Wire Arc Additive Manufacturing (WAAM) of Inconel 625 Alloy and its Microstructure and Mechanical Properties

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Abstract - *Wire Arc Additive Manufacturing (WAAM) is a manufacturing technique which uses arc as a heat source to fuse wire based on layer-by-layer cladding. In the present study Inconel 625 alloy fabricated using Wire Arc Additive Manufacturing (WAAM) has been investigated. The microstructure and mechanical properties of the fabricated Inconel 625 alloy and the influence of the heat treatment on the properties of the manufactured specimens were researched. Microstructural studies revealed variation of microstructure in different layers of the specimen, with the bottom layer consisting of fine primary cellular grains as compared to middle and top layer. Mechanical properties that include hardness and tensile properties were investigated at different temperatures ranging from 750°C to 1200°C. The ultimate tensile strength (UTS) increased from 193 MPa to 265 MPa moving from bottom layer to top layer, while the variation in hardness was irregular with increase in temperature. Further X-Ray Diffraction (XRD) test were performed on the various heat-treated samples to understand the changes which took place in the bulk of the metal due to heat treatment. Finally, all these results showed that the mechanical performance of the manufactured component by WAAM method was better than the one manufactured by other method and is much more economical when complex components are to be manufactured.*

Key Words: WAAM, Heat treatment, Inconel 625 alloy, Microstructure, Tensile test, X-Ray Diffraction.

1. INTRODUCTION

Additive manufacturing (AM) technique is raised up for directly fabricating components by adding materials, instead of removing materials from a block in traditional machining process. AM attracts more and more interests for its advantages of saving lead time and material. Wire arc additive manufacturing (WAAM) is one of AM technique, which employs arc as the heat source melting and depositing the filler wire along the designated path layer-by-layer. WAAM stands up for different AM techniques due to the benefits of producing large scale metallic structure, high platform flexibility, depositing rate, low material and equipment cost. It has been proved to be possible to adopt WAAM process for production of large metallic components. WAAM can directly fabricate fully-dense metallic large 3D near net shape components with a much higher deposition rate than most other metal additive manufacturing processes the highest rate so far being of 9.5 kg/h.

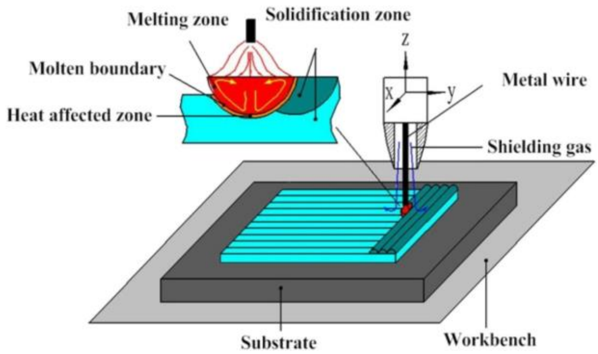


Fig -1: Schematic Representation of WAAM Process

The WAAM process has successfully produce large scale parts in stainless steel, Inconel, Titanium, Aluminum and Tungsten. Furthermore, functionally graded structure of refractory metals has also been deposited using WAAM. The manufacture of large and engineered components by WAAM is attractive also because of low system and operating costs as well as the modularity of the system design.

1.1 Why Inconel 625?

Inconel 625 is a nickel-based super alloy derives its strength mainly by solid-solution hardening effect of the refractory metals, niobium and molybdenum in a nickel chromium matrix. The alloy exhibits excellent hot corrosion resistance, fatigue resistance, wear resistance and good weldability with outstanding strength at elevated temperatures.

Table -1: Chemical Composition of Inconel-625 alloy

Element	Composition (%)
Chromium (Cr)	20-23
Molybdenum (Mo)	8-10
Niobium (Nb)	3.15-4.15
Iron (Fe)	<5
Aluminum (Al)	<4
Titanium (Ti)	<4
Carbon (C)	<1
Manganese (Mn)	<.5
Nickel (Ni)	Bal (~65)

Thus, it has been widely used in the manufacture of components for aerospace, chemical, petrochemical, marine and other high temperature and corrosion applications. The shapes of most of the Inconel 625 components are so complex that they are expensive to produce using traditional method due to extensive machining. Wire Arc Additive Manufacturing (WAAM) which uses arc as a heat source to fuse wire based on layer-by-layer cladding is an economical rapid forming method for manufacturing high quality metallic parts. It is driven by three-dimensional data of the component and is fabricated by deposition of the material without the aid of any tools and molds. Therefore, it is very necessary to explore the additive manufacturing technology for manufacturing of components from Inconel 625 alloy.

1.2 Manufacturing of Complex Structures

One of the major challenges faced by the industry is the manufacture of complex components with complex geometry like propellers in marine industry, impellers of turbocharger, turbines in power stations etc. Most commonly used technique for this purpose involves specific methods of rapid-prototyping like selective laser sintering and stereolithography. In the former technique a very fine powder (15-80 micron) of the substrate is sprinkled over a base plate which is subjected to a high-power laser (Usually CO2 laser) which draws the required pattern over the surface. The heat produced by the laser then melts the powder underneath which solidifies and the cycle continues until the required geometry is obtained. The process looks quite simple however the amount of power required to produce such laser is relatively high which makes the process expensive thereby increasing the cost of product. Similarly, stereolithography involves the use of photochemical reactions to form cross linking between monomers to forms polymeric chains, thereby limiting its application to plastic products only. To overcome the drawbacks of these techniques, Wire Arc Additive Manufacturing serves the purpose of manufacturing complex metal components with minimum power requirement thereby reducing cost of production by comparing the process parameters listed in Table -2. We can conclude that the energy required is far less than in selective laser sintering (SLS). Moreover, it provides a unique flexibility in the selection of material for different regions of the same component. This can be done by changing the wire spool before depositing the next layer. AM is a type of manufacturing which provides complete control over the inspection and control of defects in manufacturing Considering all these advantages it can be concluded that WAAM is far more phenomenal.

