Residual Stress Characterization of an Additively Manufactured Titanium Alloy

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Abstract

Additive manufacturing (AM) has emerged as a revolutionary technology for producing complex and customized components, particularly in aerospace and medical industries, using materials like titanium alloys known for their exceptional strength-to-weight ratio. However, the inherent thermal gradients and rapid solidification processes during AM can introduce residual stresses in the manufactured parts, significantly affecting their mechanical properties and structural integrity. This study focuses on the comprehensive characterization of residual stresses in additively manufactured titanium alloy components, particularly on understanding the influence of various AM process parameters, post-processing techniques, and part geometries. We employ state-of-the-art semi-destructive techniques, incremental hole drilling and strain gauging to map and quantify the residual stress distribution within the fabricated parts. We elucidate the factors contributing to residual stress formation through carefully designed experiments and numerical simulations, including thermal history, cooling rates, and build orientation. The findings of this research not only advance our fundamental understanding of residual stress mechanisms in additively manufactured titanium alloys but also provide valuable insights for optimizing the AM process and post-processing steps to minimize residual stress-induced defects and enhance the reliability of components in critical applications. Ultimately, this work contributes to the broader goal of unlocking the full potential of additive manufacturing for high-performance engineering materials like titanium alloys.

1.0 Introduction

The lifespan of all structural parts depends on the relation between the gravity of internally available defects and the stresses that are normally from external loadings and those that are naturally from the processing activities the part undergoes. In the latter scenario, stresses induced into parts due to processing activities remain within the part even without the applied force. Such stresses are referred to as residual stresses.

The contemporary aerospace industry is characterized by continuous demand for safer, durable and performance-sensitive aircraft. Those as mentioned above, and in collaboration with the global sustainable development agenda for reducing emissions by a specific percentage, have intensified the need for design complexity. It is more relevant for jet engines, as it is subjected to cyclic loading apart from the exposure to extreme temperature and stresses during the operation (Silveira, et al., 2009). The quest for fuel economy requirements and environmentally friendly, greener and leaner design has brought about lightweight part design without necessarily compromising strength. This global move for efficiency has prompted the manufacturing sector to an additional demand toward fabricating flawless or near parts to eradicate failure in service, particularly in air transport. Gohardani, et al., (2011). The traditional means of material processing tend to look obsolete when producing a complex geometry design in modern-day designs. The future generation of manufacturing technology could emanate from the Additive Manufacturing (AM) sector, where the Selective Laser Melting (SLM) technique is considered a promising choice. (Gibson, et al., 2010)

SLM is one of the AM techniques classified as a laser-based processing system that applies computer-aided models to design 3-dimensional (3D) parts in a layer-layer style. It possesses the ability to produce a superior design with promising accuracy and with less material wastage. Its versatility derives from the fact that the same machine can be used and reused to fabricate another part without changing the system. This trend attracts good interest in many industries where cost reduction per head is a priority (Facchini, et al., 2009)

Selective laser melting is one of the fabrication technologies in additive manufacturing with promising potentials that offers huge benefits, opportunities and improvement as related to other traditional fabrication processes that entail material removal. (Schajer & Clayton, 2013) However, this and other manufacturing processes are associated with residual stresses in the fabricated part. Such seriously threaten the fabricated part when put into practical use, since residual stresses inculcate micro cracks and deformations.

Selected laser melting processes unavoidably induced residual stresses into components after fabrications. While it can produce parts and components of substantial quality, residual stress is identified as major bottle neck during processing due to the large temperature difference close to the melted spot. The repetitive heating and cooling process leads to localized enlargement and reduction, a main cause of residual stress. The extent of residual stress sometimes rises to about equal the material's yield strength (Kruth, et al., 2010). Engineering parts and structures are susceptible to failure at much lesser load gravity than expected due to residual stresses. Tensile residual stress in such components has detrimental consequences on structural integrity. Even though residuals in SLM-processed components have been researched for a couple of years, functional calculations and characterization of the residual stresses of Ti-6Al-4V produced via the SLM process remain a priority.

The continuous nature of the industrial revolution has brought about scenarios where all efforts are geared towards strengthening an ever-demanding industry-driven society. The material processing and manufacturing sectors were two key areas that have been nurtured by this effort over the last two centuries. Present day digital revolution, otherwise referred to as the third industrial revolution, has brought about mass production and boundless use of the digital computer and information communication technology. Material and manufacturing engineering enjoyed a good level of automation of processes by exploiting computer-aided design (CAD), process characterization, and process simulation for material processing.

Scholars and researchers across the globe are making an effort to develop an efficient technique of measuring residual stress in metallic components manufactured by additive manufacturing (AM) process, and this research work is not an exception as it is aimed towards residual stress characterization of additively manufactured titanium alloy (Ti-6Al-4V). The exceptional ability of this alloy to possess two distinct species of crystal structure, namely hexagonal close pack (α phase) and body centre cube (β phase), is the background for the versatility of titanium alloy.

While AM as a process has the perfect ability to produce qualitative parts and components, residual stress has been identified as one of the major challenges during fabrication. It is associated with factors such as the huge changes in temperature around the final melt drop, swift cooling and heating and continuous repetitive nature of the procedure promotes localized contraction and expansion. Residual stress generally affects structural integrity and mechanical performance. Also, it causes distortions while processing, which leads to net shape loss, separation from linked structures and probably the failure of the AM component. (Amanda, et al., 2014)

Residual stress characterization is becoming imperative for aerospace and nuclear areas, typically because they are classified as safety-critical plants. Therefore, this study aims to measure residual stress in an additively manufactured Ti-6Al-4V. In the process, an overview of various additive manufacturing (AM) methods, residual stress and defects in the AM products, and residual stress characterization methods will be highlighted.

2 Additive Manufacturing

Additive Manufacturing (AM) is described as a rapidly expanding layer-based technology that is automatic and innovative fabrication processes that enable parts to be produced layer- by layer directly from a three-dimensional (3-D) digital model; it possesses the capability of producing an intricate, excellent value and individually customized parts, without necessarily using tools. Originally referred to as "3D printing", AM is regarded as a rapidly growing technology for the U.S. and other manufacturers across the globe. These made companies consider AM an instrument for subsiding period to market, components quality improvement and enhancing the economy of production price of their components. Other names for the AM found in relevant literature are additive processing, additive techniques, freeform fabrication, layered manufacturing and additive layer manufacturing. (Cozmei & Caloian, 2012)

AM is the third supporting pillar of manufacturing technology, following the earlier established formative manufacturing such as casting or forging and the subtractive manufacturing, such as milling or turning. Presently, several technologies have adopted this mode of manufacturing. The most common ones include 3D

Printers, Fused Deposition Modelling (FDM), and Stereo Lithography (S.L.) Selective Laser Melting (SLM) There are many similarities and differences between these technologies as the developmental phase of most of these technologies occurred simultaneously. (Mellor, et al., 2014)

An effort to standardize this emerging technology was started in the early 1990s in Germany. 2007 witnessed the creation of a special recommendation on rapid prototyping supervised by the German Society of Mechanical Engineers (VDI) published in 2008. In another collaborative effort, the American Society of Mechanical Engineers (ASME) and the American Society for Testing and Material (ASTM) commenced development work on their standardization methodologies on AM. By 2009, a committee called ASTM F-42, whose mission was to standardize and develop industrial standards, was inaugurated. A subcommittee on terminology referred to as ASTM F-42 91 released the first standard, F2792-09e1/F292/ referred to as standard terminology for AM technologies. This committee, among other terminologies, were able to describe AM as follows:

> *"the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies."* (ASTM International, 2012)

A notable point in the definition above based on the ASTM standard is the computer-controlled 3D model data regarded as the design foundation. This definition is also reported in the works of (Harris, 2011) (Bikas, et al., 2015), and (Mellor, et al., 2014). This signifies that software process automation and control is an important parameter in examining what belongs to and is otherwise grouped under this fabrication method.

