions (a) Preheating at 100ºC (b) Preheating at 150ºC (c) Preheating at 200ºC

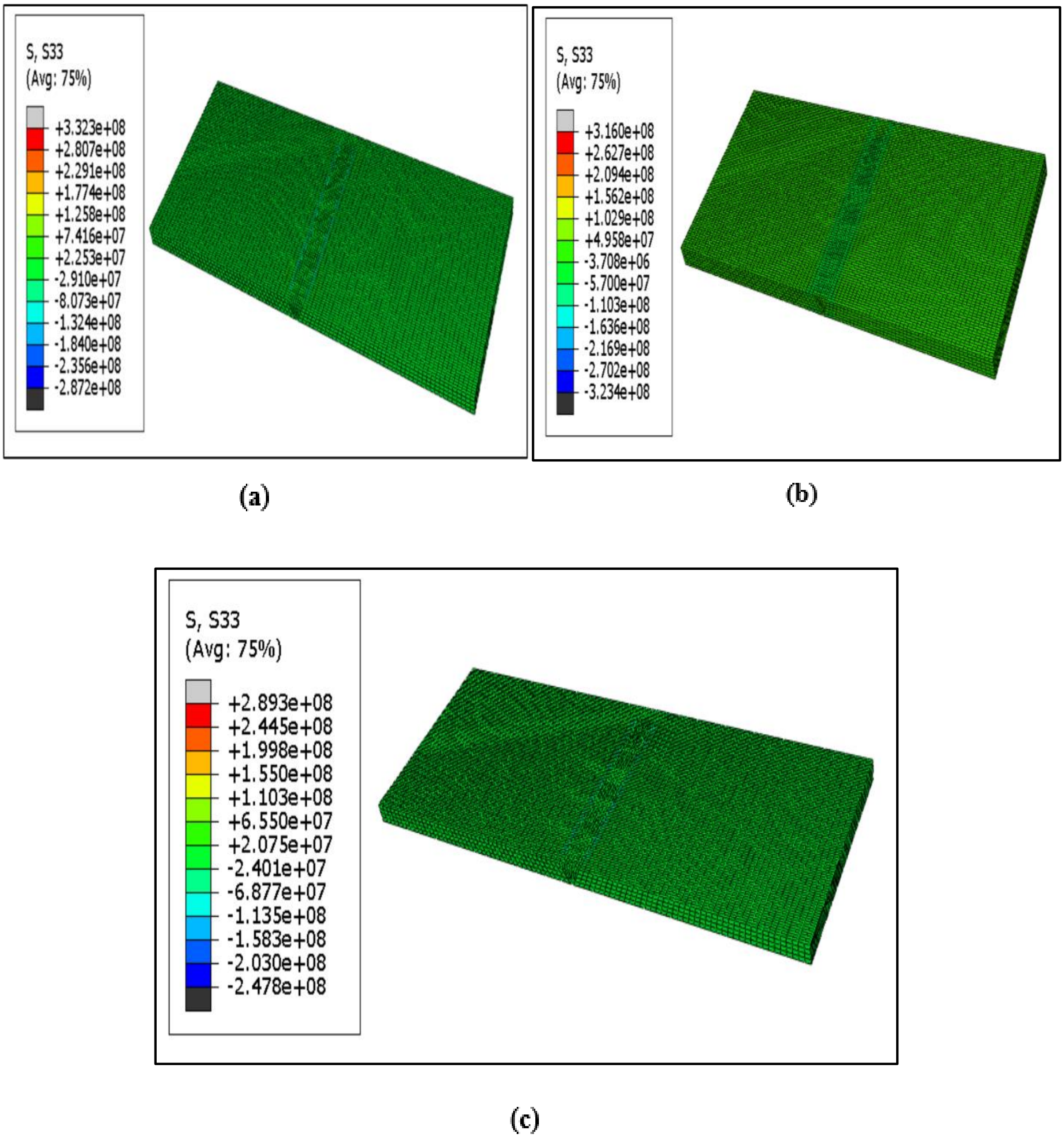


Figure XVI. Stress Distributions along weld Line (Longitudinal stresses S33) (a) Preheating at 100ºC (b) Preheating at 150ºC (c) Preheating at 200ºC

Figure XV have shown reduction in Von mises stresses due to preheating of base plate, significant reduction in overall stresses of base plate was observed because of degradation in thermal gradient. Distortions were reduced ultimately due to preheating of base plate. Increment in preheating temperature from 100ºC to 200ºC resulted in degradation on overall stresses and deformations. Joint strength may be affected due to variations in HAZ area and chance of weld joint failure get reduced due to elimination of thermal cracking. Stresses along weld path was evaluated in Abaqus and it was revealed that preheating mitigation technique applied for residual stresses was very effective. It was shown in Figure 11 that maximum stress along weld path (S33) was 355MPa, however this longitudinal stress was significantly abated due to preheating method. Figure XVI(a) revealed notable degradation in maximum longitudinal stress from

