ADDIS ABABA UNIVERSITY

COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT

SCHOOL OF MECHANICAL AND INDUSTRIAL ENGENEERING

EFFECT OF MICROWAVE HEAT TREATMENT ON ALUMINIUM 6061 ALLOY ALUMINA COMPOSITE

A Thesis Submitted to the Graduate School of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Masters of Science in Mechanical Engineering(Manufacturing Engineering)

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Effect of Microwave Heat Treatment on Aluminum 6061 Alloy Alumina Composite

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Declaration

This is to certify that the thesis prepared by Meron Workneh, entitled **"Effect of Microwave Heat Treatment on Aluminum 6061 Alloy Alumina Composite"** is hereby declared as my original work. It has been submitted, either partially or in full, for a degree in any University or Institute. This thesis complies with the regulations regarding originality and quality.

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Abstract

Aluminum matrix composites are becoming more prevalent in the automotive industry because of their advantageous properties relative to traditional materials such as Steel or even pure Aluminum, This is also applicable for automotive parts such as control arms, because they allow for lightweight designs with high strength and better stiffness.

The present work utilizes stir casting technique for the fabrication and mechanical characterization of aluminum 6061 alloy with variable weight percentages (5%, 10% and 15%) of aluminum oxide (Al_2O_3) reinforcement. The primary objective was to investigate the influence of microwave heat treatment on the mechanical properties of the composite. Mechanical tests such as hardness, tensile and flexural strength were carried out in accordance with ASTM standards to evaluate performance improvements. It was shown that as Al_2O_3 increases in levels, all the attributes evaluated significantly improved.

Stir casting combined with microwave treatment proved to be an effective processing route for the development of structural grade aluminum matrix composites.

The composite with a composition of 15 % Al_2O_3 reinforced showed the promising results for double control arm application, with a tensile strength of 330 MPa, flexural strength of 411.3 MPa and Rockwell hardness of 74.3 HRB. These properties make the composite suitable for the intended application.

Finite element analysis is carried out to validate the experimental findings using ANSYS 19.2 commercial software, demonstrate a strong correlation between experimental and ANSYS simulation the percentage error remains consistently low within 4% indicating reliability. For the application area analysis with a Von - Mises stress of 173.76 MPa and maximum total deformation of 0.135mm. The results obtained from both experiments and FEA show that the Aluminum 6061 matrix reinforced with Al_2O_3 composite is a suitable alternative for double control arm.

Key words: Aluminum 6061, Alumina, stir casting, microwave heat treatment, mechanical characterization.

ACRONYMS

ASTM	America Society for Testing and Material
AMCs	Aluminum matrix composites
CMCs	Ceramic matrix composites
FEM	Finite Element Method
FEA	Finite Element Analysis
MMCs	Metal Matrix Composites
UTM	Universal Testing Machine

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CHAPTER ONE

Introduction

1.1.Background of the study

Composite materials are results of the continuous attempts to develop new engineering materials with low weight to strength ratios and improved properties. Among the advanced composite materials, particulate reinforced metal matrix composites (MMCs) are finding increased applications due to their favorable mechanical properties such as improved strength, stiffness and increased wear resistance over unreinforced alloys. In particular, these composites show enhanced properties compared to unreinforced alloys. Metal matrix composites consists of a metallic alloy matrix typically reinforced with a ceramic phase in the form of particles, platelets, whiskers, short fibers, and continuously aligned fibers [1].

Light alloys are current prominent solutions when compared to classic steel construction, occupying a significant quota in the manufacturing economy]. Their use generates a significant decrease in density (33% and 77%, respectively for Al and Mg alloys) when compared to steel [2].

Aluminum metal matrix composites (Al MMCs) offer a combination of (a) higher stiffness-to-density ratio, (b) better elevated temperature properties and (c) improved wear resistance. These Al-MMCs have become the necessary materials in various engineering applications like aerospace, marine and automobile product applications such as engine piston, cylinder liner, brake disc/drum etc [1].

Al 6061 is the most versatile alloy among the aluminum 6XXX alloy series, and the Al 6061 composites are mostly produced by the stir-casting technique [3].

Aluminum metal matrix reinforced with silicon carbide is metal matrix composites have very good hardness, stiffness, specific strength and thermal properties which are increasingly used for making cylinder heads, pistons, liners and brake motors [4].

Current processing of MMCs may be divided into three approaches according to the matrix state during particle introduction solid, semi-solid and liquid. Solid and semi-solid routes usually use powder metallurgy and sintering techniques, in which reinforcement bonding is promoted by a well-defined temperature-pressure interaction; however, due to limitations in component volume/shape, the application of these techniques on an industrial scale is not really feasible [2].

Liquid state fabrication involves the dispersion of reinforcements in the molten matrix, followed by its solidification, either through infiltration or casting methods. These methods are cost effective compared to solid-state methods. Stir casting is the most popular and commercially used technique in liquid-state processing, since it is economical compared to other manufacturing techniques. It also provides fairly homogenous dispersion of reinforcements in matrix, better wettability, and reduced porosity [3].

One of the major concerns regarding such technique was the segregation of reinforcing elements due to settling of particles during solidification. The homogeneity of particles distribution within the composite was found to be affected by several factors such as the properties of the particles added, melt temperature, the efficiency of mixing and the cooling rate. Furthermore, and in order to enhance the mechanical properties of the composite, strong interfacial bonding (wetting) between the reinforcing elements and the molten metal matrix should be maintained [5].

1.2 Rationale

Mechanical properties of Al-based alloys largely depend on the heat treatment. Thus, characteristics of heat treatment play a vital role for a good combination of microstructure and mechanical properties [6].

Microwave post heat treatment of metal based components is a technique which is employed to provide unique microstructure and properties as a result of selective heating [7]. In microwave sintering, heat is generated internally within the material and the sample becomes the source of heat. In the conventional heat treating process, energy is transferred to the material from the surface of the material whereas in microwave heating, the energy is directly delivered to the material through the molecular interaction with the electromagnetic field [1]. Microwave heat treated composite exhibited higher hardness than the conventionally heat-treated composites [6].

1.3 Statement of the problem

Metal matrix composites (MMCs), particularly aluminum-based composites like Al6061 reinforced with ceramic particles such as Al_2O_3 (alumina), are widely used in aerospace, automotive, and structural applications due to their superior mechanical properties, including high strength-to-weight ratio, wear resistance, and thermal stability. However, achieving uniform dispersion of reinforcement particles and optimizing the interfacial bonding between the matrix and reinforcement remains a persistent challenge, especially after casting and conventional heat treatments [7].

Conventional heat treatment methods often result in long processing times, uneven heating, and undesirable grain growth, which can adversely affect the mechanical performance of the composite. Recently, microwave heat treatment has emerged as an alternative due to its rapid, volumetric, and energy-efficient heating mechanism. It has the potential to improve microstructural refinement, enhance mechanical properties, and reduce energy consumption [1].

This study aims to investigate and compare the influence of microwave and conventional heat treatments on the mechanical properties of Al6061 matrix composites reinforced with varying percentages of Al_2O_3. The research seeks to determine whether microwave heat treatment can serve as a viable alternative for improving the mechanical performance of such composites.

Though the potential of microwave heat treatment is enormous, the influence of this process on the mechanical integrity, fatigue performance, wear characteristics, and microstructural properties of Al6061- Al_2O_3 composites has yet to be explored to any extent with regard to double control arm design.