2.1 The Principles of Additive Manufacturing

AM, also referred to as generative manufacturing, direct digital manufacture, e-manufacturing, freeform manufacturing, rapid manufacturing or 3D printing, is the universal terminology used for all technologies based on the "dispersed accumulated forming principle" (Cozmei & Caloian, 2012) the technical actualization of AM is based exclusively on layers and that prompted the name "layer-based technology, layered technology or layer oriented technology" the idea of the technology is to build up a three-dimensional object refer to as part from several layers made up of equal thickness, the thickness of a layer is regarded as the printing resolution on the axis Z. However, the resolution on the y and x axis is not necessarily be same as that of the z axis. The shape is formed by modelling each layer on top of one another in line with the corresponding 3D model data set. The analogy of manufacturing based on uniform layer thickness addition successively is that it results perfect stair effect. (Gebhardt, 2012) Cartographers and architects apply this principle to express hills and other geographical reliefs and landscapes of real or proposed areas, respectively (Gibson, et al., 2010)

2.1.1 Additive Manufacturing Process and Classification

There are as many AM processes available nowadays; they can be distinguished by the layers deposition mode toward the part building, in the theory of operation, and the engineering material to be used. AM methods such as the SLM, SLS and the FDM work on the principle of melting or softening material to create the layer, while other methods, such as SLA, are based on curing liquid materials. (Bikas, et al., 2015) However, Gibson (2010) believed that classification based on raw material is faulty in that some processes are grouped in what he described as 'odd combinations' (for example, SLS grouped with 3D printing) or sometimes some method that may look likely to produce similar output may end up being parted. Yet, he proposed a popular approach based on baseline technology, for instance, technology such as lasers, extrusion, printers and so on. This research is on the residual stress characterization of titanium alloy additively produced via laser-based technology, particularly SLM.

2.1.2 Laser-Based Technology

Laser-based AM route is working on the principle of using an avenue of laser source to minimal power to generate heat for melting, solidification or curing of the powdered material. This technology generally has two broad categories, but that entirely depends on the phase transformation strategy adopted: laser melting and polymerization processes, respectively. The former process, popularly referred to as selective laser melting, involves the laser completely melting the material, generating a selective pool of melt that is completely dense upon solidification (Gebhardt, 2012). Initially, the material to be processed is provided in a powdered form. It can be carried out in two ways: by a powder bed method or through the nozzles connected to the processing head. A laser beam provides the major function of melting the material, and the part is formed when it cools down, solidifies or is cured. (Bikas, et al., 2015) However, the laser polymerization process differs in principle because the plastic is traditionally a photosensitive resin that gets hardened upon exposure to Ultra Violet (U.V.) emission, sourced from a laser of less power. This technology is very similar to selective laser sintering yet differs based on technical parameters. SLS process relies on sintering to form parts, while in SLM is about melting a powder for parts to be formed. The power requirement for the SLM, as deduced by (Bikas, et al., 2015) is usually higher, around 400W. This high power demand is mainly due to the relatively high processing temperature requirement compared to the SLS power requirement range of 7W (for plastics) to about 200W, depending on the material to be processed. (Castoro, 2013)

In light of this technology's enormous benefits, such as the ability to fabricate a fully dense product that is complex and intricate with commensurate properties comparable to that of bulk material, while ensuring shorter post-processing activities. The technology is, therefore, very much promising for fields such as the automotive, aerospace, and electronics, as well as in bioengineering technology because of the often demand for sensitive and intricate design (Knowles, et al., 2012)

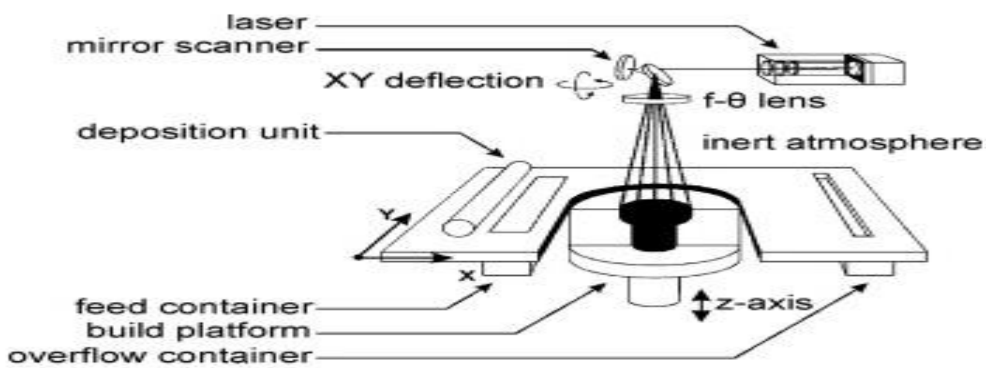

Figure 1:A typical laser system layout

2.2 Residual Stress in Additively Manufactured Products

Recent research has proved that additive manufacturing technologies could provide environmentally friendly and sustainable processing path for metals and it alloys and in specific precious metal alloys, typically titanium alloys. (Simonelli, et al., 2014) Ti-6Al-4V alloy has been identified as one the most common and commercial titanium alloys available in production and is very applicable in industries such as biomedical and aerospace. It was reportedly developed first in the United States of America (USA) in 1954 at the famous technological institute in Illinois (Gibson, et al., 2010). Ti-6Al-4V gained significant popularity mainly due to its extraordinary properties balance: it combined high strength and appreciably better toughness properties, apart from possessing a good ability to undergo heat treatment process, noting that mechanical properties are dictated by processing activities and history. (Knowles, et al., 2012)

A typical additive manufacturing process is SLS and SLM (powder bed), which offers huge opportunities and advantages compared to the olden fabrication means. However, this technology is associated with a major shortcoming in the high-temperature gradient derived from the manufacturing route. The melting process using the high energy beam mentioned above leads to the creation of thermal residual stresses to be imparted into the manufactured part due to sudden expansion and contraction of the previously cured layer. These threaten the technology's practical utilization since residual stress leads to part deformation and initiation micro cracks. Above all, if the residual stress is large, it can affect the part's ability to resist load compared to a state of free stress. (Mercelis & Kruth, 2006)

2.2.1 Residual Stresses: Origin and Definition

To justify residual stress characterization, it is paramount to first explain the origin of stresses. Residual stresses in a given part or component refer to those stresses that are not required to keep the part and the surrounding environment in equilibrium (Whithers & Bhadeshia, 2001). In other words, the stresses tend to persist inside the body or material at the end of fabrication without the influence of any thermal gradient or external force. Likewise, it may emanate from loadings that bring about non-uniform plastic deformation in the specimen. Unlike normal stress, residual stress is not a result of the application of loads, be it forces or moments (Rossini, et al., 2012) Residual stress is classified based on cause, the scale of occurrence or based on techniques applied for the measurement (Whithers & Bhadeshia, 2001) Residual stresses stem from misfits between two or more different regions, mostly these misfits stretch over long distances.

