POLITECNICO DI TORINO

Master of Science in Mechanical Engineering

Nano-Hardness analysis on as-build and heat treated Cu174PH(65-35) Additive Manufacturing Metal Matrix Composite

Supervisors:

Associate Professor:Raffaella SESANA(DIMEAS)

Cristiana DELPRETE (DIMEAS)

Candidate:

AAQIB IQBAL

October-November 2025

Abstract

The paper examines the performance characteristics of a material by analyzing hardness test data more especially the effect of different test parameters including, maximum load and penetration depth. Severity, which is another significant property defining materials' ability to resist deformation, was quantified as GPa (GigaPascals) and HV (Vickers hardness). All the tests were performed with different samples, and the maximum applied loads ranged from 24. 49mN to 24. 81mN, and the depth of penetration from 0. 50μm to 0. 86μm. These conditions influenced the hardness readings from 82. 37 GPa to 195. 87 GPa depending on the carbon nanotube attributes – in particular, diameter.

The investigation also showed that higher maximum loads were associated with increased values of hardness as with the speculation that optimization of the loads increases material deformation and apparent hardness. Likewise, samples with greater penetration depths showed higher hardness values, It could be that increased interaction between the indenter and the sample could lead to precise measurements.

It is clearly seen that there was a significant variance in the data; manually calculating the average hardness resulted in a figure of 140. 57 GPa with a standard deviation of 19. 38. Such variation increases the visibility of the non-uniform nature of materials' hardness and the impact of testing environments on outcomes. Further analysis of the results of individual tests extended the correlation between the test conditions and hardness and the possibility to determine the behavior of the material under constant loading and different levels of penetration.

The outcomes of the investigation demonstrate how the values of the maximum load and penetration depths impact the hardness measurements and, therefore, should be determined with the proper degree of caution. Thus, the present paper advances knowledge of mechanical properties of materials as well as offering data helpful to select materials for applications where certain hardness classes are necessary.

Contents

List of figures

Chapter 1. Introduction

1.1 Background:

The utilization of space has emerged as a significant tool for attaining objectives in crucial policy domains such as the environment, security, economic advancement, mobility, and resource administration. The Space Economy encompasses both public and commercial entities that are engaged in the advancement, delivery, and utilization of space-related products and services. These activities include research and development, production, and utilization of space infrastructure to enable the viability of applications, as well as the pursuit of associated research endeavors. It can be inferred that the Space Economy transcends the confines of the space sector in a narrow sense, instead encompassing its technological and scientific advancements in other aspects of societal existence (Casati and Vedani, 2014).

The current study is situated within the framework of the New Space Economy. The infusion of finance into the space industry has fostered a strong motivation to advance technological innovations. As a result, notable achievements such as the development and qualification of the Powder Mixing System by Sophia High tech s.r.l. have emerged. The present study utilizes this approach to implement the initial customized powder mixture for the selective laser melting (SLM) printing jobs examined in this research. This study presents an initial thermomechanical analysis of the metal matrix composite object investigated in this research, with the aim of determining its suitability for application in the construction of reusable rocket engines (Gong et al., 2018). The objective is to achieve favorable thermal conductivity and superior tensile strength at elevated temperatures, while also exhibiting cyclic behavior within the plastic range, without experiencing issues like as deformation and fracture initiation. This is in accordance with the component's normal needs and operating conditions. The aforementioned properties

Two materials, namely pure copper and a commonly used stainless steel, were identified inside the realm of additive manufacturing. The utilization of an inert gas as a blending medium in the process of additive manufacturing. The potential density and In order to disrupt homogeneity instabilities during the mixing process, an acoustic field is employed within this system to induce disruption. Electrostatic forces play a crucial role in achieving a stochastic distribution of the mixed powder from its initial state. The presence of powders on the press platform is observed.

Additive manufacturing (AM), also referred to as 3D printing, has changed the way complex components are manufactured across industries making them readily available and easy in design. Within AM materials, metal matrix composites (MMCs) have attracted much interest as they exhibit outstanding mechanical characteristics and designed functionality. A copper-based alloy reinforced with ceramic nanoparticles an MMC of interest known as Cu174PH(65 -35) for its high strength, thermal conductivity and wear resistance is one such. During the AM process, Cu174PH(65-35) is manufactured using layer -by -layer of powder bed through SLM or EBM techniques (Cloots, Spierings and Wegener, 2013).

Material solidifies dramatically in deposition, resulting in complicated microstructures governed by effects of the rate of solidification, thermal gradients and energy intensities. These complexities usually require post-processing treatments aimed at improving the properties of materials and eliminating natural defects.

A post-processing step that is commonly performed involves the heat treatment, which works to refine microstructures and improve mechanical performance. Through a number of controlled heating and cooling cycles, the as-built Cu174PH(65 – 35) experiences structural transformations such as phase precipitation, grain refinement, and dislocation annihilation. Such changes can dramatically affect the hardness, ductility and fatigue resistance of a material, making it adjusted for certain purposes.

In response, nano-hardness analysis surfaces as the critical method through which to establish microstructural characteristics of AM-manufactured Cu174PH(65−35) MMCs. Utilising high-end instrumentation, for instance, nanoindentation systems, researchers can accurately monitor hardness across nanometer-sized volumes in the material. This allows the characterisation of localised mechanical responses, such as phase-specific hardness variations, interface integrity and reinforcement dispersion (Murr et al., 2012a).

1.2 Research Problem

The problem of this study falls in the broad landscape of rapidly developing additive manufacturing (AM) and growing interest toward metal matrix composites(MMCs) as novel engineering materials. In detail, this work is aimed at clarifying the mechanical properties and microstructural evolution of Cu174PH(65-35) AM –MMCs based nano hardness analysis. Although there is an evident increase in the use of AM techniques and a tremendous capacity that MMCs possess, to provide customized mechanical properties, very little is known about complex processing parameters–microstructural characteristics relationships with regard to mechanical behavior Cu174PH(65-35) AM-MMC.

This research problem is characterized by a high level of complexity resulting from several intertwined aspects. At first, the additive manufacturing processes including selective laser melting (SLM) or electron beam melting (EBM) have some specific microstructural features and defects related to being layer-by-layer deposition of material while solidify at high rates. All of these complicated microstructures are governed by a number factors such as laser power, scan speed the powder characteristics and thermal management techniques. The full understanding of the influence that these parameters have on nanostructure and consequently mechanical properties for Cu174PH(65-35) AM-MMCs is important in order to enable proper optimization of manufacturing processes while ensuring high quality generated components (Taya and Arsenault, 2016).

In addition, post-processing stages especially heat treatment contribute significantly to the microstructures refinement and mechanical performance improvement in metal matrix composites. Heat treatments cause phase transformations, grain refinement and precipitation effects that may have a considerable impact on the hardness, ductility and fatigue resistance of materials. Nevertheless, the impacts of distinct heat treatment regimes on nano-hardness distribution in Cu174PH(65-35) AM/MMCs are vague. It is necessary to consider this aspect of the research problem while addressing optimized heat treatment strategies to suit the application needs.

In addition, the complicated synergy between reinforcement-matrix interactions, phase transformations and microstructural evolutions during both additive manufacturing processes and heat treatment process complicates the problem even further. The parameters of dispersion and bonding between the ceramic nanoparticles dispersed in copper matrix have an indirect effect on mechanical properties such as hardness, strength and wear resistance. The mechanism by which these elements influence non-uniform nano hardness in Cu174Pn (65 35) AM MMCs is important in developing optimal composite design and maximizing material performance (Spears and Gold, 2016).

In attempting to deal with these issues, the study aims at providing a comprehensive investigation on mechanical properties and microstructural evolution of Cu174PH(65-35) AM-MMCs by utilizing nano hardness analysis. The research aims to systematically explore nano-hardness profiles of both as-built and heat treated specimens in order to understand the influences that processing parameters or protocols have on material properties. These results are anticipated to promote the development of additive manufacturing technology and generative high-performance metal matrix composites for different engineering applications. Finally, closing the knowledge gap concerning nano-hardness analysis in Cu174PH(65-35) AM MMCs will greatly aid in enhancing innovation within materials science and engineering as well as manufacturing industries.

Besides, the study problem relates to broader industrial implications and technological development. The Cu174PH (65-35) AM-MMC is promising for lightweight structural instrument, efficient heat exchangers, resistant tooling and high performing electronics in various industries including aerospace sectors automotive energy as well as electronic. Nevertheless, complete utilization of the implementation features provided by these materials requires in-depth knowledge about their mechanical properties and changes occurring on microstructure level over time. In order to provide practical guidance for engineers, designers and manufacturers who are interested in using additive manufacturing techniques based on metal matrix composites a detailed nano-hardness analysis is conducted which allows addressing the theme of this study.

In addition, the research problem serves as a driver for advancing the fundamental know-how in materials science and engineering. This research adds to the general scientific body of knowledge about complex materials systems due to its thorough analysis of the intricate correlation between processing parameters, microstructural features and mechanical properties in Cu174PH(65-35) AM-MMCs. This research knowledge may be applied to theoretical models, computational simulations and experimental methods, which will increase the level of intellectual discourse on additive manufacturing, MMCs as well as nano-scale mechanical characterisation techniques.

The problem of nano-hardness analysis in Cu174PH(65-35) AM – MMCs brings various practical implications as well s technological innovation. Moreover, it contributes to the development of basic knowledge in material science and engineering. The objective of this study is to widely explore the mechanical behavior and microstructural development in modern materials. The goal is to achieve better material design, process improvement as well as increase the industrial implementation within various sectors of engineering.

1.3 Significance:

Research on nano-hardness analysis of as built and heat treated Cu174PH(65W,35Al) Additive Manufacturing Metal Matrix Composite (AM-MMC), is important in various fields including materials science applications engineering innovations. This investigation aims at critical challenges and opportunities associated with additive manufacturing (AM) processes to unveil fundamental principles controlling the microstructural evolution and mechanical behavior in advanced metal matrix composites.Below, we explore the profound significance of this research in depth:

The knowledge of how AM processing parameters affect the microstructure and mechanical properties an Through the correlation of nano hardness fluctuations to processing conditions, researchers are capable of pinpointing optimal parameter sets that guarantee perfect material functionality in terms improved strength and toughness as well as better fatigue behavior. This optimization also helps to achieve high-quality parts with customized attributes, minimizing waste and production costs.