1.3 Introduction to Additive Manufacturing

Additive manufacturing (AM) is the process of producing the components with layer-by-layer process. Today Wire Arc Additive Manufacturing (WAAM) is used for the manufacturing processes of large number of engineering materials like titanium, aluminum, nickel alloy, steel etc. It gives advanced capability to industries compared to the traditional type of manufacturing process like casting, machining etc. Fabrication using WAAAM mainly consists of three steps i.e. planning, deposition and post processing. For a designed CAD model, the 3D programming software creates required robot arm motions for welding process which produces defect free components with high geometrical accuracy which also helps to obtain complex geometries. The advantages of AM include sustainable manufacturing and energy efficient manufacturing process. It saves the cost of machining, reduces manufacturing time and has high material utilization as well as low equipment cost. The robot and external axis provide required motion for welding torch to make component in a layer-by-layer fashion. Due to this beneficial factor, AM is growing popularity in industries sectors to provide the manufactures with greater design of freedom. Due to its significant impacts to the manufacturing industries i.e. Jet engine, Turbine blade, rocket engine and many other applications, it is anticipated that this AM technology will change the manufacturing methods in the near future. Based on the nature of source of heat there are three types of WAAM process i.e. Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW) and Plasma Arc Welding (PAW). The deposition rate of GMAW is 2-3 times greater than that of GTAW or PAW but GMAW is not much stable and produces greater weld fume and spatter because the electric current acts directly on the feedstock. Metal AM technique has the following categories such as Power bed fusion, directed energy deposition, binder jetting and sheet lamination. Among them, powder-based AM method i.e. Selective laser melting (SLM) and electron beam melting (EBM) are greatly used. A laser or electron beam is used in powder-based system to selectively melt and sinter particles together, but due to post processing requirements, high residual stress, undesired porosity, costs of system setups, powder and system control difficulty have made this process hard to practice in small and medium sized enterprises. On the other side, wire fed arc welding systems are widely available and are less complex with established systems.

1.4 Various WAAM Techniques

Based on the difference in the heat source, the typical WAAM techniques include pulsed plasma Arc Deposition (PPAD), Tungsten Inert Gas Welding (TIG) and Metal Inert Gas (MIG) for which many investigations have focused on WAAM using PPAD and TIG as a heat source for Inconel 625 alloy. Fujia Xu et al. [14] investigated the influences of inter-pass cooling strategy (ICS) and continuous deposition strategy (CDS) on microstructure and mechanical properties of the pulsed plasma arc deposition (PPAD) for Inconel 625 alloy. Samples deposited with ICS exhibited improved surface quality and mechanical properties and CDS exhibited negative effect. Wang et al. [13] manufactured Inconel 625 using gas tungsten arc welding (GTAW) process and investigated the microstructure and mechanical properties along the build height. The authors concluded that the primary dendrite arm spacing increased with an increase in deposited height, and the segregation behavior constantly strengthened. Similar behavior was observed for the mechanical properties with the increase of deposited height. Thivillon et al. [23] studied the difference of microstructure of Inconel 625 components produced by laser-based deposition (LBD) and GTAW. Jung [24] explored that the corrosion resistance of the overlay welded Inconel 625 by Gas Metal Arc Welding. Literature indicates that when compared to other weld-based processes, research on the application of WAAM using MIG as a heat source (MIG-WAAM) is significantly less. Compared with other WAAM technologies, there are distinct advantages for additive manufacturing if performed via. MIG-WAAM. The advantages include high energy density, excellent surface forming, no splatter and very less welding related defects. Considering its outstanding advantages, MIG-WAAM is a promising option for fabricating large parts production. Consequently, it is also important to investigate the variation in microstructure and mechanical properties within the manufactured MIG-WAAM components as information on these properties is meager for Inconel 625 alloy produced by MIG-WAAM. The aim of the present study is to manufacture Inconel 625 using MIG-WAAM technology.

1.5 Super Alloy Inconel-625

Inconel 625 is a solid nickel based super alloy formed by the combination of chromium, molybdenum, iron, niobium and carbon. Inconel 625 is a nickel-based super alloy, which has good corrosion resistance properties at low as well as very high temperatures. Thus, it is the preferred material in many heavy industries. It is used in the reactor-core of nuclear power plants, boilers, piping, exhaust systems of racing cars, impellers of chemical vessels, power plant turbine blades, aerospace engine components etc. Since it has better features which plays a vital role in development of industries, where the use of super alloys is inevitable. This alloy gets wide applications in gas turbines, aircraft engines, marine industries and chemical power plants due to its superior properties in terms of strength, corrosion, resistance and creep resistance at high temperatures. The alloy is also prominently known for its unique combination of yield strength, tensile strength, hardness, fatigue strength, creep strength and good weldability property. Fabrication of Inconel-625 nickel-based super alloy components are generally done by two methods firstly; it can be made through casting and secondly; the parts can be joined to form the final component. The Components made from nickel-based super alloy when exposed to extreme operating environments such as high temperature, oxidizing and reducing conditions for longer periods of time give rise to cracks that propagate through the surface irregularities and cause failure of the components. However, the nickel-based super alloy is very costly, it is mostly economical to repair the damaged parts rather than to replace them with a new part. By the methods of gas tungsten arc welding, electron beam welding, laser beam welding, explosion welding, plasma arc welding and friction stir welding, joining of nickel-based super alloys over the years is mainly being carried out. Conventional fusion welding processes are easily available and better flexible among the existing welding methods for joining nickel-based alloys. As these processes are popular, the large heat generated through these processes, development of hot cracks, separation of Nb and Mo rich phase result in generation of Laves phase and significant change in microstructures of both heat-affected zone and weld zone that led to reduced mechanical properties and low corrosion resistance.

1.6 Non-Destructive Qualitative Analysis (XRD)

X-ray diffraction (XRD) is a powerful non-destructive technique which provides qualitative analysis and fundamental studies of properties and molecular structures of organic and inorganic compounds. It supplies information on structures, thermal behavior, crystal orientations, void size, and other structural parameters, such as average grain size, crystallinity, and other defects. It also helps to measure the thickness of thin films and multi-layer films. In this method of experiment, the sample is paced at the Centre of instrument and illuminated with the beam of the X-rays. Here the X-ray tube and the detector moves in a synchronized motion, the signal coming out of the sample is recorded in a graph. It is based on Bragg's Law for the purpose of studying the internal structure of crystals. Crystals contain lattice plane, which behaves like diffraction grating on the exposure of X-rays. The nature of X-rays on diffraction by the crystal is evaluated by the spacing between successive planes. Most materials are made up of small crystals and atoms. Each of these crystals are composed of regular arrangement of atoms. The wavelength of X-ray is similar to the distance between the atoms. If the beam of monochromatic X-rays is incident on the crystals at an angle θ, some rays get diffracted by the layers of atoms in the crystal. The difference in the path length is '2dsinθ'. The difference in path length must be an integral multiple of wavelength, for maximum diffraction of X-rays with destructive interference.

Therefore, According to Braggs Equation:

$$2d\sin\theta = n\lambda$$

Here,

'd' is the space between atomic layers

'λ' is wavelength of the incident X-ray beam

'n' is an integer

'θ' is the incident angle

This is Bragg's Equation. If the value of wavelength and the angle θ both are known then we can find the value of 'd' that is the inter spacing distance.