The major classification of residual stresses based on scale appeared as either micro or macro-stresses and sometimes both can be present at a given time in a component, as reported in the works of (Mercelis & Kruth, 2006) (Rossini, et al., 2012) and (Whithers & Bhadeshia, 2001) They are of three types:

Type 1: Macro residual stress can cause larger part deformations, varying over large distances. It is formed on a measure bigger than the size of the specimen's grain.
Type 2: A micro residual stress (intergranular stresses) that changes over an individual grain scale
Type 3: When residual stresses appear inside an atomic scale, typically referred to as micro stresses resulting from coherency at the border, crystalline defects and dislocations.

The type I residual stresses have a lot of significance on the strength of the material under study as they can extend over distance from a millimetre and above, unlike the other two categories that extend over distance in microns. (Schajer & Clayton, 2013) They mainly occur due to different phases within the material and due to dislocations at the atomic scale. Moreover, most of the available residual stress measurement techniques have no such a smaller measurement resolution that can capture type II and type III residual stresses (Mercelis & Kruth, 2006)

Generally, the literature on mechanisms that create residual stresses was summarized by (Schajer & Clayton, 2013) and (Whithers & Bhadeshia, 2001) into three major headings, as follows:

1. Inhomogeneous plastic deformation. These happen in fabrication that involves a change of shape of material as obtainable in forging, bending, extrusion, etc. and surface deformation of parts in service
2. Surface modification. Parts can pick up residual stress during manufacturing processes such as machining, grinding, carburizing, plating and peening and when exposed to corrosion and oxidation while in service.
3. Phase transformation of material with variation in density is associated with huge thermal gradients as experienced while the welding process or foundry processes

2.2.2 Effects of Residual Stresses

Even though it is not within the scope of this research work to discuss the effect of residual stress in detail, it is important to briefly answer why residual stress is measured.

Residual stresses are subject of concern mainly for the following reasons:

- Failures in parts that are suspected to have resulted from fatigue, corrosion fatigue and stress corrosion
- Assessment and examination for continued serviceability of a given part to avoid in-service unpredictable failure
- The processing process induced distortion in the part
- In-service or storage-induced distortions

Residual stresses have a common role in the strength of a part or component as the common external load stresses. However, while external load stresses are quantifiable with a certain appreciable measure, it is tedious to predict internal residual stresses. That made it mandatory to explore for a guaranteed technique capable of measuring them directly with the least damage to the part's surface (Withers, 2007).

The significant role of residual stresses in explaining or preventing the failure of a part cannot be overemphasized. One example of preventing failure by residual stress is the shot peening of part to induce compressive stresses at the surface, enhancing the component fatigue properties.

Residual stresses are sometimes beneficial. For instance, static loading of materials such as brittle glass can be improved tremendously if residual stress is properly utilized (Whithers & Bhadeshia, 2001). A typical example is pre-stressed concrete and toughened glass. In the latter, compressive surface stresses are built up due to an instant change in temperature from higher to lower temperature (cooling). The interior tensile stresses counter this. Such increases resistance to loading generally and stops crack propagation in the external layer. Yet, internal residual stresses are practically undesirable, leading to distortions of the actual geometry. Furthermore, pre-stress tensile aggravates stress from outside loading, undermining the component's capacity and supporting surface crack dissemination. (Mercelis & Kruth, 2006)

3 Residual Stress Characterization Methods

Categories of Residual Measurement Techniques

Researchers have been applying many procedures and techniques to determine residual stresses in parts and components made of metals and their alloys, usually as picked from manufacturing processing. Generally, the techniques are classified into three categories: destructive technique, semi- destructive and non-destructive, as shown in Figure 2 below. Destructive and the semi- destructive are further referred to as mechanical methods. These methods work on the principle of monitoring the difference in deformation that might occur to the part/component during or after residual stress formation by deliberate material removal to give room for stresses to relax. (Whithers & Bhadeshia, 2001) This technique was described as a stress-relaxing method because it analyses the stress relaxation achieved in metal due to material removal. By quantifying the deformation induced as a result of the relaxation, the magnitude of residual stress available in the specimen before the removal of the material can be deduced via simple analysis of the equilibrium condition (Rossini, et al., 2012)

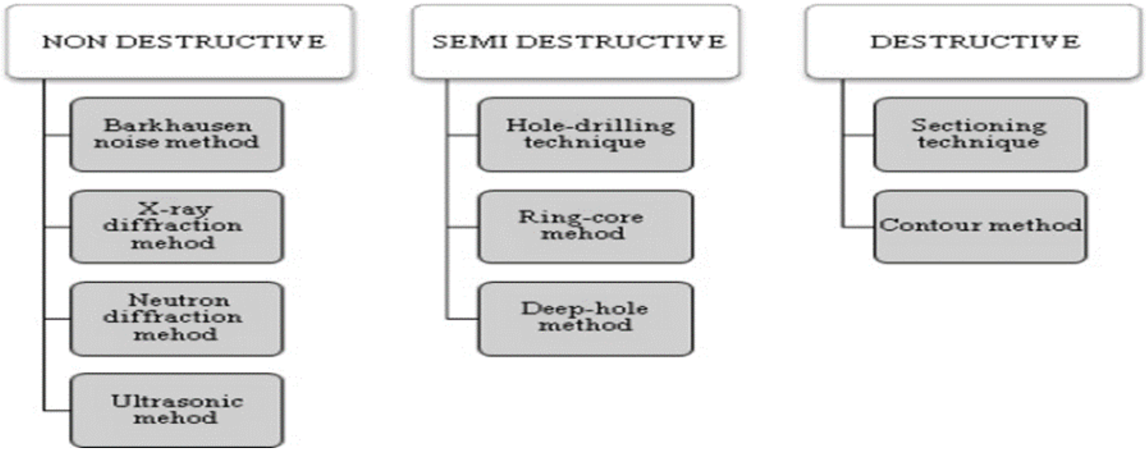

Figure 2:Classification of residual stress measurement techniques

This research work shall consider the incremental hole drilling methods for the measurement of residual stress of the specimens provided

3.2 Incremental Hole Drilling Technique

The incremental centre hole drilling technique (ICHD) is considered one of the most popular materials' residual stress measurement methods. Its procedural activities are standard and very user-friendly, guaranteeing accurate measurement and ensuring reliability. The measurement procedure consists of little sample impairment, but the impairment is not beyond the limit and can mostly be patch-up. It is a term classified as a semi-semi-destructive technique (Schajer & Clayton, 2013) (Valentini, et al., 2011) concludes that it is more economical than the XRD. The application of 8 stages hole increments is detailed in (ASTM E837-08, 2008), and it was reported as an effective technique for the improvement of the quality of residual stress characterization (ASTM International, 2012)

IHD, as the name implies, entails identifying the spot of interest on the specimen and drilling a small hole at the spot where residual stress is to be measured. Residual stress distribution at trough thickness generated by shot peening surface treatment is mostly non-uniform. (Valentini, et al., 2011) Reported that ASTM E837-01e1 as standard was bound for only uniform residual stress; however, this technique (IHD) has also been applied to measure incremental depth applications. The primary technicality involved a series and sequence of increments of the hole depth and taking note of the relaxed strain. The residual stress distribution is obtained by the resolving the problem in the reverse direction, which is done by applying the integral method. (ASTM E837-08, 2008) Research and development has arrived at a stage in which the latest version of standard ASTM E837-08 has taken care of the non-uniform residual stress aspect that the previous standards have neglected. The standard suggests using an integral method to compute the residual stress distribution using a rosette strain gauge. (Valentini, et al., 2011)

To address the unavoidable errors and uncertainties associated with IHD (Grant, et al., 2006) discussed in their publication a good practice, covering as many as possible sources of error, methodology, hole eccentricity and zero depth uncertainty.

