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EFFECT OF MULTIPLE TECHNOLOGIES ON MINIMIZING THE RESIDUAL STRESSES IN ADDITIVE MANUFACTURING

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ABSTRACT

Additive Manufacturing (AM) is rapidly becoming the directing technology for manufacturing components in many industries, including automotive, aerospace, medical, etc. Wire-arc additive manufacturing (WAAM) technology with a higher rate of deposition is becoming prominent technology in AM. Wire-based additive manufacturing involves high heat input for melting the wire for deposition. While the component builds up in multiple layers, it involves various heating and cooling cycles, causing non-homogenous thermal loads. Due to repeated cycles, residual stresses get trapped inside the parts and lead to various defects such as cracks, deformation, warpage, the reduced life cycle of the components, etc. It is required to reduce the residual stresses to minimize the defects. This paper talks about the effect of multiple technologies such as pre-heating and compressive loading by hammering to minimize the residual stresses. Pre-heating the substrate (over which deposition takes place) will decrease the thermal gradient and thus, reduce the residual stress. Since tensile residual stresses are generated during the wire-based cladding process, which is to be nullified by applying compressive loading, a pneumatic-based setup developed in-house for imparting the compressive residual stresses was used to minimize the tensile residual stresses. In this work, four different samples were prepared; 1) as-deposited (without pre-heating and hammering), 2) deposition followed by hammering, 3) pre-heating then deposition, 4) Pre-heating followed by deposition and then hammering to measure the residual stress through the X-ray diffraction method. It was found that pre-heating and hammering individually minimize the residual stresses, and the combined effect has shown much reduction in tensile residual stress.

Keywords: Residual stress, additive manufacturing, WAAM, pre-heating, hammering.

1. Introduction

Additive manufacturing (AM) is an advanced manufacturing technology in which material is added layer by layer, which otherwise uses conventional manufacturing processes (subtractive manufacturing) where products are made with different technology by removal of material in the form of chips (e.g., milling, drilling, threading, etc.) or by plastically deforming the base material (e.g., rolling, forging, etc.) Metal additive manufacturing (MAM) is becoming more important in many industries, including aerospace, automotive, biomedical, military, and energy, because of its flexible process capacity to create functional metal parts with complicated geometry in a short period of time. Directed energy deposition (DED) and Powder bed fusion (PBF) are two of the most common MAM methods. Because of the greater layer thickness and

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faster energy deposition rate, DED has a substantially higher material deposition rate than PBF [1]. Powder-based techniques may require post-process densification through hot isostatic pressing (HIP).

1.1. Residual stress in additive manufacturing

Residual stress (also called internal stress) is defined as the left-out stress that would exist in a component or structure even if there is no applied force on the component. These stresses are generated in metals during the process of welding, forming, heat treatment, quenching, casting, machining, and grinding operations, which leads to a non-uniform change in the volume or shape of a workpiece. Numerous research on process improvement to minimize residual stress in AM have been performed. To date, the initiation of residual stress is primarily attributed in the prior studies to the "temperature gradient mechanism" [2-4]. The exceptional thermal cycle of metal AM is accompanied by fast heating, cooling rates, and melt-back involving instantaneous melting of the upper material layer and re-melting of earlier solidified layers. Hence, non-uniform thermal expansion and contraction occur around the melt pool, where large thermal gradients exist during the deposition process, and therefore metal experiences repeated spatially varied heating and cooling cycles, resulting in thermal deformations and residual stresses, which is analogous to welding. Welding and MAM have a lot in common when it comes to the generation of residual stress [5-7].

1.2. Effect of residual stress

Residual stress can be very detrimental to the performance of the material, and when it is inside a component influences dimensional stability, fatigue life, corrosion resistance, and brittle fracture [8]. Therefore, the quantitative study of residual stress formation and the process parameters that cause the residual stress has become a key step in the additive manufacturing process [9]. The major effects of the residual stress in any process are deformation, low static strength, low dynamic strength, poor fatigue resistance, lower magnetization [10-11].