1.4 Objectives of the research

1.4.1 General objective

Investigate effect of Microwave Heat Treatment on **Aluminum 6061 Alloy alumina Composite.**

1.4.2 Specific objectives

- To fabricate Al 6061/ Al_2O_3 composite with weight percentages of 5%, 10% and 15% of Al_2O_3 by stir casting.
- To evaluate and compare the mechanical properties, particularly tensile, flexural and micro-hardness of conventional and microwave treated Al6061/Al_2O_3 composites.
- To investigate the interaction effect of Al_2O_3 content and heat treatment method on mechanical performance and strain behavior of composites,.
- To validate the experimental result using FE analysis.
- To determine the optimal combination of Al_2O_3 reinforcement percentage and heat treatment technique that provides best balance of strength and ductility for the double control arm

1.5 Scope of the research

This work contained the fabrication of Aluminum 6061 Alloy alumina Composite by stir casting. The fabrication process involves incorporation of ceramic particulate into liquid Aluminum melt and allowing the mixture to solidify. Fabricated composites were subjected to microwave and conventional heat treatment that is aging for enhancing the mechanical properties. Alongside it characterized hardness, tensile strength and flexural strength properties using ASTM standards. And compare the effect of microwave heat treatment with conventional heat treatment. To verify the appropriateness and application of the double control arm, FE analysis was performed. The study solely included FE analysis and modeling for the double control arm.

1.6 Significance of the research

Microwave heat treatment is a process that allows for rapid and uniform heating, reduces processing time, and has the potential to improve microstructure and optimize performance. Despite its advantages, microwave heat treatment has so far been limited in its use in Al6061-Al_2O_3 composites, especially in highly stressed utility parts such as double control arm.

This energy-efficient heat treatment process can reduce manufacturing time and costs in the process. Also can enhance the mechanical properties of the composite by improving the uniformity by way of providing unique microstructure. This can supports the development of lightweight, durable chassis components that can help improve vehicle performance and sustainability.

1.7 Research questions

- How the methods of heat treatment affect the properties of composite materials?
- Is Aluminum 6061 Alloy alumina Composite suitable for microwave heat treatment?
- Is there a substantial mechanical property difference on the composite due to microwave heat treatment?
- Can the selected composite composition be deemed suitable for double control arm application based on finite element analysis (FEA) results?

CHAPTER TWO

Literature Review

2.1 Composite material

Nowadays, the development of modern machinery and devices is related to the use of fibrous composite materials and the correct utilization of their properties. The growth of the production of a variety of composite materials and the rapid development of technology and research in this field clearly show advantages of composites over traditional materials such as steel, glass, polymers [8]. Composite materials provide design engineers with superior quality and long life span of materials [9].

2.2 Classification of composites

There are three types of composite materials, namely: polymer–matrix composites, metal–matrix composites and ceramic–matrix composites and they are widely used in numerous engineering applications. Depending on the reinforcement type, composite materials can be classified into particulate composites, fiber-reinforced composites and structural composites [9].

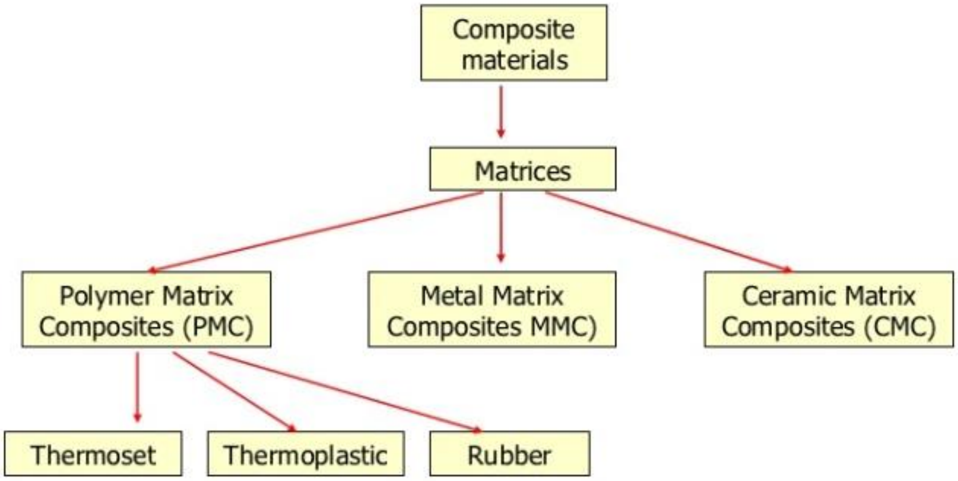


Figure 2.1 Classification of composite material based on matrix material [9]

2.2.1 Ceramic matrix composites

Ceramic materials in general have a very attractive package of properties: high strength and high stiffness at very high temperatures, chemical inertness, low density, and so on. This attractive package is marred by one deadly flaw, namely, an utter lack of toughness. They are prone to catastrophic failures in the presence of flaws (surface or internal). They are extremely susceptible to thermal shock and are easily damaged during fabrication and/or service. It is therefore understandable that an overriding consideration in ceramic matrix composites (CMCs) is to toughen the ceramics by incorporating fibers in them and thus exploit the attractive hightemperature strength and environmental resistance of ceramic materials without risking a catastrophic failure [10].

Ceramic composite materials reinforced by continuous or discrete fibers, whiskers, or particles have the best physical and chemical properties. Currently, the best known and most commonly used materials of the ceramic matrix composite are following:

a) Aluminum oxide matrix: Al2O3-SiC, Al2O3-ZrO2, Al2O3-SiC- ZrO2, Al2O3-SiC,

b) Silicon nitride matrix: Si3N4-TiN, Si3N4-SiC,

c) Silicon carbide matrix: SiC- SiC, SiC-MeB2, SiC-TiB2 [8].

2.2.2. Polymer matric composites

Polymeric matrix materials can be conveniently classified as thermosets and thermoplastics. Recall that thermosets harden on curing. Curing or cross-linking occurs in thermosets by appropriate chemical agents and/or application of heat and pressure. Conventionally, thermal energy (heating to 200 ^{0}C or above) is provided for this purpose.

This process, however, brings in the problems of thermal gradients, residual stresses, and long curing times. Residual stresses can cause serious problems in nonsymmetrical or very thick PMC laminates, where they may be relieved by warping of the laminate, fiber waviness, matrix micro cracking, and ply delamination [10]. Polymer composite materials are reinforced by long or short fibers. The most commonly used fiber types are

Glass fibers - for their production are used various compositions of mineral glass (based on SiO2). They have an amorphous structure, and only at high temperatures and after long-term annealing crystallization can be observed. They are manufactured in different types of fibers depending on the additives of oxides of the elements: B, Fe, Al, Ca, Mg, Na, K.

The glass fibers are resistant to most chemicals and moisture. As they have a low thermal expansion coefficient and good thermal conductivity, may also be used at elevated temperatures. They have very good electrical insulating properties and low dielectric constant. These apply finish to easily connect the fibers forming a beam bundle and improve wettability.

Carbon fiber – It is one of the most important reinforcement fibers in all types of composites. This material is mainly used as unidirectional or woven roving structures. They are produced in two forms: high-strength fibers (HS) and fibers with a high Young's modulus (HM). In the Anglo-Saxon literature, they bear different names, the first of which are referred to as carbon fibers, the second as graphite fiber. This difference is caused by technological processes of their preparation. The HS fibers are produced at a temperature below 1700°C and the HM fibers are made at temperature higher than 1700°C. The temperature rise in the case of HM fibers will decrease the anisotropy of graphite crystals. If the base plane of the crystal would be parallel to the axis of the fibers, Young's modulus can reach the theoretical value even if about 920 [GPa]. Individual carbon fibers have a diameter of about 8 microns. They are usually made of a polyacrylonitrile (PAN). They have a high fatigue resistance. A characteristic feature of carbon fibers is poor wettability of the epoxy resins. For this reason, the fibers must always be covered by finish.