2. EXPERMENTAL PROCEDURE

Welding experiments were carried out using the WAAM setup as shown in Fig -2 which is comprised of a power source, multi-axis robot, pressure regulator, computer control system, wire feeding system and gas shielding system. The Inconel 625 wire of 1.2mm diameter was used as the filler metal, while the base metal used was Q235 steel with dimension of 125mm × 100mm × 6mm (length × width × thickness). The experiment was carried out with the height of 3.5mm between each layer and different travel speed until the optimum parameters were obtained as shown in the Table -2.

Table -2: Process Parameters of WAAM

S.No.	Process Parameters	Values
1.	Wire Feed Rate	5 m/min
2.	Welding Speed	900 mm/min
3.	Average Current	115 Ampere(A)
4.	Voltage	20.2 Volt (V)
5.	Time of Pass	25.93 sec/layer
6.	Total Number of Layers	50
7.	Height of each Layer	1.55 mm

In the WAAM process, the wire was melted by the arc and then solidified on the layer deposited in the preceding pass. The deposition direction of each layer was parallel to previously deposited layer and was vertical with a proper aim to improve the forming of deposited layer in order to reduce cracks and porosity. A continuous deposition results in significant heat accumulation and remelting of the layers which led to significant variation in the size of the layer. In order to avoid this problem inter-pass cooling strategy was carried out to ensure the quality of the sample. The deposition torch tip to work distance was kept to 15 mm, and contact angle was 90°for all the experiments.

Fig -2: Experimental Setup of WAAM

All specimens tested for mechanical properties were machined by wire electric discharge machine (WEDM) and were subsequently ground and polished. The tensile tests were performed in such a way that the strength of the deposits i.e. along the build direction and horizontal direction could be analyzed. The specimens for microstructure examinations were etched with aqua regia solution (10 ml glycerin, 15 ml HCl, 5 ml HNO_3) for 15s and were subsequently cleaned. The microstructure of the specimens was investigated by using optical microscope (OM) and scanning electron microscope (SEM) respectively. Tensile test was carried out at a loading rate of 1 mm/min.

Fig -3: Layer by Layer deposition

3. RESULTS AND DISCUSSION

The final fabricated sample deposited under the optimum parameters is shown in Fig -4 which consists of Fifty layers with the height of each layer as 1.55 mm were deposited, which gives a layered appearance. All the deposited samples were free from defects such as inter-layer crack between base layer and substrate or pores in the deposits. The deposition strategy in which the build direction for every layer remains parallel with respect to the direction of previously deposited layer was employed.

Fig -4 reveals the presence of a well-defined layer and bead interface. It has been reported in the literature that the dendrite growth direction is mostly perpendicular to the substrate of the laser deposited samples. The heat flux direction mainly determines the growth direction of the grains, the grains preferentially grow opposite direction to the heat flux in order to follow the maximum temperature gradient. If the cooling process of the melt pool fully occurs via the substrate, then the growth direction of the crystal will be vertical i.e. perpendicular to the substrate. However, the growth direction of the grain is not strictly perpendicular to the solid-liquid interface.

During the process of the wire arc additive manufacturing, the main cooling occurs via the substrate and the previously deposited layers. Hence, the direction of grain growth is slightly tilted to the vertical direction. When a new layer is deposited over the previous layer the material undergoes remelting and new grains are formed at the layer boundary.

3.1 Microstructure without Heat Treatment

Fig -6 shows the microstructure of different regions. The variation in the microstructure in the difference regions depends on the cooling rate and heat dissipation during the weld deposition process. It should be noted that the heat in the near-substrate region can flow to the substrate and release through substrate, flow to the air around the substrate or flow through the deposited layer. The flow of heat due to these three ways, the heat of the near substrate region releases heat considerably. Eventually, the cooling effect is improved remarkably resulting in fine cellular structure without any secondary branch crystal as the microstructure of the bottom layer of sample. However, the heat in the middle region is difficult to dissipate and the cooling rate is low due to the heat accumulation, as shown in the Fig -6(b). Hence, the microstructure of middle region forms cellular dendritic structure with some amount of secondary dendrite. The microstructure of top region is a dendritic structure. Compared with the microstructure of the middle region, continuous accumulation of the heat leads to coarser dendritic crystal in the top region, as shown in Fig - 6(a). The dendritic crystal spacing of the top region is found to be relatively fine. The absence of equiaxed crystals at the bottom and middle microstructure could be because the heat of deposition of subsequent layer acts on the previous layer and would cause the equiaxed crystals of previous layer to remelt completely.

3.2 Microstructure after Heat Treatment at 750°C, 850°C and 1200°C

Three of the samples were subjected to a heat treatment at 750°C, 850°C and 1200°C for a time period of one hour and subsequently cooled in water. The samples were cleaned thoroughly to remove any dirt particles and cold molding technique was used to make the molds followed by emery and disc polishing. The microstructure was observed at different layers for each of the samples using an optical microscope. As Inconel 625 is having a dendritic microstructure which extends in perpendicular direction to form parallel branches, the same was observed after heat treatment but with slight anomaly i.e. as the temperature increases the disintegration of the dendrites takes place. As shown in the Fig -7 (c)&(d) the long dendrites are no longer visible after heat treatment at 750°C but are rather short and disintegrated. Moreover, as the temperature further increases as shown in Fig -8 (c)&(d) the shorter dendrites are much randomly distributed and appears to be disoriented. As far as the variation in microstructure among different layers is considered, it remains the same moving across the layers with the finest one at the bottom layer. A drastic change is observed when the sample is heated to a temperature as a high as 1200°C as shown in the Fig -9. It appears as the complete disintegration of the dendrites have taken place and forming shorter individual nodes. The small dotted structure in fig -9 is formed due to the oxidation of a small percentage of molybdenum present in Inconel 625 forming molybdenum oxide. This shows that although the melting point of Inconel 625 is approx. 1300°C, it cannot be used above 1000°C as the oxide formation takes place.