355MPa to 332MPa because of preheating base plate at 100ºC. 21.3% reduction in longitudinal stresses was observed when base plate temperature maintained at 100ºC. Increment in preheating temperature will inversely be related with longitudinal stresses, so ultimately decrease residual stresses along weld path. Further degradation in longitudinal stresses was observed in Figure XVI(b) at preheating temperature 150ºC, stresses were reduced from 355MPa to 316MPa. 44% reduction in stresses was achieved due to increment in preheating temperature. Longitudinal stresses were further decreased as shown in Figure XVI(c) from 355MPa to 289MPa due to further increase in preheating temperature from 150ºC to 200ºC. Implementation of this mitigation method reduced longitudinal stresses from 44% to 52.4%.

6. Conclusion. - This study focused on analyzing the impact of thermal processes and preheating on the residual stresses and structural integrity of AH-36 steel welded plates. Thermal analysis declared a maximum temperature of 1500ºC was achieved during welding, which is greater than the liquidus temperature of AH-36 steel. Due to large thermal gradient between base plate and WZ, thermal stresses produced which ultimately results in high residual stresses. The study identified High stress concentrations were identified in the Heat Affected Zone around the weld zone. The maximum stress was observed along the weld line, indicating a critical area for potential failure due to microcrack formation and stress amplification. Significant variations in stresses were noted in Z axis direction, with a peak compressive stress of -313 MPa and a peak tensile stress of 355 MPa. This variation could lead to deformation if the tensile strength threshold is exceeded. Compressive stresses were prominent along weld path due to expansion and contraction of weld zone due to large temperature difference. Compressive stresses have shown negative pattern with increasing distance from the weld line. Overall analysis of stress distribution across the plate's length showed pronounced tensile stresses in the base plate contrasting with compressive stresses in the surrounding metal. Mitigation method was utilized to lower residual stresses, Preheating the base metal to 100ºC, 150ºC, and 200ºC right before welding significantly reduced the temperature gradient. Reduction in thermal gradient mitigated residual stresses and distortions as well. Notably, preheating at 200ºC reduced Von Mises stresses from 103 MPa to 56 MPa. Longitudinal stresses were substantially reduced with preheating. Preheating at 200ºC decreased these stresses from 355 MPa to 289 MPa, highlighting the effectiveness of preheating in mitigating residual stresses. The findings highlighted the significant potential of preheating as a mitigation technique for residual stresses in welded joints. Future research could explore the optimization of preheating temperatures and durations for different materials and welding conditions. Additionally, integrating preheating with other stress mitigation techniques, such as post-weld heat treatment or advanced welding processes, could further enhance the structural integrity and lifespan of welded structures.

References

[1] Al-Samhan, A., & Darwish, S. M. H. (2003). Finite element modelling of weld-bonded joints. Journal of materials processing technology, 142(3), 587-598.

[2] Anca, A., Cardona, A., & Fachinotti, V. (2008). Finite element modeling of welded joints. Mecánica Computacional, (19), 1445-1470.

[3] Colegrove, P., Ikeagu, C., Thistlethwaite, A., Williams, S., Nagy, T., Suder, & Pirling, T. (2009). Welding process impact on residual stress and distortion. Science and technology of welding and joining, 14(8), 717-725.

[4] Cozzolino, L. D., Coules, H. E., Colegrove, P. A., & Wen, S. (2017). Investigation of post-weld rolling methods to reduce residual stress and distortion. Journal of Materials Processing Technology, 247, 243-256.

[5] Dragi, S. & V. Ivana (2009). “Finite element analysis of residual stress in butt welding two similar plates.” J. Scientific Technical Review. 1(1), 57–60.

[6] Garipova, N., Batigün, C., & Gür, C. H. (2014). Numerical and Experimental Determination of the Residual Stress State in Multipass Welded API 5L X70 Plates. Materials Testing, 56(10), 831-836.

[7] Gannon, L., Liu, Y., Pegg, N., & Smith, M. (2010). Effect of welding sequence on residual stress and distortion in flat-bar stiffened plates. Marine Structures, 23(3), 385-404.

[8] Han, S. H., Cui, C., Zheng, Q. S., Zhang, Q. H., & Bu, Y. Z. (2023). Effect of ultrasonic impact treatment on welding residual stress and fatigue resistance of doubly-welded rib-to-deck joints in OSD. Journal of Constructional Steel Research, 211, 108157.

