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THERMAL ANALYSIS OF MIG BASED WIRE ARC ADDITIVE MANUFACTURING PROCESS USING FINITE ELEMENT METHOD

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Abstract: Among the direct energy deposition methods, one of the most energy-efficient is the wire and arc additive manufacturing (WAAM) technique based on metal inert gas welding (MIG-WAAM). The MIG-WAAM technique uses wire and arc to deposit a material layer by layer. The temperature distribution during layer-by-layer deposition in the wire arc additive manufacturing (WAAM) method is influenced by the route planning in the metal deposition process. The quality of the metal deposition and its dimensional precision are influenced by temperature distribution. This study represents the development of a Finite Element Analysis (FEA) based model for the MIG-WAAM process to analyze the impact of temperature distribution on the metal deposition process. Using the MIG-WAAM technique, the proposed model has been utilized to simulate metal deposition of SS304L multilayer rectangular box structures on mild steel substrates. The distribution of temperatures across the material that has been deposited has been observed. The findings demonstrated that temperature concentrations occur at every step in the deposition process, potentially resulting in a decline in deposition quality. To enable smoother and higher-quality metal deposition, the established model may be further utilized to construct a feedback-based temperature control system.

Keywords – MIG, WAAM, Finite Element Analysis.

I. INTRODUCTION

As product complexity rises and industrial applications demand greater flexibility, Additive manufacturing (AM) processes are gaining prominence. While laser powder bed processes are established, their restricted build volumes and lengthy processing times pose limitations. Wire and arc additive manufacturing (WAAM) emerges as a promising solution for economically large parts with moderate complexity. Its potential applications span load bearing steel structures in construction to light weight metal parts in aviation, often crafted from aluminium or titanium alloys. WAAM falls under directed energy deposition (DED) processes, with cold metal transfer (CMT) being a notable method characterized by low energy input and process stability. By depositing weld beads layer by layer, WAAM offers an alternative to traditional manufacturing, integrating seamlessly into existing process chains. This technology improves Buy-to-Fly ratios ad reduces tool wear, particularly beneficial for cost-intensive materials like titanium alloys. Subsequent milling ensures net shape and surface quality compliance. Achieving geometric accuracy is crucial, especially for minimizing Buy-to-Fly ratios, a significant challenge in near-net shape manufacturing. Selection of process parameters and build-up strategy determines WAAM part geometry and accuracy. Authors highlight travel speed and wire feed speed as key parameters influencing single bead wall geometry, with tool path planning crucial for complex part geometries.

Furthermore, the dimensional accuracy is notably impacted by the dwell times, apart from the mentioned process parameters. Dwell time refers to the duration between the cessation and commencement of welding between successive layers. Within this interval, the component undergoes cooling. Decreasing dwell times elevate interlayer temperature, potentially inducing heat accumulation and consequent deformation of the part. Numerous scholars have investigated this phenomenon extensively.

Many of the research attempts have been reported for the development of a thermo-mechanical and numerical model of the additive manufacturing process. The effect of process variables on the temperatures and residual stress has been predicted by some of the authors.

Figure 1: MIG-WAAM process setup

a finite element simulation of micro plasma arc and laser based additive manufacturing process for metallic structure. In another study, they have developed a similar model for predicting the geometric shape of the deposited material in terms of deposition width and deposition height[1], [2]. [3]based on a altered Goldak model to give the filler material’s heat flow dispersion a more accurate representation. Ultimately, the FE findings produced with the suggested and Goldak heat source models are compared with the observed distortion of a test case component that was created using the WAAM technique. [4], [5]developed a thermo-mechanical model for gas metal arc welding (GMAW) based additive manufacturing process using finite element analysis software. The heat transfer coefficient for GMAW process has been considered instead of modelling the whole welding process. [3,8] a finite element model to assess the real power distribution between the substrate and deposited material in GMAW-based additive manufacturing. A comparable model for forecasting the geometric form of the deposited material in terms of deposition height and breadth was created in a different research [8], [9]. [10]highlighted the potential of additive manufacturing (AM), particularly gas metal arc welding-based AM (GMAW-based AM), for producing complex metal components with high deposition rates. Studies have focused on analyzing the internal quality, microstructures, and mechanical properties of components manufactured using GMAW-based AM, emphasizing its suitability for critical load-bearing applications. Comparisons with traditional manufacturing methods, such as wrought mild steel fabrication, have been made to assess the feasibility and performance of GMAW-based AM for real-world applications. [11]have extensively explored the Wire Arc Additive Manufacturing (WAAM) process, focusing on parameters like distortion and residual stress. Different heat source models, such as Goldak's double-ellipsoid and rectangular, have been investigated to understand their impact on process outcomes. However, there's a need for further research to develop effective methodologies for analyzing distortion and residual stress in WAAM of stainless steel, particularly considering complex geometries and material behavior. [12]literature highlights the growing interest in wire-based direct energy deposition of lightweight metallic materials like titanium and aluminum alloys, driven by industry and academia. While high-throughput deposition faces challenges such as poor surface quality and coarse microstructures due to high temperatures, laser systems offer enhanced controllability, enabling manipulation of process temperatures and resulting microstructures. Studies focus on elucidating temperature gradients, cooling rates, and thermal cycles with varying laser beam irradiances, revealing insights into heat accumulation, process stability, and microstructure refinement in laser additive manufacturing of aluminium alloys. According to [13], in wire-based LMD conduction welding conditions should be used in order to achieve a homogeneous melting to solidification behaviour and minimum heat accumulation during deposition. [14], [15] Strategies for optimizing welding procedures, informed by simulation results, aim to enhance muffler productivity and mitigate deformation challenges. This study explores the use of MIG cladding and CNC milling to fabricate components from H-13 tool steel, aim to enhance productivity and mitigate deformation challenges.