Knowles, et al., (2012) used the hole drilling strain gage technique to characterize residual stress and found out that there are high residual stresses in Ti-6Al-4V produced via the SLM technique. The gravity of the residual stresses was reported to have approached and exceeded the material yield strength, resulting in deformation observed during processing. He concluded by attributing these high residual stresses to TGM. (Mercelis & Kruth, 2006) Have researched this and made some vital conclusions concerning residual stress measurement explicitly in part nearer to the base plate. He found that parts that continued to be attached to the base plate may have a stress capacity of near the yield strength of such material. In contrast, low stress is reported in parts removed from the base plate, a comparison of stresses perpendicular to the scanning direction and those along the scanning direction proves that the former were significantly higher for specimens fabricated by one directional strategy. Residual stresses were reported to be increasing concerning the height of the specimen. However, Mercelis & Kruth work was carried out on stainless steel 316L.

The work of (Nicholas, et al., 2014) shows the characterization of residual stresses in the Ti-6Al-4V part produced by arc wire-based AM, where they reported that residual stress was larger in the longitudinal direction and it was observed to be more concentrated around the boundary between the deposited wall and the base plate. Figure 3 shows a maximum longitudinal stress of around 565 ± 35 MPa, which is virtually 70% of the yield strength of Ti-6Al-4V. However, this work was analyzed quantitatively based on the neutron diffraction technique.

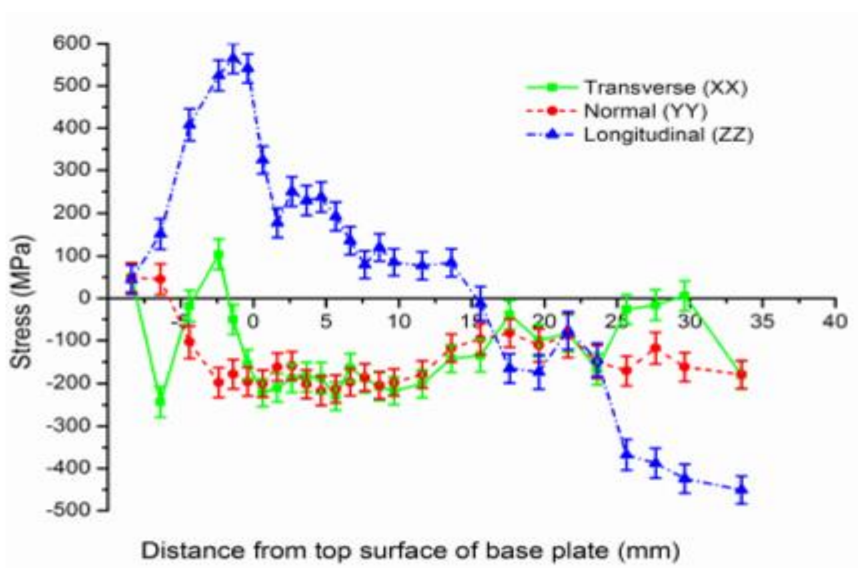

Figure 3:Behaviour of stresses in transverse, longitudinal and normal directions

There is a significant contribution from authors in the studies of residual stresses from several different points of view. Still, there is less research on residual stress from the viewpoint of different scanning strategies. The laser beam's scanning strategy greatly influences the thermal gradient during the part production in the SLM process. (Bo, et al., 2012) Recent research has presented the utilization of different scan strategies to contain and control the thermal stresses that arise from each layer deposition. (Gibson, et al., 2010) (Mercelis & Kruth, 2006) It has been reported, for instance, that alternating the scan vector direction at each layer decreases residual stresses in the building part. Other researchers have advocated that residual stresses are proportional to the scan vector's length. Thus, it has been proposed to use the checkerboard strategy and then scan haphazardly to reduce the temperature inconsistency and thus reduce the internal stresses' growth. The checkerboard is a scan strategy that splits the entire area of the part into small squares referred to as islands. (Gibson, et al., 2010) Qiu et al (2013) used a unique scanning strategy on the SLM Ti-6Al-4V part that divides the surface into square islands to produce a larger, even heat distribution. The island scan showing the scan spacing and the island size is demonstrated in Figure 4

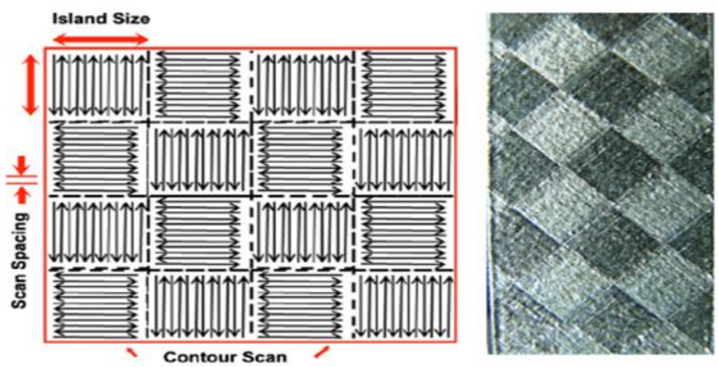

Figure 4:scanning strategies in AM

As the length of the scan track is found to be correlated with the internal stresses, the build orientation adopted also affects the strength of the internal stresses. It was observed that orientations with smaller cross-sectional areas are less vulnerable to warpage. Regrettably, the relation between the microstructure and laser scan strategy has not yet been thoroughly researched. However, it has been revealed that varying the scan direction at each layer could impact the growth direction of the prior β grain. On the other hand, the relationship's basis is pragmatic and unclear. (Thijs, et al., 2010)

4 Materials and Methods

4.1 Materials

The material used for the research was additively manufactured Ti-6Al-4V produced as a rectangular block of size 50mm x 50mm x 10mm via SLM technique. There were four different specimens processed with different scanning strategies.

4.2 Mechanical Properties

Table 1:showing mechanical properties of Titanium alloy

Material Properties	Wrought form of Ti-6Al-4V	Source	SLM form of Ti-6Al-4V	Source
Elastic modulus	113.8 GPa	(Donachie, 2000) (Ming & Peng, 2015)	110 ± 10 GPa	(EOS GmbH - Electro Optical System, 2011) (Ming & Peng, 2015) (Ramosoeu, et al., 2010)
Poisson's ratio	0.342	(Donachie, 2000) (Ming & Peng, 2015)	0.3	(Ramosoeu, et al., 2010) (Ming & Peng, 2015)
Hardness	349 HV	(Donachie, 2000) (Ming & Peng, 2015)	400 – 430 HV	(Ramosoeu, et al., 2010) (Ming & Peng, 2015)
Yield strength	880-1100 MPa	(Donachie, 2000) (Ming & Peng, 2015)	1090 ± 100 MPa	(EOS GmbH - Electro Optical System, 2011) (Ming & Peng, 2015)
U. T. S	950-1200 MPa	(Donachie, 2000) (Ming & Peng, 2015)	1180 ± 100 MPa	(Ramosoeu, et al., 2010) (Ming & Peng, 2015)
Extension	14%	(Donachie, 2000) (Ming & Peng, 2015)		
Reduction of area	36%	(Donachie, 2000) (Ming & Peng, 2015)		
Fracture toughness	75 MPa x $m^{1/2}$	(Donachie, 2000) (Ming & Peng, 2015)		
Material Density	4.43 g/cm^3	(Donachie, 2000) (Ming & Peng, 2015)	4.43 g/cm^3	(Ramosoeu, et al., 2010) (Ming & Peng, 2015)

The mechanical properties of SLM-produced Ti-6Al-4V are not well established in the research literature compared to the traditional wrought Ti-6Al-4V. These are not unconnected with the former being a new system in the manufacturing sector. Therefore, it is important to present the broader material properties found in any common species of Ti-6Al-4V to serve as the basis of the initial broader valuation of SLM parts. Table 2 Compares the properties of Ti-6Al-4V as found in wrought form with available properties of SLM Ti-6Al-4V from recent works of literature.