Researchers carried out modeling and analysis of weldments for multi-pass welding, welding sequences, thin steel plates, sheet metal, and cylindrical pipes showed high residual stresses in welding [12-13]. The residual stress-causing deformation and cracks restrict rapid manufacturing [10]. Residual stress also causes the lowering of mechanical performance and premature failure; thus, the study of residual stress plays a key role for AM components [11]. There are multiple technologies, such as pre-heating and hammering, which help reduce/remove the residual stress from the component through pre/post methods.

Pre-heating leads to more homogeneous heat input, and residual stress is also less compared to the case without pre-heating [14]. Xiong et al. [15] studied the thermal behavior in GMAW-based additive manufacturing with various substrate pre-heating temperatures; they proposed substrate pre-heating as an effective approach to overcome the problem of cracks and distortion. Pre-heating makes the thermal cycle much smoother and reduces the cooling rate of the molten pool. The molten pool temperature at various layers under different substrate pre-heating is shown in Fig. 1.

Hönnige et al.[16] had carried out the experiment to minimize the residual stress with a roller. Different rolling techniques, vertical and side rolling, were used to minimize residual stress and distortion. Vertical rolling was applied after every layer of deposition on the top of the wall to deform each layer. Side rolling was applied after complete deposition on the side surface of the wall. Substrate out of plane distortion with vertical rolling is shown in Fig. 2.

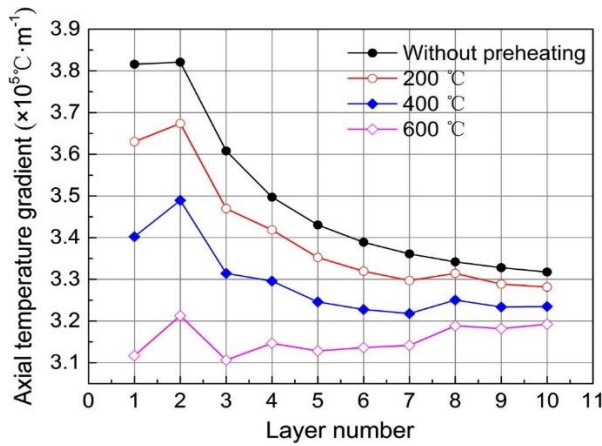


Fig. 1. The temperature gradient in the molten pool for various layers [15]

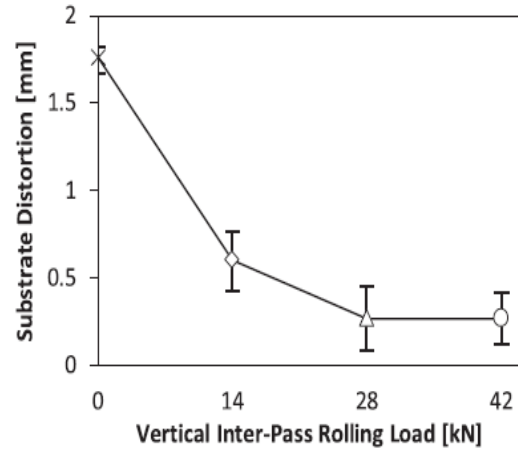


Fig. 2. Substrate distortion in vertical inter pass rolling [16]

2. Measurement of residual stress

There are three techniques to measure the residual stress, which depend on whether the component is destroyed (completely or partially) or not, and based on the level of destruction, it can be classified into three categories; destructive technique, semi-destructive technique, and non-destructive technique. The measuring methods can also be classified according to the physical principle, such as relaxation, diffraction, or other phenomena [17]. The detailed classification of various methods based on the principles is shown in Table 1.

Table 1. Classification of residual stress measurement techniques based on the principle

Techniques	Relaxation	Diffraction	Other Principle
Destructive	-Sectioning		
	-Contour		
	-Slitting		
Semi-Destructive	-Hole Drilling		
	-Ring coring		
	-Deep hole drilling		
Non-Destructive		-X-ray diffraction	- Ultrasonic
		-Neutron Diffraction	-Magnetic
			Barkhausen noise

3. Experimentation

To examine the effect of pre-heating and hammering on the residual stress of the component made by the WAAM process, samples were prepared, and standard size was cut through wire EDM (Electrical Discharge Machining) process, and then the testing was carried out for residual

stress measurement by X-ray diffraction test. The details for sample preparation and testing are discussed in the following section.