Based on the literature, most of the simulation work has been done for laser-based, micro plasma arc based and tungsten inert gas additive manufacturing process. Numerous researches looked at how the process parameters of the WAAM method affected the temperature produced during thin-walled metal deposition. Less work has been reported on MIG-WAAM process.
In this article, a MIG-WAAM process has been simulated for the visualization of heat distribution in the specimen of stainless wire. the effect of temperature concentration at bottleneck points in the deposition has been observed. The findings of this work will be useful in the development of feedback control systems that regulate temperature cycles in WAAM processes of kinds

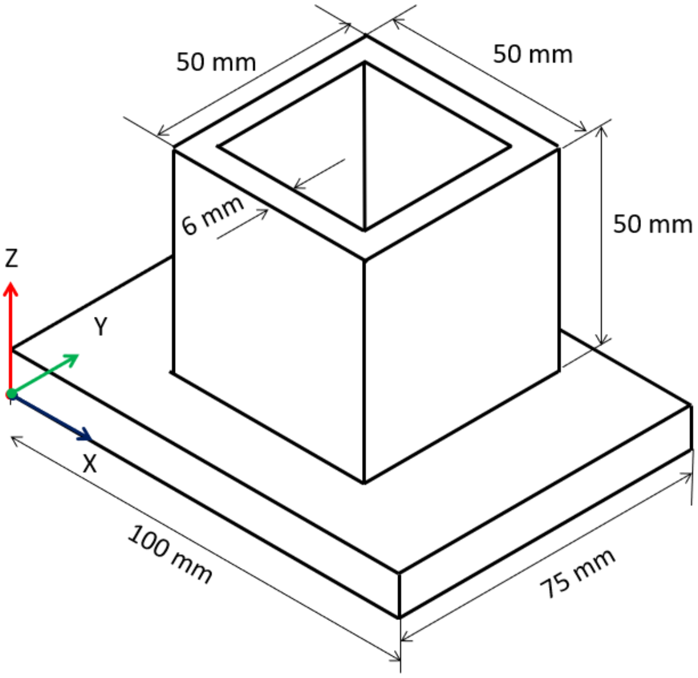

Figure 2. Part Model

II. Modelling of MIG-WAAM process for single-layer deposition

A finite element analysis method powered by ANSYS software was used to develop a thermal model of a single layer metal deposition process. The temperature generated due to the heating cycle of WAAM process has been predicted by this method. A 3D FEM model has been developed which consist of a single layer deposition using MIG-WAAM process. The considered model is having substrate plate of dimensions (100mm X 80mm X 10mm) and a single layer of dimensions deposited over it. Nine number of beads have been considered in a single layer. A uniformly moving heat source was used to simulate the heat generation during MIG-WAAM based process. The meshed model of the MIG-WAAM process is shown in

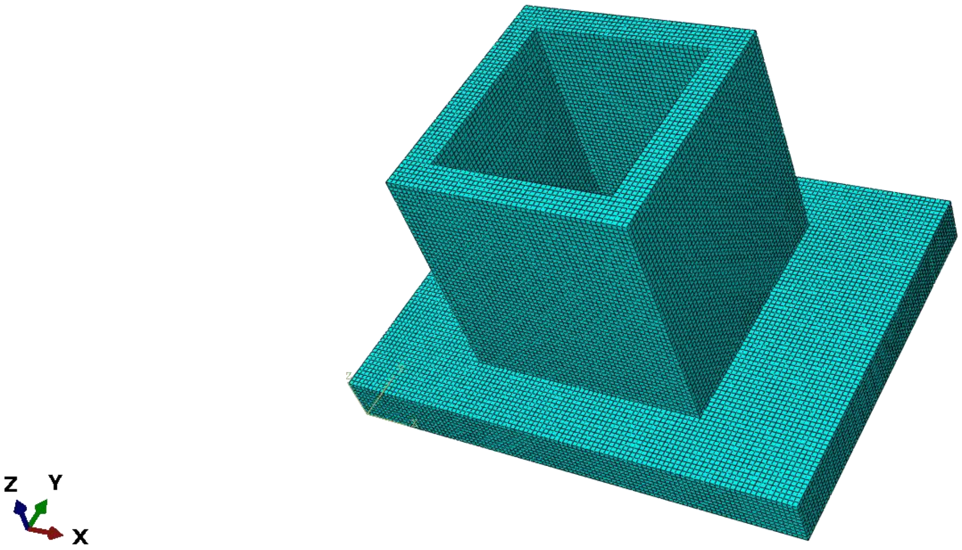

Figure 3. The mesh size has been finalized after getting negligible changes in the simulation results with the change in the mesh size.