Natural fibers - are increasingly being considered as reinforcements for composites. In general, they are composed of cellulose which potentially has a Young’s modulus about 140 GPa. The plants which are currently attracting the most interest are fibers made from hemp, jute, flax, silk, sisal, bamboo, coconut and kenaf. Natural fibers have low stiffness (up to forty few GPa for the fibers made of bamboo), very high tensile strength (several hundred MPa) and a high degree of deformability (about 20%) and high resistance to impact. Such fibers have diameters approximately from 30 to 350 microns, additionally; it is not uniform along the length. There is a considerable scatter in mechanical properties.

Natural fibers are generally short fibers. An important element is the selection of appropriate sizing agent (or coupling agents). Typically, the natural fibers are produced as a fabric of two or three dimensional [8].

2.2.3. Metal matrix composites

Generally MMC consist of a metal or a metallic alloy being the matrix and of the reinforcement made of metallic or ceramic materials.

Beside properties of MMC like high specific strength and stiffness which sometimes may not be those most important, there are others equally valuable. Mainly, ability to control thermal expansion in applications involving electronic devices, reduced the coefficient of linear thermal expansion, high electrical and thermal conductivity (provide elevated thermal conductivity even in case of an accidental quench) or wear resistance. Furthermore, one can list others including good transverse properties, temperature stability, improved cyclic fatigue characteristics or low contamination [8].

Composite materials based on light metal alloy bases are characterized by very good mechanical properties and find applications in the production technology of aircraft and cars, in defense technology and in astronautics. Composite materials based on light metal alloys are reinforced with dispersion particles, platelets, short fibers and continuous fibers [11].

Aluminum Alloys

Aluminum alloys, because of their low density and excellent strength, toughness, and resistance to corrosion, find important applications in the aerospace field. Of special mention in this regard are the Al–Cu–Mg and Al–Zn–Mg–Cu alloys, very important precipitation-hardenable alloys [10].

Composite materials on aluminum alloy matrices are manufactured by powder metallurgy, applying the mechanical alloying process, and the co-spray deposition process of dispersion particles in atomized aluminum alloys as well as by squeeze casting methods [11].

Al6061 is a precipitation-hardened aluminum alloy primarily alloyed with magnesium and silicon. It is widely used in structural and mechanical applications due to its balanced combination of mechanical strength, corrosion resistance, thermal conductivity, and formability. In the T6 temper condition—achieved through solution heat treatment followed by artificial aging—Al6061 typically exhibits a tensile strength of approximately 310 MPa, yield strength around 275 MPa, and a Brinell hardness of about 95 HB. The alloy maintains moderate ductility, with elongation values ranging from 8 to 10% [38]. Additionally, Al6061 possesses good thermal conductivity (~167 W/m·K), making it suitable for applications requiring efficient heat dissipation, such as in automotive or aerospace components. The alloy is also known for its excellent corrosion resistance in atmospheric and marine environments, and it responds well to anodizing, which further enhances its surface durability [39].

The reinforcement of Al6061 with ceramic particles such as aluminum oxide (Al_2O_3) leads to the development of aluminum matrix composites (AMCs) with significantly enhanced performance. The inclusion of Al_2O_3 particles improves the material's hardness, wear resistance, and overall mechanical stability under load-bearing conditions. These enhancements make Al6061–Al_2O_3 composites particularly attractive for high-stress applications such as automotive suspension systems, including components like the double control arm, where lightweight materials with superior mechanical performance are essential [40] [41]. The presence of the ceramic reinforcement acts as a barrier to dislocation motion and contributes to load sharing, which improves the composite's ability to withstand cyclic and impact loading.

Furthermore, the effectiveness of these composites is highly dependent on the heat treatment process applied. Conventional heat treatment methods, such as solutionizing and aging, can enhance the mechanical properties by promoting precipitation hardening. However, such treatments are often energy-intensive and may result in uneven microstructural evolution. Recent studies have highlighted the potential of microwave heat treatment as a more energy-efficient and rapid alternative. Microwave heating enables volumetric and uniform heating, which can result in finer and more homogeneous microstructures. This leads to improvements in mechanical properties such as tensile strength, wear resistance, and fatigue life, especially when applied to particle-reinforced composites like Al6061–Al_2O_3 [42]. These advantages position microwave heat treatment as a promising technique for optimizing the performance of AMCs in demanding engineering applications.

Magnesium alloys

The physical properties of magnesium alloys and especially the combination of mechanical properties, Young's modulus and density make them very useful for applications as the matrix of composite materials [11]. Magnesium alloys, especially castings, are used in aircraft gearbox housings, chain saw housings, electronic equipment, etc. Magnesium, being a hexagonal close-packed metal, is difficult to cold work [12].

Copper

Copper has a face centered cubic structure. Its use as an electrical conductor is quite ubiquitous. It has good thermal conductivity. It can be cast and worked easily. One of the major applications of copper in a composite as a matrix material is in niobium-based superconductors [10].

Due to the fact that small additions of alloying elements to copper and existing impurities lower considerably its electrical conductivity (the addition of 0.3% Zn to copper lowers the electrical conductivity to 85% IACS, of 1.25% Al to 70% IACS and of 0.1% P to 50% IACS, taking into account that the electrical conductivity of pure copper is 58 MSmÿ1 ˆ 100% IACS) the increase of its mechanical properties by conventional alloying methods is associated with considerable lowering of its electrical conductivity. On the other hand composite materials on a copper basis having good mechanical properties are characterized by relatively good electrical conductivity. Currently copper-based composite materials are produced by powder metallurgy methods, by mechanical blending of copper powders with dispersion powders, cold pressing and then hot consolidation processes by forging or extrusion. The production of composite materials by this method is relatively simple, but on the other hand there are problems with the blending of powders characterized by different densities (the segregation effect) and the distribution of the dispersion particles in matrix depends on the diameter of the copper matrix particles [11].

Titanium Alloys

Titanium is one of the important aerospace materials. It has a density of 4.5 g/cm3 and a Young's modulus of 115 GPa. For titanium alloys, the density can vary between 4.3 and 5.1 g/cm3 , while the modulus can have a range of 80–130 GPa. High strength/weight and modulus/weight ratios are important. Titanium has a relatively high melting point (1,672C) and retains strength to high temperatures with good oxidation and corrosion resistance. All these factors make it an ideal material for aerospace applications. Titanium alloys are used in jet engines (turbine and compressor blades), fuselage parts, etc. It is, however, an expensive material [10].

Nickel-based super alloys

Nickel-based super alloys produced by powder metallurgy methods are characterized by better high temperature mechanical properties than conventional high temperature alloys. They find applications especially in jet engine technology and industrial turbines.

Composite material MA6000 produced by mechanical alloying is based on nickel alloy reinforced with very stable dispersion yttrium particles (Y_2O_3). MA6000 is characterized by very good mechanical properties at elevated temperatures, is resistant to creep and is of special importance in jet engines production technology [11].

2.3. Reinforcing materials for Metal Matrix Composite

Reinforcing materials are essential for improving the mechanical, thermal, and wear characteristics of metal matrix composites (MMCs). These materials are generally incorporated into a ductile metal matrix, such as aluminum, magnesium, or titanium, to address the shortcomings of monolithic metals, especially in scenarios that require high strength-to-weight ratios, wear resistance, and superior thermal performance [43].

Reinforcements can be categorized by shape into particulates, short fibers, whiskers, and continuous fibers, and by material type into ceramics, carbides, oxides, and even metallic or hybrids [44]. Among these, ceramic particulates like aluminum oxide (Al_2O_3), silicon carbide (SiC), and titanium carbide (TiC) are commonly utilized in aluminum matrix composites due to their exceptional hardness, thermal stability, and rigidity [45], [46].