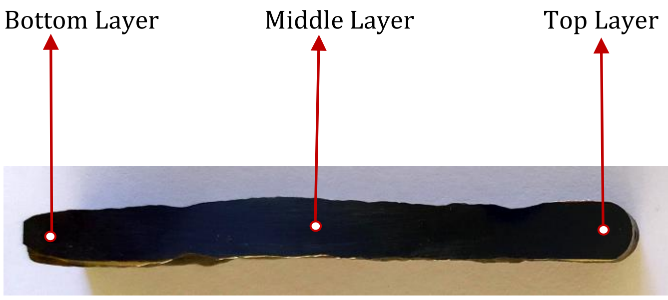
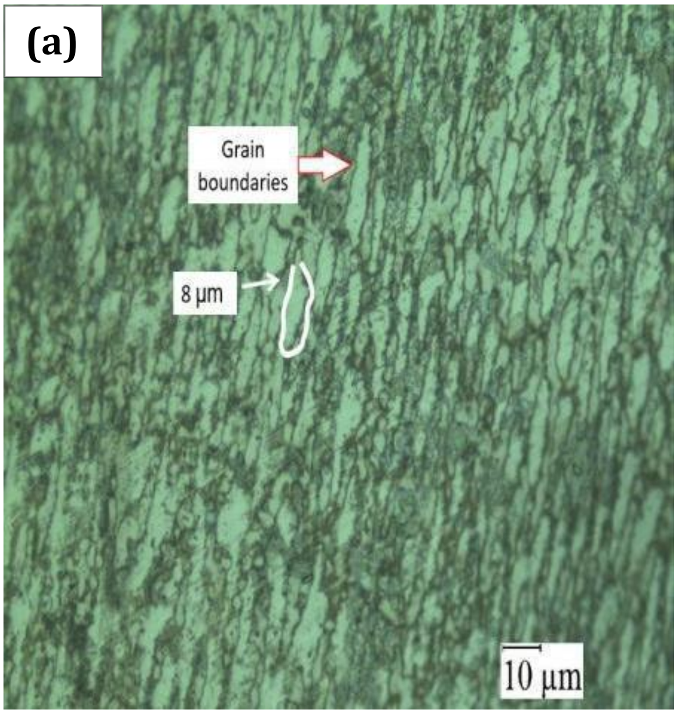


Fig -5: Cut piece longitudinal Section of the Sample



(b)

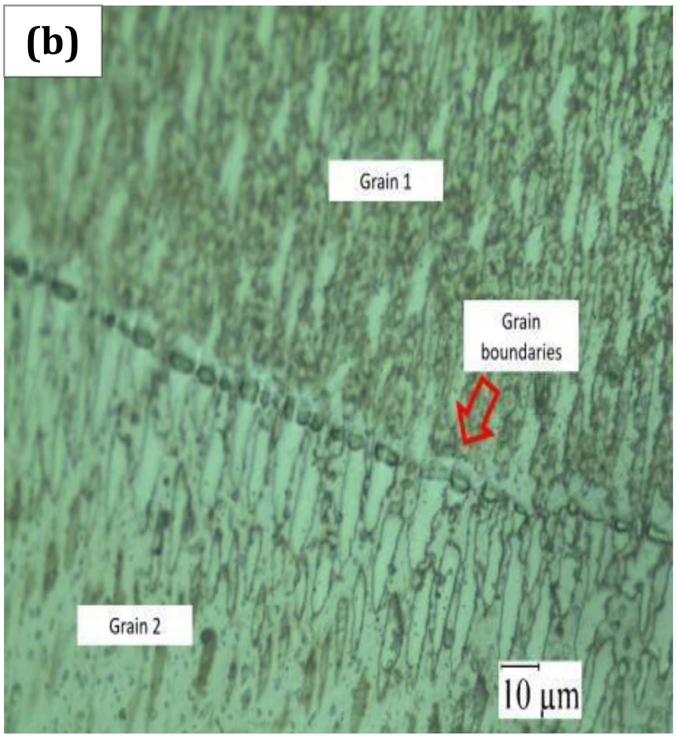
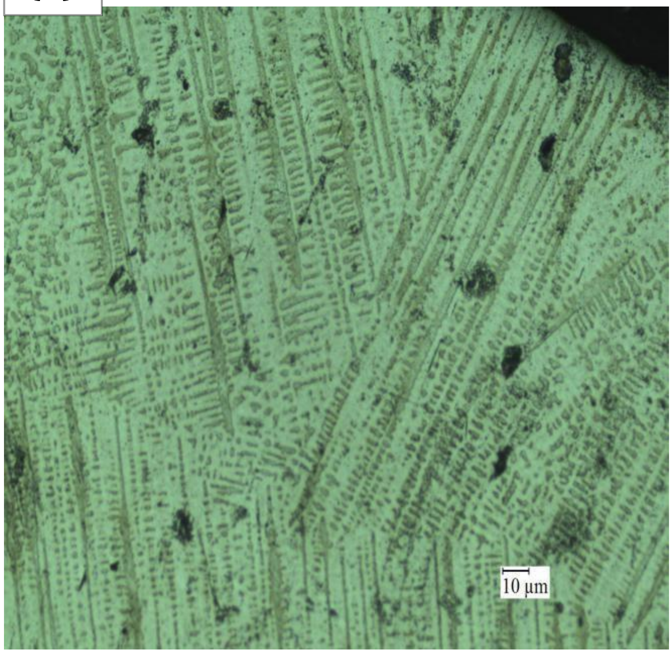


Fig -6: Microstructure at (a) Top Layer (b) Middle Layer (c) Bottom Layer

1) At 750℃

(a)



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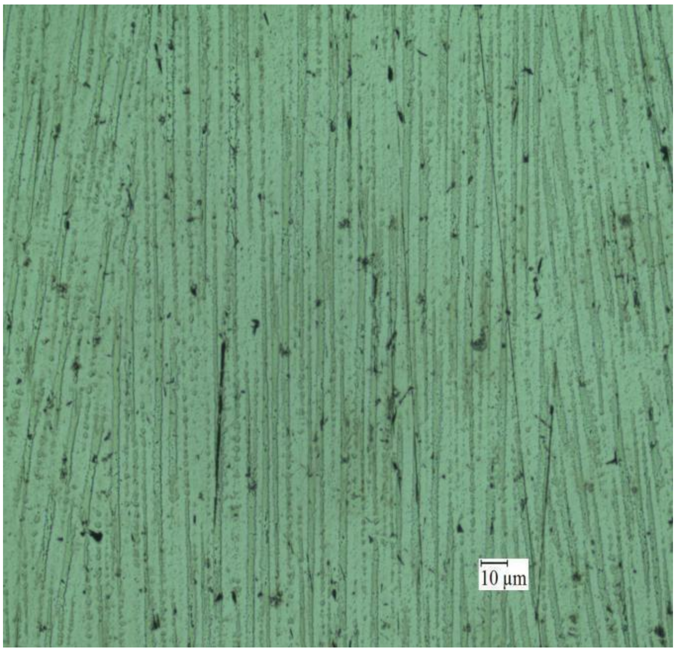