The deposition of the layer takes place in a square shaped path. The path followed for the deposition is clock wise and counter clockwise

The heat source dimensions were taken as a square section having area of cross section equals to MIG source molten pool. The moving heat source was simulated by synchronization with the time step function. The birth element and death element method as described by [4]. was used for getting the temperature generated during deposition. The uniform distribution of heat was considered for the initial condition. The room temperature was assumed as 25 °C for the initial condition. The values of other process parameters selected for FEM model are given in Table 1

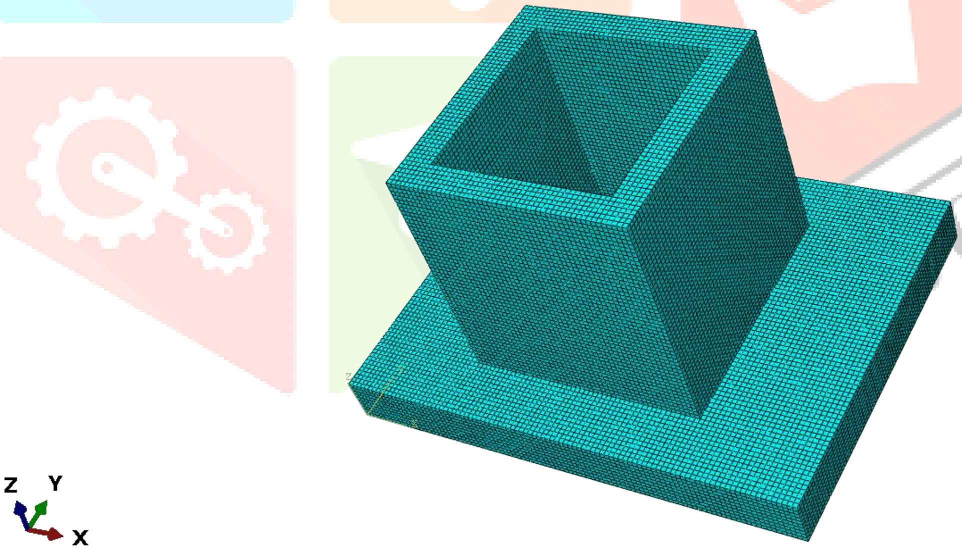

Figure 3: FEA model for MIG-WAAM based deposition

Table 1: process parameters considered for the simulation process

Parameters	Value
Wire material	SS 304L
Wire Diameter	0.80mm
Wire material melting point	1450 °C
Density of wire material	8000 kg/m^3
Substrate material	Mild steel
Substrate melting point	1400 °C
Torch movement velocity	600 mm/min
Initial temperature of substrate and wire	25 °C
Power of MIG source	1200 W

The distribution of temperature during the metal deposition process has been recorded at different points in the deposition. For analyzing the effect of temperature concentration during thermal cycles, six distinct points have been identified. Figure 4 shows the exact location of the points selected for recording temperatures history.

As discussed in previous section, a birth and death element method were used for simulation. The temperature at each node element is recorded till the last point in the deposition. the simulated MIG arc will remain at one point in the deposition path for the required deposition time as per the considered torch velocity. The MIG arc will move to next point after completing the deposition time that point and will continuously moving for entire single layer deposition. Figure 5 represent the process flow used for simulation process for obtaining distribution of the temperature in a single layer of deposition.

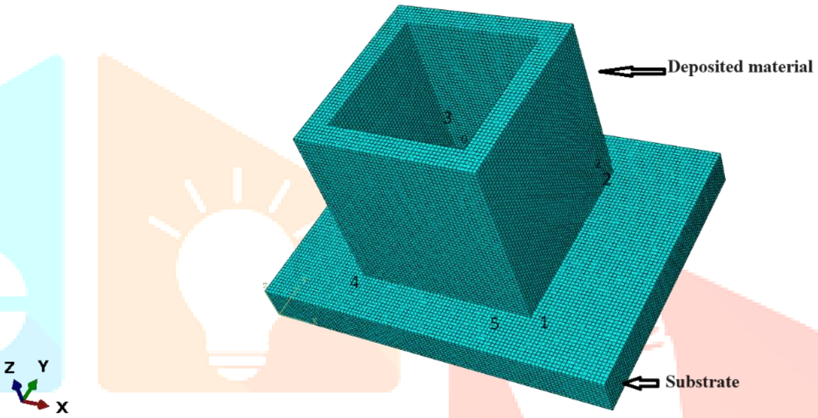

Figure 4: Location of points selected for recording temperatures

III. Results and Discussion:

3.1. The distribution of temperature during heating in single metallic deposition

Figure 6 shows the temperature distribution over the deposited material. The substrate undergoes a continuous thermal cycle of heating. The molten material temperature increases gradually for each successive point in the deposition but at turning points in the deposition path, the concentration of the temperature has been observed. . The molten pool gets expanded due to this concentration of temperature. The temperature at point 5 will exceed the melting point temperature (ref. Figure 6) and causes defects in the deposition. Whereas, no concentration of temperature was observed at all other intermediate points in the deposition. Figure 6 shows the distribution of temperature fields at edges. More amount of heat gets accumulated in this region and will cause deterioration in the shape and geometry of the deposited material.