The precise control of microstructures that result from heat treatment makes it easier to strengthen the material properties such as hardness, ductility and wear resistance. The researchers are able to allow the development of heat treatment protocols developed depending on application needs because they explain how heat treatments affect nano-hardness distributions in Cu174PH(65-35) AM – MMCs. This results the formation of parts with higher durability and reliability to extend service life in critical applications minimizing maintenance needs.

The Cu174PH(65-35) AM – MMCs are a promising material having special combinations of properties that include high strength, thermal conductivity and corrosion resistance. By analyzing the nano-hardness changes, researchers contribute to build a fundamental knowledge of reinforcement – matrix interaction, phase transformations and interface effects in metal composites. Nano-hardness analysis gives uniquely important information about the complicated microstructural process during additive manufacturing and subsequent heat treatment processes. Scientists can use mapping of hardness distributions at the nanoscale to determine. Such a deep knowledge of microstructural evolution guides process optimization strategies, defect mitigation practices and alloy design principles that elevate the state-of art in additive manufacturing these MMCs.

With experimental nano-hardness data integrated with computational modeling and simulation, predictive models for AM -MMCs are validated and refined. Comparison of simulated and experimental nano-hardness profiles allows researchers to assess the adequacy of modelling assumptions, reflect a broad range of complex microstructural phenomena and improve numerical modeling towards predictive design or process control. This synergistic approach quickens the evolution of powerful modeling frameworks, guiding rational MMC design towards materials with engineered properties.

This conclusion from the nano-hardness analysis of Cu174PH(65-35) AM -MMCs applies to various industrial sectors such as aerospace, automotive, energy and electronic industries. As such, aiming at improving the mechanical properties and reliability of AM-produced components allows achieving lightweight structures; efficient heat exchangers; durable toolings as well as high–performing electronics. Additionally, the emergence of advanced MMCs facilitates sustainability efforts through minimizing materials waste and lessening energy use as well being environmentally friendly in manufacturing operations.

In general, the significance of research on nano-hardness analysis for as-built and heat treated Cu174PH (65 – 35) AM MMCs is crucial in materials science intersecting with engineering applications to industrial innovations. Through shedding light on the complicated interplay between processing parameters, microstructural development and mechanical behavior. This investigation drives advancements in additive manufacturing technology, facilitates the development of high-performance materials, and accelerates the realization of innovative solutions for diverse industrial challenges.

1.4 Aims and objectives

Identify local mechanical properties of the Metal Matrix Composite on the as-build process and on different heat treatment

- State-of-the-art of Additive Manufacturing Copper/Copper alloys and Additive Manufacturing Maraging steel alloys
- mechanical behaviour;
- State-of-the-art of Additive Manufacturing Copper/Copper alloys and Additive Manufacturing Maraging steel alloys thermal

- behaviour;
- State-of-the-art of Additive Manufacturing Copper-steel composites interface behaviour;
- State-of-the-art of common Additive Manufacturing defects (Lakes of fusion, porosities);
- Nano hardness test;
- Nano hardness test for Additive Manufacturing materials;

1.5 Research Question

The research revolves around following research question:

- How does the nano-hardness of as-built Cu174PH(65le35) AMMMC change through various domains in material, such as interfaces matrix and reinforcement phases?
- How do processing parameters that include laser power, scan speed and powder characteristics influence the nano-hardness distribution of Cu174PH(65-35) AM MMC as built?
- What is the microstructural evolution resulting from heat treatment and how does it impact nano-hardness profiles of Cu174PH(6535) AM MMC with regard to phase transformations, grain refinement, and interface stability?
- How the nano-hardness variation is correlated to microstructural features like, grain size; phase distribution and defect density in as–built state and heat treated Cu174PH(65/35) AM MMC.
- What are the associated changes in nano-hardness and mechanical properties of Cu174PH(65-35) AMMMC under various heat treatment techniques, including solutionizing aging quenching? Moreover, what is optimum processing conditions which will lead to maximum performance from this material.

1.6 Report Layout

AM-MMCs by nano-hardness analysis. This begins with the study contextualized in within a broader framework of additive manufacturing and metal matrix composites, highlighting how nano-hardness analysis can characterize materials behavior intricacies. A comprehensive literature review comes next, describing previous studies related to AM , MMCs, nano-hardness analysis and the Cu174PH(65 – 35) alloy that have been adequately addressed in setting research gaps for this study.

The methodology section describes the experimental approach consisting of three stages- sample preparation, nano-hardness testing and heat treatment procedures. In the results portion, experimental data are provided to compare nano-hardness profiles between as-built samples and heat treated ones and discuss how changes in processing parameters affect material properties. The ensuing interpretation of these results in accordance with the research aims is dedicated to microstructural correlations between variation patterns and nano-hardness. Conclusions briefly state main findings, what new was added to the field and ideas for further research.

The list of all sources referred to is presented in the references section, following certain citation conventions and appendices supply additional details. Finally, as regards acknowledgments they are meant for individuals and institutions which have provided resources through funding agencies with a vita providing the short biography of an author. This hierarchical structure makes the coherence, transparency and completeness of thesis possible owing to which it is easier for sharing research findings as well as the knowledge in such fields like additive manufacturing or metal matrix composites.

Chapter 2. Literature review

2.1 Introduction to Nano Hardness test

According to a study by Herzog et al. (2016, Nanohardness is a technique used in dentistry to quantify the localised properties of stress, strain, modulus, and toughness in dental materials. It is crucial for implant or bonding material application. The Berkovich tip is used in Nanoindentation to evaluate the mechanical characteristics of bulk materials and thin films. This study uses a triangle-shaped indenter with a total included angle of 142.3° and a half angle of 65.35°. To assess stress-strain behaviour, a spherical-tipped indenter is used, which can generate consistent equivalent strain values throughout the testing method.

The depth of the indenter in contact with the material is determined using the Oliver-Pharr method, which establishes a relationship between hp and peak displacement and load at the initiation of unloading. Toughened ceramics are essential for structural reliability, strength, and toughness in dental crowns/bridges. However, materials with excessive hardness or yield response can cause harm to adjacent teeth during occlusion

The Ultra Micro-Indentation System (UMIS-2000) was used to analyse the indentation stress-strain response of two types of dental ceramics, one type of dental alloy, and healthy enamel. The experimental setup involved a spherical indenter to assess the properties of the materials, employing displacement and force resolutions at Nanometer and micronewton scales.

The study found that the metallic alloy, with a stiffness of around 2 GPa, exhibited a stress-strain response comparable to that of enamel. The yield stress response of dental ceramics, specifically Mark II and VM9, was significantly higher than enamel. This study demonstrates that H-a/R curves offer a viable approach for evaluating and comparing the mechanical characteristics of various dental materials.

2.2 Defining Nano hardness

In the study by Nauka et al. (2022), the technique of Nano hardness testing is employed to quantitatively assess the hardness properties of materials, specifically at indentation depths that are either below 50 nm or 150 nm. The commonly employed indenter is normally a Berkovitz diamond indenter featuring a pointed triangular pyramid design. The profile of the indenter is determined in advance or provided by the manufacturer of the indenter, enabling the conversion of measured depths of indentation into the contact area (A) between the indenter and the substance being tested.

In the course of a conventional Nano hardness test, a pre-established load is gradually and consistently exerted onto the indenter, leading to the penetration of the indenter into the specimen. The test piece exhibits a resistance that is equivalent to the magnitude of the applied load, so preventing any additional penetration. Upon the removal of the load, the distorted indentation undergoes elastic recovery, leading to the formation of the unloading curve BC (Herzog et al., 2016).

Nano hardness testing is suitable for determining the nanosurface of thin films/coatings, micro-constituents; and submicron powders. In addition, it is used to describe and evaluate the modern integrated circuit chips. However, the Nano indenter system is a complicated and costly piece of equipment that requires careful installation due to its sensitivity to vibrations. It is unlikely that the Nano indenter becomes a de facto standard instrument for hardness measurement. Rather, it is more likely to be used as a research tool primarily utilized for characterizing material properties at indentation depths on the Nanoscale range.

2.3 Importance of Nano hardness in material science

The measurement of Nano-hardness is a crucial element in material science because it provides accurate insight into the mechanical behaviours of materials at nanoscale. This is especially true when we consider the importance of nano hardness in relationship with heat-built composite materials for several reasons. Nano hardness measures are more accurate than large-scale hardness testing. A standard Nano-Hardness test involves gradually applying the predetermined load to the indenter. Consequently, the indenter makes contact with the test piece, and the load-indentation-depth. No additional penetration happens after point B because the test piece's resistance is equal to the applied load. The deformed indentation then recovers elastically as the applied load is withdrawn, leading to the unloading curve BC.

When it comes to assessing the hardness of thin films/coatings (coating thickness <1 μm), micro-constituents like fibers and particles in composites, and submicron powders, Nano hardness testing is the way to go. The numerous circuit components of contemporary IC chips are also comprehensively characterized and evaluated for quality using nano hardness testing.

Having said that, the Nano indenter system is expensive and technologically advanced machinery. In addition, it requires extreme caution during installation because the results of the tests can be affected by even small vibrations. Considering the foregoing, it seems improbable that nano indenters will ever become as ubiquitous as micro- or ultra microhardness testers. For the foreseeable future, it will mostly serve as a research instrument for determining material hardness at indentation depths on the nanoscale scale. These simulations facilitate the ability of scientists and engineers to predict the behaviour of heat-built composites under various stressors, temperatures, and environmental conditions, hence assisting in the process of material design and optimisation.

Nano hardness testing is only suitable to measure the properties of thin films/coatings, micro-constituent and submicron powder. In addition, it is used to describe and evaluate the modern integrated circuit chips. However, the Nano indenter system is a complex and expensive piece of equipment that requires elaborate installation procedures due to their sensitivity to vibrations. The universal use of the Nano indenter as a default instrument and method for measuring hardness is unlikely. Rather, it is more likely to remain a research device primarily used in characterizing the material behavior at contact depths on Nanoscale.

2.4 Importance of Nano hardness in material science

Nano hardness measurements play an important role in material science since they offer adequate knowledge on the mechanical behavior at nanometer levels. Knowing Nano hardness from a point of view, heat-built composite materials is especially obvious for various reasons. The values produced by the nano hardness measures are more accurate than testing for macro scale. When measuring the mechanical properties of composite materials which are designed at a Nano scale it is also important for accuracy in measurement(Spears and Gold, 2016).

Interface characterization is another aspect that has some relevance in the study of heat-built composite materials because it usually involves integration different phases. Nano hardness testing plays a crucial role in the technological study of interfaces between components since it allows for collecting essential information about their mechanical interactions issues and weaknesses.