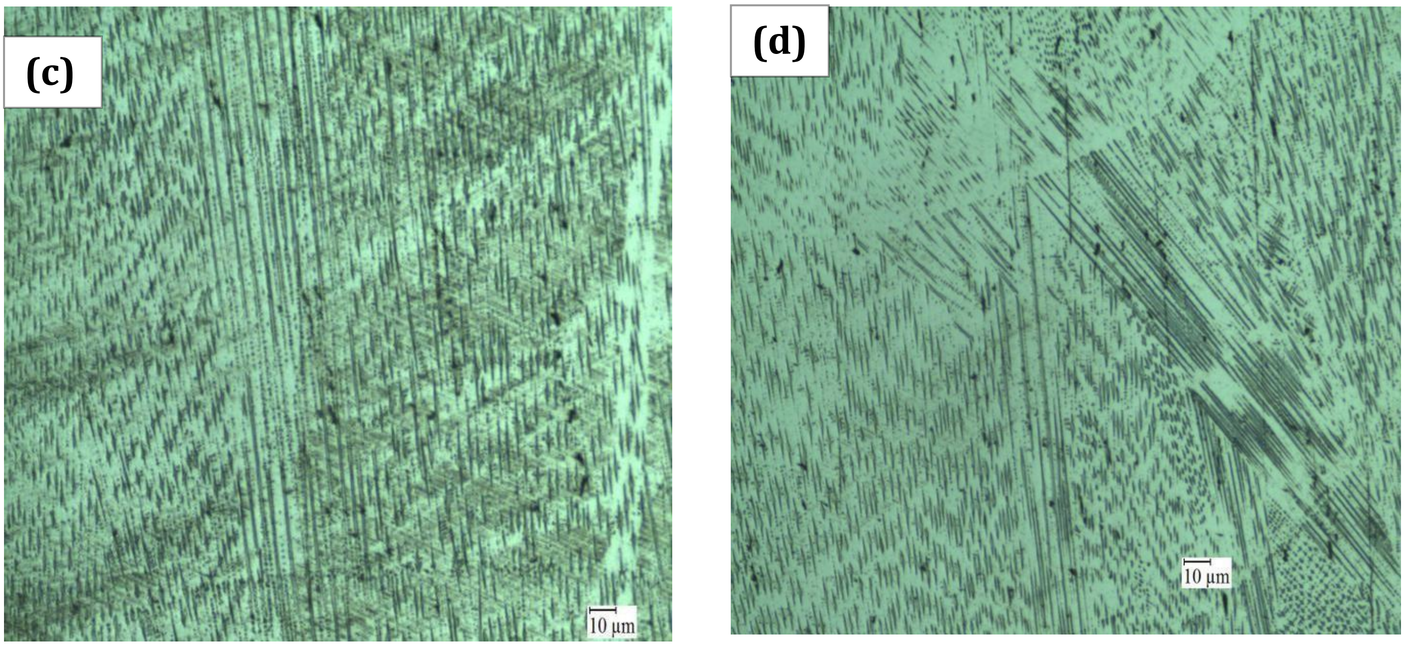
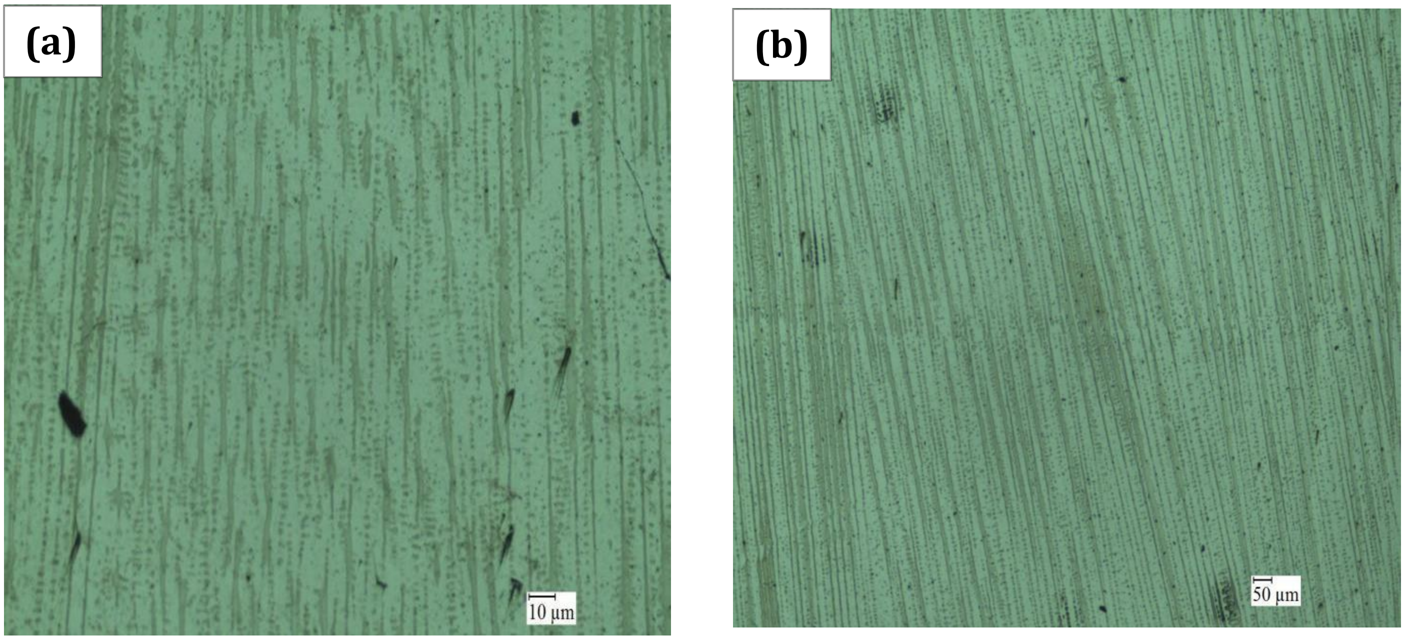