3.1 Sample preparation

Samples of 10x100x9 mm³ were prepared with four different conditions; 1. As Deposited (without pre-heating and hammering), 2. Deposition followed by hammering 3. Pre-heating followed by deposition, and 4. Pre-heating followed by deposition and hammering. All the samples were deposited using CMT 2700 MIG setup from Fronius (CMT-Cold Metal Transfer, MIG- Metal Inert Gas) with 1.2 mm wire diameter of mild steel (Grade-ER 70S-6), composition for deposited material is shown in table 2.

Table 2. Composition of Mild Steel (ER70S-6) material (in wt%) [18]

Mn	Si	Cu	C	Ni	Cr	V	Mo	S	P	Fe
1.60	0.90	0.20	0.09	0.05	0.05	0.05	0.05	0.007	0.007	Balance

The blocks were prepared with the layer thickness of 1.5 mm and height of 9 mm achieved in 6 layers of deposition. Process parameters for deposition of all samples are shown in table 3. CAD model for the block and actual deposition is as shown in Fig. 3. Gas flow rate is in the direction of material flow and perpendicular to the direction of deposition.

Table 3. Process parameters for deposition

Parameters	Values
Current (A)	100
Voltage (V)	22.5
Stand of Distance (mm)	12
Gas flow rate (l/min)	15
Feed (mm/min)	800
Step over (mm)	2

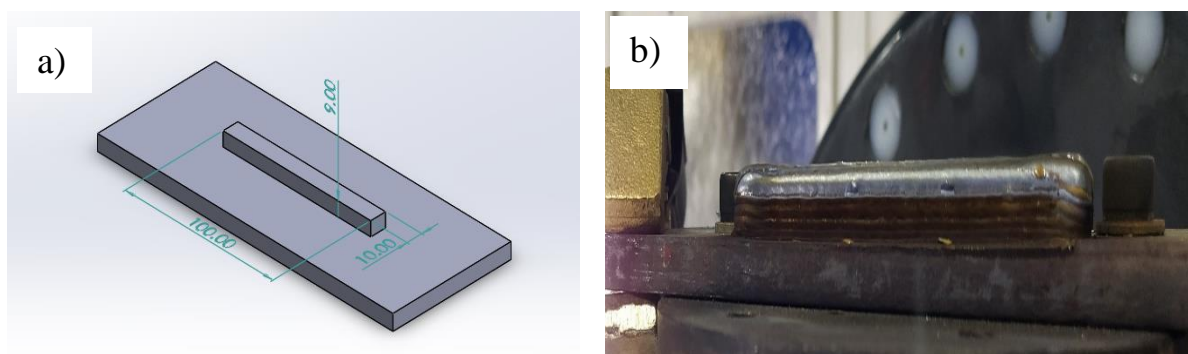


Fig. 3. a) CAD model of the block (b) actual deposition of block

After every layer of deposition, the top surface is machined for maintaining the z-accuracy and repeating the same process for six layers with a layer thickness of 1.5 mm each gives the final height of 9 mm. Blocks were deposited for all four conditions, keeping all other parameters the same, as shown in Fig. 4.

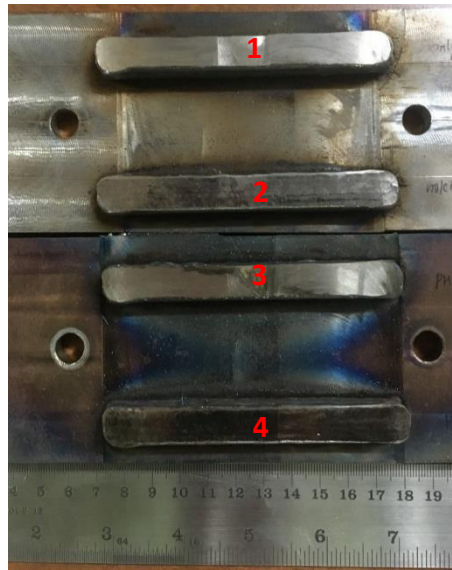


Fig. 4. Samples for testing

Induction-based 25 kW pre-heating setup developed for pre-heating the substrate and previously deposited layer. Pre-heating was carried out at the temperature of 350 °C every time; pre-heating was done for samples 3 and 4. The setup for the induction-based pre-heating with the water-cooled coil system is shown in Fig. 5.

