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Review on Influence of Residual Stress in Metal Additive Manufacturing Process

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Abstract: Additive Manufacturing (AM) has been widely accustomed to fabricate purposeful metal components in automobile, aerospace, energy with advanced pure mathematics, purposeful hierarchical materials, and free usage of tools. In metal additive manufacturing, two major processes embody directed energy deposition (DED) and powder bed fusion (PBF), through the melting of feedstock materials parts are produced within the type of either powders or wires directly from a CAD model. Residual stress caused by the distinctive thermal cycle in AM, which is the crucial issue for the unreal metal components since the steep residual stress gradients generate half distortion that dramatically deteriorates the property of the component. In Additive manufacturing metal components, the relationship between residual stress and its relevant microstructure of that location is mentioned and discussed. The residual stress, which is present due to the AM process is identified and also the control ways for the residual stress and the future developments of AM are also discussed.

***IndexTerms* – Metal Additive Manufacturing, Residual Stresses, Rapid Prototyping, Sintering.**

1. Introduction

Additive producing (AM) has been widely accustomed to fabricate purposeful metal components in automobile, aerospace, energy, and medical device industries because of its versatile method capability and free usage of tools. For the past two decades, subtractive manufacturing methods like CNC, Milling, grinding, lathe operations were used for building the raw materials into a product. In traditional moulding methods, the cost of the mould may be high and sometimes difficult for the complex shapes. Advancements in the field of manufacturing have led to the development of the new trend called the Additive manufacturing which was further categorized and developed based on the materials, manufacturing methods and its outcome [42]. In ordinary manufacturing processes, the parts are machined from large blocks to the desired geometry. Hence, the chipped or cut materials may take a longer time to be recycled but in AM, waste material generation is eliminated [18]. Different techniques or methods are adopted for different materials and the current research is going on the development for implementation of Additive manufacturing technique to build metallic components, the so-called technique is Metal Additive Manufacturing. Metal Additive Manufacturing technique can be extensively used for manufacturing components and it can be done with a number of metals like aluminium, Titanium, steel, etc. In Metal Additive Manufacturing processes, many methods can be used to produce a component based on its geometry, complexity and mechanical properties. The methods are different in their processing mechanism such as the nature of feedstock, binding mechanism, etc.

One of the notable properties of a metal which has undergone a manufacturing process is, Residual stress. Each and every component will have a stress which is induced in it, due to the processes it has come through. Due to the thermal cycles and the repeated heating and cooling cycles in Metal Additive Manufacturing, residual stresses come into a considerable account in deciding the life of the product. Based on the input parameters, there are different methods of manufacturing [8] in which PBF, EBM, DED, SLM are some of the important and most extensively used methods. In powder bed fusion method, metal powders of thin layers are melted using either electron or laser beam in a vacuum atmosphere out of a power bed to generate required output [14]. Electron beam melting (EBM), is another type of PBF process which uses electron beams as heat source to melt metal powder materials in a high vacuum chamber with a layer thickness (100 µm) typically higher than laser PBF process. DED directly melts feedstock material (feeding powder or wire) through which parts are produced in this method using laser or electron beam (source of heat) and the deposition rate in DED is higher in contrast to PBF.

2. Rapid Prototyping

Rapid prototyping [22], which differs fundamentally from shaping and material removal manufacturing techniques, refers to techniques that manufacture formed parts by progressively adding solid material. Rapid Tooling [23] is interested only in tools that have stability for a long-term period and can also form thousands or millions of parts consistently until they wear out. Laser forming techniques used to be rapid prototyping and rapid tooling, and improved to rapid manufacturing processes [12].

3. METAL ADDITIVE MANUFACTURING

Megahed et al. in 2016 [27] discuss additive manufacturing, which is a direct digital manufacturing process in which a part is created layer by layer from 3D digital data with no or limited machining, moulding, or casting. Lewandowski et al. in 2016 [24] discuss primarily on the different forms of metal additive manufacturing as well as published data on additively processed metallic materials. Mostafa Yakoutain et al. 2018 [29] provides a comprehensive review of metal additive manufacturing technology, which discusses various methods under metal additive manufacturing process based on input raw material such as liquid, molten, powder and solid layer process. The formation mechanism of residual stress and also its measuring methods and impacts was discussed [25]

The method of producing parts from 3D model data is known as additive manufacturing [14]. In 2014, Amanda S. WU et al. [50] described that additive manufacturing (AM) is a technology which allows for the production of macro scale net-shape geometries by microscale processing. Chua et al. in 2017 [7] describes the Sheet lamination, Powder jetting, Binder jetting [8], PBF, and DED, which are the five types that can handle metallic materials.

