JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Thermal analysis of metal deposition process based on TIG-WAAM using FEM

Nikhil Kumar Verma,
M.Tech. (Production Technology and Management) Student
Department of Production Engineering,
BIT Sindri, Dhanbad, India

Abstract : Tungsten Inert Gas Welding-based Wire and Arc Additive Manufacturing (TIG-WAAM) is one of the direct energy deposition techniques that uses the least amount of energy. The TIG-WAAM process layer-by-layer deposits material using wires and arcs. Path planning in metal deposition processes influences the temperature distribution during layer-by-layer deposition in Wire Arc Additive Manufacturing (WAAM) processes. Temperature distribution affects the quality of metal deposition and its dimensional accuracy. In order to examine how temperature distribution affects the metal deposition process, this article created a model of the TIG WAAM process based on finite element analysis (FEA). The suggested model is intended to be used to simulate metal deposition utilizing the TIG-WAAM process for a single layer of structural steel. The temperature distribution over the material deposited is to be taken. The developed model can find its uses in the future on temperature management systems which may be based on feedback that helps produce better quality smooth deposition of metal.

***IndexTerms* - Wire and arc additive manufacturing (WAAM), Thermal analysis, TIG-based WAAM, FEM Finite Element Analysis.**

I. INTRODUCTION

Metal items can be 3D printed or repaired using the production technique known as wire arc additive manufacturing (WAAM). It is a member of the family of additive manufacturing technologies known as Direct Energy Deposition (DED). Metal is deposited in layers, one on top of the other, to generate the required three-dimensional shape in WAAM. It combines the use of additive manufacturing and gas metal arc welding (GMAW), two different production techniques. GMAW is a type of electric arc welding used to join metal parts, and additive manufacturing is the technical word for 3D printing. Using WAAM, pieces are produced by a welding robot that also functions as a power supply. The robot's welding torch is used to melt the wire feedstock used to create 3D objects. WAAM constructs 3D forms using arc deposition using arc welding power sources and manipulators. Typically, wire is used in this technique to form the required shape, and it follows a predefined course. Robotic welding equipment is typically used to carry out this additive manufacturing process.

II. RESEARCH GAP

Many academics have been working on the TIG-WAAM technique for metal part additive manufacturing in recent years due to its competence. The temperature of the thin-walled structure was determined using a radiation thermometer during the deposition process [12], distortion predictions based on temperature simulations [12], and novel heat source model that takes into account the actual power distribution between filler and base materials proposed process modelling allows to accurately simulate the WAAM process [6]. The temperature changes in each additional layer of travel due to the heat created at the metal deposition path, which varies depending on the location. The quality and precision of the metal deposition are impacted by this temperature distribution. The deposition quality may be compromised at several locations along the deposition path, which could result in the failure of a manufactured component.

2.1 Objective of Research

For the purpose of visualizing the distribution of heat in the single layer of structural steel, a TIG-WAAM process simulation has been performed. Researchers have looked into the impact of temperature concentration at deposition bottlenecks. The findings of this study may also aid in the creation of a feedback control system for regulating thermal cycles in any kind of WAAM process. FEM analysis for the temperature and heat concentration point of concern. Examine the model's maximal equivalent stresses, strains, and deformations as well.

III. Overview of the Program

An ANSYS-powered finite element analysis technique will be utilized to create a thermal analysis of a single - layered metal deposition process. This method is used to forecast the temperature that is produced during the heating period of the WAAM process. Therefore, it is suggested to create a 3D FEM model that comprises a single layer that was deposited utilizing the TIG-WAAM procedure.

Structural steel is the material taken into consideration for this study since it is frequently utilized as a structural and engineering material in a variety of shapes and dimensional sizes. This carbon steel has general carbon (C) concentration between 0.31% and 1.5%, copper (Cu) content between 0.4% and 0.5%, manganese (Mn) content below 1.6%, and silicon (Si) content below 0.6%.. Different modified grades of structural steel may contain more elements like Tungsten (Tu), Cobalt (Co), Nickle (Ni) or Zirconium (Zr). It is low in alloying but the steel has high strength and hence used for various structural pipes, channels, plates and tubes. Structural steel is also often used in the form of a long beam having to offer a variety of cross sectional shapes such as I-shaped, T-shaped and HSS shaped beams for construction works.

.

3.1 Process Flow

The process flow used for simulation process for obtaining distribution of the temperature in a single layer of deposition is below.