4.3 Fabrication stage of SLM Specimen used for this work

Our research collaborator, the Net Shape Centre at Birmingham University, provided two sets of SLM specimens built on a single base plate. Even though the fabrication aspect of the specimen is not within the scope of this work, it is pertinent to highlight some important aspects of it to have a clear overview of the specimen under investigation.

The material used for this investigation was Ti-6Al-4V powder of size range within 20-50 µm. The SLM system used for fabrication of specimen is the Concept Laser M2 Cusing, shown in Figure5, which utilizes an Nd: YAG laser with a 1075nm wavelength. The specimen was built with a maximum laser power is 400W as the maximum laser scan velocity is up to 2300mm/s. All the specimens studied in this work were built on wrought Titanium Base plate Figure 7 Other technical information about the Concept Laser M2 Cusing are provided in Table 2 below.

Table 2:Details of the laser equipment used

Laser Equipment Name	Concept Laser M2 Cusing
Build volume	250×250×280 (x,y,z)
Laser Type	Nd: YAG laser of wave length 1075nm
Layer thickness	20 **µm**
Scanning Speed	2300mm/s
Power	400W
Base Plate Material	Wrought titanium
Ti6-4 Powder Size	20-50 **µm**

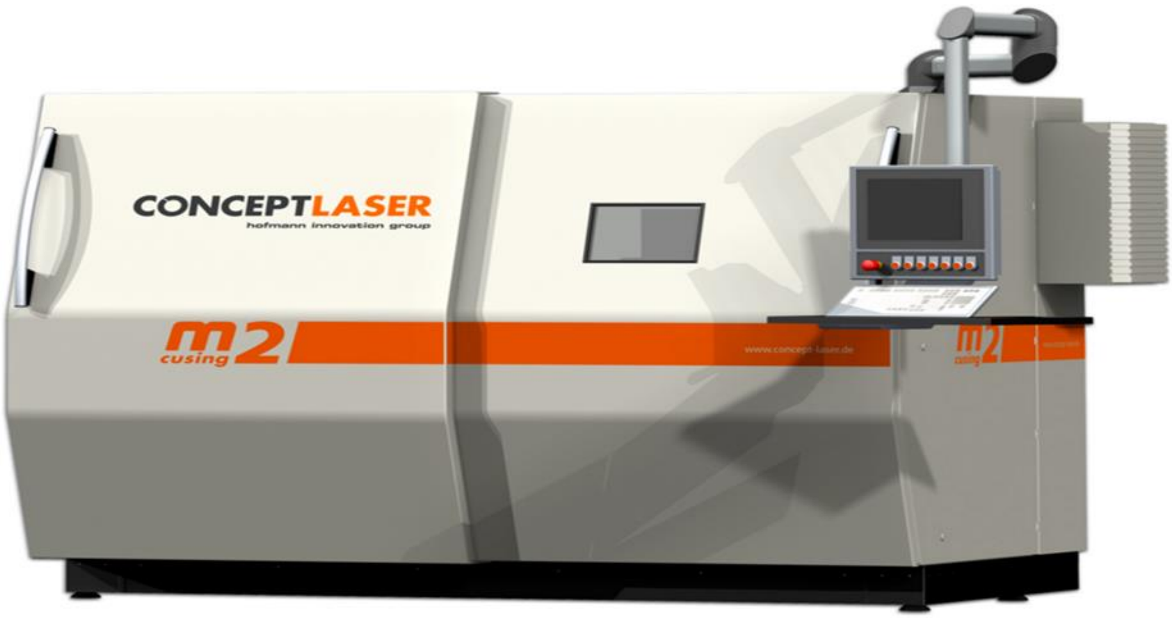

Figure 5: Concept laser M2 cusing

4.4 Specimen Preparation and Experiments

Surface preparation and installation is a crucial process that demands a high level of expertise and is done based on the manufacturer's guides and instructions. This stage of the experiment was done bearing in mind the fact that installation quality determines the quality of the strain reading expected. The surface of the specimen was fully prepared to ensure excellent bonding of the strain gauge. The surface was cleaned chemically, with appropriate roughness and was neutralized to attain a pH7 scale of alkalinity. The surface of the specimen was polished before the bonding of the strain gauge, and the first process was degreasing, where medical gauze with acetone was used to clean from the identified area to the sides. Then followed by conditioning the surface. This was done by applying the acid solution to the area with a cotton bud and continuously wiping until the cotton bud was without any dirt. Then, the neutralizer, a basic solution, was applied to return the specimen's surface to optimum alkalinity.

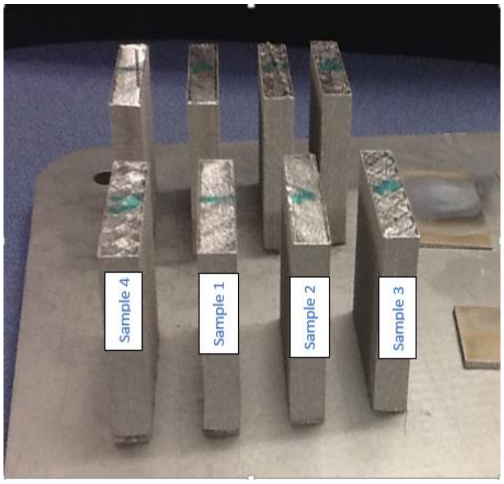

Figure 6:specimen on the based plate

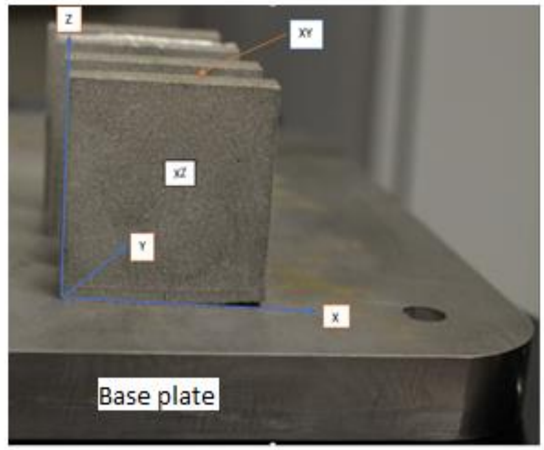

Figure 7:Specimen used

4.5 Strain Gauge Attachment

A plastic box and the tweezer were cleaned with a neutralizer, and the cleaned tweezer was used to pick the strain gauge from the pack and place it on the top surface of the plastic box. Then, a layer of sticky tape was applied on top of it with the view of picking it up. The sticky tape was removed from the surface of the plastic box at a low angle of 300. At the same time, the strain gauge was attached to the sticky tape at this stage. The sticky tape was applied to the surface of the specimen this time around at the specific point of measurement marked earlier. The sticky tape was lifted carefully, and the catalyst was applied at the back of the strain gauge and allowed to dry up before a drop of glue was applied. The sticky tape was re-attached back to the surface of the specimen and pushed with medical gauze for an even distribution of the glue and avoidance of air bubbles. It was kept under pressure for at least one minute by pressing with a finger, then allowed for some 20-25 minutes before the sticky tape was removed at an angle of 180^0c. A little application of M-line rosin solvent eased the removal of the sticky tape without harming the strain gauge.