3.1. POWDER BED FUSION [PBF]

The PBF device, which includes a recoating mechanism that spreads a powder layer onto a substrate plate and a powdered reservoir, employs a powder deposition method [7]. PBF tracks the geometry of an individual layer of slices from a 3-D version at the powder beds floor by the usage of thermal power from a heat supply such as a laser beam or an electron beam till the powder is uniformly distributed. The thermal energy emitted through the laser beam will melt the powders, and the fusion area is the place wherein the powders are uncovered to the laser beam. The various characteristics and mechanical properties of fabricated alloys were measured and its effects were studied [44]. Figure 1 illustrates about the parts used in PBF process.

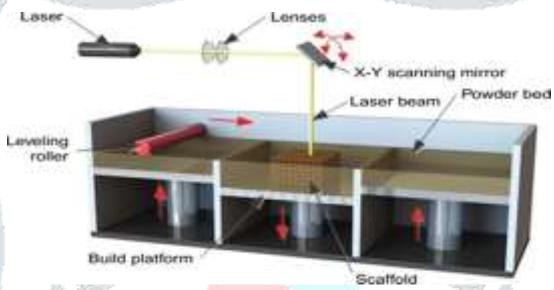

Figure 1. Setup for PBF Process [33]

Barrett et al. in 2017 [2] confessed that in PBF, the necessary melting temperature is maintained only for the current working layer whereas the previously done layers get solidified and cool down, which in turn results in thermal gradient within that metallic component [2]. Pure argon atmosphere in the Powder Bed Fusion method can be replaced with the Helium-Argon mixture because helium exhibits better thermal conductivity and improved build rate around 40% [39]. J. Robinson et al. 2018 [34] determines the scan strategy effects on residual stress in the LPBF additive manufacturing process. To reduce the stress and to transmit it evenly throughout the manufacturing part, the scan strategies were investigated.

3.1.1. SELECTIVE LASER SINTERING [SLS]

Selective laser sintering [22] creates components by fusing or sintering several layers of powder material together. Lasers, optics, temperature regulation, and materials are among the most recent advancements in this area. The dual-beam has a high-power core beam for sintering and a low-density surrounding beam for preheating the powder to minimize thermal stresses. When a material has achieved equilibrium with its environment, residual stresses remain within it. The binding mechanism that exists between the powder particles is the difference between SLS and SLM. In the selective laser melting process, the powder particles are used in a completely molten state. The residual stress comparison is well discussed and stresses due to high thermal gradient is determined [28]. Figure 2 describes the schematic diagram of SLS process.

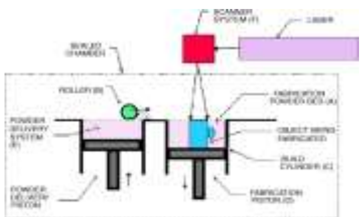

Figure 2. Setup for Selective Laser Sintering Process [12]

3.1.2. SELECTIVE LASER MELTING [LBM/SLM/DMLS/LPBF]

S. Kolossov et al. 2004 [21] discuss about FE model of thermal phenomena of the SLS process and the experiments were conducted in both physical and numerical methods. L. Costa et al. 2005 [9] infers that one of the promising rapid manufacturing techniques is the LPBF process. Parts made by LPBF process often have non uniform microstructure and properties etc. M. Simonelli et al. 2015 [26] study the dominant fracture mechanism in the SLM process and its performance during high cycle fatigue.

Laser Beam Melting is a type of powder bed system of additive manufacturing. LBM is carried out in a closed inert gas chamber so as to prevent the undesired chemical reactions from the environment. Pre-heating of the build plate is performed to reduce the thermal gradients thereby reducing the Residual stresses. The metal powder is given from a reservoir or a hopper. A galvanometer scanner is used to provide single mode laser fiber in continuous mode as per the process requirements. The metal powder is exposed to the laser beam based on the cross-section area of the part. The laser with melting temperature of the metal melts the powder in the contour. The metal gets solidified after this process and the build plate is moved lower and a new metal powder layer is spread over the melted surface with the help of a re-coater or levelling system and the process is repeated until the part is manufactured [17]. Figure 3 shows the setup and working principle of SLM process.