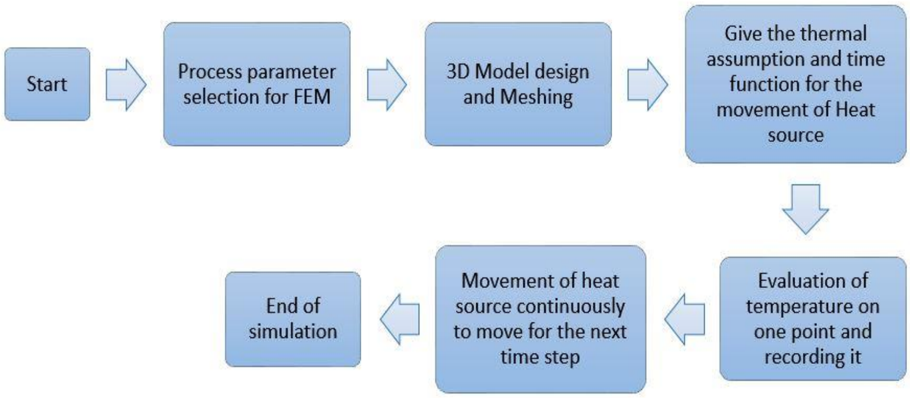


Figure 1 Flow chart of work

3.2 Process Parameters considered for the simulation process

Table 1 Process parameters

Material (Substrate and Wire deposited)	Structural steel
Dimension (mm)	150 x 100 x 6
Volume (mm^3)	900000
Density (kg m^{-1})	7850
Mass (kg)	0.7065
Tensile Ultimate Strength (MPa)	460
Young's Modulus (MPa)	200
Tensile Yield Strength (MPa)	250
Poisson's Ratio	0.3
Bulk Modulus MPa	166.67
Time taken in sec	36
No. of Steps	36
No. of points in consideration	36
Heat flux given through TIG torch (W/m^2)	8700000
Convective Heat coefficient (100. $W/m^2 \cdot °C$)	100
Ambient Temperature (°C)	22
Melting point of substrate(°C)	1550
Melting point of wire(°C)	1510
Coefficient of Thermal Expansion C^{-1}	1.2×10^{-5}
Specific Heat (J kg^{-1} C^{-1})	434
Thermal Conductivity (W m^{-1} C^{-1})	60.5
Resistivity ohm m	1.7×10^{-7}

IV. RESEARCH METHODOLOGY

The findings of this study are also anticipated to contribute to the creation of a feedback controller for regulating temperature cycles in any kind of WAAM process. These are the procedures to be followed:

- TIG-WAAM process modelling for single-layer deposition. An ANSYS-powered finite element analysis technique will be utilised to create a thermal analysis of a single - layered metallic deposition process. This method uses a 3D FEM model of a single layer formed using the TIG-WAAM process to forecast the temperature generated as a result of the heating cycle of the WAAM process.

- A heat source that moves uniformly, simulating the heat produced during a TIG-WAAM-based process. The structural steel mesh model is applied.

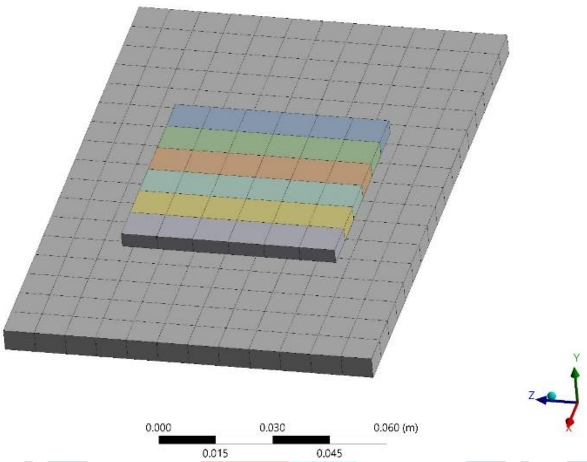


Figure 2 Modelling of TIG-WAAM process for single-layer deposition

The layer is continuously deposited in the form of a zigzag pattern. The size of the heat source should be assumed to be a square section whose cross-sectional area is equal to the molten pool from the TIG source. Synchronizing using the time interval function will imitate a moving heat source.

- To obtain the temperature created during deposition, apply the birth element & death element methods as indicated. When an mesh's element gets born, it becomes inactive as soon as the following element is born, continuing to provide for the possibility of metal deposition..