Al_2O_3 provides high hardness and excellent chemical stability, making it ideal for wear-resistant applications, while SiC offers a favorable combination of thermal conductivity and strength. TiC is recognized for its ability to enhance both strength and corrosion resistance. These reinforcements enhance mechanical performance by obstructing dislocation movement and distributing applied loads across the matrix–reinforcement interface [46].

Fiber reinforcements, such as carbon fibers and alumina fibers, are favored in applications that demand high strength and stiffness in a specific direction. Although they are more costly, fiber-reinforced composites demonstrate superior fatigue resistance and are utilized in the aerospace and high-performance automotive industries [47].

Recent advancements have also concentrated on hybrid reinforcements, where two or more types of reinforcements are employed to synergistically improve composite performance. For instance, the combination of Al_2O_3 with graphite or carbon nanotubes can enhance both wear resistance and self-lubricating properties, which is advantageous for moving mechanical assemblies [48].

Despite the advantages, challenges persist in attaining consistent distribution and robust interfacial bonding between the matrix and reinforcement. Several processing techniques such as stir casting, powder metallurgy, ultrasonic-assisted casting, and microwave sintering, have been created to tackle these challenges [49].

The use of reinforcing materials in metal matrix composites (MMCs) plays a crucial role in enhancing their mechanical, thermal, and wear properties. These materials are integrated into ductile metal matrices like aluminum, magnesium, or titanium to overcome the limitations of monolithic metals, especially where high strength-to-weight ratios and superior wear and thermal performances are desired [43].

Reinforcements are categorized by shape into particulates, short fibers, whiskers, and continuous fibers, and by material type into categories such as ceramics, carbides, oxides, and metallic or hybrid materials [44]. Ceramic particulates, including aluminum oxide (Al_2O_3), silicon carbide (SiC), and titanium carbide (TiC), are widely used in aluminum matrix composites for their hardness, thermal stability, and rigidity [45],[46].

Aluminum Oxide (Al_2O_3) Known for high hardness and chemical stability, making it suitable for wear-resistant applications while Silicon Carbide (SiC) Offers a good balance of thermal conductivity and strength and Titanium Carbide (TiC) Enhances both strength and corrosion resistance. These materials enhance mechanical performance by hindering dislocation movement and distributing applied loads across the matrix–reinforcement interface [46].

Fiber reinforcements, such as carbon and alumina fibers, are preferred in applications requiring high directional strength and stiffness. Despite being more expensive, they exhibit excellent fatigue resistance, making them ideal for the aerospace and high-performance automotive industries [47].

Emerging advancements focus on hybrid reinforcements, using two or more types of reinforcements together to improve composite performance synergistically. For example, combining Al_2O_3 with graphite or carbon nanotubes can improve wear resistance and self-lubricating capabilities, beneficial for mechanical assemblies in motion [48].

However, achieving consistent distribution and strong interfacial bonding between the matrix and reinforcement remains challenging. Techniques like stir casting, powder metallurgy, ultrasonic-assisted casting, and microwave sintering have been developed to address these issues, improving the quality and performance of MMCs [49].

2.3.1. Aluminum oxide (Al_2O_3)

Different crystalline structures of Al_2O_3 exist, among which α-Al_2O_3 or corundum is the most stable and commonly used phase. This phase has high compressive strength, a Mohs hardness of about 9 and a melting point of about 2072 °C [50]. Because of these characteristics, it is well suited to be used as a reinforcing agent for metal matrix composites (MMCs), particularly aluminum matrix composites such as Al6061–Al_2O_3 which exhibit a dramatic increase in wear resistance, strength, and stiffness [52].

Alumina is advantageous when high strength to weight ratios are needed, with a high modulus of elasticity, ~380 GPa and low density, ~3.95 g/cm 3 . In addition, it is an excellent electrical insulator and chemically inert, which is the reason for its use in electronic substrates and corrosion resistant" environments" [51].

The addition of Al2O3 particles in a metal matrix in composite applications helps in pinning dislocation motion to enhance the load supporting capability and wear resistance of the composite. More importantly, it also makes the material thermally stable, thus also suitable to operate at high temperature [52],[53].

But, the reinforcement of Al 2 O 3 suffers some drawbacks, like lack of good wettability with the aluminum matrices and possible agglomeration of the particles in the processing steps. The problem of poor interfacial bonding and particle distribution is often overcome by use of surface treatments, or via processing techniques such as stir casting, powder metallurgy or microwave sintering [53].

Though this brittleness is a drawback for monolithic forms, it is actually beneficial when Al_2O_3 is used in composites because in that instance it serves as reinforcement for the metal matrix without having a major impact on ductility. It is continually being developed for automotive, aerospace, and biomedical applications as processing techniques and hybrid reinforcements continue to evolve [54].

2.4. Fabrication methods of metal matrix composite materials

Composite materials with a metal matrix are produced by casting and powder metallurgy methods. By means of casting methods, composite materials reinforced by dispersion particles, platelets, non-continuous (short) fibers and continuous (long) fibers as well as composite materials with hybrid reinforcement composed of particles and fibers are produced. By powder metallurgy methods, composite materials reinforced by dispersion particles, platelets, non-continuous fibers and continuous) fibers are manufactured [11].