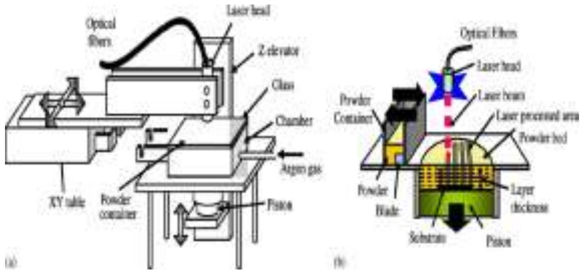

Figure 3. (a)Setup for SLM & (b)Working principle of SLM process [12]

The earlier cracks and reducing part fatigue life is because of porosity. Porosity could be closed by Hot Isostatic Pressing the microstructure of the specimen. Fatigue striation and ductile tearing were the two dominant mechanisms for the fractures on specimens with fatigue. Resistance of high cycle fatigue was drastically increased by Hot Isostatic Pressing the specimen [26]. Sochalski-Kolbus LM et al. 2015 [41] study residual stress by comparing simple Inconel 718 parts made by EBM and DMLS processes. They studied the experiment using diffraction methods. For this study secondary data has been collected. From the website of KSE the monthly stock prices for the sample firms are obtained from Jan 2010 to Dec 2014. And from the website of SBP the data for the macroeconomic variables are collected for the period of five years. The time series monthly data is collected on stock prices for sample firmsand relative macroeconomic variables for the period of 5 years. The data collection period is ranging from January 2010 to Dec 2014. Monthly prices of KSE -100 Index are taken from yahoo finance.

3.1.3. Electron Beam Melting [EBM]

EBM [4] is an addictive manufacturing process which comes under the type of Powder Bed Fusion, in which an electron beam is used to fuse the layer of powder in vacuum. The process used in EBM is the same as that of SLM, in which an electron beam is used in EBM to fuse the powdered layer whereas laser is used in SLM. Jamshidinia M et al. 2013 provides an overview to understand the effects of process parameters on the heat distribution in part produced using EDM [19]. Shen N et al. 2012 [37] investigated the effect of sintering powder on the thermal phenomena of EBAM by developing an FEA model. The porosity of powder and beam size and their relationship is studied using the FEA model. Figure 4 illustrates the schematic representation of EBM mechanism.

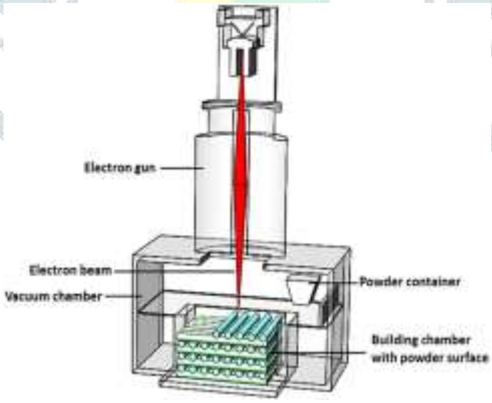

Figure 4. Schematic representation of EBM mechanism [33]

EBM is performed in a vacuum chamber of less than 0.01Pa. To increase the pressure and to avoid the electric charging of powder, helium is supplied into the chamber. Electron beam is produced in an electron which is focused by electromagnetic lenses. The beam is then directed with the help of magnetic scan coils. The bed plate is preheated with a defocused electron beam. The beam power, scan speed, focus is based on the beam current, offset of the beam focus and the speed function. Bed is preheated with the help of a defocused beam by scanning it a few times. Current and the scan speed is increased (30mA and 10000m/s) for the materials with high melting temperature which leads to sintering. Therefore, scan speed and current are reduced (10mA and 100mm/s) so as to melt the powder completely [17]. Electron Beam Melting offers high productivity compared to Selective Laser Melting [51]. Figure 4 shows the schematic of EBM mechanism.