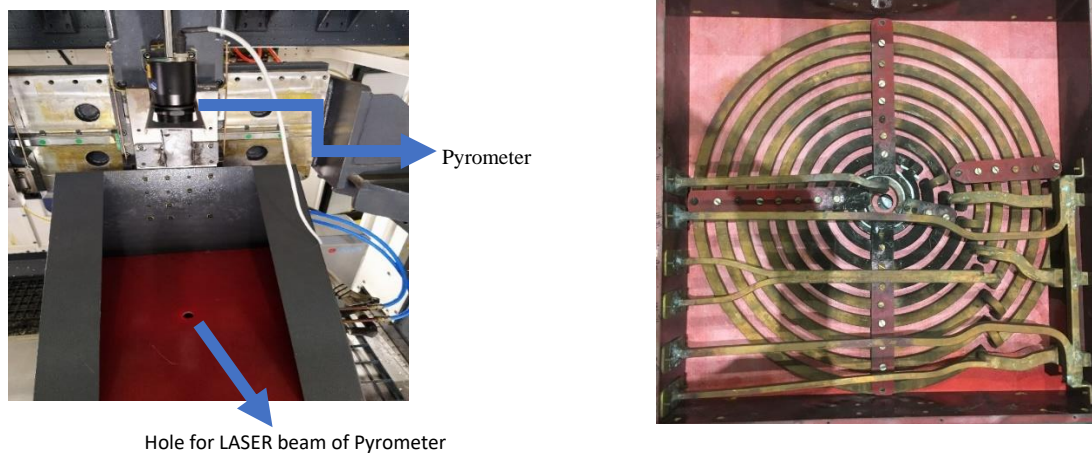


Fig. 5. Setup for pre-heating and the water-cooled induction coil.

Also, the pneumatic hammering system is in-house developed to provide compressive loading. The loading condition depends majorly on; air pressure, stand-off distance, and pitch. The CAD and the actual hammering setup are shown in Fig. 6. Hammering was done for samples 2 and 4 with the parameters as mentioned in table 4. Indentation marks can be observed on the top surface of sample 2 and 4.

Table 4. Hammering parameters

Parameters	Sample 2	Sample 4
Pressure (Bar)	5	5
Pitch (mm)	3	3
Stand of Distance (mm)	-12	-12
Feed (mm/min)	200	200