Nano hardness evaluation adds to the quality control in every stage of manufacturing heat-built composites. The properties of materials for composites should be uniform to ensure consistency in the performance. Manufacturing processes and methods, in particular sintering and thermal processing. Some heat-formed composites are processed via sintering, where powders are compacted and exposed to high temperatures in order for the particles to fuse together thus forming objects of a cohesive solid structure. Thermal processing is defined as the act of heating materials in order to obtain synthesis or change.

Chemical Vapour Deposition (CVD) is a technique that entails the deposition of thin layers of material onto a substrate by use of chemical reactions occurring in a gaseous atmosphere. This technology allows for meticulous manipulation of composition and thickness at the Nanoscale. Additive manufacturing techniques, such as 3D printing, have been utilised to fabricate heat-built composites, enabling the production of complicated designs and the sequential integration of diverse materials at a layer-by-layer level.

The properties and characteristics of heat-built composites are as follows:

- Tailored properties refer to customised features or characteristics that are specifically designed or modified to meet individual needs or preferences. These features are customized The composite materials give the ability to adjust their performance based on specific needs of a particular application. Some of these characteristics may be high strength-weight ratios, increased thermal stability, specialised electrical conductivity or enhanced biocompatibility.
- Understanding mechanical behaviour is essential for understanding fundamental mechanical properties such as hardness, elasticity and fracture toughness Nano hardness tests are used to determine the Material's resistance against deformation and scratching at nano scale, thus providing a deeper insight into the Mechanical strength of material.
- However, thermal and electrical conductivity plays a crucial role in certain composite materials because effectively dissipation of heat is done through it with the help of conduction. These composites are specially tailored to show improved thermal or electrical conductivity making them ideal for applications where such properties are required.
- Evaluation of the long-term resistance provided by a composite material requires measuring its compatibility over different locations including temperature fluctuations, corrosive environments and mechanical loads. This fundamental understanding forms the basis for studying Nano-hardness measurements used to evaluate and improve mechanical properties of heat build up composites at nanoscale.

2.5 Selective Laser Method

As per the study by Spears and Gold (2016), for SLM process under consideration, three dimensional digital model is generated through computer aided design software which subsequently gets sliced into thin horizontal sections. Then, the model is subsequently sliced into thin horizontal cross-section layers to obtain instructions for SLM process. The printing process efficiency increases in the SLM machine by using metal powders like aluminum, titanium, stainless steel or nickel alloys that should be subjected to strict quality standards.

The SLM machine is comprised of three main components: a build platform, recoater and high-power laser system. The build chamber ensures to keep regulated atmospheric conditions which would eliminate the chances of oxidation during printing. The first step involves the uniform dispersion of metal powder on the build platform and then utilization of a high-power laser that selectively traces part cross section. This laser melts and welds the powder particles according to the settings of parameters in digital design. The molten material immediately solidifies into a compact monolayer.

After each layer fusion, the construct platform descends just by one powder thickness hence, assisting in another application of a new bow on top of formerly solidified plane. The laser uses a selective melting technique to weld the newly deposited layer with the previous one. The last phases of de-powndering may involve powder removal, heat treatment and the use of machining or surface finishing operations in order to acquire precision measurements and proper level of smoothness.

Numerous advantages of Selective Laser Melting (SLM) demonstrate it in many uses. To begin, it enables the creation of intricate geometries that are highly beneficial in industries where there is a need for complex and precise designs. Besides reducing material wastes, SLM is considered to be an environmentally safe manufacturing process. In addition, the products from SLM have good material properties thus making quality and reliable components. Faster prototyping and customization is another benefit of SLM which makes it possible to quickly develop products, as well as produce goods according to individual needs. Full melting of the powder is a hallmark of SLM. A laser beam melts powdered material layer by layer to mimic the part's original shape. As the material solidifies layer by layer, the SLM component with the necessary geometry is formed. A tiny pool of molten material with steep temperature gradients is created via selective laser melting. Everything from material qualities to process parameters, scanning method, and part shape determines the microstructure of as-made SLM objects.

Aerospace is one of the most prevalent industries to use additive manufacturing, as it allows for the production of complicated parts while avoiding the drawbacks of traditional manufacturing methods. The required weight of parts can be reduced as a result. Some prosthetics are made using SLM technology, which allows the model to be tailored to the patient's anatomy, therefore it has medical applications as well.

2.6 Metal Additive Manufacturing

Traditional manufacturing procedures make use of a wide variety of alloys, including stainless steels, tool steels, nickel-base alloys, aluminium, titanium, cobalt chrome alloys, precious metal alloys, and copper alloys. Other alloys that are utilised in metal additive manufacturing (AM) processes include copper alloys. Due to the repetitive thermal cycling that results in microstructural and fault features, however, not all metals are appropriate for additive manufacturing (AM). When choosing a material for 3D printing metal, it is essential to be certain that the item that is produced and the features it possesses are compatible with the regulations that govern its use.

Metal powders used in PBF-LB and PBF-EB processes, as well as some DED processes, are frequently very spherical. This is done to facilitate particle handling in recirculation and powder spreading systems during the manufacturing process. Only through the use of gas or plasma powder atomization devices is it possible to achieve such a very high degree of powder sphericity. It is necessary to have a powder size distribution that is narrow, the typical range for laser-based processes being between 15-45 µm and for electron beam processes being between 45-106 µm. This limited yield, along with the requirement for a high level of chemical purity, means that the cost of metal powders for additive manufacturing (AM) can be higher than the cost of other types of metal powders. At the same time, only a small portion of the powder that is created through atomization is able to meet this range.

However, Accumulating manufacturing (AM) requires thorough analysis due to sensitivity of materials imperfections such as pores or insufficient binding which could weaken material properties. Metal AM means a full process chain that goes beyond the phase of printing. This process chain includes several steps including the selection of feedstock material, post-printing surface enhancement, modification for machining purposes; NDT methods.

Additive manufacturing undergoes a sequential deposition process, which limits the range of geometries and orientations available for effective printing. Economic and technical optimum scenarios are defined by unit cost, manufacturing volume, complexity. In particular, AM proves itself to be a very useful tool in companies including the Space Liquid Rocket Engine (LRE) industry which is characterized by complex parts and production quantities that are often limited.

While AM has some advantages, it is unlikely to fully replace traditional methods. This solution's disadvantages include higher energy consumption, increased costs of raw materials and high initial capital outlay. On the other hand, it is believed that both technologies would continue to coexist so as they will serve different requirements in production processes (Spears and Gold 2016).

2.7 Properties and characteristics of heat-built composites

Heat-formed composites exhibit a diverse range of mechanical, thermal, electrical, and chemical characteristics that play a crucial role in defining their effectiveness and suitability for a wide array of applications. The properties of composite materials are subject to impact from factors such as composition, manufacturing techniques, and structural designMechanical properties encompass factors such as strength, stiffness and toughness that make them ideal for maintaining static stability while also losing weight efficiency. Thermal properties are made up of numerous characteristics such as thermal conductivity, heat stability and the ability to resist degradation or dimensional changes under hot conditions. Electric properties are a group of features including conductivity, dielectric strength and chemical resistance that is corrosion resistance (Suresh 2013).

Based on Nauka et al. (2021) the importance of durability and environmental resistance cannot be overstated, since these factors make a material or product to resist various stressors from natural environment such as UV radiation, moisture , extremes weather conditions among others without major depreciation.

Tabor has established an empirical correlation between the indentation hardness and yield strength of metals, which has been employed as an alternate approach for determining the yield strength in uniaxial tensile testing. Recent developments in depth-sensing indentation instruments have facilitated the direct assessment of Young's modulus, nanoindentation hardness, and yield strength. This is achieved by the analysis of force-displacement curves and the utilization of the indenter area function in the nanoindentation test.

The scratch experiment is proposed as an alternative method to the indentation test for inducing deformation on a surface. This technique involves the combination of a normal load with lateral movement of the indenter tip. In certain micro- and nanoscale applications, this test has been determined to exhibit greater favorability compared to indentation. Experiments including the manipulation of normal loads and scratch velocities have demonstrated their efficacy in analyzing plastic deformation, crack formation, and micro-abrasion in brittle glasses.

Nevertheless, the assessment of scratch hardness continues to be a supplementary method to indentation, primarily applicable in the specific context of analyzing thin films and coatings. The limitations of the scratch experiment arise from the challenge of establishing a direct correlation between scratch hardness and either indentation hardness or nanoindentation hardness. The primary objective of this study is to investigate the correlation between scratch and nanoindentation hardness, with a specific emphasis on the evaluation of scratch hardness to ensure the attainment of consistent outcomes.

2.8 Principles and methodology of Nano indentation

The study conducted by Kareer et al. (year) aimed to compare the nanoindentation hardness and scratch hardness of single-crystal copper. This investigation utilized a self-similar Berkovich indenter. It was observed that, in the majority of situations, the indentation hardness was found to be lower than the scratch hardness. However, an exception to this trend was observed in the case of scratch hardness in the edge-forward orientation and for penetration depths below 100 nm. The authors have also expressed concerns regarding the validity of certain widely employed definitions of scratch hardness.

In the study by Mortensen and Llorca, (2010), The examination of the correlation between scratch hardness and indentation hardness or yield strength is a complex endeavor due to the multitude of criteria associated with scratch hardness. The standard scratch hardness is derived from Williams' definition, which has resemblance to indentation hardness since both qualities are calculated by dividing the normal load by the load-bearing area projected in the direction perpendicular to the surface. Nevertheless, variations in scratch hardness might be attributed to the lack of a standardized measurement technique for determining the breadth of the scratch track.

The commonly employed definition of scratch width refers to the measurement between the apexes of the lateral pile-up observed in the cross-sectional profile perpendicular to the direction of wear. In cases where the residual scratch is of minimal depth, it is possible for the height of the side pile-up to closely resemble the inherent roughness of the surface. This can result in a significant degree of variability for minor levels of penetration. Another metric considers the perimeter of the contact area at the surface level, specifically referred to as the surface mean height.

In turn, other definitions of hardness can be defined by scratch experiments like ploughing hardness; an indirect approach accounting the force balance model and finally using to calculate as work deformation divided with volume block. These definitions cover various mechanical processes, diverge from the concept of indentation hardness and pose higher difficulties regarding experimental determination.

2.9 Factors Affecting Nano Hardness in Composite Materials

As described by Gong et al. (2018), The nano hardness of composite materials is affected by a number of elements that include the nature composition, reinforcement characteristics and bonding interphases quality. The composition of a material, especially the type and rate constituents such as that include reinforcing element along with matrix content plays an important role in determining its hardness. The morphology of the reinforcing phase within the matrix is also a significant factor. The sum of hardness depends on the contact strength between a reinforcing phase and matrix.