Setting up the electrical connection involves soldering six wires to the strain gauge, two to each of s1, s2 and s3. Wires soldered to the s1 were connected to the input 1 of the P3 strain indicator and recorder. The same was done for the s2 and s3. The connection was checked by looking at the channel values on the P3. The wiring has a colour code, which is a standard and was observed strictly: two green wires and a black wire, two blue wires and a white wire, then two yellow and a red wire. The connection as soldered to the strain gauge was demonstrated in Figure 8

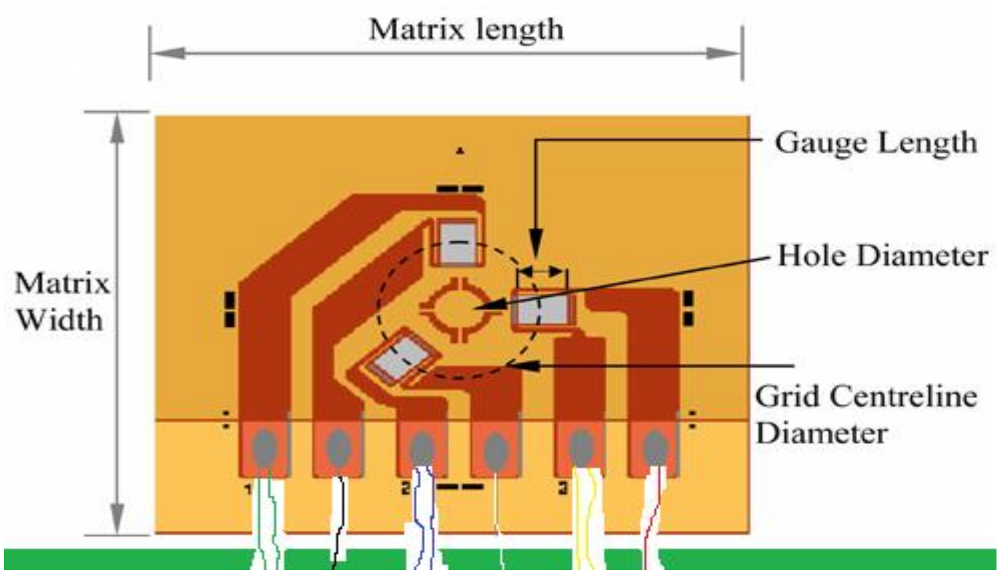

Figure 8:strain gauge layout

The sample was placed under the drilling device, and the viewfinder aligned the hole with the device. The optical head was replaced with a drill, implying a sample ready for drilling. Residual stress measurements are highly affected by misalignment and eccentricity between the strain gauge target and the drilled hole centre, and misalignment are minimized to maximum. For the drill to be perpendicular to the surface a sprit level was used to determine the flatness of the surface. ASTM E837 stipulates that the gauge and drilled hole centres should coincide within ±0.004D or ±0.025mm.

The drill suitable for this sample is the inverted cone made of tungsten carbide F.G. 36, all drills used for the experiment were exposed to a short visual examination before use and drills were discarded after one usage. To change the drill the rotation has to be blocked by placing a screwdriver in a small hole in the big cylinder, then another small spanner was used to unscrew holder to release the drill bit. To replace the drill bit it was manually screwed, followed turning with the small spanner 1/8 of circle. At that point the light was directed towards the hole for clear visibility.