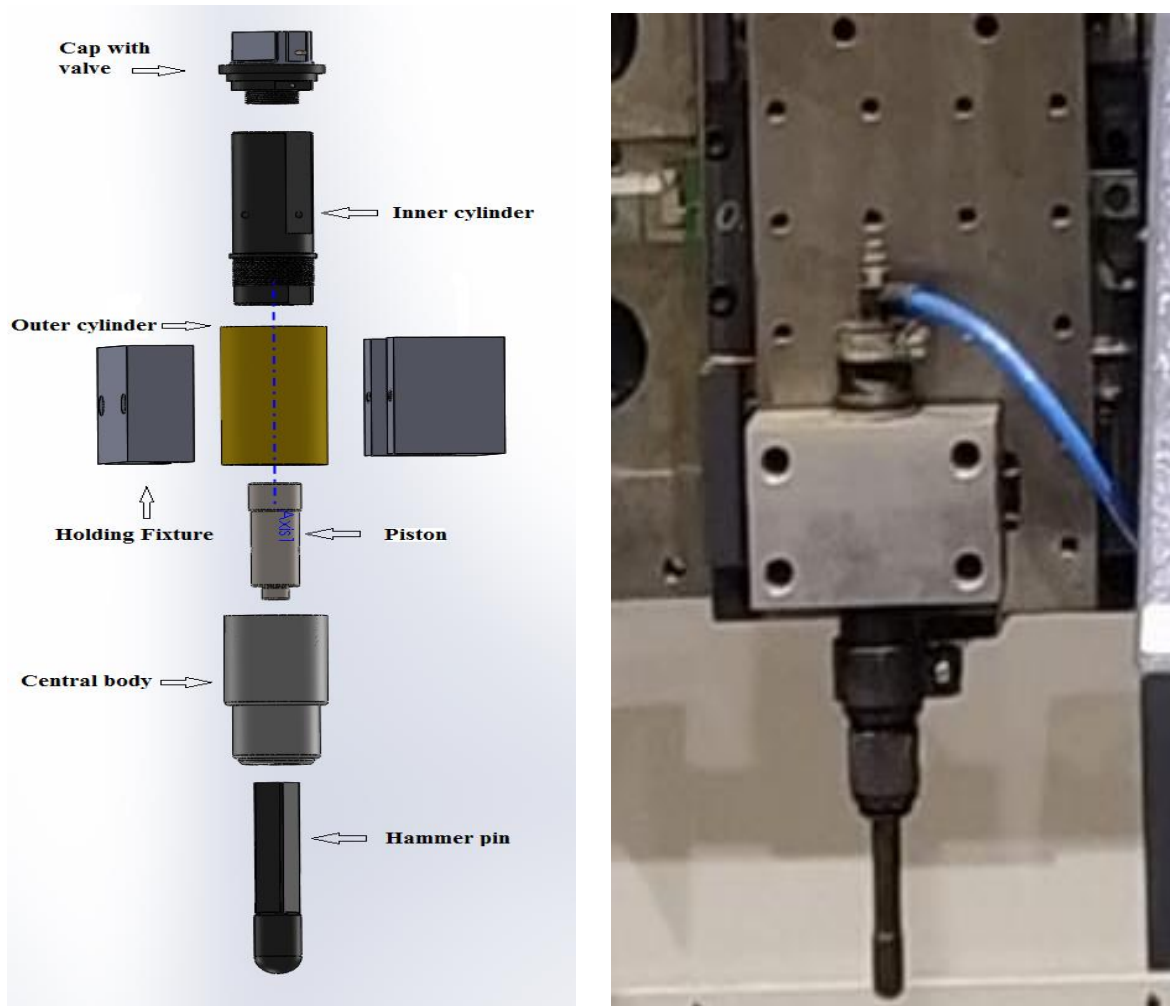


Fig. 6. Setup for Pneumatic hammer (a) CAD Model; (b) Actual Model

A sample from each block is cut through a wire EDM process for measurement of residual stress through x-ray diffraction. Sample of $9 \times 9 \times 5 \text{ mm}^3$ is cut from the one end of the deposited block as shown in Fig. 7 (all samples for measuring the stress are wire EDM cut for the same dimension and at the same location). Four samples with different conditions are shown in Fig. 8 for the measurement of residual stress.

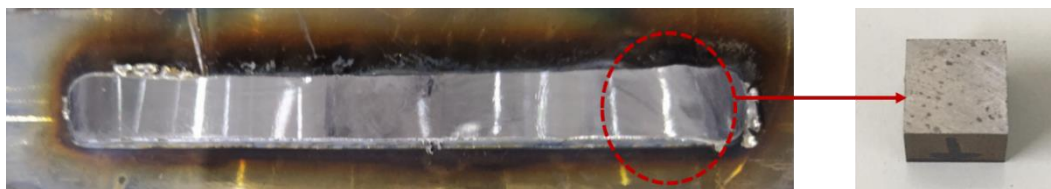


Fig. 7. Sample for measuring the residual stress

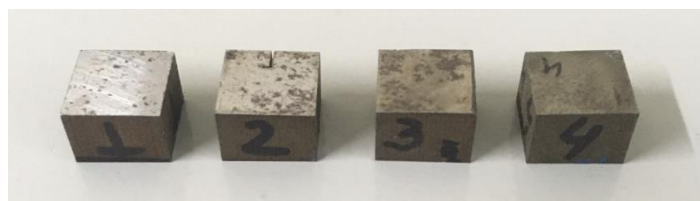


Fig. 8. Samples for residual stress measurement

3.2 Residual stress measurement

The test was carried out with the following parameters as mentioned in table 5. Parameters were kept constant for the testing of all the samples. The testing was carried on X-Y plane and at the top surface.