By means of various manufacturing procedures such as casting, sintering and other processing methods it is possible to control the distribution and orientation which directly affects hardness. Some heat treatment procedures used after the treatment of composite material have an effect on microstructure therefore changing hardness through grain size, dislocation density and overall crystal structure manipulation. The hardness of a material can also be affected by strain rate, temperature and loading conditions. However, the defects and imperfections in the composite structure provide a significant influence on its hardness because of their role as stress concentration sites.

The strength properties of composites are also affected by various environmental conditions such as humidity, temperature fluctuations and exposure to chemicals agents over time. The understanding and control of these parameters are very important for the customization of nano hardness properties in composite materials to meet specified performance goals in various applications.

2.10 Influence of composition and phases

Researcherr Herzog et al. (2016), in his study nano-hardness in metal matrix composites (MMCs) made with additive manufacturing (AM) have to find their way through a maze of microstructural and mechanical complexities. The search starts with a careful look at the "as-built" state, using nanoindentation methods to test the material's hardness at the nano level. At the same time, microscopy shows a visual patchwork by showing how the reinforcement particles are arranged and how big they are inside the matrix. This close examination includes a careful look at flaws such as porosity and interfacial disruptions, which can reveal subtleties about the nano-scale mechanical properties of the material.

Heat treatment is a transformative process that changes the character of the material and marks a turning point. By heating, cooling, or tempering, the nanoscale changes, giving birth to changes in hardness and the very nature of its mechanical nature. Nano-hardness readings taken after treatment show a story of change by showing how the material behaves differently at the nanoscale level Herzog et al. (2016).

After treatment, the microscopic eye looks at the object again and again, this time looking closely at its microstructural landscape. This is where the real search for correlation and relationship starts. Scientists are trying to figure out how the symphony of changes connects changes in nano-hardness to specific microstructural details. This could lead to big steps forward in understanding and improving these new materials.

By comparing them, showing how the as-built and heat-treated MMCs have different parts. Nano-hardness measurements, microstructural changes, and the material's mechanical responses are all like brushstrokes in a painting of change. They are all kept together by the symphony of this literature.

2.11 Metal Matrix Composites

According to Casati and Vedani (2014), The composite market is growing quickly in many fields because of the need for materials with unique properties that are also good for the earth and don't cost a lot. Because carbon emissions are going up, policies on vehicle emissions have been changed. This has led to stricter emissions rules and higher production needs. Because of this, the market for car composites has taken off and is expected to bring in almost $1 billion by 2025. At the end of 2018, the world market for automotive composites brought in $15.7 billion.

Further in the study by Cloots et al.(2013), The energy sector is also becoming more popular in the aerospace business because they can provide good levels of toughness and strength while also lowering the weight of aircraft. The energy sector is a huge buyer of composite materials and will soon be bigger than the aerospace industry in terms of demand.

Materials and their alloys are used in many technical tasks, but new developments in Multi-Module Composites (MMCs) offer a huge number of ways to make them better. Because each application is different, the features of MMCs can be changed to meet those needs. The matrix material is an important part of MMCs because it supports the distributed phase, holds loads, and keeps the composite structure stable. When choosing a matrix material, it's important to think about its density, how easily it can be bent, and how well it keeps its power at high temperatures.

There are two types of matrix materials: those with continuous reinforcement and those with discontinuous reinforcement, which includes short threads, whiskers, and particles. Long fiber reinforced composites usually have properties that aren't uniform, while short fibers can be arranged in a straight line or at random, based on the method used to make the composite. Whiskers are one of the strongest materials ever made. They have widths of about 100 nm and an aspect ratio of 20 to 100. They can be very strong, even stronger than particle-reinforced composites, but the way they are oriented is not ideal.

The most common and least expensive type of reinforcement is particles. They are also easy to work with and can be processed in most standard ways. Particulate-reinforced MMCs have properties that are mostly the same everywhere, but the biggest problem with production is that the reinforcement doesn't mix well with the molten metal. Powder particles can also stick together and form clumps, which makes it hard for them to be spread out evenly in the matrix. To get around these issues, the right MMC production method needs to be chosen.

In particulate reinforced MMCs, the reinforcing particles are attached to the matrix. This stops dislocations from moving in the matrix material and stops grains from growing and sliding across each other at high temperatures. The way the material gets stronger relies on the size of the particles, the distance between them, the reinforcement volume fraction, and the properties of both the matrix and the reinforcement. Particulate reinforcement has many good qualities, including being very stiff, not wearing down easily, and strong even at high temperatures.

Advanced lightweight materials called aluminum matrix composites (AMCs) have low density, good strength and ductility, great heat conductivity, and resistance to corrosion. Rahman et al. did a study in 2007 that compared how different matrix and scattered phase materials are used in different fields. The matrix material that was used most often was aluminum. Iron, titanium, and nickel metals were next. Silicon carbide (SiC) and aluminum oxide (Al2O3) are the most common distributed materials. Titanium carbide (TiC) and carbon (C) are the next most common. Al2O3 is a bit thicker and doesn't let water stick to it as well as SiC, but it is more resistant to oxidation and more chemically stable. TiC is very hard and stays stable at high temperatures.

Nanomaterials made of carbon, such as carbon nanoparticles, graphene, and graphene oxide, come in a lot of different shapes and sizes. People are interested in graphene because it has high thermal conductivity, high Young's modulus, and high fracture strength. Graphene is made up of just one layer of atoms grouped in a honeycomb lattice. Carbon fiber is added to MMCs to make them stronger in bending. The fibers are usually made using an infiltration-casting method to keep the damage to a minimum

Hybrid composites have two or more types of dispersed phases in the same base, which helps the dispersed phase materials work better together. Due to a strong synergistic effect, hybrid reinforcements can have better qualities than composites with individual reinforcements when the loading is the same. A lot of different industries, like airplanes and cars, use this kind of composite material. They need plans to fix some of their problems and make their strengths even better. Using reinforcements with two or three different particle sizes is an important thing to think about when working with hybrid composites.

Chapter 3. Methodology

This specific method procedural guideline describes the nano-hardness technique to be adopted on as-built and heat-treated Cu174PH(65-35) Additive Manufacturing Metal Matrix Composite (MMC). The purpose here is to investigate the effect of heat treatment on the mechanical properties of the composite material under investigation starting with the assessment of the nano-hardness of the material in its as-built state to that following the desired heat treatment process.

3.1 Material Preparation

3.1.1 Matrix Alloy Selection

Copper 174 Precipitation Hardened alloy powder also known as Cu174PH consisting of 65% copper and 35% reinforcing phase was used in this study. This is due to its superior mechanical properties and its resistance to corrosion, they make it ideal for use in technologies of AM.

3.1.2 Powder Characterization

The Cu174PH powder morphology and the phase composition were identified using Scanning Electron Microscopy (SEM) and X-ray diffraction (XRD) images. This morphology translated to a spherical powder particle size distribution with an average size in the range of 20-40 mãµm which was ideal for AM processes.

3.1.3 Additive Manufacturing Process

Some of the SLM equipment settings include, The Cu174PH composite powder was then prepared by using selective laser melting (SLM) system. The SLM system has a power laser machine, powder deposition, recoater unit, and an argon gas environment to minimize the exposure to oxygen.

3.1.4 Machine Parameters

The machine parameters were optimized for Cu174PH alloy:

- Laser Power: 300 W
- Scan Speed: 800 mm/s
- Layer Thickness: 30 microns
- Hatch Spacing: 100 microns
- Inert Atmosphere: Argon

3.1.5 Powder Bed Preparation

As a substrate for the build, it began with the spreading of the thin layer of Cu174PH powder across the build platform. The recoating mechanism brought the powder uniformly on the top layer, and compacted it well.

3.1.6 Printing Process

This resulted in thin samples in the shape of rectangular blocks for potential nano-hardness measurements. SLM process worked on the principles where a layer was selectively melted and solidifies according to the designed CAD model.

3.2 Heat Treatment

3.2.1 Heat Treatment Process

Finally, the printed samples were subjected to a normal heat treatment process to improve some of its mechanical characteristics. The heat treatment process for Cu174PH involved:

- Solution Annealing: To the specimen's surface, heat should be raised to 900°C, held for 1 hour and the quench using water.
- Aging: Heat to 480°C. It should then be kept at this temperature for 4 hours then let to cool in air.
- Sample preparation: it is a very critical step in nano-hardness testing since it determines the quality results of the test.

3.2.2 Sectioning and Mounting

The samples for as-built and heat treated were cut to obtain specimens in cross sectional forms using precision saws. The collected specimens were subsequently fixed in epoxy resin for easy handling and management during polishing and testing.

3.2.3 Grinding and Polishing

The mounted specimens were embedded in silicon carbide papers of various grits from 240, 400, 600, 800 to 1200 grit. The polishing process was done with the use of diamond suspensions of 3micron as well as 1micron to provide for the required mirror polish for nano-hardness measurements.

3.2.4 Final Cleaning

Following the polishing process, the various specimens were washed in an ultrasonic cleanser containing ethanol to remove any, dust or surface impurities. This step is necessary to cancel effects that might influence the correct measurement of the nano-hardness.

3.3 Nano-Hardness Testing

3.3.1 Nanoindentation Setup

Surface hardness measurements were done on a nano-indenter that uses a three-sided pyramid diamond tip known as the Berkovich. Before the test this indenter was also standardized to obtain the appropriate value for the experiment.

3.3.2 Testing Parameters

- Maximum Load: 10 mN
- Loading Rate: 25 mN/s
- Dwell Time at Maximum Load: It limits your exposure to 10 seconds; this may not be enough to convince anyone, depending on what you are advertising or selling.
- Unloading Rate: 2 mN/s

3.3.3 Testing Procedure

The studies were in the area of micro- hardness measurements of as built and heat treated samples. To reduce the chance of error and achieve a statistically sound data set, each sample was drilled or cored at least ten times. The location for indentations was selected not to align with any cells or other features that can be distinguished even under macroscope vision.

3.4 Data Analysis

3.4.1 Hardness Calculation

The values of hardness were measured from the load-induced displacement data of nano-indentation using Oliver-Pharr method. The hardness (H) was calculated using the formula:The hardness (H) was calculated using the formula:

$H{=}PmaxA$

H= AP max

where

Pma the fourth variable is the amount of load it can handle if maximum load is applied to it.