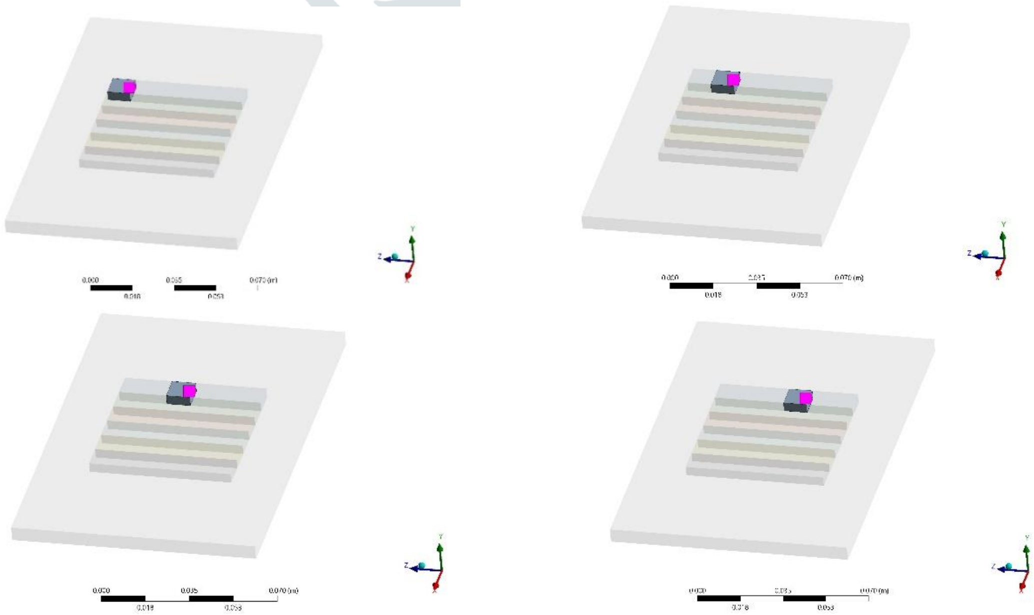


Figure 3 Birth element and death element method

- For the initial condition, the uniformly distribution of heating must be taken into account. The base metal's initial condition and the environment temperature parameter of 22 degrees C are both flexible.
- At various times during the metallic deposition process, the temperature distribution has been recorded. There are a few key areas that need to be pinpointed in order to analyze the impact of temperature concentration throughout thermal cycles. The precise position of the points chosen for temperature history recording.

Until the very end of the deposition, the temperatures at each nodal element must be recorded. According to the assumed torch velocity, the modeled TIG arc will stay in one place along the deposition pathway for the necessary deposition duration. After the deposition time at that spot, the TIG arc will shift to the next site and continue to move throughout the single layer deposition.
At several stages of the metal deposition process, the temperature distribution is to be recorded. It is necessary to pinpoint certain places and display their precise locations in order to analyze the impact of temperature concentrations during thermal cycles.
A birth & death element approach is employed for simulation, as is explained in the previous section. Each node element's temperature is recorded all the way through the deposition process.
According to the assumed torch velocity, the simulated TIG arc stays in one place along the depositing path for the necessary deposition duration. After the deposition period at that place, the TIG arc would move to the next point and continue moving continuously for the duration of the single layer deposition. This motion represents the process flow employed for simulation to determine the temperature distribution in a single layer during deposition.

V. RESULTS

Throughout the metal deposition each second a point is considered for the thermos-mechanical analysis. Total time for the metal deposition and hence the simulation is 36 sec. So, in total 36 points is considered for the analysis.