3.2. Direct Energy Deposition Process [DED]

The DED process [7] is a metal-based AM method that allows 3D parts to be created by melting materials as they are deposited. According to the material distribution mechanism, the DED method is divided into two categories: powder feeding and wire feeding. In the DED process, the mechanical properties, microstructure, and the geometry of the part is affected by complex thermal activity of metal deposition where stacking of layers takes place [20]. Figure 5 illustrates about the DED process.

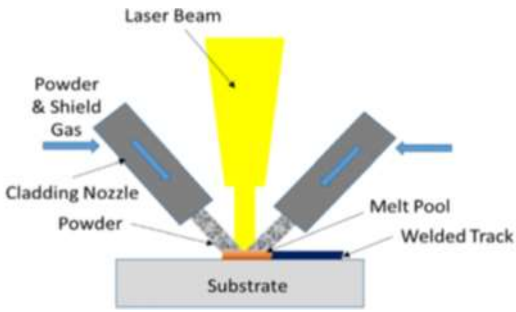

Figure 5. DED Process Schematic with Powder Feeding Mechanism [7]

3.3. LASER METAL DEPOSITION [LMD]

Laser Melt Deposition method is one of the AM in which the previous metal surface is heated and a layer of metal powder is added over it based on the need. In some systems the part is held stationary and the deposition head is moved over the metal surface and vice versa. Scan speed, power and focus depends on the layer thickness of the metal powder. Nowadays the metal powder is replaced by wire as feedstock, this method is known as the nozzle-based approach of Laser Melt Deposition [17]. Figure 6 illustrates about the setup for laser metal deposition process.

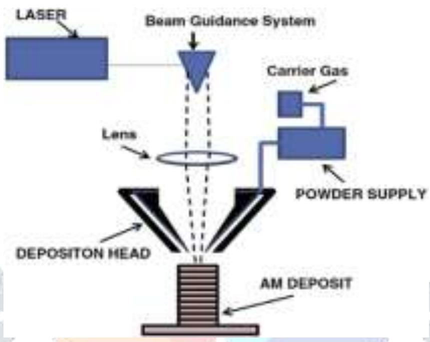

Figure 6. Setup of Laser Metal Deposition process [17]

3.4. FUSED DEPOSITION MODELLING [FDM]

Swapnil et al. 2020 [43] provides a detailed review about the FDM method under the categories as optimization of process parameters, the environmental factors that affect the quality of the parts printed, improving the quality of parts by post production finishing technique, process based on numerical simulation, advanced technique in FDM that was found recently. The mechanical properties, surface finish, dimensional accuracy and material behavior of the FDM process were discussed. The nozzle helps in melting the filament material and extrudes it in a semi-liquid state which is added in a layer by layer [40]. Figure 7 represents the schematic of FDM process.

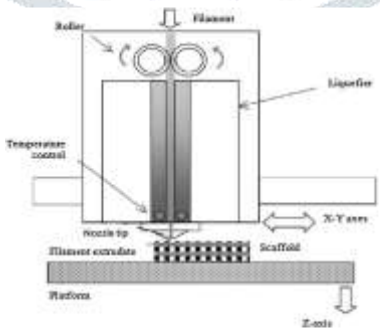

Figure 7. Schematic representation of FDM process [40]

4. RESIDUAL STRESS IN METAL ADDITIVE MANUFACTURING

Generally, the stresses produced during the manufacturing process, present within the component even after removing the external load (after completion of manufacturing) is known as residual stress [31]. It also occurs while solidification is induced (does not occur in liquid phase) when the object is not allowed to expand or contract due to the thermal stresses [38]. Erik R. Denlinger et al. 2015 [10] studied the residual stress and distortion affected by the changing path plan and time taken for dwell. They measured the effects of dwell time and material behavior in situ distortion and the post distortion and the residual stress. Stress relaxation and distortion reduction is investigated in the paper using the FEA model. Mechanical and thermal analysis is performed for the FEA model [11]. O Fergani et al. in 2016 [13] published about the stresses that remain in the body after thermo-mechanical processing are known as residual stresses. They have a significant impact on a manufactured component's performance (fatigue life, corrosion resistance, crack propagation, distortions, dimensional precision, and so on).