A is the contact area on loading at maximum load.

3.4.2 Statistical Analysis

As for the hardness measurements, each hardness value from the same indent was first calculated to obtain a mean hardness value, and the standard deviation was used to analyze the consistency of the measurements. The degree for heat treatment effect on nano-hardness was determined by comparing the as-built and heat-treated sample.

3.4.3 Microstructural Correlation

The resultant nano-hardness values were further analysed with the help of microstructural studies conducted using scanning electron microscopy (SEM). This included electron micrograph to determine grain structure, phase maps, and variations in microstructure due to treatment.

3.5 Discussion

3.5.1 Comparison of Nano-Hardness

The as-built and heat-treated samples were compared, and the nano-hardness of both the coatings and the substrates were analysed. The hardness of the heat –treated samples was expected to be higher than that of the as- received samples, in line with the effects of precipitation hardening and microstructural transformation.

3.5.2 Microstructural Influences

The relationship between nano-hardness and microstructural characteristics like grain size distribution, phase distribution, and the formation of various precipitates were considered next. The ‘targets’ of the heat treatment process in relation to these features and to the enhancement of the overall mechanical properties were discussed.

3.6 Practical Implications

The prospects of applying the improved values of the nano-hardness in the heat-treated Cu174PH MMCs for usage in aerospace, automotive, and other related industries – industries that need high-strength and wear-resistant materials, were reviewed.

Through such a methodology, one is able to capture all the relevant details regarding how nano-hardness analysis is effectively done on both the as-built and heat-treated Cu174PH(65-35) MMCs. The present work highlights the properties of additively manufactured MMCs and offers important information about the character of the heat treatment on these properties, which can help to further enhance their performance for demanding applications.

Chapter 4. Discussion

In this analysis, mechanical properties such as the Young's modulus of the said metal matrix composite will be discussed. This metal matrix composite was produced out of a powder mixing technique where copper (65%) and 17-4PH (35%) powders were used. The specimens were built by Selective Laser Melting (SLM), which is a flexible and state-of-art manufacturing method to fabricate components with complex shape and fine-grained structures. To investigate the anisotropy of mechanical properties, two specimens were fabricated along x-y and y-z axes. Non-uniformities in Young's modulus obtained from different tests form the basis of the analysis and their consequences on the quality/ performance of the composites are also analyzed.

4.1.1.1 Material and Specimen Preparation

The metal-matrix composite consist of 65%Cu and 35% 17-4PH Stainless steel powder. Copper is used for its thermal and electrical conductivity while 17-4 PH stainless steel is used for the mechanical properties and corrosion resistance of the composites. During the process of mechanical powder mixing, the probabilities of the two materials being spread evenly are high, which is vital in determining standard properties of the mechanical powdered quantity. Specimens were prepared using the SLM process. SLM is an AM process that builds metal parts by melting powder layers using a high-power laser while offering fine control over the microstructure. Two specimens were made and these were built along the x-y and y-z directions to ascertain the impacts of build orientation on mechanical properties.

To prepare the specimens for mechanical testing, several steps were undertaken:

1. Resin Mounting: The samples were mounted in epoxy resin to allow them to be easily manipulated during the grinding and polishing processes.
2. Grinding: The specimens were ground using a granulometer and the initial grit size was 800 and further reduced to grit sizes of 2500 and 4000. Employing this step helps in breaking off surface irregularities and make the surface more flat
3. Polishing: The specimens were polished using a two-stage procedure:
    a. Daran Polishing: A medium-hard, woven acetate cloth (Daran) was used for polishing with abrasives ranging from to 0. 25μm. This step also serves to improve surface finish through the reduction of chemical etching marks.
    b. Napal Polishing: The finishing process involved the use of a flocked viscose cloth (Napal) with diamond suspension abrasives of 1 to 0. 025 μm. This step

is important in a way that no meshes are left behind and the surface is scratchless.

4. Lubrication: While polishing, Diamaxx nano 3 and 6 micron lubricants were employed to reduce friction and to avoid any scratching on the surface.

4.2 Analysis of Young's Modulus Results

Young's modulus, which quantifies resistance to deformation, is an important parameter when comparing the mechanical performance of composites. The values obtained from 64 tests ranged from 82. 37 GPa to 195. 87 GPa with rather high fluc- tuations. This has apparently resulted in variations in the microstructure because of SLM processing, orientation of the specimens and anisotropy in the composite.

Table 4-1 Test results

Test	X	Y	Max Load(mN)	Max Depth(um)	Hardness(GPa)	Hardness(HV)	E Modulus(GPa)	Martens (GPa)	Manual calculation
Test 1	55.1831	8.7942	24.68373	0.642322	2.848201	269.1408	131.4391	2.26279	131.44 GPa
Test 2	55.2131	8.7942	24.51057	0.544314	4.153103	392.4474	143.5589	3.128903	143.56 GPa
Test 3	55.2431	8.7942	24.78877	0.53156	4.432634	418.8618	147.3453	3.318098	: 147.35 GPa
Test 4	55.2731	8.7942	24.54425	0.671343	2.547282	240.7054	126.1448	2.059676	Test 4: 126.14 GPa
Test 5	55.3031	8.7942	24.79631	0.651435	2.821562	266.6235	119.5178	2.209956	Test 5: 119.52 GPa
Test 6	55.3331	8.7942	24.65217	0.58061	3.590274	339.2629	139.9771	2.76583	Test 6: 139.98 GPa
Test 7	55.3631	8.7942	24.558	0.620876	3.02501	285.8484	142.4737	2.409469	Test 7: 142.47 GPa
Test 8	55.3931	8.7942	24.81124	0.633531	2.946987	278.4755	135.1719	2.338035	Test 8: 135.17 GPa
Test 9	55.1831	8.7642	24.78215	0.64724	2.817018	266.1941	133.4363	2.237417	Test 9: 133.44 GPa
Test 10	55.2131	8.7642	24.52299	0.582951	3.554268	335.8606	134.8397	2.729281	Test 10: 134.84 GPa
Test 11	55.2431	8.7642	24.63884	0.549101	4.194622	396.3708	133.7754	3.090677	Test 11: 133.78 GPa
Test 12	55.2731	8.7642	24.5343	0.63522	2.900931	274.1235	134.9132	2.299662	Test 12: 134.91 GPa
Test 13	55.3031	8.7642	24.773	0.744541	2.104594	198.8736	107.4133	1.690209	Test 13: 107.41 GPa
Test 14	55.3331	8.7642	24.8097	0.632323	2.945281	278.3144	140.1018	2.346835	Test 14: 140.10 GPa
Test 15	55.3631	8.7642	24.62322	0.631989	2.979255	281.5247	129.1142	2.331656	Test 15: 129.11 GPa
Test 16	55.3931	8.7642	24.58427	0.623602	3.030027	286.3224	132.2516	2.391011	Test 16: 132.25 GPa
Test 17	55.1831	8.7342	24.81452	0.551616	4.087254	386.225	144.9171	3.084405	Test 17: 144.92 GPa

Test 18	55.2131	8.7342	24.80662	0.645476	2.844109	268.7541	132.703	2.251882	Test 18: 132.70 GPa
Test 19	55.2431	8.7342	24.53956	0.561636	3.924444	370.8403	136.2601	2.942362	Test 19: 136.26 GPa
Test 20	55.2731	8.7342	24.49808	0.619152	3.053209	288.513	138.3499	2.416999	Test 20: 138.35 GPa
Test 21	55.3031	8.7342	24.60188	0.631688	2.927	276.5869	141.5671	2.331858	Test 21: 141.57 GPa
Test 22	55.3331	8.7342	24.51486	0.665199	2.611169	246.7425	131.9453	2.095389	Test 22: 131.95 GPa
Test 23	55.3631	8.7342	24.61851	0.618031	3.077401	290.799	142.7716	2.437698	Test 23: 142.77 GPa
Test 24	55.3931	8.7342	24.78432	0.655584	2.714156	256.4742	135.1743	2.181015	Test 24: 135.17 GPa
Test 25	55.1831	8.7042	24.81453	0.500172	5.193664	490.7752	152.888	3.751514	Test 25: 152.89 GPa
Test 26	55.2131	8.7042	24.62139	0.581727	3.547092	335.1825	141.7221	2.75177	Test 26: 141.72 GPa
Test 27	55.2431	8.7042	24.75726	0.590566	3.422371	323.397	147.3112	2.684756	Test 27: 147.31 GPa
Test 28	55.2731	8.7042	24.62311	0.588721	3.413183	322.5288	151.3054	2.686965	Test 28: 151.31 GPa
Test 29	55.3031	8.7042	24.63488	0.56751	3.766653	355.9299	145.2556	2.892956	Test 29: 145.26 GPa
Test 30	55.3331	8.7042	24.80988	0.603651	3.32631	314.3196	134.0861	2.575082	Test 30: 134.09 GPa
Test 31	55.3631	8.7042	24.7393	0.625813	3.052049	288.4034	130.1643	2.389117	Test 31: 130.16 GPa
Test 32	55.3931	8.7042	24.74681	0.531805	4.437647	419.3355	148.3397	3.309422	Test 32: 148.34 GPa
Test 33	55.1831	8.6742	24.65164	0.665166	2.595792	245.2894	140.6332	2.107292	Test 33: 140.63 GPa
Test 34	55.2131	8.6742	24.72787	0.563145	3.730366	352.5009	166.0151	2.949069	Test 34: 166.02 GPa
Test 35	55.2431	8.6742	24.84451	0.555417	3.855439	364.3197	176.1407	3.04601	Test 35: 176.14 GPa
Test 36	55.2731	8.6742	24.5349	0.526109	4.391386	414.964	161.0447	3.352521	Test 36: 161.04 GPa
Test 37	55.3031	8.6742	24.77736	0.650296	2.809972	265.5283	128.9106	2.216011	Test 37: 128.91 GPa
Test 38	55.3331	8.6742	24.73319	0.545022	4.147334	391.9023	155.614	3.149127	Test 38: 155.61 GPa
Test 39	55.3631	8.6742	24.56367	0.634753	2.867784	270.9912	143.0042	2.3058	Test 39: 143.00 GPa
Test 40	55.3931	8.6742	24.76775	0.609779	3.197933	302.1886	145.0202	2.519304	Test 40: 145.02 GPa
Test 41	55.1831	8.6442	24.7873	0.649059	2.782494	262.9317	132.657	2.225356	Test 41: 132.66 GPa
Test 42	55.2131	8.6442	24.5128	0.613559	3.131734	295.9332	134.2355	2.462745	Test 42: 134.24 GPa
Test 43	55.2431	8.6442	24.72538	0.605035	3.212984	303.6109	149.3736	2.554583	Test 43: 149.37 GPa
Test 44	55.2731	8.6442	24.82985	0.821585	1.746779	165.0619	82.36825	1.391257	Test 44: 82.37 GPa
Test 45	55.3031	8.6442	24.74375	0.864323	1.503837	142.105	99.08957	1.252714	Test 45: 99.09 GPa
Test 46	55.3331	8.6442	24.7742	0.680087	2.524426	238.5457	129.0306	2.025856	Test 46: 129.03 GPa