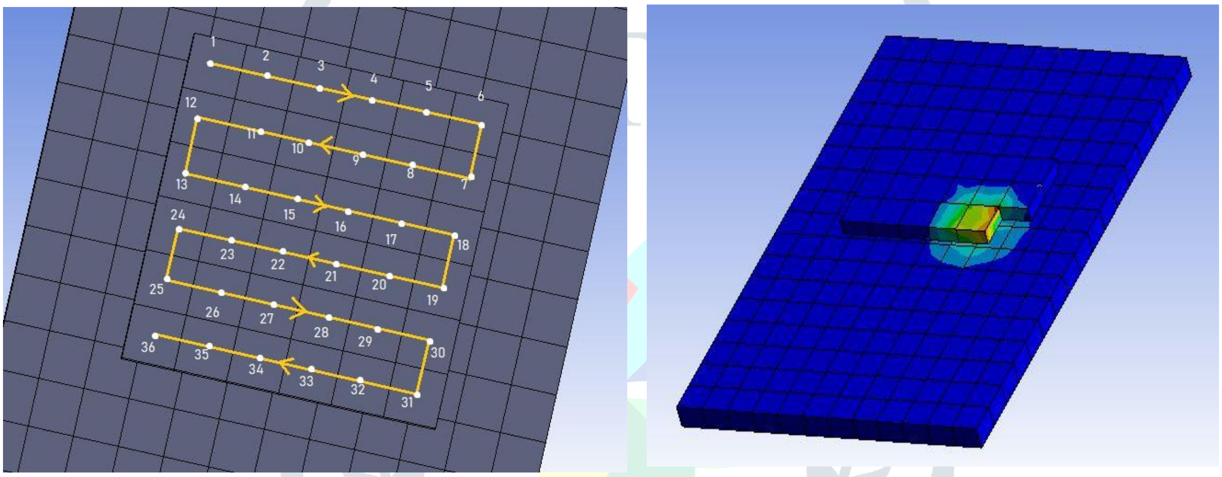


Figure 4 Points of considerations

5.1 Steady-State Thermal Analysis

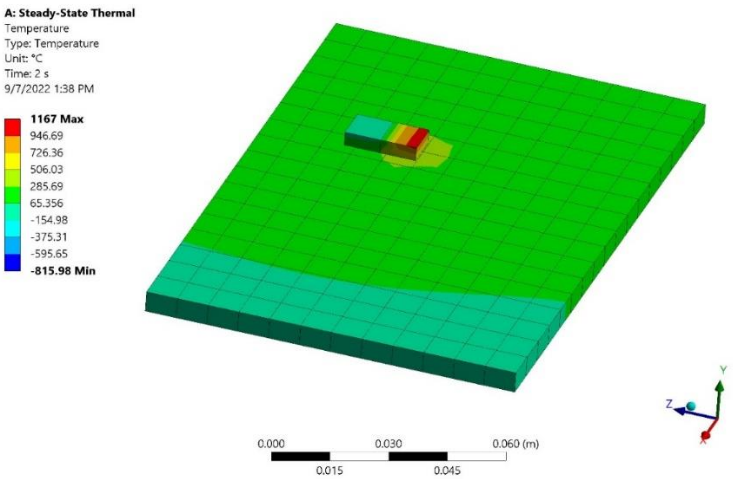


Figure 5 Temperature distribution w.r.t time or point of consideration

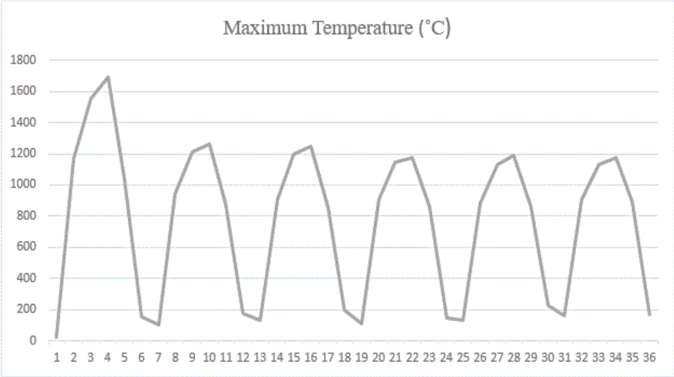


Figure 6 Variation of Max. Temperature (°C)

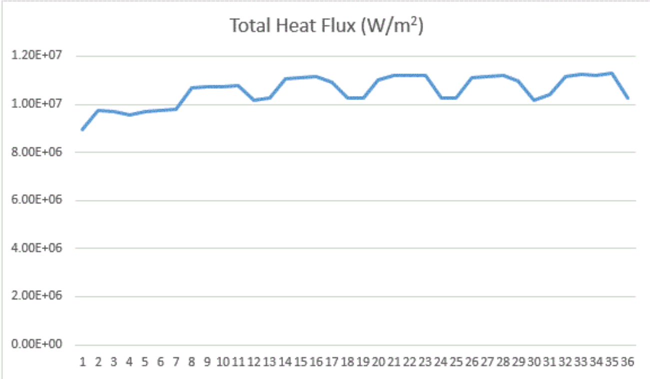


Figure 7 Variation of total heat flux (W/sq. m) w.r.t. time (s)