Quem chen et al. 2019 [6] study the reduction of residual stress and deformation in metal additive manufacturing. stress and compliance minimization analyzed using FEA models. Improvements and scanning path gap free were investigated. Distortion and Thermal residual stress were the main cause for failure of parts manufactured in the MAM process. R. Acevedo et al. 2020 [32] study the advantages and disadvantages of UT by measuring residual stress. Ultrasonic waves types and source were discussed. Characteristics of UT for measuring residual stress was discussed [32]. The average residual stresses are lower in magnitude as the HAZ grows larger [13]. Figure 8 illustrates the temperature distribution for one path in the imaging direction and in the end, the melt pool and heat-affected zone (HAZ) elongate, as is typical of additive manufacturing.

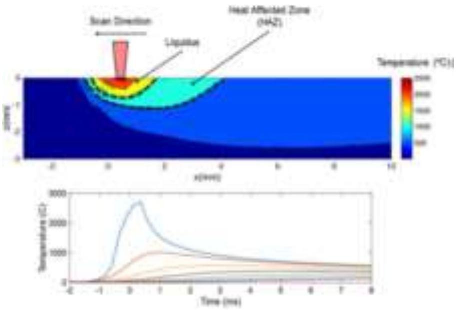

Figure 8. Temperature distribution (°C) in 2D during laser melting of the power, heating rate at various depths of additive manufactured layers [13]

One of the advantages of AM is that they can produce the product at a faster rate when compared to other usual traditional methods [5]. In exchange for higher speed production, the parts are being attacked by residual stresses. These residual stresses will create distortions in geometries and failures in quality inspection. The impact of residual stress over the part can be identified by finding the level of residual stress and its distribution [51]. When the first layer is solidified the top section shrinks and exhibits a tensile stress and the cold bottom section of the first layer tries to maintain the equilibrium and have a compressive stress. When the next layer is added, the top section of the first layer will try to expand due to the temperature of the second layer but it is restrained by the stress at the bottom layer to maintain the stress equilibrium resulting in the mechanism of residual stress [1].

5. MEASUREMENT OF RESIDUAL STRESS

N.S. Rossini et al. 2012 [35] explain about the residual stress phenomena and mechanical properties effects on components. Residual stress measurement by different methods was defined and classified in this paper. original stress is analyzed by the Finite element model. Residual stress measurement is very important in manufacturing processes to prevent failure and to get dimensional accuracy. Residual stress values which exceed the yield limit causes greater impact in the mechanical, topological properties and life of the component. The heat input may be doubled to get very low residual stresses but it increases the thermal distortion up to 2.5 times. So optimum heat input must be given [30]. There are many methods [35] discussed through which two of them are discussed.

5.1. CRACK COMPLIANCE METHOD

Crack Compliance Method is the simple and effective method to find the overall distribution of residual stress. In this method, the residual stress is measured by creating an artificial crack so as to relieve the Residual Stress. It is performed by assuming that the stress is distributed uniformly throughout the crack line. According to the principle of this method, the part with residual stress is equivalent to the artificially cracked part plus the stress applied on deformed part to attain its original shape. For a perfect crack consideration, the length of the part must be greater than the crack. Following these considerations, the linear elastic fracture equations can be used to obtain the value of residual stresses. Residual stress can be calculated from the strain measured at the point of crack. It can be noted the strain and residual stress are related by stress intensity factor [51].

5.2. HOLE DRILLING STRAIN GAUGE METHOD

This is a type of semi-destructive test, in which hole is drilled in the centre of the AM part with a three-grid strain gauge rosette. The rosette is set up over the part to measure the strain exerted by the part while drilling the holes. Those measured strains are used for calculating the residual stresses. Calculation was done in MATLAB which gave only the near approximate values of residual stresses [36].

6. CONTROLLING OF RESIDUAL STRESS IN MAM

In 2016, Vastola et al. discuss about residual stress formation in Ti6Al4V (EBM method) [47]. Ti-6Al-4V parts were manufactured using SLM and EBM in which parts manufactured in SLM technique had a higher hardness due to its high cooling rate than EBM. Hot Isostatic Process may be done to improve mechanical properties of Nickel alloy components in AM [46]. The properties like alternating work-hardening behaviour of the component, tension and compression asymmetries can be reduced by the heat treatment of the component, which also has an effect in relieving the microscale residual stresses [49]. The nozzle must be kept parallel so as to avoid the collision between the surface of the part and the nozzle. The space or gap between the nozzle and the layer to set precisely, if the space is great, the molten metal will solidify before it reaches the layer. Sudden decrease and increase in the speed of nozzle motion may be controlled by designing the part without sharp edges and providing curves [48]. Support members given in the AM are very much helpful in resisting the external and internal forces, thermal stresses, residual stresses and the impact of gravitation. In Metal Additive Manufacturing, supports have an additional role in heat dissipation. The supports may be removed from the part after building, which may be a risky process in some cases. Hence, design for additive manufacturing must be concerned with the supports to be given so as to compete for both thermal and mechanical needs [45]. Supports may be automatically generated in the building process [40].