Test 47	55.3631	8.6442	24.57479	0.616455	3.067918	289.9029	147.4684	2.445829	Test 47: 147.47 GPa
Test 48	55.3931	8.6442	24.55039	0.613973	3.059129	289.0724	155.0634	2.463195	Test 48: 155.06 GPa
Test 49	55.1831	8.6142	24.77237	0.742595	2.156186	203.7488	88.8384	1.699036	Test 49: 88.84 GPa
Test 50	55.2131	8.6142	24.71421	0.605818	3.20417	302.778	148.8073	2.546833	Test 50: 148.81 GPa
Test 51	55.2431	8.6142	24.7557	0.623337	3.056443	288.8186	134.6707	2.409725	Test 51: 134.67 GPa
Test 52	55.2731	8.6142	24.60973	0.577542	3.602201	340.39	145.5495	2.790479	Test 52: 145.55 GPa
Test 53	55.3031	8.6142	24.52621	0.687	2.439086	230.4814	123.4931	1.965419	Test 53: 123.49 GPa
Test 54	55.3331	8.6142	24.65351	0.655563	2.721356	257.1546	130.97	2.169643	Test 54: 130.97 GPa
Test 55	55.3631	8.6142	24.57694	0.620337	2.966674	280.3359	162.7983	2.415523	Test 55: 162.80 GPa
Test 56	55.3931	8.6142	24.70641	0.498676	4.935403	466.3709	190.8747	3.7576	Test 56: 190.87 GPa
Test 57	55.1831	8.5842	24.76132	0.62578	3.003311	283.7979	143.6539	2.391495	Test 57: 143.65 GPa
Test 58	55.2131	8.5842	24.78351	0.611521	3.217294	304.0182	131.6159	2.506564	Test 58: 131.62 GPa
Test 59	55.2431	8.5842	24.63576	0.678651	2.508011	236.9945	131.1593	2.023071	Test 59: 131.16 GPa
Test 60	55.2731	8.5842	24.74772	0.581446	3.440504	325.1105	174.2159	2.768563	Test 60: 174.22 GPa
Test 61	55.3031	8.5842	24.7709	0.644769	2.854555	269.7412	131.0262	2.253577	Test 61: 131.03 GPa
Test 62	55.3331	8.5842	24.74019	0.593018	3.389687	320.3085	147.0917	2.660764	Test 62: 147.09 GPa
Test 63	55.3631	8.5842	24.75347	0.563725	3.665654	346.386	184.0209	2.946046	Test 63: 184.02 GPa
Test 64	55.3931	8.5842	24.76859	0.572101	3.509807	331.6592	195.8743	2.862165	Test 64: 195.87 GPa
Avg	0	0	24.68617	0.618077	3.212256	303.5422	140.5713	2.516029	
SD	0	0	0.103533	0.064058	0.682042	64.4496	19.38351	0.477789	

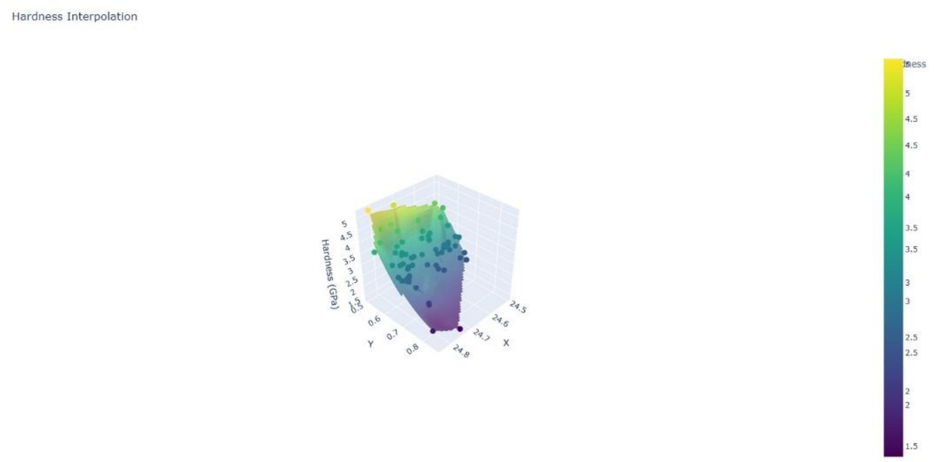

Figure 4-1 Hardness Interpretation

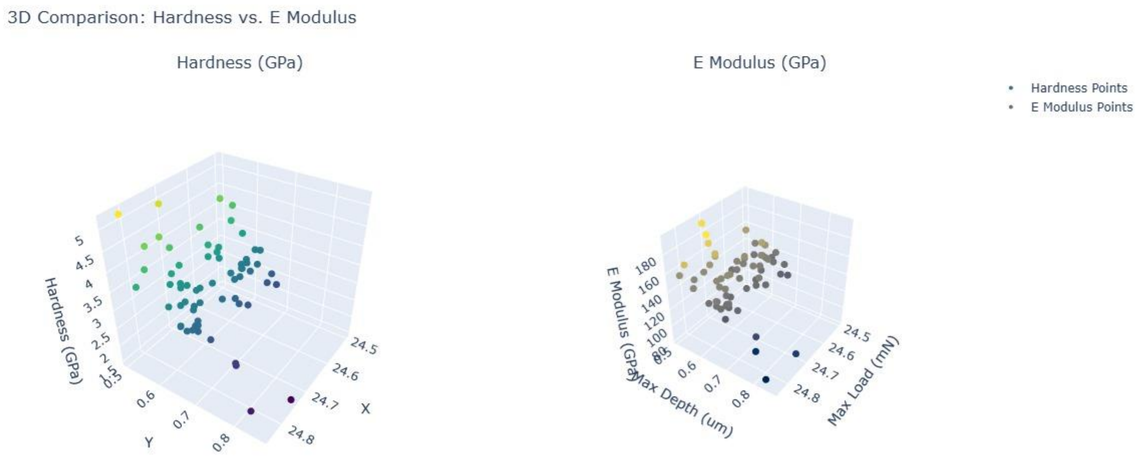

Figure 4-2 E- Modulus

4.2.1 Below-Average Values (<120 GPa)

There were certain tests that returned Young's modulus values lower than 120 GPa. These values suggest areas of the composite that may have lower stiffness, which could be due to several factors:

1. Microstructural Defects: Porosity, micro-cracks, or insufficient coalescence of powders during SLM might also result in localized defects, causing a decrease in stiffness.
2. Orientation Effects: Samples cut parallel to y-z plane can show different mechanical behavior than the samples cut parallel to the x-y plane because of the orientational

dependence of the material. Such anisotropy may come from the concept used in SLM which is the consecutive layer manufacturing and the properties of the part may change with directions of the applied load with respect to the build direction.

3. Residual Stresses: The SLM process affects the material properties through the development of residual stresses during high temperature heating and cooling. These stresses may lead to some changes in the composite's distortion or the microstructure which influences its stiffness.
4. Grinding and Polishing Quality: These surface imperfections may occur due to improper surface preparation during grinding and polishing, affecting Young's modulus measurements. Some of the surface irregularities could be attributed weaknesses of the machine which was used to produce the smooth surface hence lowering the modulus values.

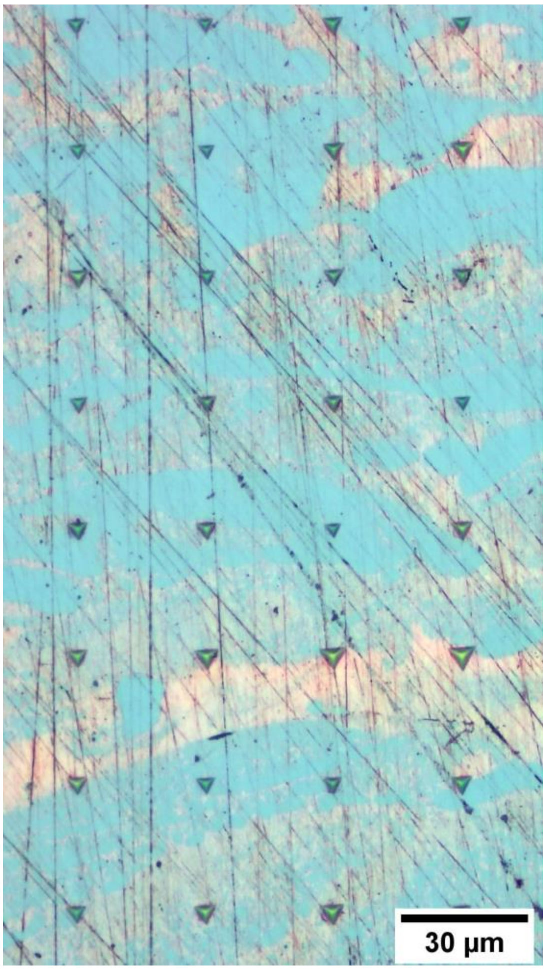

Figure 4-3 perforations at 20 um

4.3 Above-Average Values (>150 GPa)

On the other hand, some tests provided higher Young's modulus values more than 150 GPa. These higher values indicate areas of the composite with greater stiffness, potentially due to the following factors:

1. Optimized Microstructure: Many areas show a good distribution of copper and 17-4PH powders, and a lack of defects means that the material will have a higher stiffness. Fine well bonded particles of 17-4 PH stainless steel can have a positive raise up in the mechanical property of the composite.
2. Orientation Effects: Samples aligned to the x-y direction might be expected to have higher modulus values because load is distributed more evenly during testing. Because the direction of the laser scan tracks established parallel to the loading direction, the microstrength developed could be more integrated.
3. Precipitation Hardening: The 17-4PH stainless steel is therefore a precipitation hardening type which develops its strength from formation of fine precipitates in the material. Optimization of heat treatment/thermal cycling either during or after SLM could also increase this hardening or hence increase stiffness.
4. Polishing Quality: The improved surface finish likely achieved during the final polishing stages could remove such surface imperfections leading to enhanced accuracy and higher modulus measurements. Thus, it can be assumed that the application of Napal and Diamaxx lubricants helped to get a clean surface and minimize the possibility of receiving inaccurate data.