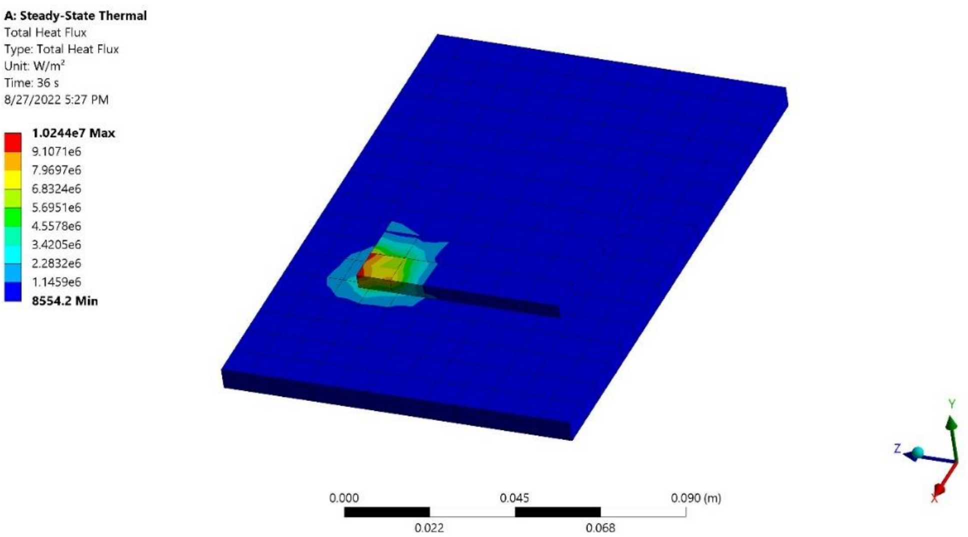


Figure 8 9 Overall variation of Total heat flux

5.2 Static Structural Analysis

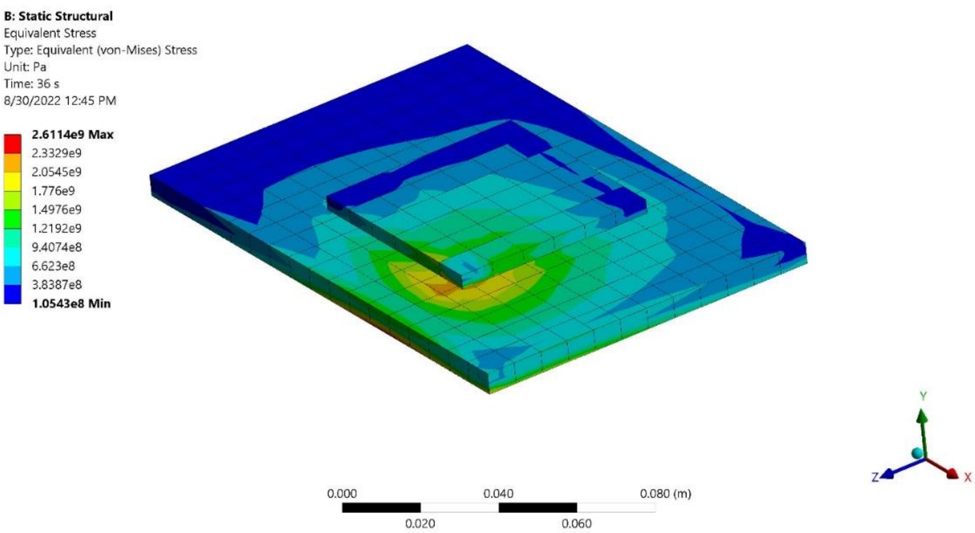
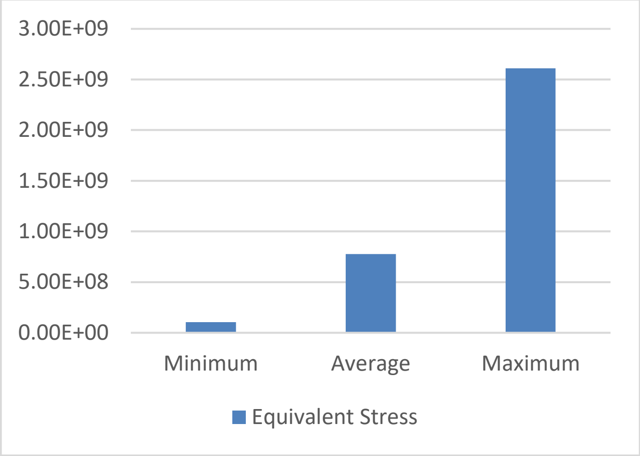


Figure 10 Equivalent Stress developed in the simulation

Table 2 Equivalent Stress developed

Equivalent Stress	Values
Minimum	1.0543e+008 Pa
Average	7.7803e+008 Pa
Maximum	2.6114e+009 Pa