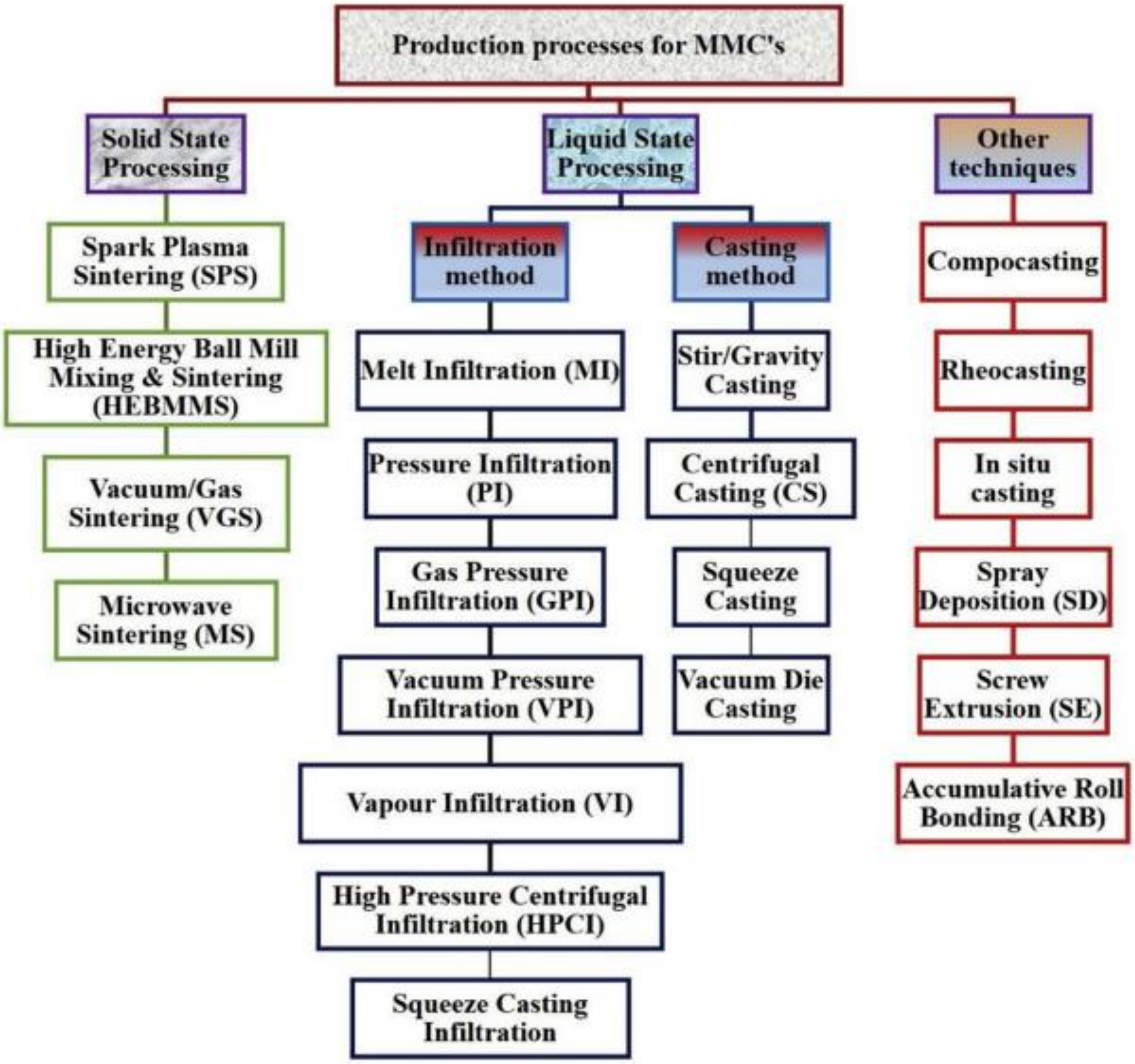


Figure 2.2 Fabrication methods of metal matrix composite materials [26].

2.4.1. Solid state processing/powder metallurgy: Solid state fabrication of MMCs is the process of bonding matrix material and reinforcements due to mutual diffusion arising between them in solid states at a higher temperature and under pressure.

2.4.2. Liquid state processing of MMC's: is eye-catching to many industries as they are relatively simple and economical. These processes include either the infiltration methods of molten metal into preforms or fiber pack or by the casting methods such as mixing of molten metal with reinforcement particles. Infiltration methods include melt, pressure, gas pressure, vacuum pressure, vapor, high pressure centrifugal and squeeze casting. Casting methods include processes such as stir gravity, stir squeeze, stir vacuum and centrifugal casting [26].

Stir casting is the most popular and commercially used technique in liquid-state processing, since it is economical compared to other manufacturing techniques. It also provides fairly homogenous dispersion of reinforcements in matrix, better wettability, and reduced porosity. Stir-casting process parameters have a substantial impact on determining the characteristics of AMCs. Nevertheless, process parameters such as the reinforcement size, speed of stirrer, stirring time, stirrer blade design, and melt temperature are found to have a maximum impact. Conveniently, those parameters can be easily altered without any additional effort and expense throughout the process. Hence, the selection of process variables is of considerable importance [3].

2.5. Heat treatment

2.5.1. Conventional heat treatment

Heat treatment is the process of heating and cooling to achieve desired physical and mechanical properties through modification of their crystalline structure of the materials. Temperature, length of time, and rate of cooling after heat treatment will impact all properties dramatically. Most common reasons to heat treat include increasing strength, increasing hardness, increasing toughness, improving ductility and increase in corrosive resistance. It is an important operation in the manufacturing process of many machine parts [57].

Solution heat Treatment: This handle includes heating the AMC to a temperature (ordinarily 480–540°C depending on the matrix) dissolve alloying components into the solid solution. However, the presence of reinforcements may hinder diffusion, requiring optimized soaking times.

Quenching: Quick cooling is performed to hold the solute iotas in a supersaturated strong arrangement. Care must be taken to avoid thermal stresses that will lead to micro cracking at the matrix–reinforcement interface.

Aging: The supersaturated arrangement is aged to accelerate strengthening stages. In T6 treatment (artificial aging), temperatures around 120–200°C are utilized. Fortification particles can act as heterogeneous nucleation sites, influencing the size and distribution of precipitates.

2.5.2. Microwave heat treatment

Microwave heat treatment is an inevitable, realistic and economic method over than the conventional heat treating method. This process requires a microwave furnace and a simple masking arrangement and help to obtain uniform temperature distribution throughout the material, maximize the physical and mechanical properties and to minimize the power consumption [12].

Conventional processing methods involve heating of the surface and then transferring heat into the materials by the phenomenon of conduction, convention, and radiations; whereas in microwave heating, the atomic level heating is present, which gives volumetric heating in the processed component.

Material when being heated by microwaves, electromagnetic energy is converted to heat from the inside out. The mechanism behind this approach to microwave heating entails several advantages over conventional heating for the following reasons:

The direct absorption of microwaves within materials allows volumetric heating which produces enhanced diffusion rates, reduced power consumptions, and lower processing times.

These characteristics of higher heating rates and higher diffusion rates allowed improvements in physical and mechanical properties of the microwave-processed materials or components owing to which the formation of defects are lower.

Further phenomenon of volumetric heating provides selective heating and uniform heating, leading to decreased processing temperatures, reduced thermal gradient, reduced heat-affected zone, and lower environmental hazards [58].

The recommended time and temperature for the microwave heat treatment depends on several factors such as reinforcement content and type, desired material property and size of heat treated material.

Table.2.1. General Parameter guideline for microwave heat treatment [1], [12], [58].

Parameter	Recommended rate
Temperature	450 °C - 650°C
Microwave power	700 W – 2500W
Pre heat time	2 min - 3 min
Holding time	5 min - 15 min

2.6. Related Literature

The study conducted by D. Loganathan et al. focused on evaluating the effect of microwave heat treatment on the mechanical properties of Al6061-T4 sheet metal. Cold-rolled aluminum alloy sheets with a thickness of 1.15 mm were used for the investigation. Tensile specimens were prepared according to ASTM E-8 standards. An 850 W microwave furnace was employed to carry out the heat treatment at 350°C for 10 minutes, with temperature control maintained via an embedded controller. The results from mechanical testing showed significant improvements in tensile strength, yield strength, and hardness when compared to conventionally heat-treated samples, demonstrating the potential of microwave treatment in enhancing the mechanical performance of Al6061 alloy [12].

The study by Nazim Mahmutyazicioglu et al. examined the effects of alumina (Al_2O_3) addition on the mechanical behavior and cell structure of PCM-processed Al6061 alloy foams. Al6061 and Al_2O_3 foams were fabricated using the Powder Compact Melting (PCM) method with varying Al_2O_3 contents of 0, 3, 5, and 10 vol%, followed by heat treatment via annealing and quenching. The resulting foams were characterized through metallographic analysis, micro hardness testing, and compression testing. Fully heat-treated foams exhibited the highest hardness values and showed up to a 100% increase in collapse strength compared to untreated samples. The addition of up to 5 vol% Al_2O_3 led to improved cell structure and reduced drainage. Compression test outcomes were analyzed in relation to the foam microstructure, with correlations drawn between the relative density and both the unloading modulus and compression strength of the foams [13].

The study conducted by V. Mohanavel et al. focused on investigating the influence of alumina (Al_2O_3) particle reinforcement on the mechanical properties of aluminum 6082 alloy. Composites were fabricated using the stir casting method with varying alumina volume fractions from 0% to 3% in 1% increments. The prepared samples were subjected to hardness and tensile tests, along with microstructural analysis. The mechanical performance of the composites was compared with that of aluminum 6061 alloy. The results demonstrated that both hardness and tensile strength increased with the rising weight fraction of alumina particles in the aluminum 6082 matrix [14].