Table 5. Parameters for XRD test

Parameters	Input/Values
Model	PANalytical (System-EMPYREAN)
Target	Cu (K α average 1.5405 N-m)
Tilt Angle	0-40 ° (interval of 8°)
In-plane rotation angle	(0°, 45°, 90°), (180°, 225°, 270°)
2 θ	82.4°
Plane	(2,1,1)

4. Results

Through X-ray diffraction test, it was found that residual stress in the deposited block corresponding to sample 1 has the highest residual stress values, 473 MPa in the x-direction and 415 MPa in y-direction, similar sample when treated with hammering, shows the reduction in the residual stress values 11 MPa in the x-direction and -77 MPa in y-direction corresponding to sample 2 and for the pre-heating followed by deposition, the stress in x-direction was 218 MPa and 255 MPa in y-direction corresponding to sample 3. The combined effect of pre-heating and hammering has shown a drastic change in the residual stress value -293 MPa in the x-direction and -193 MPa in the y-direction. Pre-heating the substrate and previously deposited layer reduces the thermal gradient and thus, reduces the residual stress values too, but, as seen in the result for sample 3, there are still some stresses left in the component, which is removed by hammering. The comparative results for residual stresses with the standard deviations in x-direction and y-direction are shown in Fig. 9.

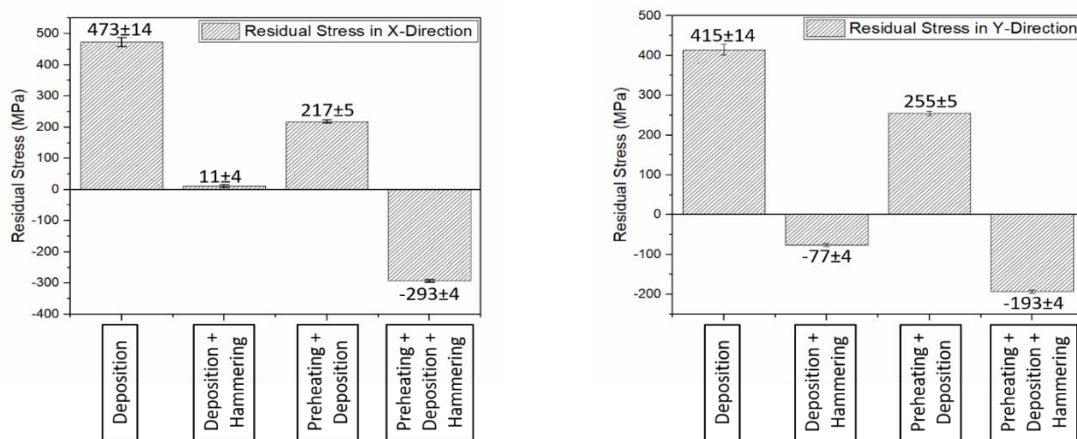


Fig. 9. Residual stress comparison in; (a) x-direction (b) y-direction

On increasing the pre-heating temperature, residual stress value will decrease, but up to a certain temperature only, beyond the recrystallization temperature, the metallurgical behavior may change. Also, during the application of compressive loading, an increase in the compressive loading will decrease the tensile residual stress, but the component may get some cracks in the component.

5. Conclusions

Based on the current experiments and its study, the following statements can be concluded:

1. The individual effect of pre-heating and hammering has shown a decrease in the tensile residual stress value.

2. The combined effect of both the technologies has shown a drastic decrease in tensile residual stress value, 765.5 MPa in the x-direction and 607.6 MPa in the y-direction.
3. The results can further be varied by changing the pre-heat temperature. Pre-heating the substrate minimizes the thermal gradient and, thus, the residual stress.
4. Compressive residual stresses can further be added to the component by changing the hammering parameters.
5. There is a limitation of pre-heating temperature and compressive loading, which varies from material to material. It needs to be optimized.

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