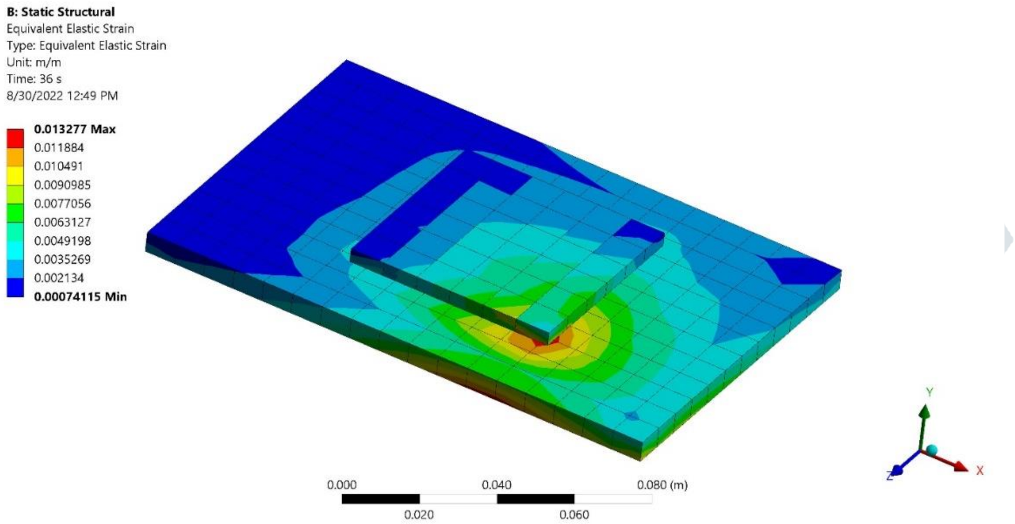
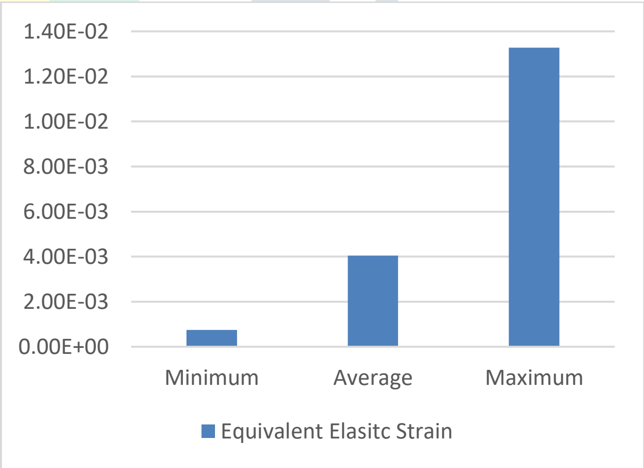


Figure 11 Equivalent Elastic Strain produced

Table 3 Equivalent Elastic Strain produced

Equivalent Elastic Strain	Values (m/mm)
Minimum	7.4115e-004
Average	4.0421e-003
Maximum	1.3277e-002



5.3 Requirements for the amount of Pre-Heating

Suggested minimum preheat or interpass temperature, °F[a][b]

Plate thickness, inches	Produced to published tensile properties	Produced to minimum BHN hardness requirements[c]
Up to 1/2, incl.	50(d)	100
Over 1/2 to 1, incl.	50(d)	150
Over 1 to 2, incl.	150	200
Over 2	200	250

[a] Applicable to shielded metal arc, submerged arc, gas metal arc, flux cored arc and gas tungsten arc welding processes.

[b] A preheat or interpass temperature above the minimum shown may be required for highly restrained welds; however, preheat or interpass temperature should not exceed 400°F for thickness up to and including 1-1/2 in. or 450°F for thicknesses over 1-1/2 In.

[c] Minimum BHN of 321, 340 or 360

[d] Welding a steel which is at an initial temperature below 100°F may require localized preheating to remove moisture from the surface of the steel.

Figure 12 Preheat and inter-pass temperature recommendation by Arcelor Mittal for welding their T1 Steel (ASTM A514)

Credits: Arcelor Mittal official website. Link-shorturl.at/efl26

The whole study is repeated with Pre-Heating the base metal to 250˚F which comes equivalent to around 120℃ before the start of the TIG-WAAM process then the results of concentration of temperature changes. Also, the value of Equivalent stress and Equivalent Elastic Strain decreases. This shows that for smoothening the temperature distribution and lowering the stress generated within the base metal pre-heating can be an well accepted option in most of the cases given all the rest conditions unaltered. In this part of the project all the process parameters are kept as it is except for the temperature of the base metal which earlier had value 25 ℃ which then increased to 120 ℃ as per the recommendations from some of the top manufacturers of steel in the industry. Steel manufacturing companies do not disclose their information with such level of details, but it's worth checking in their official websites and published information and whenever it if found should be taken in consideration.

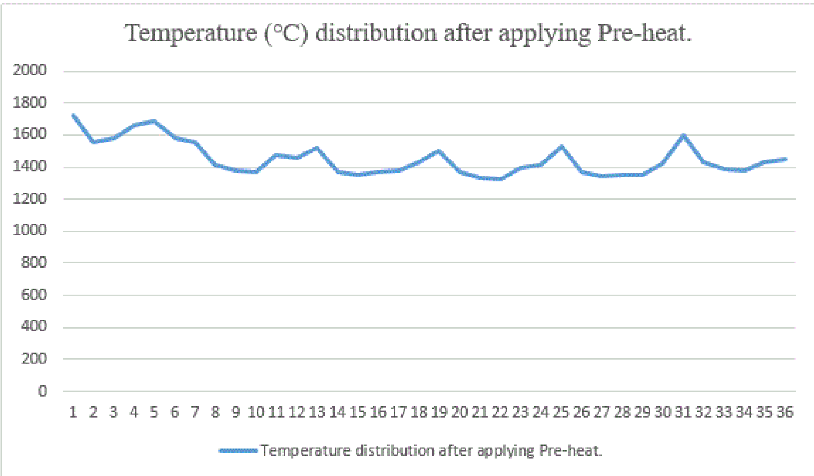


Figure 13 Distribution of temperature after applying pre-heat

Table 4 Equivalent stress and Equivalent elastic strain after applying pre-heat

Equivalent Stress	Values (Pa)
Minimum	5.2654e+006 Pa
Maximum	2.2008e+009 Pa
Average	4.7046e+008 Pa