The temperature history at some of the selected locations has been recorded as shown in Figure 4. For better understanding temperature generated at six points, five on the substrate with one in the middle of the part model and one at first layer after immediate deposition. Figure 7, Figure 8, Figure 9, Figure 10, Figure 11 shows the temperature history recorded at these points.

From the recorded temperature history, it can be seen that the temperature at all points expect 5 are below the temperature at point 5. In Figure 12 the temperature at 5 is slowly decreased as by increasing the layers of deposition.

A similar trend has been observed throughout the deposition process. From Figure 12, it can be concluded that the concentration of the temperature takes place at while depositing the material. The concentration of the temperature leads to change in the shape of a molten pool. 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 MIG-WAAM process.

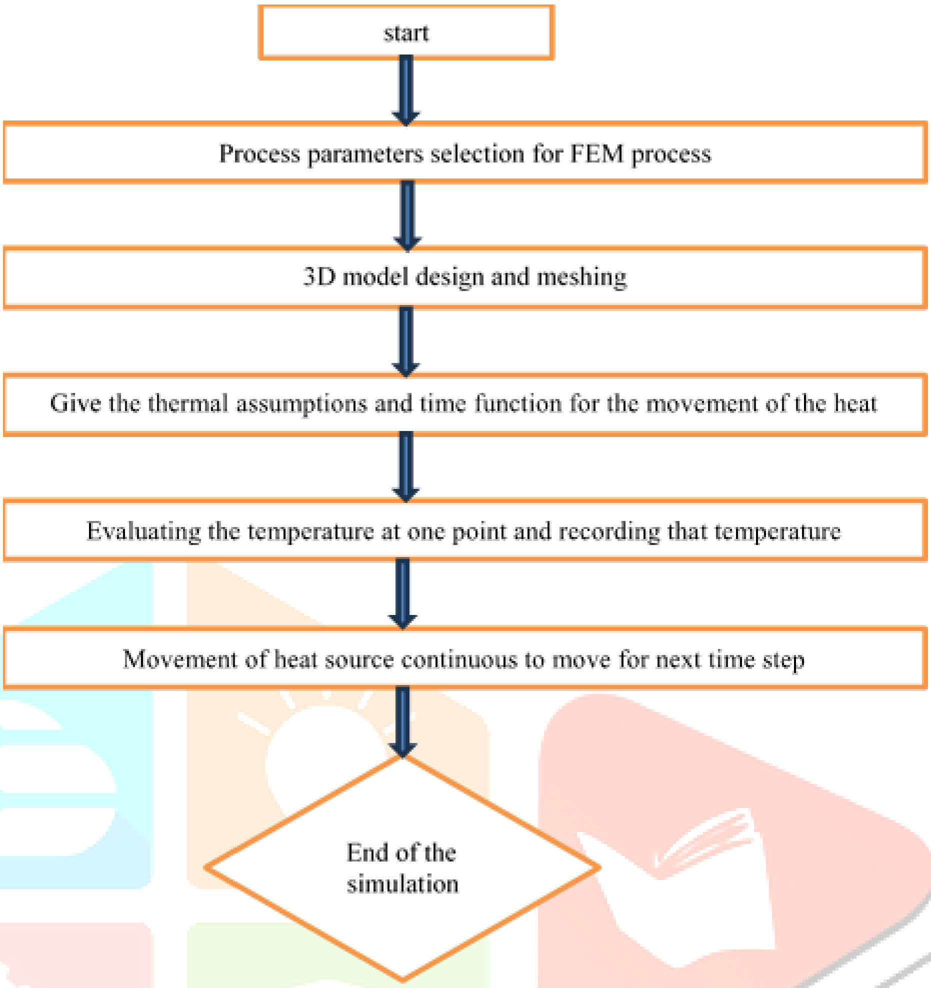

*Figure 5**:** Process flow for simulating temperature distribution of a single layer*