Fig -7: Microstructure at (a) Top Layer (b) Middle Layer (c) & (d) Bottom Layer

2) At 850℃



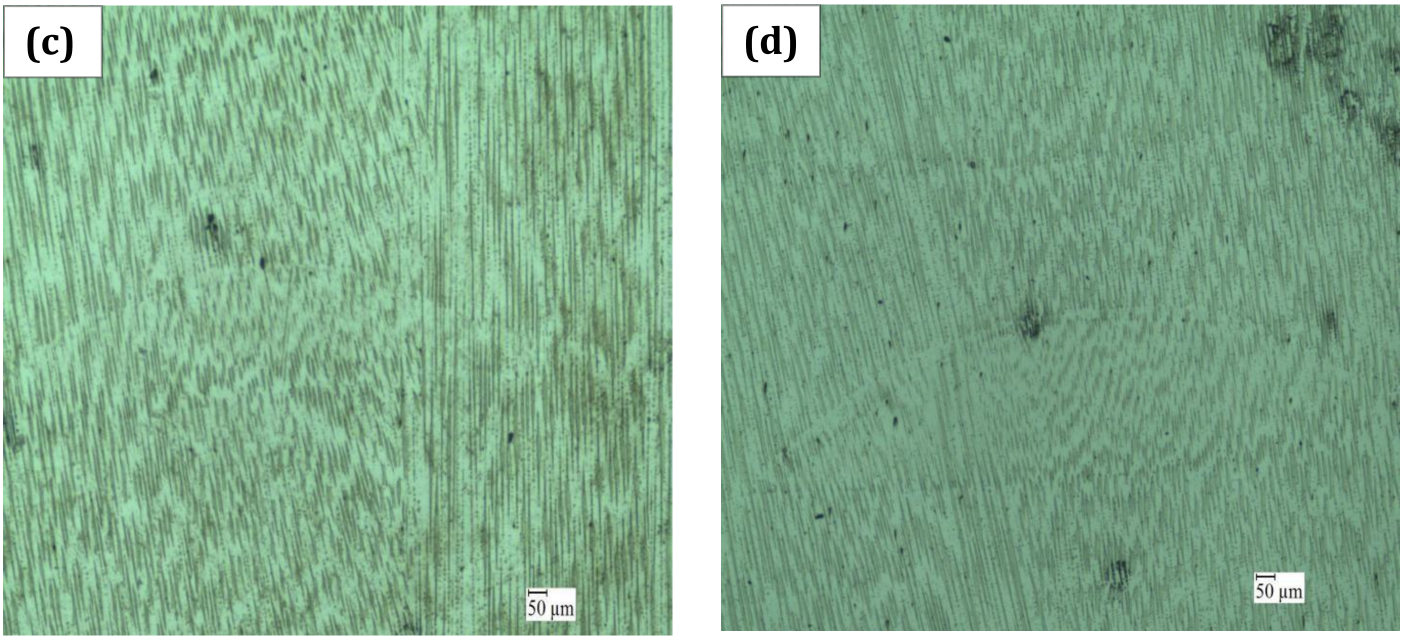


Fig -8: Microstructure at (a) Top Layer (b) Middle Layer (c) & (d) Bottom Layer

3) At 1200℃

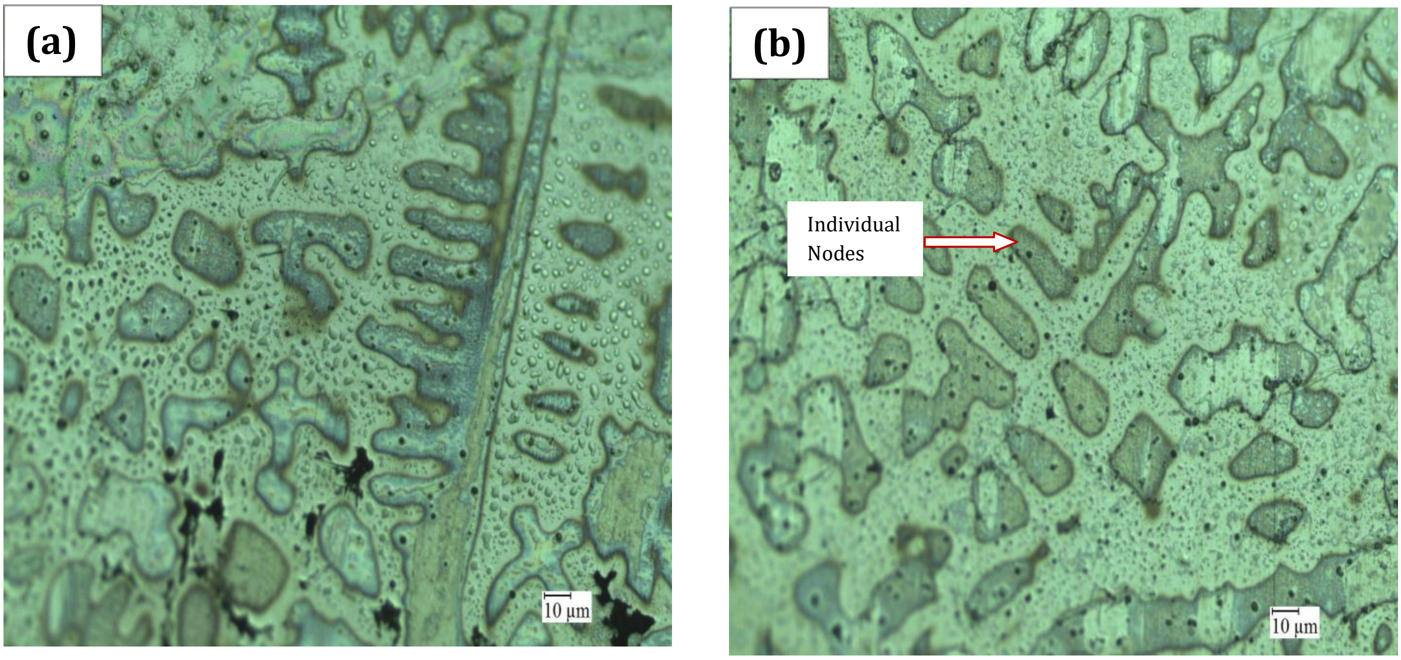


Fig -9: Microstructure at 1200℃

3.3 Tensile Test

A Universal Testing Machine (UTM) as shown in the Fig -10 is used to perform the tensile test of samples machined in both the horizontal as well as the vertical direction. EDM technique was used for machining the samples and a loading rate of 1mm/min was used to obtain the results.