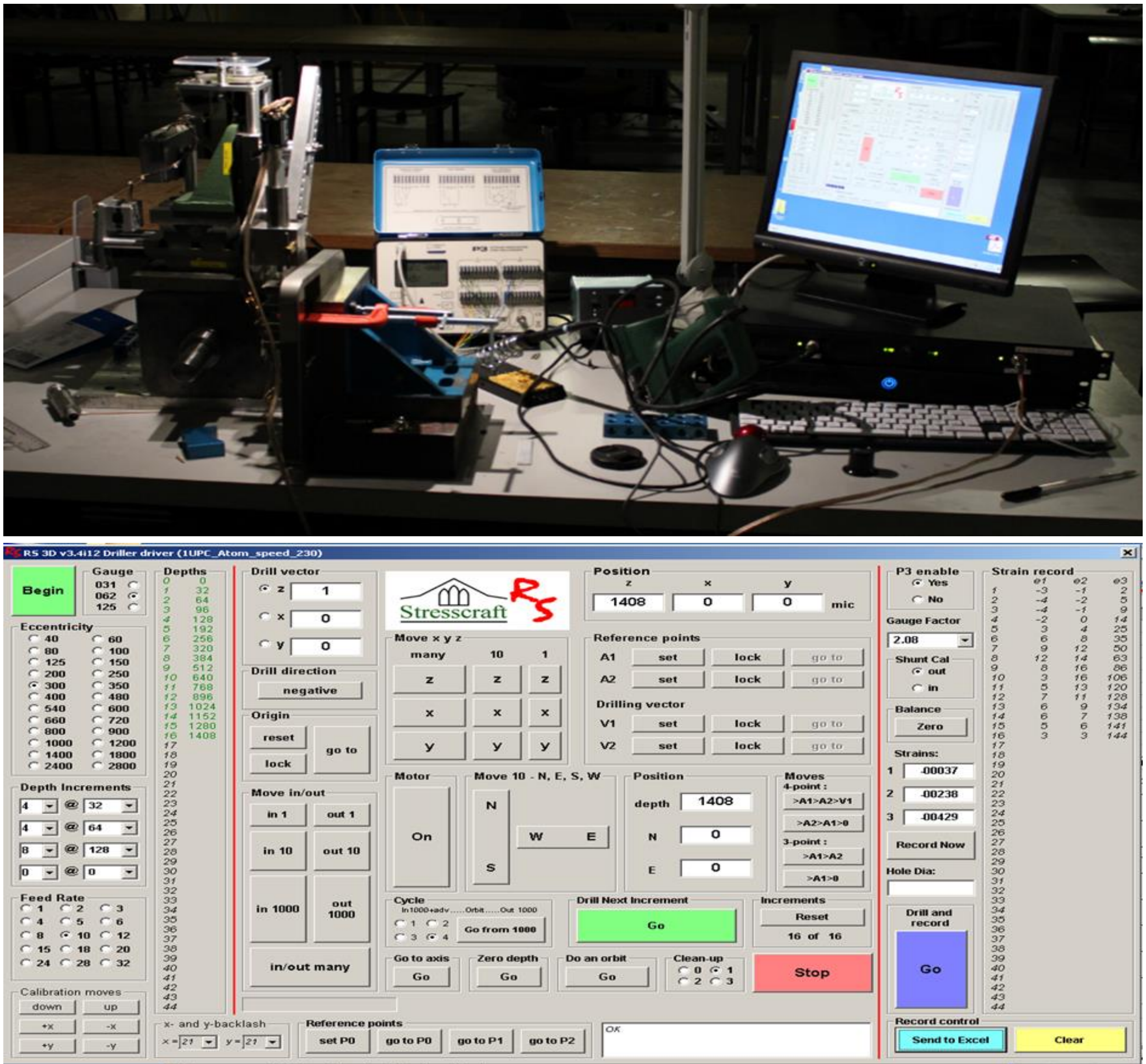

Figure 9:workstation for the experiment and stresscraft RS screen

This research used the Stresscraft RS drilling machine for the residual stress measurement. The software was launched by clicking the R.S. icon, a program as one found on Figure 9 would appear on the screen. The Begin button, a green squared button located at the top left corner of the screen, was clicked to start the program, then the gauge size 062 was selected. An eccentricity of 300 µm was chosen for the drilling exercise; the eccentricity describes the radius of orbital movement while drilling. The gauge strain amplifier (P3) was enabled, a gauge factor of 2.08 was inserted and this information was obtained from gauge box. Balancing to zero brings the P3 strain readings to zero. The specimen clamping was checked again to ensure it was levelled and no strain was introduced.

The move XYZ command was used to go as much as possible closer to the surface gauge while the motor was on. This was continued until the gauge was scratched. The assurance that the gauge was touched, then the origin was set by clicking the origin reset. The move-in/out command was used to move out 1000 microns. That moved the driller 1000 microns out in the Z direction.

Locating the sample surface where drilling shall commence, the cycle function with step 1, 2, 3, and 4 microns was used at 4 microns then the go from 1000 command was activated while observing through the eyepiece. That allowed the driller to move in 4 + 1000 microns and then moved out by 1000 microns. This process continued for about seven rounds while the holes bottom shiny surface was not observed. The step was changed to 3, 2 and 1 micron and same process was repeated until the shiny surface that reflects the light was observed as described in the final stage. Move in 1000 micron was used and that position was set as the real surface, it was set using origin reset.

Finally, after drilling through the 16 points, data containing the strain record was generated at the top right corner of the screen as the strain values e1, e2 and e3. Send to Excel command was used to send the strain record to M.S. Excel, which was named as a file and saved. Converting the relaxed strains recorded during the incremental hole drilling requires using the M.S. Excel file RS INT V5-1. This file contains cell functions that deals with such computations based on integral method as developed by Schajer (Schajer & Clayton, 2013). This workbook that works with the Stresscraft driller contains three different worksheets. However, the RS INT v5.1.2 workbook was used for this research based on the gauge size and the standard drilling increment adopted. The strain record was copied from the Excel worksheet and pasted into the RS INT v5.1.2 workbook to compute residual stresses, and results were saved for analysis.

4.6 Closed-form solutions

Third in the series of experimental procedural processes of residual stress characterization is the residual stress measurement (computation) one of the major feature that characterized the hole drilling technique and almost all the remaining classes of destructive techniques for residual stress characterization is that they encompass stressed material removal in one part of the workpiece and the recording of the strain in an entirely nearby part of the workpiece. A huge computational contest arises due to the difference in the location of the target stresses and the recorded strain. (Schajer, 2010)

Two types of stress computation arise, uniform and non-uniform stresses. In the former, the in-plane stresses are assumed not to vary with depth from the surface of the specimen, while the latter do vary with depth. The uniform stresses are easier because there are specified unknown in-plane residual stresses to be detected from the recorded data. Ideally, there are three unknown in- plane stresses. Residual stress characterization of a uniform stress case using strain gauge involves making 3- strain measurements to compute for 3- unknown residual stresses. The two are related by equation 1, showing the relationship between in-plane residual stresses and the measured deformation (strain) (Schajer, 2010)

$$\varepsilon = \frac{(\sigma x+\sigma y)}{2}\frac{\tilde{a}(1+v)}{E} + \frac{(\sigma x-\sigma y)}{2}\frac{(\bar{b})}{E} cos2\theta + \tau xy\frac{(\bar{b})}{E} sin2\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where $\sigma x + \sigma y$ are the in plane Cartesian stresses in x and y direction and τxy represent the shear component and θ is the angle between the strain gauge axis and the x-direction, while are calibration constant

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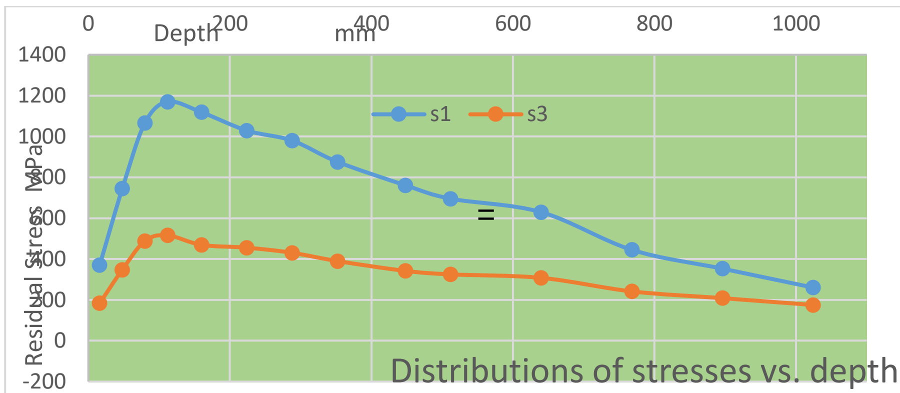
5 Results and Discussions

The residual stress profile for this specimen in the direction perpendicular to the scanning direction is tensile of magnitude 279MPa at the near surface the corresponding stress along the scanning direction is also tensile of 101MPa. Both stresses rises to their peak sharply within the first phase of measurement. Both reach peak at a depth of 160 µm from surface. The magnitude of the transverse stresses at the peak 1340MPa exceeds the yield strength of the material. However, there are similarities in terms of distribution trend which suggest uniformity of stress distribution. The longitudinal stress settles at nearly constant value for the last six measurement points exhibiting stability of stress. This point of measurement is approximately 10.25mm from the top surface of the specimen.



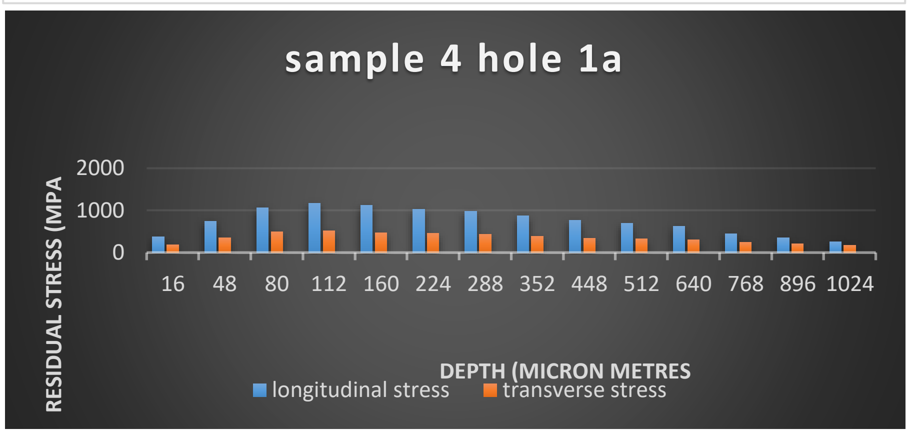


Figure 10: stress distribution vs depth

The transverse and longitudinal stress at near surface of 16µm were found to be 370 and 183 MPa, respectively, both shoot to peak tensile stress values of 1170 MPa and 516 MPa at just a point 112µm of depth. From there, both decline linearly to nearly just little above and below 200MPa at the total depth of the hole, approximately just above 1400µm. Longitudinal stress along the scanning direction exhibits a similarity of stress level of around 200MPa at both start and end points. This measurement is taken from a point just less 10 mm from the base plate, therefore exhibiting lower residual stresses. This goes along with the opinion of Yadroitsava et al (2014) who claimed that residual stresses augment with building height of the specimen.