[9] Jiang, W., & Yahiaoui, K. (2012). Effect of welding sequence on residual stress distribution in a multipass welded piping branch junction. International Journal of Pressure Vessels and Piping, 95, 39-47.

[10] Kollár, D., Völgyi, I., & Joó, A. L. (2023). Assessment of residual stresses in welded T-joints using contour method. Thin-Walled Structures, 190, 110966.

[11] Kurtz. G. W. "Finite Element Analysis of Welded Structures," Welding Research Supplement, 1978.

[12] Kassab, R. K., Champliaud, H., Van Lê, N., Lanteigne, J., & Thomas, M. (2012). Experimental and finite element analysis of a T-joint welding. Journal of Mechanics engineering and automation, 2(7), 411-421.

[13] Marin, T., & Nicoletto, G. (2009). Fatigue design of welded joints using the finite element method and the 2007 ASME Div. 2 Master curve. Frattura ed Integrità Strutturale, 3(9), 76-84.

[14] Malikoutsakis, M., & Savaidis, G. (2009). An approach to the effective notch stress concept to complex geometry welds focusing on the Fe modeling of weld ends. Aristotle University of Thessaloniki, Greece.

[15] Murugan, S., Kumar, P. V., & Raj, B. (1998). Temperature distribution during multipass welding of plates. International journal of pressure vessels and piping, 75(12), 891-905.

[16] Perić, M., Garašić, I., Nižetić, S., & Dedić-Jandrek, H. (2018). Numerical analysis of longitudinal residual stresses and deflections in a T-joint welded structure using a local preheating technique. Energies, 11(12), 3487.

[17] Raftar, H. R., Ahola, A., Lipiäinen, K., & Björk, T. (2023). Simulation and experiment on residual stress and deflection of cruciform welded joints. Journal of Constructional Steel Research, 208, 108023.

[18] Reed, R. C., & Bhadeshia, H. K. D. H. (1994). A simple model for multipass steel welds. Acta metallurgica et materialia, 42(11), 3663-3678.

[19] Ramos, H. M. E., Tavares, S. M. O., & de Castro, P. M. S. T. (2018). Numerical modelling of welded T-joint configurations using SYSWELD. Science and Technology of Materials, 30, 6-15.

[20] Schenk, T., Richardson, I. M., Kraska, M., & Ohnimus, S. (2009). A study on the influence of clamping on welding distortion. Computational Materials Science, 45(4), 999-1005.

[21] Shazad, A., Jadoon, J., Uzair, M., & Muzammil, M. (2023). Material Modelling and Failure Study of Different

Fiber Reinforced Composites for Pressure Vessel. Memoria Investigaciones en Ingeniería, (24), 92-104.

[22] Shazad, A., Jadoon, J., Uzair, M., Akhtar, M., Shakoor, A., Muzamil, M., & Sattar, M. (2022). Effect of composition and microstructure on the rusting of MS rebars and ultimately their impact on mechanical behavior. Transactions of the Canadian Society for Mechanical Engineering, 46(4), 685-696.

[23] Stamenković, D., & Vasović, I. (2009). Finite element analysis of residual stress in butt welding two similar plates. Scientific technical review, 59(1), 57-60.

[24] Tabatabaeian, A., Ghasemi, A. R., Shokrieh, M. M., Marzbanrad, B., Baraheni, M., & Fotouhi, M. (2022). Residual stress in engineering materials: a review. Advanced engineering materials, 24(3), 2100786.

[25] Yang, X., Meng, T., Su, Y., Qi, Z., Wu, D., Vairis, A., & Li, W. (2023). Study on relieving residual stress of friction stir welded joint of 2219 aluminium alloy using cold spraying. Materials Characterization, 206, 113417.

[26] Yan, R., Yu, Z., Wang, S., & Liu, J. (2023). Influence of welding residual stress on bending resistance of hollow spherical joints. Journal of Constructional Steel Research, 208, 108004.

Nota contribución de los autores:

1. Concepción y diseño del estudio
2. Adquisición de datos
3. Análisis de datos
4. Discusión de los resultados
5. Redacción del manuscrito
6. Aprobación de la versión final del manuscrito

NS ha contribuido en: 1, 2, 3, 4 y 5.
MA ha contribuido en: 5 y 6.
MU ha contribuido en: 5 y 6.
AS ha contribuido en: 5 y 6.
AAZ ha contribuido en: 5 y 6.

Nota de aceptación: Este artículo fue aprobado por los editores de la revista Dr. Rafael Sotelo y Mag. Ing. Fernando A. Hernández Gobertti.