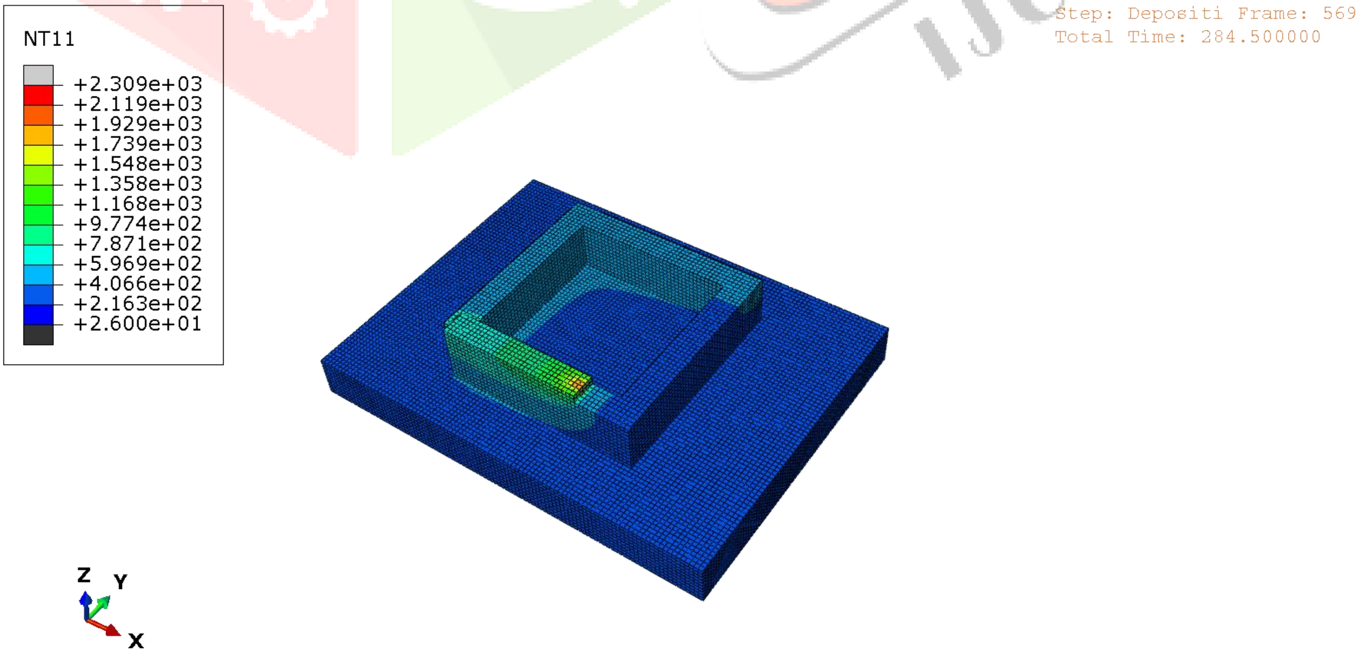

Figure 6: ***Distribution of temperature of the part model***

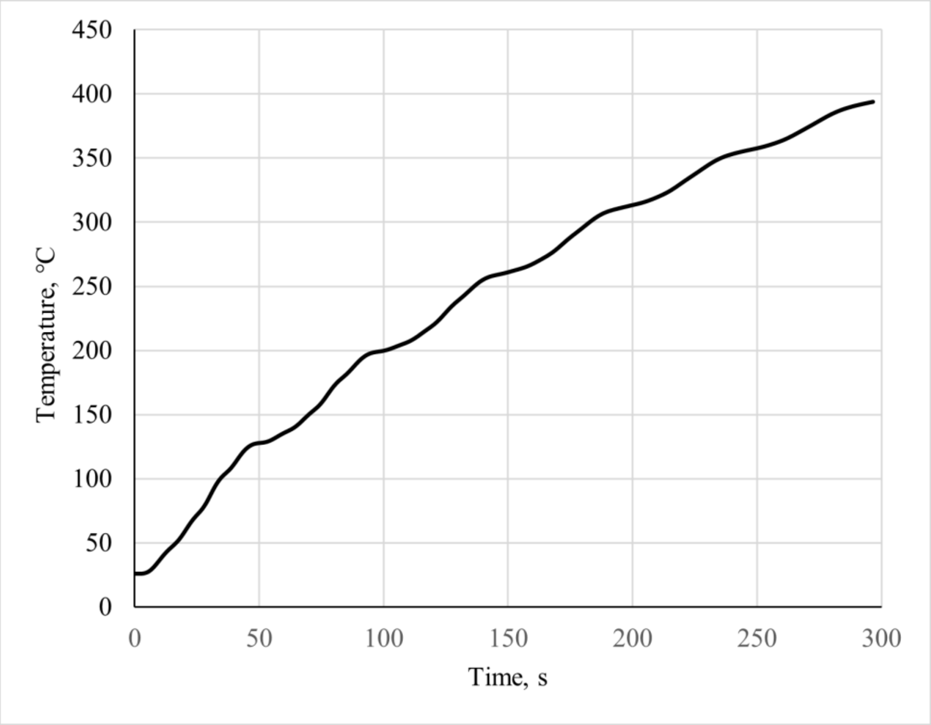

Figure 7: Temperature history recorded at point 0

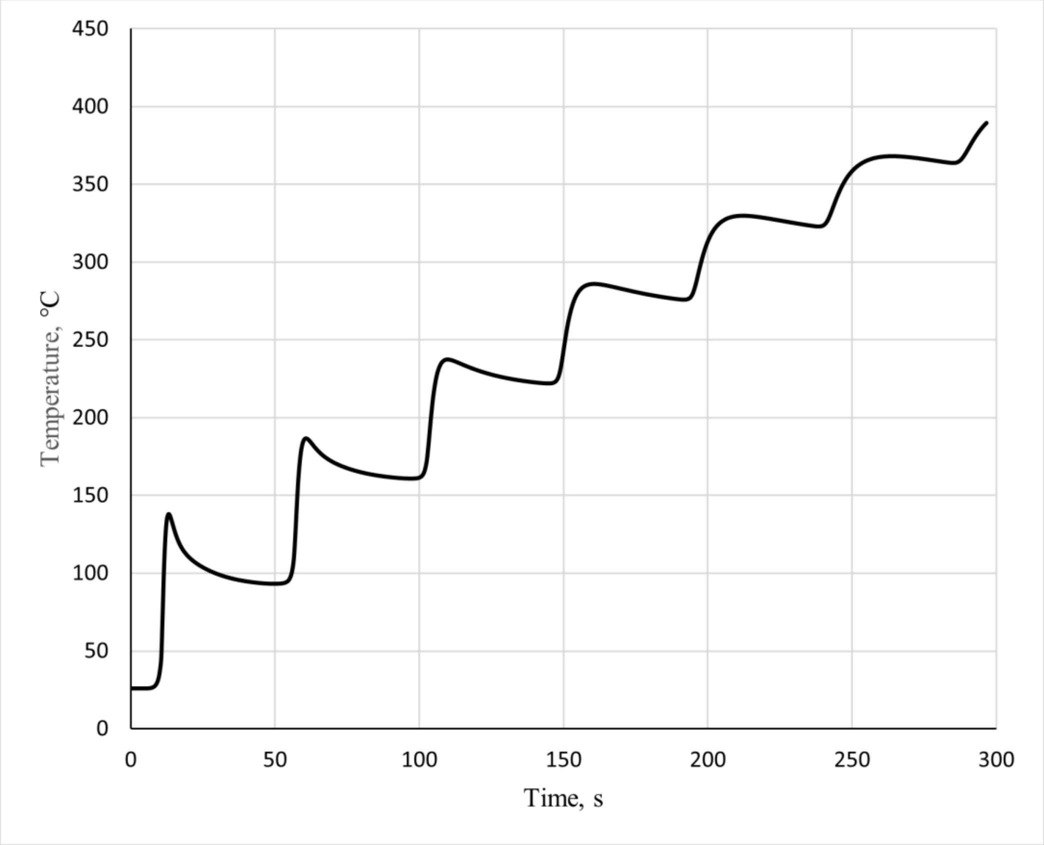

Figure 8: Temperature history recorded at point 1

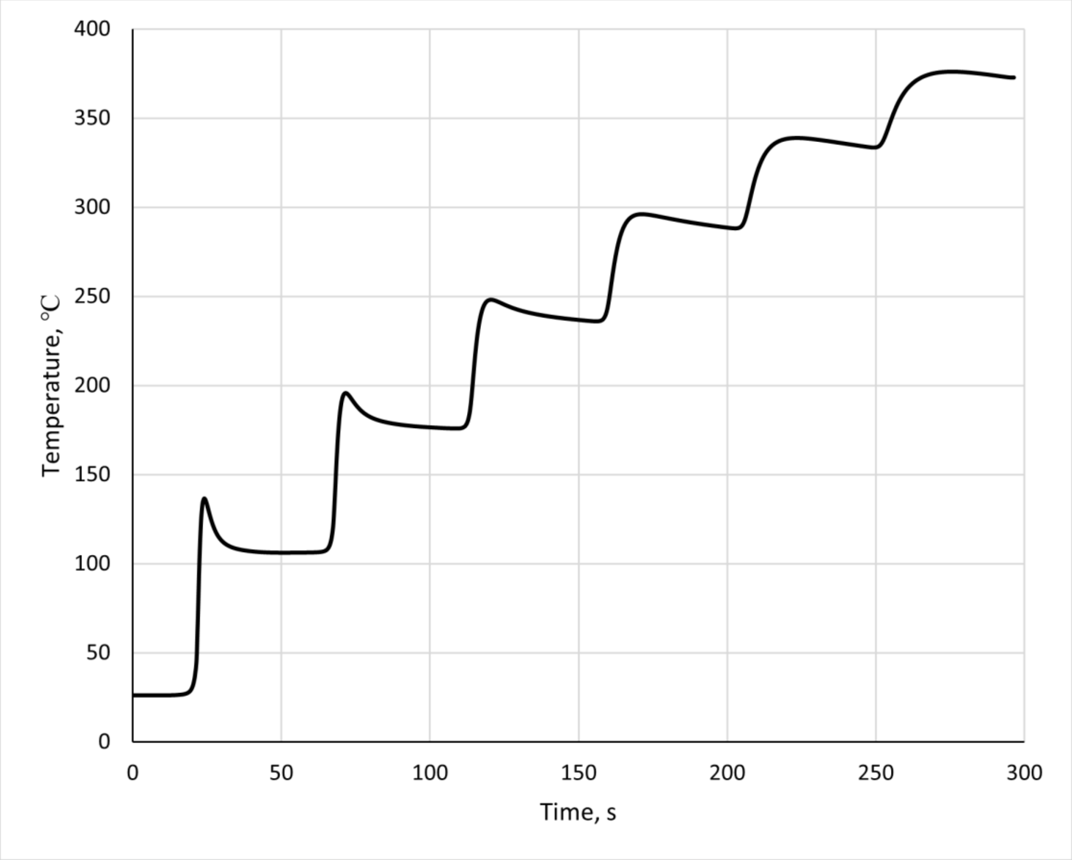

Figure 9: Temperature history recorded at point 2

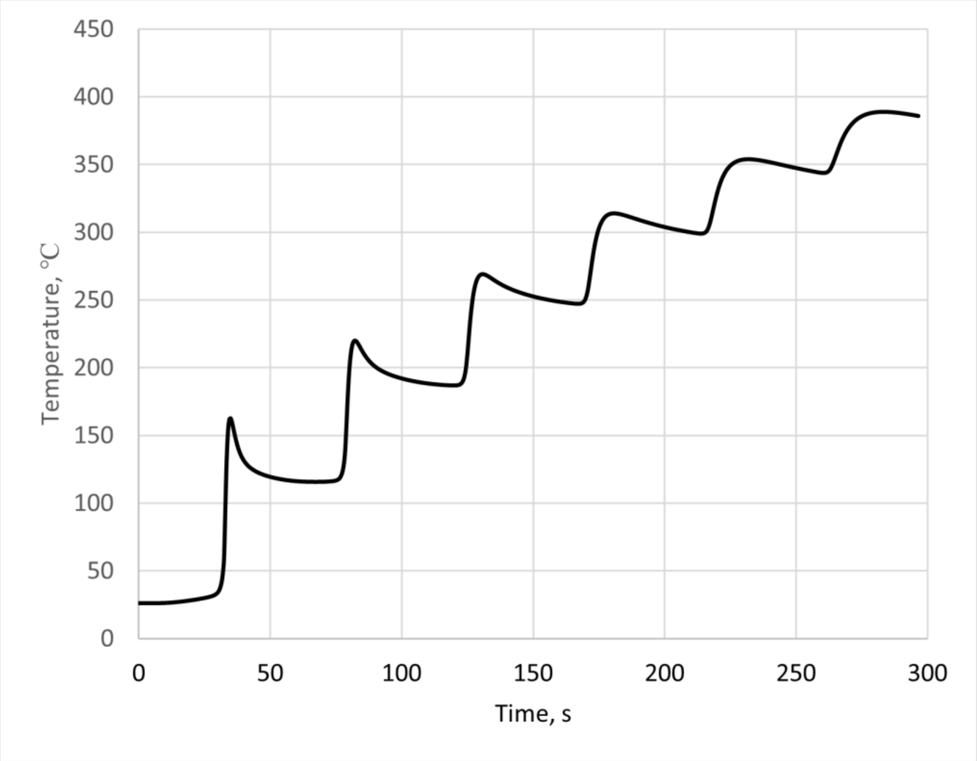