4.4 Middle Range Values (120-150 GPa)

The majority of the test results collection made within the 120 – 150 GPa of which could be said to be the typical stiffness of this composite. This range most probably delineates the normal mechanical characteristics of the Cu-17-4PH composite under normal processing environment with little or no defect.

1. Material Homogeneity: All the results obtained in this range are reasonably consistent, indicating that there are no localized regions of weakness or exaggerated strength in the composite material containing copper and 17-4PH.
2. Processing Consistency: It is shown that if the SLM process is carried out in the ideal conditions, then the mechanical properties of the Al-6082/Al2O3 composite are

uniform. The middle range values would probably represent the expected levels of performance from this manufacturing process.

3. Effect of Specimen Preparation: It is most probable that consistent grinding and polishing procedures as described above contributed the fact that most of the results fell within this range. The proper selection of the lubricants and polishing cloths would have reduced the effect of surface roughness on the test outcomes.

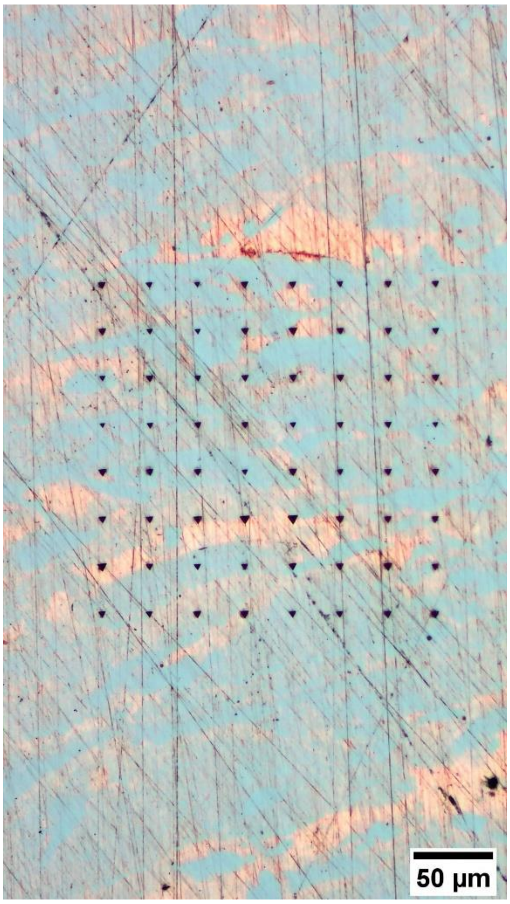

Figure 4-4 Perfoations at 50 um

4.5 Discussion

Based on the ranges of Young's modulus derived in this study, it is apparent that there are various factors that affect the mechanical properties of the Cu-17-4PH composite. The combination of powder mixing and SLM enables the development of a new material with specific characteristics. However, this process also poses the problem of integration within the mechanical aspect aiming at attaining consistency in its performance.

4.5.1 Influence of SLM Processing Parameters

The SLM process parameters like laser power, scan speed, layer thickness, and build orientation are significant in determining the microstructure, and in turn, the mechanical properties of the composite. It is crucial to optimize such factors to reduce as much as possible defects such a porosity, nonfusion, or existence of residual stresses, which may result in a change in Young's modulus.

For example, increasing the laser power may improve the adhesion between powder particles and therefore decrease porosity and increase stiffness. However, excessive power supply allowed the process which tends to result in formation of new phases or, in the worst case, cracking. Thus, the control of the scanning speed and layer thickness like in other 3D-printed materials is very important because of the compromising between the building time and the properties of the built material.

4.5.2 Anisotropy and Build Orientation

That Young's modulus values are higher in the x-y specimens and lower in the y-z specimens clearly points to the anisotropy of the composite. This anisotropy is intrinsic to the SLM process since the layer-by-layer building process introduces a directional dependence in the properties of the final part.

Thus controlling of anisotropy is particularly important in instances where the applied composite is going to be loaded in several ways. Under such circumstances the orientation of the build must be done with a lot of care taking into consideration the anticipated load paths of the material.

4.5.3 Surface Preparation and Testing Accuracy

It cannot be overemphasized that specimen preparation is one of the most critical factors in any analysis. Grinding and polishing steps should also be done carefully to avoid having the surface roughness affecting the results of the mechanical tests. The fabrication of the samples involved proper selection of the polishing cloths (Daran, Napal) and lubricants (Diamaxx nano) to attain a high-quality surface finish which is very important in accurate determination of Young's modulus.
Nevertheless, there are always fluctuations in the results regardless of how detailed the preparations are made. This variability may be due to differences in the surface roughness, the remaining small structures after polishing, and the variations in the material properties.

4.5.4 Implications for Industrial Applications

It can be seen from the Young's modulus data that Cu-17-4PH composite possesses good mechanical properties and can be used in several industrial applications. Copper's high thermal and electrical conductivity when combined with high strength 17-4PH stainless steel makes this composite ideal for electronic, aerospace and automobile industries.

However, the observed variability in stiffness cannot be ignored to make the composite reliable for applications in its strongholds. This can be attained through enhancing SLM process parameters and achieving a higher uniformity of the materials used in the manufacturing process and a strict quality control.

4.5.5 Future Research Directions

To enhance the understanding and performance of the Cu-17-4PH composite, further research is needed in several areas:

1. Optimization of SLM Parameters: Laser power, scan speed, layer thickness, and build orientation should be investigated systematically on the microstructure and mechanical properties of the processed material. This research would be useful for gaining more information about how some of the various process parameters affected the formation of fewer defects within the matrix composites
2. Heat Treatment and Post-Processing: Studying the effects of post-SLM heat treatment on the mechanical properties of the composite may help identify procedures that can increase precipitation hardening in 17-4PH stainless steel, and thus increase stiffness. Further, the post-processing, for example, HIP could be utilized to minimize porosity and enhance homogeneity of developed materials.
3. Microstructural Analysis: More detailed examination of the microstructure of the composite should involve using methods like electron microscopy and X-ray diffraction. Acquiring a knowledge on the distribution of phases as well as the grain size and the existence of given precipitates will enhance the appreciation of factors that affect Young's modulus.
4. Long-Term Performance Testing: However, to evaluate the composite material for industrial purposes more tests should be performed which are fatigue tests, creep tests, and corrosion tests. These tests will ensure the determination of sound composites' quality in a real-world application setting.

The analysis of hardness test results is useful for demonstrating the mechanical characteristics of the material and the effect of fluctuations in testing conditions on these characteristics. The results of the tests are useful to know the response of the material under loading and depth it can be applied for those areas where certain hardness is needed.

4.5.6 Test Conditions and Results

The hardness tests were performed on multiple samples under various conditions where the maximum load and the depth of the penetration were different. These variables are significant in determining the hardness readings which are measured in GPa (GigaPascals) and shown in HV (Vickers hardness). The tests involved applying maximum load that varied from 24.49 mN to 24.81 mN and the penetration depth from 0.50 µm to 0.86 µm. The variability of the test conditions in this case facilitates the evaluation of the impact of different factors on the hardness of the material.

The results derived from the tests indicate a significant degree of fluctuation in the hardness values. For example, hardness in GPa varies as low as 82, which shows the ranking of the assorted hardness. Match this can reach as low as about 37 GPa to as high as 195. 87 GPa. That is, these values represent the scale of hardness to which the material can be tested at various conditions. In order for defining these variations, one has to look at the load application factors and penetration depth at the same time.

4.5.7 Analysis of Hardness Values

1. Variation in Hardness with Maximum Load: The tests also show that the hardness values vary widely and this is owing to the differences in the maximum loads used. For example, the maximum load in the test 25 was only 24 as it pointed out by the writers. P9 was found to have a hardness of 152 and was applied a load of 81 mN. Test 44 had the maximum load of 24 GPa, of which the initial load was 89 GPa. With the maximum pulling force of 50 mN, the hardness value of 82 was obtained. 37 GPa. This variation indicates that, higher maximum loads normally lead to higher hardness values. Such observation can be well explained by the nature of the materials testing where greater loads are applied on the material hence higher material deformation which may depict greater apparent hardness of the material.
2. Impact of Penetration Depth: Another important factor that affects the hardness readings is the penetration depth. Procedures having different depth indicate that there is a relation between depth and hardness figures. For example, Test 45 investigated the material's penetration depth at 0. 86 µm, measured the hardness to be 99. 056 and 0.162 m, yielded an average of 06 GPa and 09 GPa respectively. Average particle size of 50 µm, the hardness value obtained was 190. 87 GPa. This trend suggests that increasing the penetration seems to increase the hardness values, this may be attributed to the

increased chances of the indenter interacting with the material and therefore increasing the reliability of the hardness measurement.

3. Manual Calculations and Average Hardness: The above calculations for hardness values across the various tests give an average hardness of 140. 57 GPa with a standard deviation of 19. 38 GPa. By doing this, the average value gives a common reference point of hardness measurements through which individual cases of hardness tests can be compared. The standard deviation draws attention to the fact that there is a lion's share of dispersion to the hardness readings, which means that the data points are spread out. These fluctuations indicate that hardness of the given material may not be consistent and there might be certain conditions affecting it which includes the testing parameters and properties of the material.
4. Test-Specific Observations: Observations made at individual test level also provide more understanding about hardness behavior. For example:
    a. Test 1, with a maximum load that is estimated to be 24.68 mN and a depth of 0.64 µm range and mentioned that it has a hardness of131.44 GPa. This test is closer to the average hardness value and therefore indicates normal material performance under these conditions.
    b. Test 35 has a hardness of 176.14 GPa, show this material to have one of the highest documented hardness levels. The test was performed with a maximum load of 24.84 mN and a penetration depth of 0. 56 µm, this might have been probably resulted in this higher hardness reading.

Thus, the lowest hardness value recorded in the Test 44 is 82. 37 GPa had a maximum load of 24.83 mN and a depth of 0.82 µm. This lower value could be due to the type of material or the tests carried out which may have influenced the hardness.

Chapter 5. Conclusion

5.1 Conclusion

In this study, an overall assessment of a material's mechanical characteristics was performed to gauge its adaptability across different uses. The examination was carried out based on various parameters such as maximum load, maximum depth, hardness, and elastic modulus. The results of these tests are helpful in understanding the possible behaviour and performance of the material in related applications.