The review conducted by Dipti Kanta Das et al. explored the current state of research and development in the fabrication and heat treatment techniques of ceramic-reinforced aluminum matrix composites. A key challenge identified in composite fabrication is achieving a uniform distribution of the reinforcing phase within the matrix, as this significantly influences the resulting properties and overall quality of the composite. The review emphasizes that mechanical properties can be effectively enhanced through appropriate heat treatment processes. Based on an extensive survey of existing literature, it was observed that most researchers employ either the powder metallurgy method or the molten metal stir casting technique, with the latter being more prevalent. Furthermore, the stir casting process was detailed and summarized into eight systematic steps [15].

The study by P. Subramanya Reddy et al. focused on investigating the mechanical properties of aluminum metal matrix composites (AMMCs) reinforced with silicon carbide (SiC) and boron carbide (B_4C), produced using the stir casting technique. The process involved melting aluminum 6061 alloy at 800 °C, followed by the addition of preheated (450 °C) SiC and B_4C reinforcements after vigorous stirring of the molten metal. Four composite samples were prepared by varying the weight percentages of the matrix and reinforcements. Morphological analysis using Scanning Electron Microscopy (SEM) was conducted to identify internal defects such as blow holes, hot spots, and reinforcement accumulation. Mechanical testing—including tensile, flexural, hardness, and impact tests—revealed that Sample 4 (96% Al6061, 2% SiC, 2% B_4C) exhibited the highest tensile and flexural strength, as well as the highest Brinell hardness, due to its higher reinforcement content. Conversely, Sample 1 (99% Al6061, 0.5% SiC, 0.5% B_4C) showed the highest impact energy absorption, attributed to its higher aluminum content. Overall, the results indicated that hybrid composites demonstrated superior mechanical performance compared to pure aluminum [16].

The study conducted by K. Rajkumar et al**.** focused on comparative analysis of the mechanical properties of Al6061-B_4C composites subjected to microwave and conventional heat treatment methods. The composite was fabricated using a two-step stir casting method, where aluminum 6061 alloy was melted at 700 °C and reinforced with varying volume percentages (5%, 10%, and 15%) of boron carbide (B_4C) particles sized at 25 µm. For heat treatment, an 850 W microwave oven and a 1450 W muffle furnace were used to process the 10% B_4C-reinforced samples. In the conventional method, it took 208 minutes to reach 520 °C, whereas the microwave method achieved the same temperature in just 15 minutes. The study found that microwave heating resulted in a finer microstructure due to the rapid and uniform heating, ultimately improving the mechanical properties and machinability of the composite material [1].

The review by Satnam Singh et al. provides a comprehensive overview of microwave processing technology as a relatively new, energy-efficient method for fabricating and treating engineering materials. The authors emphasize the advantages of microwave heating—especially its volumetric heating effect—over traditional conductive heating methods. Operating typically at a frequency of 2.45 GHz, microwave processing results in superior microstructures, significantly reduced processing times, and lower energy consumption. The review discusses fundamental microwave-material interactions, focusing on dielectric properties such as permittivity and dielectric loss tangent, which govern heating behavior. To address challenges with materials that poorly absorb microwave energy, the authors explore hybrid microwave heating using susceptors, which improve thermal uniformity and core heating. The review also highlights applications where microwave processing outperforms conventional techniques, particularly in the sintering of ceramics, metallic powders, and composites. These advantages include enhanced densification, controlled grain growth, improved mechanical properties (e.g., hardness and tensile strength), and reduced defects like porosity and cracking. Notably, materials such as W-Cu alloys, Al_2O_3/ZrO_2 nan composites, and stainless steels have exhibited near-full densification and finer microstructures through microwave sintering. Beyond composites, the authors also discuss emerging applications in metal melting, biofilm detection, thermal barrier coating evaluation, and carbon nanotube purification. The review concludes by noting gaps in research related to large-scale industrial implementation and processing of bulk metals and coatings, and suggests that microwave processing holds strong potential as a green, cost-effective manufacturing technology for future material development [58].

The review by G. Rajeshkumar et al**.** examined the potential of Al6061 alloy for use in automotive, aerospace, and marine applications through the incorporation of various natural and ceramic reinforcements. Al6061 is favored for its lightweight nature, low cost, and excellent corrosion resistance, making it an ideal matrix for reinforcement. The study highlights that ceramic reinforcements such as SiC (Silicon Carbide), Al_2O_3 (Alumina), and B_4C (Boron Carbide), as well as natural reinforcements like fly ash and neem leaf ash, contribute significantly to improvements in hardness, tensile strength, wear resistance, and other mechanical properties. SiC enhances hardness, elastic modulus, and thermal conductivity; Al_2O_3 boosts tensile and yield strength; B_4C adds high hardness, strength, and thermal stability; while fly ash and neem leaf ash offer economical reinforcement with improved wear and tensile properties. Notably, hybrid combinations such as Al6061 + SiC + Neem Ash and Al6061 + B_4C + Fly Ash demonstrated superior performance compared to mono-reinforced systems, offering a balanced improvement in cost-effectiveness and mechanical behavior. The review underscores the effectiveness of the stir casting method for fabricating these composites and stresses the importance of process parameters like preheating, stirring conditions, and material selection in achieving optimized properties. Overall, hybrid reinforcement is recommended for enhanced mechanical and thermal performance in Al6061-based composites [59].

2.7. Summary of literatures

Table.2.2. Summary of related research works

Author name	Title of the research	Methodology used	Gaps to solve	Finding and solution
D. Loganathan et al [12].	Effect of Microwave Heat Treatment on Mechanical Properties of Al6061 Sheet Metal	Comparison of the effect of conventional heat treatment and microwave heat treatment	Addresses the lack of experimental comparison between conventional and microwave heat treatment for thin aluminum alloy sheets	Microwave heat treatment significantly enhances the mechanical performance, microstructure, and energy efficiency of AA6061 sheets compared to conventional heat treatment methods
Nazim Mahmutyazicioglu et al [13].	Effects of alumina (Al_2O_3) addition on the cell structure and mechanical properties of 6061 foams	comparing the effect of different heat treatment and percent ratio on microstructure, hardness, and compression testing	Addresses this by integrating ceramic reinforcement with post-processing heat treatments and correlating it with both structure and mechanics	3–5 vol% Al_2O_3 improved foam structure. 10 vol% Al_2O_3 resulted in poor structure: fewer, larger, irregular cells, and high drainage. Heat-treated samples showed a hardness enhancement.

				Al_2O_3 did not affect hardenability
V. Mohanavel et al [14].	Mechanical behavior of Al-matrix Nano composites produced by stir casting technique	The experiment is done by varying the Wt% of alumina particles from 0 to 3%	The research sought to fill this gap by analyzing the effect of increasing nano-alumina volume fraction on the mechanical properties (hardness and tensile strength) and microstructure of the composite.	In addition to wt % in studying the mechanical properties stirring speed and stirring time have to consider be considered since they affect the material.
Dipti Kanta Das et al [15].	Fabrication and heat treatment of ceramic reinforced	Review related papers and give conclusion	Aim to review the development in fabrication and heat treatment	Preheating temperature of the mould and pouring temperature is

	aluminum matrix composites - a review		techniques of ceramic-reinforced aluminum matrix	critical step. Stir casting is a more suitable fabrication method for aluminum
P. Subramanya Reddy et al [16].	Investigation of Mechanical Properties of Aluminum 6061-Silicon Carbide, Boron Carbide Metal Matrix Composite	Fabrication of composite with stir casting, Morphological Analysis, Testing some mechanical properties of Composite	Address common stir casting challenges like particle agglomeration and non-uniform distribution, observed through SEM.	Hybrid composites had better mechanical property enhancement than pure aluminum.
K. Rajkumar et al [1].	Microwave Heat Treatment on Aluminum 6061 Alloy Boron Carbide Composite	comparison studies analyzed by SEM	Address on how microwave treatment influences machinability (cutting force, surface finish) in such composites.	Microwave heat treatment offers efficient alternative to conventional methods. It improves mechanical properties and machinability of Al6061–B_4C composites.