Pure argon atmosphere in the Powder Bed Fusion method can be replaced with the Helium-Argon mixture because helium exhibits better thermal conductivity and improved build rate around 40%. Even if only the Helium atmosphere is maintained, it provides a controlled melt profile. In some cases, Nitrogen gas is also shown the same result [39]. Preheating helps in decreasing the cooling and thermal gradient which in turn produce negligible residual stress in MAM. If preheating is not done, the parts are subjected to residual stress which are tensile in both top and bottom, compressive in the centre of the part [51]. Energy density of the beam must be maintained so to get rid of pore formation in the AM parts. It has been experimentally proven that higher energy density values offer a higher residual stress in the top and lateral surfaces of AM parts [381]. As conventional methods, shot-peening can also reduce the residual stresses. But it extends the production time and cost expenditure for the post processing techniques are also high. Hence, controlling the process parameters like preheating the built plate to bed, speed of the beam, beam power and scan speed can help to reduce the residual stresses [3]. Important effects on SLM and EDM processes are due to processing parameters. Defects generated during the AM process are because of marginal parameters. Deviation of SLM and EBM process from processing parameters with optimization leads to the formation of defects generated on the product [16]. Powder bed must be tightly packed so that it gives a uniform layer thickness. Overhanging structures are prone to different heating conditions so they are subjected to severe residual stresses [31].

7. Applications of Metal Additive Manufacturing

The application of Metal additive manufacturing technology can be seen in a growing wide range of industries, including aviation, national security, hospital instruments, automobile manufacturing, injection moulding, and others, through which a component is fabricated and also the components can be altered based on the requirements [42]. Parts that are slightly damaged may often only be substituted. Metal additive manufacturing technology now allows for the fast formation and repair of any damaged parts by using addictive manufacturing process. Figure 9 illustrates the AM-repaired turbines.

Figure 9. The AM-repaired turbines [42]

Features must be developed to eliminate the air pockets which can control the layer thickness. This is very much helpful for overhanging structures. A system must be developed to recognize the material thickness during the manufacturing process and it could give response to the laser system so that it can reduce the laser power at the minimum thickness area and hence thermal shocks can be reduced. [31]. Embedding of any components can be done by pausing the AM process and resuming after fixing the component in the voids of the AM printed parts. Embedding becomes easier in AM [15]. This eliminates the need for sub-assemblies. This will be a major advantage in manufacturing robotic limbs, motors and sensors, etc., when compared to the conventional methods.

8. Discussions and Future Scope

Metal Additive Manufacturing is the current trend of manufacturing components in many fields like aerospace, defense, medical, automobile, etc., This technique is now developed such that complicated shapes can also be easily manufactured and produced without the cost of molds and other manufacturing necessities. This review discusses residual stresses produced by the different main metal additive manufacturing techniques namely Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Selective Laser Sintering (SLS) and Selective Laser Melting (SLM). These methods are directly involved in melting of the metals which produce residual stresses due to distinctive thermal cycles. These residual stresses are the reason for distortion of the end use components. The main reason for the residual stresses is the high temperature gradient and rapid cooling done during the MAM. As we all know heat treatment can reduce a small portion of residual stresses in the MAM components. Subsequently designing a perfect controlled cooling process can eliminate the residual stresses in a better way. Though, there are many factors like beam size, beam power density, scan speed and bed preheating temperature which causes residual stresses, it is found that the bed preheating temperature has the largest quantitative effect in the residual stresses. It has been experimentally and analytically verified that the residual stresses are lower at the high temperature bed. Many factors are involved in production of the residual stresses and different metals possess different mechanical and thermal properties while undergoing Metal Additive Manufacturing. In future, MAM can be seen in a wide range of applications and hence mitigation of residual stress will play an ideal role for the development of MAM.

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