Equivalent Elastic Strain	Values (m/m)
Minimum	6.1198e-005 m/m
Maximum	6.1198e-005 m/m
Average	6.1198e-005 m/m

VI: Conclusion

- Results shows that the Concentration of temperature and heat is mostly observed at points when the TIG torch is taking turn for example at points 1, 5, 7, 13,19, 25, 31 with highest at point 1 (i.e. 1724.4 °C) followed by point 5 and 31.
- A FEM based model of the TIG-WAAM process has been developed. The model has been used for predicting the distribution of the temperature in the deposited material.
- A heat source model based on birth and death element method was successfully used for simulating moving heat source.
- The concentration of temperature and heat was observed at turning points of the zigzag shaped metal deposition path. The highest temperature was recorded at all turning points in the deposition path up to 1724.4 °C, whereas at all intermediate point temperature levels were remains within the range of melting point.
- The drastic increase in temperature may cause a change in the shape of a molten pool. The Thermal Stress, Strain and Deformation all of them are found to be maximum at the starting point (i.e. point 1). The change in the shape of a molten pool may lead to the deterioration of the geometric shape of the deposited layer.

Hence, the developed model will be useful for the development of a feedback control system for temperature management of TIG-WAAM process in future.
The geometry of the deposited material will also get deteriorated due to this elevated temperature. Hence, the developed model shows good agreement for effectively predicting the temperature history of TIG-WAAM process,
The model can used for predicting the distribution of the temperature in the deposited material. The concentration of temperature and heat was observed at turning points of the zigzag shaped metal deposition path. The highest temperature will be recorded and checked if it is within the range of melting point. The drastic increase in temperature may cause a change in the shape of a molten pool. The change in the shape of a molten pool may lead to the deterioration of the geometric shape of the deposited layer. Hence, the model will be useful for the development of a feedback control system for temperature management of TIG-WAAM process in future.
Some inferred methods to avoid temperature concentration from the study of the methodology can be:

Back-stepping: As analyzed above there are temperature concentration occurring mostly on the turning points of the TIG torch where the metal deposition takes a U turn and the deposition spends relatively more time in less space over the base metal. Thus, deposition happens over a relatively smaller area. This result seems to adds up in the very critical point of discussion i.e. temperature and stress concentration which in turn adversely affect the quality, smoothness and dimensional accuracy of metal deposition.

Pre-heating the base metal: Pre-heating the Structural Steel in the volume around the TIG process points to a least required temperature before, during and after the TIG-WAAM process. The heat is maintained until the complete process is over that help reduce the effect of a potential heat shock that generally occurs without the present of it which in turn affects the quality of the weld. Possible benefits of the pre-heating seems as follows:

- Rate of cooling of the Structural steel that is at the base, Heat affected zone decreases.
- Improvement of the Microstructure.
- Prevents brittleness and Martensitic formation.
- Expansion and contraction i.e. Thermal strain reduces.
- Impurities gets burn out and improves mechanical properties.

VII. Acknowledgment

This research paper could not be completed without the constant support of my project guide Prof. Mukesh Chandra, Dept. pf Production and Industrial Engineering BIT Sindri. Special thanks to all my other Professors for the key motivational support.

References

[1] J. Ding , P. Colegrove , J. Mehnen , S. Ganguly , P.M. Sequeira Almeida, F. Wang, S. Williams[2011] Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts.

[2] M. Graf, A. Hälsig, K. Höfer, B. Awiszus, P. Mayr, Thermo-mechanical modelling of wire-arc additive manufacturing (WAAM) of semi-finished products, Metals (Basel) 8 (2018), https://doi.org/10.3390/met8121009.

[3]Kohei Oyamaa , Spyros Diplasb , Mohammed M'hamdib [2019] Heat source management in wire-arc additive manufacturing process for AlMg and Al-Si alloys . https://doi.org/10.1016/j.addma.2019.01.007

[4]Bintao Wu, Zengxi Pan, Guangyu Chen, Donghong Ding [2019] Mitigation of thermal distortion in wire arc additively manufactured Ti6Al4V part using active interpass cooling,

[5]Ruwei Geng, Jun Du, Zhengying Wei [2021] Modelling and experimental observation of the deposition geometry and microstructure evolution of aluminum alloy fabricated by wire-arc additive manufacturing.