2.8. Gap identified

Previous studies have shown that heat treatment via microwave applications can enhance the mechanical properties of aluminum alloys and metal matrix composites (MMCs) the majority of existing work has been done on metals reinforced with alternate reinforcements such as SiC and B4C, or foamed structures. Al6061 sheet metal, showing enhancement in mechanical properties like tensile strength and hardness after heat treatment using microwaves but did not study the effect of ceramics reinforcements. Also demonstrating the advantages of processing time and microstructural refinement when using microwave methods. But, most of these works are focused on hybrid systems or on single-phase systems.

It is known that Al_2O_3 used as a reinforcement for aluminum alloys (i.e. 6082or 6061) enhances its mechanical properties and that stir casting is generally employed for fabricating composites.

Hence, the present study explores the unknown by seeking to systematically observe the mechanical and microstructural performance of Al6061/Al_2O_3 composites after microwave heat treatment, and will report findings that could be useful within the context of engineered applications such as control arms for automotive that need to be lightweight and strong.

CHAPTER THREE

3. Research Methods and Materials

3.1. Research Methodology

The general methodology that is indispensable for achieving objectives of this research work are shown in figure 3.1.

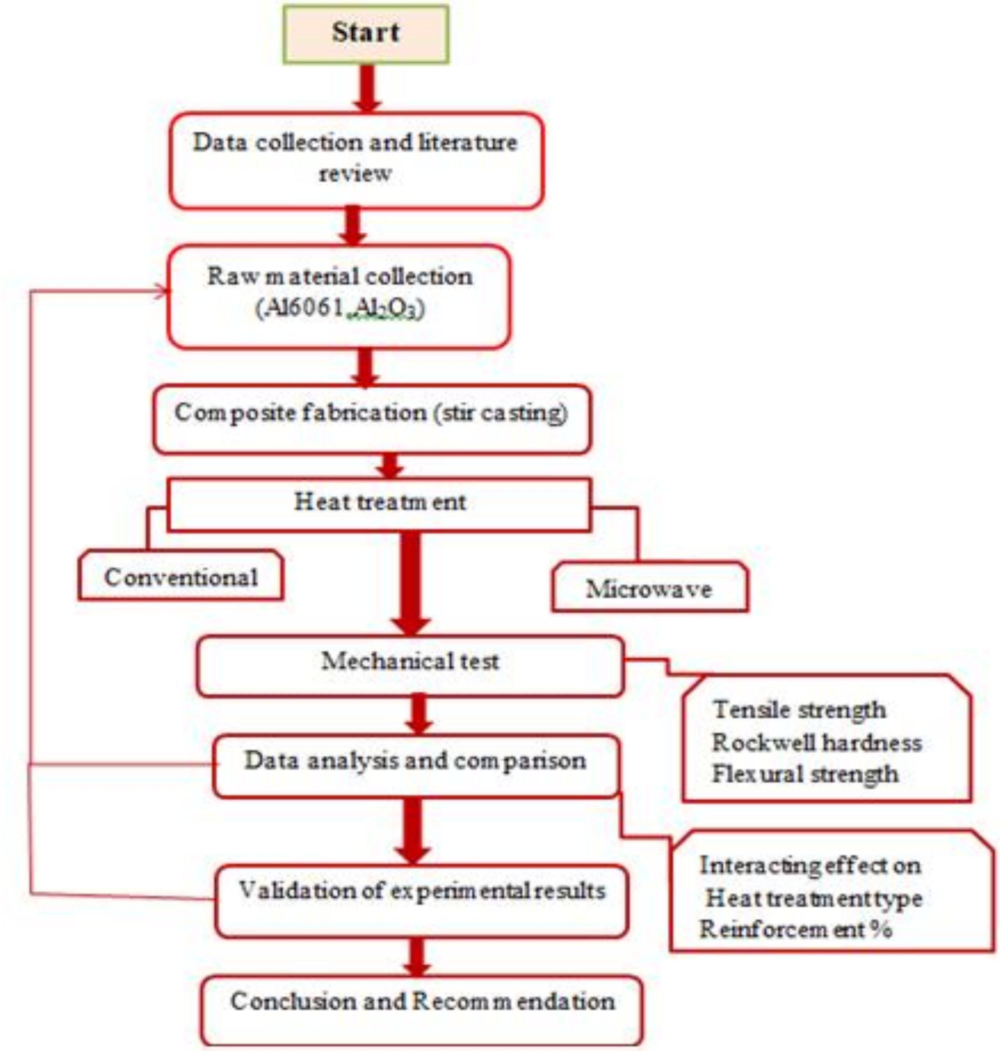


Figure 3.1 Schematic diagram of Methodology and procedure of research study

3.2. Materials

The materials that will be used in the present study are 100 percent chemically pure alumina (Al_2O_3) particles and Aluminum 6061 alloy which served as the matrix.

3.2.1 Aluminum 6061 alloy

Al 6061 aluminum alloys are heat treatable, can be appreciably strengthened, and are used for various applications in which strength and corrosion resistance are inevitable.

Al 6061 is one among the most popular alloy in 6XXX series, being used as matrix material in numerous AMCs because of the possibility to alter the composite strength through suitable heat treatment [3].

The composition of the Aluminum 6061 alloy which is gained from the spectroscopy test at Ethiopian technical university is shown in table below.

Table.3.1.Chemical composition of Al 6061 from spectroscopy test.

Element	Al	Mg	Si	Fe	Cu	Cr	Zn	Ti	Mn
Composition (mass percentage)	98.92	0.109	0.345	0.02	0.238	0.185	0.005	0.001	0.179

Figure 3.2 Aluminum 6061 sheet metal

Table.3.2. General Characteristics of Al 6061 aluminum alloy [29].

Characteristic	Appraisal
Strength	Medium to High
Corrosion Resistance	Good
Weldability & Brazability	Good
Workability	Good
Machinability	Good

Table.3.3. Physical properties of Al 6061 aluminum alloy [29].

Density	2.70 g/cm³
Melting Point	650 °C
Thermal Expansion	23.4 x10-6 /K
Modulus of Elasticity	70 GPa
Thermal Conductivity	166 W/m.K

3.2.2. Alumina (Al_2O_3)

Alumina powder is a ceramic of chemical composition Al_2O_3. The structure, the purity, the hardness and the specific surface area are the main characteristics of these powders.

For this research work, Al_2O_3 with analytical reagent grade with a particle size ranging of 70-230 mesh /63-210µm has imported by parafinos Chemicals Trading, located in Addis Ababa, Ethiopia. To fabricate the composite samples, Al_2O_3 with different weight percentages has used which will help to characterize the morphological and mechanical property of the composite.

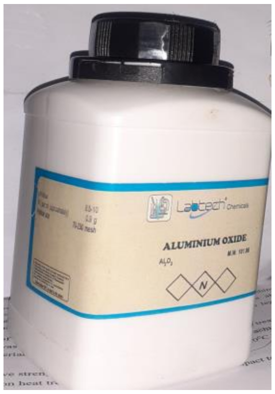


Figure 3.3 Laboratory grade Aluminum oxide (Al2O3)

The aforementioned literature indicates when the weight fraction of the Al_2O_3 increased linearly the hardness of the composite increase in the same case the toughness and ductility of the composite decrease this is due to increase in brittleness between the alloy Al 6061 and Al_2O_3 interface. In this research the volume fraction of 5%, 10% and 15% of Al_2O_3 is used [13] [27].