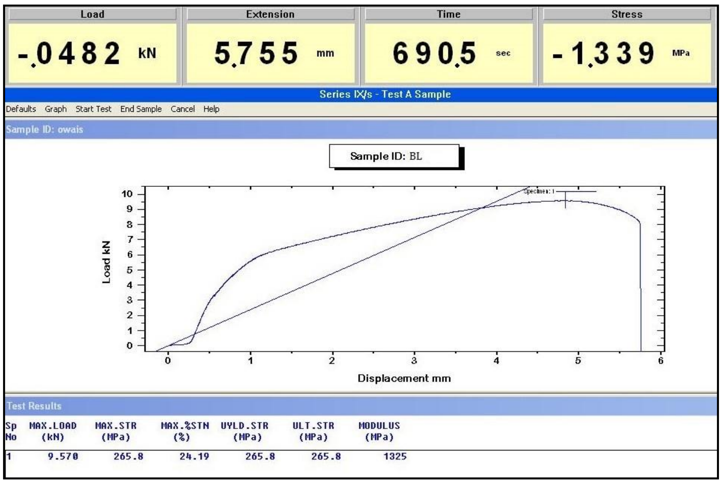
Fig -10: Universal Testing Machine

A total of approx. 2500 values were obtained which were analyzed and a graph was plotted for every sample as shown in the Fig -11. It could be observed from the Table -3 that as we move on from the bottom layer to the top layer, the ultimate tensile strength decreases but the percentage elongation increases.

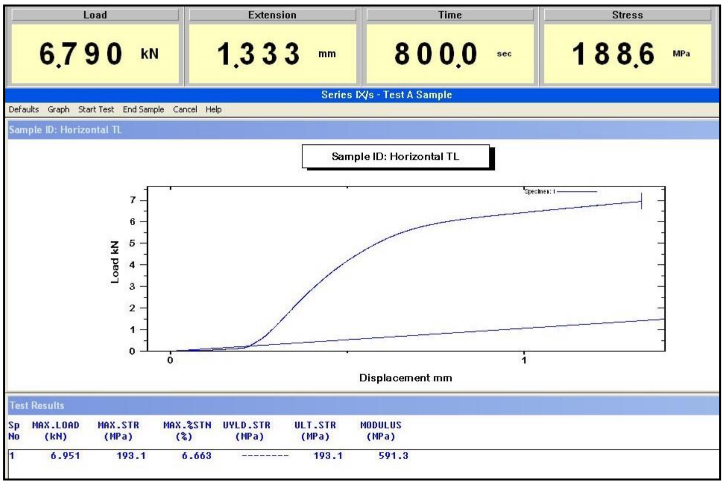
Table -3: Tensile Test results of Samples

Position	Max Load (KN)	Max % STN (%)	Max STR (MPa)	ULT STR (MPa)
Bottom Layer	9.57	24.19	265.8	265.8
Top Layer	6.951	6.663	193.1	193.1
Vertical	6.278	6.666	174.4	174.4
Vertical (850°C)	6.503	6.659	180.6	180.6

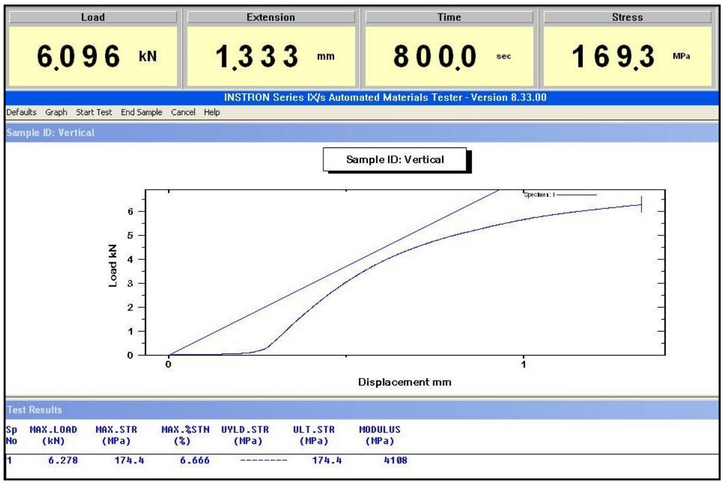
Such a variation is due to the difference in the microstructure, as the presence of fine grain can improve mechanical property to a large extent, whereas for the sample machined in the vertical direction the ultimate tensile strength was least i.e. 174.4 MPa. This is due to layer separation which takes place, when it is loaded in direction perpendicular to layer deposition.



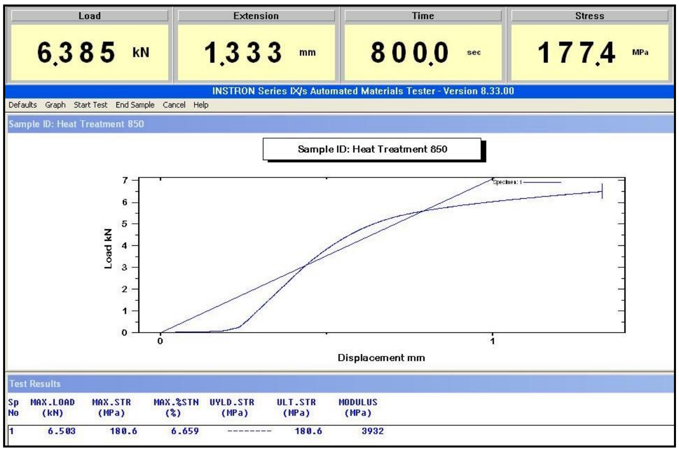
(a)



(b)



(c)



(d)

Fig -11: Loading Curves For (a) Bottom Layer, (b) Top Layer, (c) Vertical & (d) Vertical (H.T @850°C)

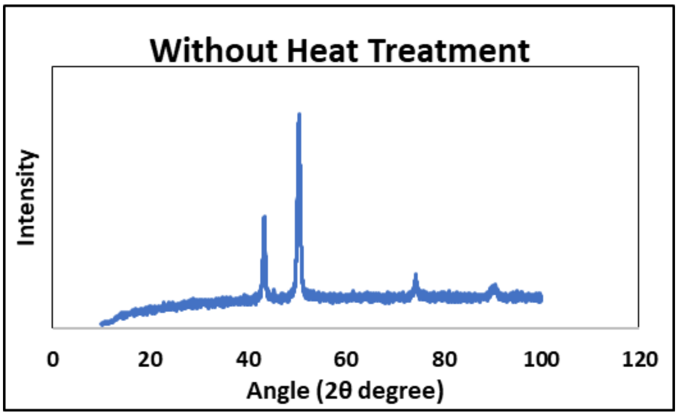
A similar sample was subjected to heat treatment at 850°C and an increase in tensile strength of about 6 MPa was obtained from 174.4 MPa to 180.6 MPa. Compared with parts manufactured by casting, percentage elongation, tensile and YS of the specimens deposited by WAAM are better, with the UTS being slightly lower than the casting process parts.