[6] J. Xiong, Y. Lei, R. Li, Finite element analysis and experimental validation of thermal behavior for thin-walled parts in GMAW-based additive manufacturing with various substrate preheating temperatures, Appl. Therm. Eng. 126 (2017) 43–52, https://doi.org/10.1016/j.applthermaleng.2017.07.168.

[7]Filippo Montevecchia, Giuseppe Venturinia , Antonio Scippaa [2016] Finite element modelling of Wire-Arc-Additive-Manufacturing process

[8]Richard Martukanitz, Pan Michaleris, Todd Palmer [2014] Toward an integrated computational system for describing the additive manufacturing process for metallic materials.

[9] M. D. Barath Kumar1 · M. Manikandan1[2021] Assessment of Process, Parameters, Residual Stress Mitigation, Post Treatments and Finite Element Analysis Simulations of Wire Arc Additive Manufacturing Technique

[10] John Goldak, Aditya Chakravarti, and Malcom Bibbly A New Finite Element Model for Welding Heat Sources the FEM calculated values (surface heat source model) of Krutz and Segerlind.

[11] S. Cadiou, M. Courtois*, M. Carin, W. Berckmans, P. Le masson [2020] 3D heat transfer, fluid flow and electromagnetic model for cold metal transfer wire arc additive manufacturing (Cmt-Waam)

[12] Takeyuki Abea, *, Jun'ichi Kanekoa , Hiroyuki Sasaharab [2020] Thermal sensing and heat input control for thin-walled structure building based on numerical simulation for wire and arc additive manufacturing.

[13] S.H. Nikam, N.K. Jain, Three-dimensional thermal analysis of multi-layer metallic deposition by micro-plasma transferred arc process using finite element simulation, J. Mater. Process. Technol. 249 (2017) 264–273, https:// doi.org/10.1016/j.jmatprotec.2017.05.043.

[14] X. Bai, H. Zhang, G. Wang, Modeling of the moving induction heating used as secondary heat source in weld-based additive manufacturing, Int. J. Adv. Manuf. Technol. 77 (2015) 717–727, https://doi.org/10.1007/s00170-014- 6475-2.

[15] M.S. Sawant, N.K. Jain, S.H. Nikam, Theoretical modeling and finite element simulation of dilution in micro-plasma transferred arc additive manufacturing of metallic materials, Int. J. Mech. Sci. 164 (2019), https://doi.org/10.1016/j. ijmecsci.2019.105166.

[16] S.H. Nikam, N.K. Jain, S. Jhavar, Thermal modeling of geometry of single-track deposition in micro-plasma transferred arc deposition process, J. Mater. Process. Technol. 230 (2016) 121–130, https://doi.org/10.1016/j. jmatprotec.2015.11.022.

[17] S.H. Nikam, N.K. Jain, 3D-finite element simulation and image processing based prediction of width and height of single-layer deposition by micro plasma-transferred arc process, Int. J. Adv. Manuf. Technol. 95 (2018) 3679– 3691, https://doi.org/10.1007/s00170-017-1472-x.

[18] Z. Gan, H.W. Ng, A. Devasenapathi, Deposition-induced residual stresses in plasma-sprayed coatings, Surf. Coatings Technol. 187 (2004) 307–319, https:// doi.org/10.1016/j.surfcoat.2004.02.010.

[19] F. Montevecchi, G. Venturini, A. Scippa, G. Campatelli, Finite element modelling of wire-arc-additive-manufacturing process, Procedia CIRP 55 (2016) 109–114, https://doi.org/10.1016/j.procir.2016.08.024.

[20] A. Kumar, T. DebRoy, Heat transfer and fluid flow during gas-metal-arc fillet welding for various joint configurations and welding positions, Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 38 (2007) 506–519, https://doi.org/10.1007/ s11661-006-9083-4.

[21] Y. Ogino, S. Asai, Y. Hirata, Numerical simulation of WAAM process by a GMAW weld pool model, Weld. World. 62 (2018) 393–401, https://doi.org/10.1007/ s40194-018-0556-z. [27] X. Zhou, H. Zhang, G. Wang, X. Bai, Three-dimensional numerical simulation of arc and metal transport in arc welding based additive manufacturing, Int. J. Heat Mass Transf. 103 (2016) 521–537, https://doi.org/10.1016/j.ijheatmasstransfer.2016. 06.084.

[22] M. Ito, Y. Nishio, S. Izawa, Y. Fukunishi, M. Shigeta, Numerical simulation of joining process in a TIG welding system using incompressible SPH method, Q. J. Japan Weld. Soc. 33 (2015) 34s–38s, https://doi.org/10.2207/qjjws.33.34s.

[23] T.A. Rodrigues, V. Duarte, J.A. Avila, T.G. Santos, R.M. Miranda, J.P. Oliveira, Wire and arc additive manufacturing of HSLA steel: effect of thermal cycles on microstructure and mechanical properties