Figure 10: Temperature history recorded at point 3

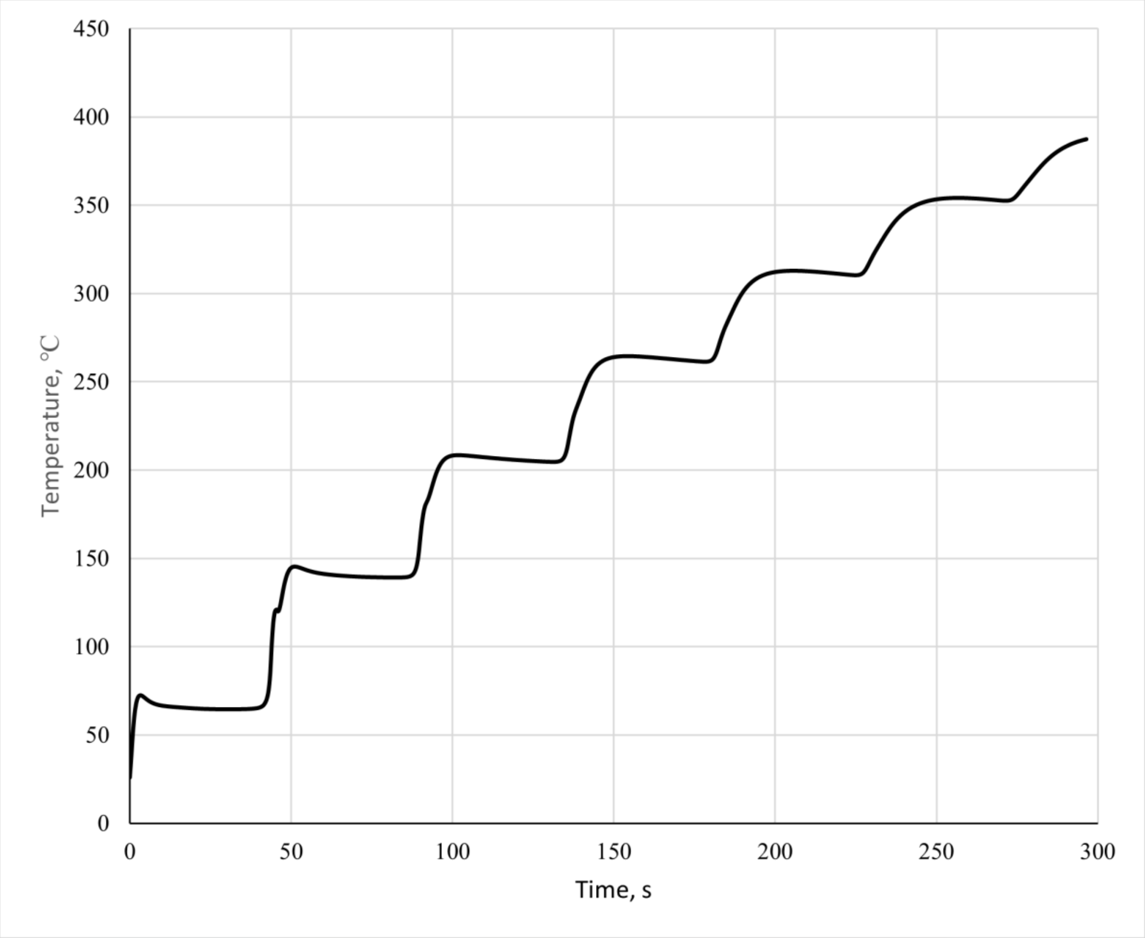

Figure 11: Temperature history recorded at point 4

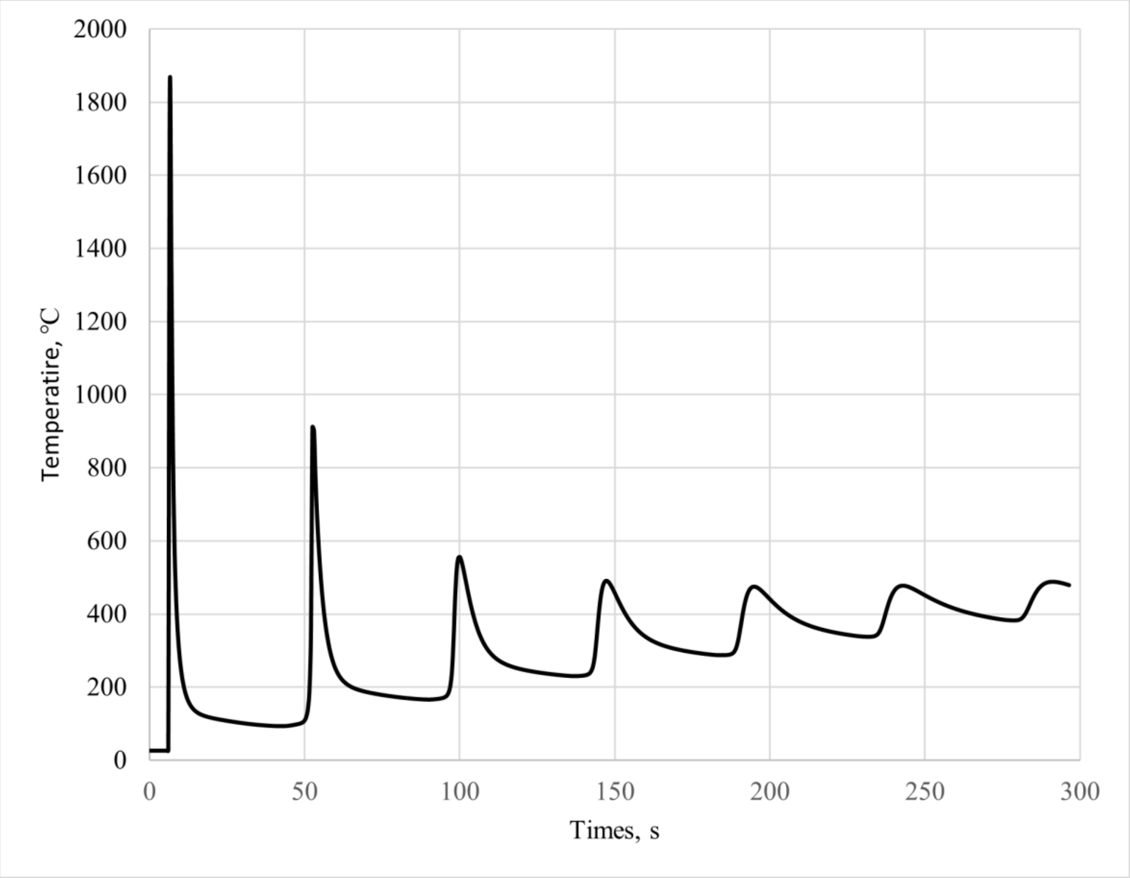

Figure 12: Temperature history recorded at point 5

IV. Conclusion: This article presents the development of a Finite Element Method (FEM) based model for the MIG-WAAM process, aimed at predicting temperature distribution within the deposited material. A heat source model utilizing the birth and death element method was effectively employed to simulate the movement of the heat source. Analysis revealed concentrated temperature and heat levels at the turning points of the zigzag-shaped metal deposition path. At these turning points, temperatures peaked at 2119°C, while temperatures at intermediate points remained within the melting range. Such a significant temperature increase could potentially alter the molten pool's shape, leading to deterioration in the geometric accuracy of the deposited layer. Consequently, this developed model holds promise for the future development of a feedback control system to manage temperatures in the MIG-WAAM process effectively

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