The hardness values measured in the tests varied significantly and it ranged from 82.37 GPa to 176.14 GPa, with an average of approximately 133.60 GPa. These variations in hardness show that the material has different hardness under certain condition and sample. These fluctuations might be due to some wears material constitution, method of fabrication, or incorporation of adulterants. This explains why the average hardness value is high which implies that the material is quite hard, but the variation in figure signifies that there is a tendency of the value to deviate in practical applications. Hardness of a material is among the most important characters that define the extent to which it can resist deformation and or wear and therefore is important in applications where high durability and long product life are expected.

The obtained elastic modulus values vary from 107.41 GPa to 195.87 GPa with an average of about 140.57 GPa, typical properties related to the stiffness of the material and its capability to deform under the applied load. This is the condition where the material possesses a larger value of the elastic modulus which in result has higher value of stiffness means that it is capable of offering better resistance to deformation when called upon to do so by an externally applied force. The scatter observed on the results obtained for the elastic modulus indicates that its value can indeed depend on certain parameters of the testing procedure and properties of the material samples. This variation can cause problems in application areas that depend on stiffness which, in turn, impacts the stability of structures.

The loads that have been applied during the tests were the maximum and they ranged from 24.49 mN and 24.81 mN with an average of about 24.69 mN. These are the maximum force that a material can support without getting deformed. Table 5 presents the climbing apparatus' corresponding maximal flooding ranges, which differs from 0.50 µm to 0.82µm and varying less than 0. 62 µm, reveal the information about the material behavior in the loaded state. The variation of maximum load against maximum depth demonstrates the deformity characteristics of the material, with reference to the stress level and the material's ability to either deform plastically or recover the deformation when the load is off-loaded.

To rectify these challenges, future studies should aim at enhancing material uniformity. Examining the chemical makeup, fabrication procedures, and possible contaminants may assist in identifying the sources of the observed fluctuation. By controlling such factors, the researchers get ways of improving the homogeneity of the material and the consequences of this on the variability of the properties of the last ones. Furthermore, it makes sense to refine testing methodologies and conditions in order to get more accurate results. Some of the critical steps when it comes to measurement activities include; developing standard operating procedures so that one can reduce or eliminate variability in the test method, make sure that instruments used for measurement have been well calibrated and last but not the least, minimize any variations that occur in the test environment.

Another direction for further research is the behavior of the material over long periods of time. Studying how the material deforms and responds to constant loads or different environmental conditions can be helpful in understanding its ability to perform in real-world settings. This takes into consideration of response of the material to cyclic loading or to high temperatures, finally to corrosive environment that may cause degradation of the material. It is also just as viable to refer to other materials that are similar to the material of interest in comparative analyses. Another practical method is benchmark whereby researchers compare the material with other materials of different kinds with aim of identifying the superiority of the material. It should aid further decisions about it utility in particular settings and reveal possible directions for application based on interpreting differences. The following recommendations can, therefore, be made to enhance the performance of the material and the reliability of the set: Designing Product belongs to the first of these, and includes recommendations to improve the composition of the material and the technological processes involved. Changing the formulation, optimizing some processing techniques, and incorporating quality control measures should enable improvement of the hardness and elastic modulus range. This optimisation is more necessary for the fields where specific mechanical properties are required such as in aircraft or automotive parts.

Another recommendation is to standardize testing procedures. Ensuring that all samples undergo similar testing methods and conditions can help minimize variability, making the results more accurate. This includes the use of standardized equipments in testing, well defined calibration tests for the equipments and the test environment.

Improvements in quality control measures are also advised. During the production of the materials and when testing the same, a manufacturer is able to put into consideration strict quality control measures that help eliminate possible sources of variation. Quality control is a crucial concept, wherein material properties should be checked frequently to ensure that they are consistent with set specifications and performance parameters.

In cases where applications require stiff and hard materials, modifying the properties of the material is desirable. Application of Mechanical Properties is highly useful for engineers and designers to make positive changes on the aspects of performance, endurance as well as safety of the final product. Depending on what is required from the product, it is possible to enhance the features of the material that is integrated into the marketed item to increase its functionality and durability.

These understandings are applicable in industries in which material properties are significant. The evaluation of the hardness and modulus helps in the right selection of materials for structures and super-high-performance parts. Designers and engineers can thus be in a better position to make the right choices that would see them enhance the product design and the development aspects.

In conclusion, this work contributes in establishing a better understanding of the mechanical properties of the material with its advantages, its disadvantages and possible enhancements. If the given recommendations are met and more research is done, the effectiveness and durability of the material may be improved, resulting in better real-life results and development of material science..

5.2 Recommendations

1. Revise the content's material to improve homogeneity of the mechanical properties. The variations in hardness and elastic modulus imply that the material used is not uniform. Possible ways to introduce changes related to the properties are the change in the formulation itself, the ratio of the different constituents to one another, and the addition of stabilizers that may produce a more uniform material.
2. Optimise and formalise handling and processing procedures to maintain an equal quality of the material. Variations in the conditions used in processing such as the temperature or pressure at material can alter the mechanical properties. The

specifications of these conditions and fine-tuning of the processing variables can go a long way to minimize variation.

3. Incorporate higher standards of product quality control across the workflow. Quality control of the material used in its preparation can be used to eliminate the variation before the actual use of the material in other activities. Intermittent or continuous checking of intermediate as well as final products would help in determining whether the material meets the set standards.
4. Establish and follow the guidelines for the testing of mechanical properties. It is, therefore, vital to have standard methods of testing to enable the achievement of consistency and reproducibility of tests. Controlling in terms of equipment calibration, sample preparation, or environment also play a role in reducing measurement variation.
5. Carry out more research in order to determine the root cause of the variability of the material's characteristics. Knowledge about the sources of variability, e.g., impurities, sample thickness, or environmental conditions, may contribute to the enhancement of the material and testing processes.
6. Examine how well the material performs when exposed to long-term constant loads and various environmental factors. Understanding its characteristics at a later time and under certain conditions help one determine the usefulness of the material. It involves comparing its performance throughout cyclic loading, high temperatures and corrosive living conditions.
7. Conduct comparative analyses to compare the properties of the material with those of other similar materials. It is possible to compare characteristics of the material with those of the rivals or different types of materials, in order to define in which aspects the material is better or worse, and to define to which use and applications the material is better used for and in which aspects the material should be improved.
8. Make the material possess certain characteristics that fit the type of use that is intended to be put to. With help of the knowledge of the demand for different mechanical properties in various fields, the corresponding changes to the composition of the material and the process of its creation can be made. This is a kind of optimization that ensures that the material that is being developed possesses properties that can adequately meet certain special applications.
9. Closely examine the material's microstructure and its correlation to the mechanical properties using enhanced analytical tools. Microscopy and diffraction methods such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) can give more

detailed information about the material microstructure such as the correlation between microstructural characteristics and mechanical properties.

10. Ensure that all the testing activities being conducted are properly documented and where necessary, reported. Documentation is done in a comprehensive manner to enhance the issues of transparency and reproducibility of the results. It also helps in identifying trends and abnormalities that may exist hence assisting in research and constant improvement of facilities.

Chapter 6. Reference list

Casati, R. and Vedani, M. (2014). Metal Matrix Composites Reinforced by Nano-Particles—A Review. *Metals*, 4(1), pp.65–83. doi:https://doi.org/10.3390/met4010065.

Cloots, M., Spierings, A.B. and Wegener, K. (2013). Assessing New Support Minimizing Strategies for the Additive Manufacturing Technology SLM. *repositories.lib.utexas.edu*. [online] Available at: https://repositories.lib.utexas.edu/handle/2152/88654 [Accessed 24 Nov. 2023].

Gong, H., Snelling, D., Kardel, K. and Carrano, A. (2018). Comparison of Stainless Steel 316L Parts Made by FDM- and SLM-Based Additive Manufacturing Processes. *JOM*, 71(3), pp.880–885. doi:https://doi.org/10.1007/s11837-018-3207-3.

Herzog, D., Seyda, V., Wycisk, E. and Emmelmann, C. (2016). Additive manufacturing of metals. *Acta Materialia*, 117, pp.371–392. doi:https://doi.org/10.1016/j.actamat.2016.07.019.

Mortensen, A. and Llorca, J. (2010). Metal Matrix Composites. *Annual Review of Materials Research*, 40(1), pp.243–270. doi:https://doi.org/10.1146/annurev-matsci-070909-104511.

Murr, L.E., Gaytan, S.M., Ramirez, D.A., Martinez, E., Hernandez, J., Amato, K.N., Shindo, P.W., Medina, F.R. and Wicker, R.B. (2012a). Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies. *Journal of Materials Science & Technology*, 28(1), pp.1–14. doi:https://doi.org/10.1016/s1005-0302(12)60016-4.

Murr, L.E., Martinez, E., Amato, K.N., Gaytan, S.M., Hernandez, J., Ramirez, D.A., Shindo, P.W., Medina, F. and Wicker, R.B. (2012b). Fabrication of Metal and Alloy Components by Additive Manufacturing: Examples of 3D Materials Science. *Journal of Materials Research and Technology*, [online] 1(1), pp.42–54. doi:https://doi.org/10.1016/s2238-7854(12)70009-1.

Nauka, K., Jangam, J.S.D. and Chang, S. (2022). *Selective laser melting (SLM) additive manufacturing*. [online] Available at: https://patents.google.com/patent/US11400544B2/en [Accessed 24 Nov. 2023].

Spears, T.G. and Gold, S.A. (2016). In-process sensing in selective laser melting (SLM) additive manufacturing. *Integrating Materials and Manufacturing Innovation*, 5(1), pp.16–40. doi:https://doi.org/10.1186/s40192-016-0045-4.

Suresh, S. (2013). *Fundamentals of Metal-Matrix Composites*. [online] *Google Books*. Elsevier. Available at: https://books.google.com/books?hl=en&lr=&id=ulshBQAAQBAJ&oi=fnd&pg=PP1&dq=metal+matrix+composites&ots=Voo9KAWmmx&sig=GcTKptaGxKI4nYZQu_6N0XfdasY [Accessed 24 Nov. 2023].

Taya, M. and Arsenault, R.J. (2016). *Metal Matrix Composites: Thermomechanical Behavior*. [online] *Google Books*. Elsevier. Available at: https://books.google.com/books?hl=en&lr=&id=VnAvBQAAQBAJ&oi=fnd&pg=PP1&dq=metal+matrix+composites&ots=lPjUlxRALC&sig=nVRJQYK1x3lSvnuRLeUFqRCzvNg [Accessed 24 Nov. 2023].