3.4 X-Ray Diffraction (XRD)

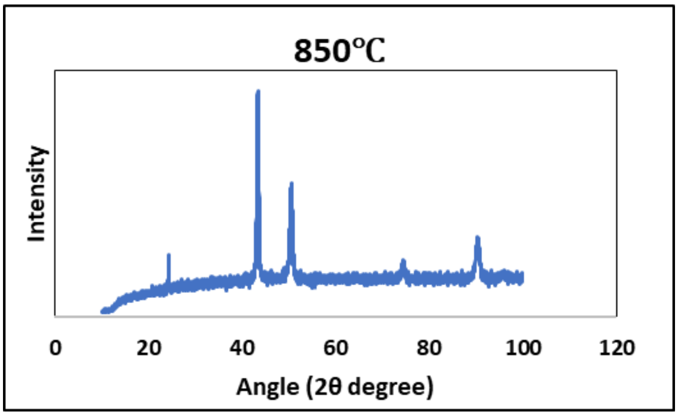
X-Ray Diffraction abbreviated as XRD is a non-destructive test method used to analyze the structure of crystalline materials. XRD analysis, by way of the study of the crystal structure is used to identify the crystalline phases present in a material and thereby reveal chemical composition information. Identification of phases is achieved by comparison of the acquired data to that in reference databases.

X-ray diffraction (XRD) pattern analysis is exceptional for examining microstructures and is widely used in the material sciences because it allows phase retrieval, quantitative, crystal structure and domain size analyses. This test method is performed by directing an x-ray beam at a sample and measuring the scattered intensity as a function of the outgoing direction. Once the beam is separated from scatter also known as diffraction pattern, indicates the sample crystalline structure

The X-ray diffraction measurements was carried out on different samples using a high-resolution BRUKER D8 Advance Davinci diffractometer. The diffraction diagram was measured from 10 degree to 100 degree in 2θ range with step size 0.02 degree (2θ) and 2 s counting time as shown in the Fig -12(a) the diffraction peaks were observed at an angle of 43°, 49°, 74° and 90° for the sample at room temperature. But as the temperature reaches 850°C an additional peak is observed at angle of 24°. This trend continues to the temperature of 1200°Call the distinct peaks vanishes and rather a widely spread pattern is observed in Fig -12(c).



(a)



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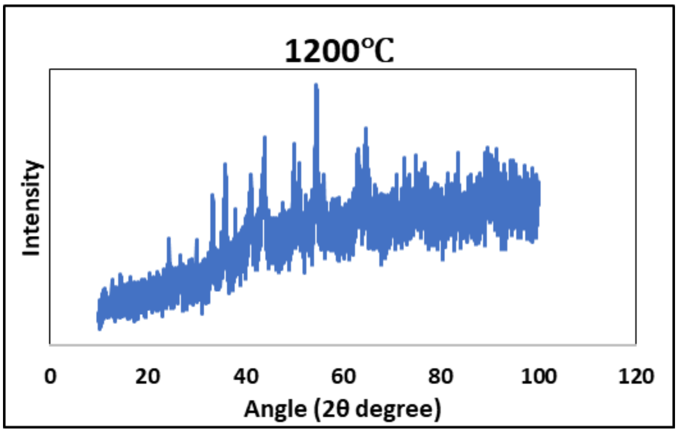

(c)

Fig -12: XRD Pattern of (a) Sample without Heat Treatment (b) Sample after Heat Treatment at 850°C (c) Sample after Heat Treatment at 1200°C

It should be noted that the peak intensities represent the crystallinity of a particular plane. The X-Rays are diffracted producing peak intensities depending on the distance between the parallel planes of the atoms. Moreover, if we inspect the pattern at 1200°C, it is much more similar to that of glass which also doesn't show peak intensities. Therefore, we can conclude that at 1200°C Inconel alloy no longer behaves as a crystalline substance but rather an amorphous.

4. CONCLUSION

In the present work, Inconel 625 alloy was fabricated using WAAM technology. The resulting microstructure and mechanical properties were investigated and the influence of heat treatment on these properties were identified. The following are the conclusions that could be drawn.

(1) The WAAM Inconel 625 sample was deposited with good forming quality by using layer by layer deposition strategy. Different microstructures were identified at the different layers of the specimen, with the bottom layers consisting mainly of fine primary cellular structures. As the distance from interface increased, the main structure became columnar dendrite with classical secondary dendrite arms, and the sample microstructure of the last layer tends to form equiaxed structure.

(2) As the temperature was increased, the cellular branching of the dendrites in the microstructure reduced leaving behind small independent strands until finally the complete disintegration of the dendritic structure was observed at 1200°C

(3) With the increase in temperature for heat treatment, the hardness at a point first increases then is found to decrease slightly as the temperature reaches 1200°C This is due to complete disintegration of the dendritic structure at such very hightemperatures.

(4) The UTS and % elongation of the sample is maximum at the bottom layer and decreases gradually on moving upwards. This can be explained due to the presence of fine crystalline structure at the bottom which becomes coarser in the above layers.

(5) Precipitate formation was observed as the samples were heated to a temperature beyond 1000°C This was due to the presence of a small % of Molybdenum in the composition which reacts with the atmospheric oxygen to form metal oxide.

5. FURTHER ENHANCEMENT

WAAM has been one of the most promising methods in the manufacture of complex three-dimensional metallic components but has certain limitations. Scientists are currently working on modifying the current methodology to overcome these drawbacks to make the process more efficient and highly accurate. Because of these recent advancements the scope of WAAM has been expanded considerably. In WAAM an electric arc is used as a heat source and the material is supplied in the form of wire due to which the component is having low dimensional accuracy. This is usually compensated by generating larger structures than desired and machining away the excess material. Another alternative which is being researched is using the combination of arc in atmospheric conditions with high precision laser. Structures generated using the arc-laser-hybrid process is found to improve the topological capabilities of WAAM and promoting higher depositionrates. One aspect that is not yet well explored concerns the possibility of using WAAM for repair applications This will greatly decrease cost associated with the need to completely renew a given structural part, since with WAAM technology it is possible to perform localized repairs. Another key aspect which is not yet established is related to certification of WAAM parts. This step is crucial to further expand the range of applications of this technology and open the door for more demanding structural applications, where the advantages associated with WAAM can be of special interest. Concurrent to the need for certification procedures for WAAM parts, the need to develop effective and integrated non-destructive testing systems capable of detecting defect formation during parts production. The need for the development of these in-situ monitoring methods lies in the fact that with such an approach any generated defect can be repaired right after its formation and not only at the end of production. Inspection only at the end of the parts production may lead to significant material waste and higher production times, since the location where the defect exists may be difficult to access, thus preventing this overhaul.

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