6 Conclusions

In conclusion, the study of residual stress characterization in additively manufactured titanium alloys represents a crucial aspect of advancing the field of additive manufacturing. This research has shown that the complex and intricate nature of 3D printing processes can result in significant residual stresses within the final product. Understanding and characterizing these residual stresses is essential for ensuring the structural integrity, performance, and safety of additively manufactured components.

Through advanced analytical technique, of incremental hole drilling and finite element analysis, researchers have made significant strides in identifying, quantifying, and mitigating residual stresses in titanium alloy parts. This knowledge has practical implications for various industries, including aerospace, automotive, and medical, where titanium alloys are increasingly used due to their exceptional strength-to-weight ratio and biocompatibility.

As additive manufacturing continues to gain prominence as a manufacturing method, the insights gained from residual stress characterization will play a pivotal role in optimizing the process, reducing defects, and enhancing the overall quality of additively manufactured titanium alloy components. Additionally, ongoing research in this area will likely lead to the development of innovative solutions and techniques that further improve the reliability and performance of 3D-printed titanium parts.

In summary, the characterization of residual stress in additively manufactured titanium alloys is a vital study area with far-reaching implications. As technology and materials advance, a deeper understanding of residual stresses will enable us to unlock the full potential of additive manufacturing while ensuring the highest levels of quality and safety in the products we create.

References

Amanda, W., Wayne, K., Gallegos, G. & Mukul, K., 2014. Lawrence Livermore National Laboratory, Livermore, CA: Lawrence Livermore National Security, LLC.

ASTM E837-08, 2008. Standard Test Method for Determining Residual Stresses by the Hole Drilling Strain Gage method, PA: ASTM International Conshohocken,.

ASTM International, 2012. Book of Standard volume 10.04. West Conshohocken, PA: ASTM International.

Bikas, H., Stavropoulos, P. & Chryssolouris, G., 2015. Additive manufacturing methods and modelling approaches: a critical review. International Journal of Advance Manufacturing Technology, Issue 0268-3768, pp. 1-17.

Bo, Q., Yu-sheng, S., Qing-song, W. & Hai-bo, W., 2012. The helix scan strategy applied to the Selective Laser Melting. The International Journal of Advanced Manufacturing Technology, 63(5-8), pp. 631-640.

Castoro, M., 2013. Impact of laser power and build orientation on thr mechanical properties of selectively laser sintered parts. Proceedings of the National Conference on Undergraduate Research (NCUR) University of Wisconsin , 11-13 April.

Cozmei, C. & Caloian, F., 2012. Additive Manufacturing Flickering at the Beginning of Existence. Procedia Economics and Finance, pp. 457-462.

Donachie, M. J., 2000. Titanium: A Technical Guide. 2nd ed. Materials Park, Ohio: ASM international .

Facchini, L., Magalini, E., Robotti, P. & Molinari, A., 2009. Microstructure and Mechanical Properties of Ti-6Al-4V produced by selective laser sintering of pre-alloyed powders. Rapid Prototyping Journal , 15(3), pp. 171-178.

Gebhardt, A., 2012. Understanding Additive Manufacturing. Munich: Carl Henser Verlag GmbH and Co.

Gibson, I., Rosen, D. & Stucker, B., 2010. Additive Manufacturing Technologies 3D Printing, Rapid Prototyping and Direct Digital Manufacturing. 2nd ed. New York: Springer Science + Bussiness Media.

Gohardani, A. S., Doulgeris, G. & Singh, R., 2011. Challenges of future aircraft propulsion: A review of distributed propulsion technology and its potential application for the all-electric commercial aircraft. Progress in Aerospace Science, 47(5), pp. 369-391.

Grant, P. V., Lord, J. D. & Whitehead, P. S., 2006. The measurement of residual stress by incremental hole drilling techniques. NPL Measurement good practice guide No. 53, 53(2).

Harris, I. D., 2011. Development and Implementation of Metals Additive Manufacturing. New Orleans, DOT International.

Knowles, C., Becker, T. & Tait, R., 2012. Residual stress measurements and structural integrity implications for selective laser melted TI-6al-4v#. South African Journal of Industrial Engineering, 23(3), pp. 119-129.

Kruth, J.-P.et al., 2010. Part and material properties in selective laser melting of metals. Shanghai-China, Proceedings of the 16th International Symposium on Electromachining.

Mellor, S., Zhang, D. & Hao, L., 2014. Additive Manufacturing: A framework for implementation. Intrenational journal of production economics, pp. 194-201.

Mercelis, P. & Kruth, J., 2006. Residual Stresses in Selective Laser Sintering and Selective Laser Melting. Rapid prototyping journal, 12(5), pp. 254-265.

Nicholas, H., Huijun, L., Dominic, C. & Paradowsk, A., 2014. Measurement of Residual Stresses in Titanium Aerospace Component formed via Additive Manufacturing. Material Science Forum, 777(124), pp. 124-129.

Qiu, C., Nicholas, J. A. & Moataz, M. A., 2013. Microstructure and Tensile Properties of Selectively Laser Melted and of HIPed laser melted Ti-6Al-4V. Materials Science and Engineering: A, Volume 578, pp. 230-239.

Rossini, N., Dassisti, M., Benyounis, K. & Olabi, A., 2012. Methods of measuring residual stresses in components. Materials & Design, Volume 35, pp. 572-588.

Schajer, G. S., 2010. Hole-Drilling Residual Stress Measurements at 75: Origins, Advances, Opportunities. Experimental Mechanics, 50(2), pp. 245- 253.
Schajer, G. S. & Clayton, R. O., 2013. Practical Residual Stress Measurement Methods. Somerset, NJ, USA: John Wiley & Sons.
Silveira, E., Atxaga, G. & Irisarri, A. M., 2009. Influence of the level of damage on the high-temperature fatigue life of an aircraft turbine disc. Engineering Failure Analysis, 16(2), pp. 578-584.
Simonelli, M., Tse, Y. & Tuck, C., 2014. Effect of build orientation on the mechanical properties and fracture modes of SLM Ti-6Al-4V. Material Science and Engineering: A, Volume 616, pp. 1-11.
Thijs, L. et al., 2010. A study of the microstructural evolution of selective laser melting of Ti-6Al-4V. Acta Materialia, Volume 58, pp. 3303-3312.
Valentini, E. et al., 2011. Procedure to Perform a Validated Incremental Hole Drilling Measurement: Application to Shot Peening Residual Stresses. STRAIN, Volume e618, p. e605.
Whithers, P. J. & Bhadeshia, K. D. H., 2001. Residual Stress, Part 1: Measurement Techniques. Material Science and Technology, April, 17(4), pp. 355-365.