3.3. Aluminum 6061 Alloy alumina Composite fabrication

The quantity of Aluminum (6061) alloy and alumina (Al_2O_3) particles required to produce composites having 10 volume percent alumina were evaluated using charge calculations. Stir casting is used to prepare metal matrix composites. Aluminum 6061 alloy is melted in an electric furnace and the melt temperature increased above the melting point of aluminum. After melting the aluminum alloy, degasser is used to remove the gases which eliminate the porosity in castings. Meanwhile, alumina is preheated using a muffle furnace to help improve wettability with the Al 6061 alloy.

The liquid alloy then allowed cooling in the furnace to a semi solid state at a temperature of about 600^0 C. Then preheated reinforcement particles are slowly added to aluminum 6061 alloy melt when it's stirred manually. The composite slurry was then superheated to 720^0 C and a second stirring performed. The stirring operation help improve the distribution of the alumina particles in the molten Al 6061. The molten composite is then cast into prepared sand molds. The Al6061 – alumina composite melt is poured into the mould and it allowed to solidification which produced metal matrix composite castings [21] [22] [23].

Step 1. Preparing of matrix metal and reinforcing agent

Step 2. Determination of weight/volume fraction of reinforcement

Step 3. Preheating and/or melting of matrix alloy

Step 4. Additions of all cover flux during melting and degasser after melting

Step 5. Preheating of reinforcement

Step 6. Manual stirring, addition of preheated reinforcing agent and wetting agent and temperature control of the abrasive slurry

Step 8. Pouring the abrasive slurry to mold.

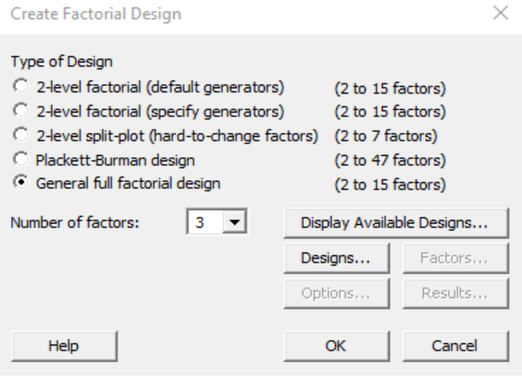
3.3.1. Design of experiment (DOE)

Experiments are carried out for researchers to collect data. These data then can be analyzed or processed to produce meaningful conclusions.

Experiments can be standard testing methods, independently developed procedures or laboratory scale model investigations. Standard testing methods such as according to BS or ASTM or other established standards, are commonly used to test materials and systems to be used in or related to the research or investigation.

Sample size is the number of observations used for determining the estimations of a given experiment. In this research Minithub software is used to know how many samples of specimens is needed using factorial method.

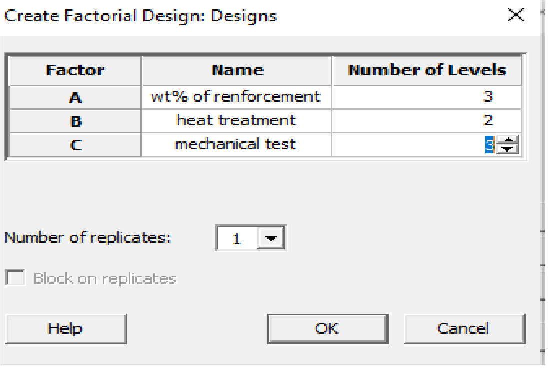
Step 1: **step 2**



Create Factorial Design

Type of Design
- ○ 2-level factorial (default generators) (2 to 15 factors)
- ○ 2-level factorial (specify generators) (2 to 15 factors)
- ○ 2-level split-plot (hard-to-change factors) (2 to 7 factors)
- ○ Plackett-Burman design (2 to 47 factors)
- ● General full factorial design (2 to 15 factors)

Number of factors: 3



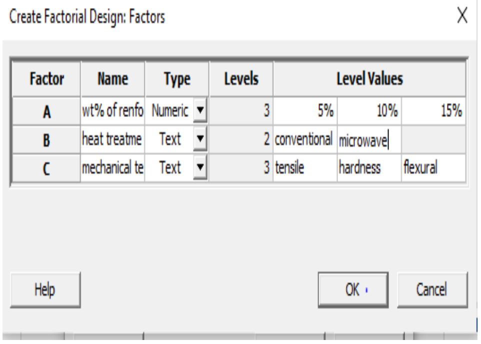
Create Factorial Design: Designs

Factor	Name	Number of Levels
A	wt% of renforcement	3
B	heat treatment	2
C	mechanical test	3

Number of replicates: 1

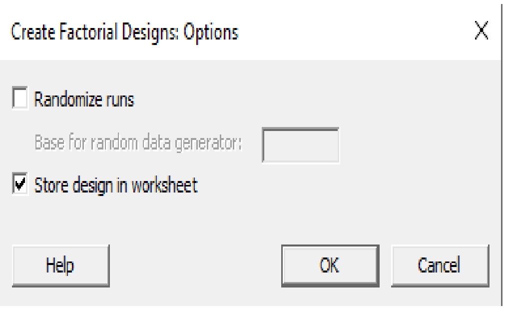
☐ Block on replicates

Step 3 **Step 4**



Create Factorial Design: Factors

Factor	Name	Type	Levels	Level Values		
A	wt% of renfo	Numeric	3	5%	10%	15%
B	heat treatme	Text	2	conventional	microwave	
C	mechanical te	Text	3	tensile	hardness	flexural



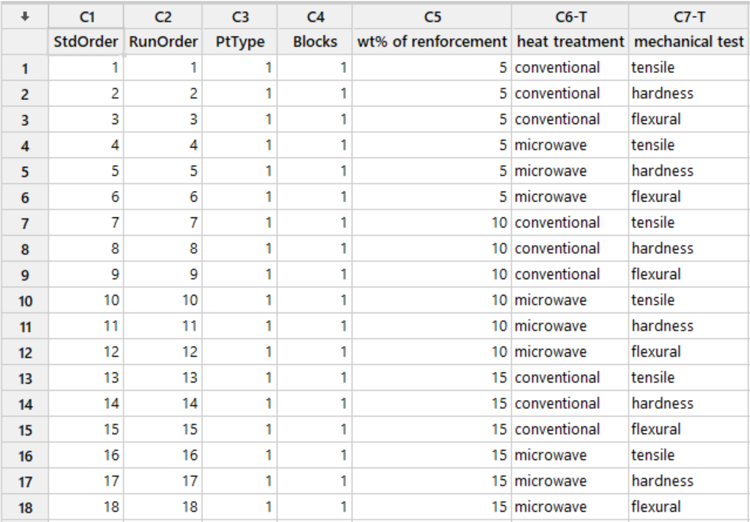
Create Factorial Designs: Options

☐ Randomize runs

Base for random data generator:

☑ Store design in worksheet

Step 5: create factorial design results in summary table



↓	C1	C2	C3	C4	C5	C6-T	C7-T
	StdOrder	RunOrder	PtType	Blocks	wt% of renforcement	heat treatment	mechanical test
1	1	1	1	1	5	conventional	tensile
2	2	2	1	1	5	conventional	hardness
3	3	3	1	1	5	conventional	flexural
4	4	4	1	1	5	microwave	tensile
5	5	5	1	1	5	microwave	hardness
6	6	6	1	1	5	microwave	flexural
7	7	7	1	1	10	conventional	tensile
8	8	8	1	1	10	conventional	hardness
9	9	9	1	1	10	conventional	flexural
10	10	10	1	1	10	microwave	tensile
11	11	11	1	1	10	microwave	hardness
12	12	12	1	1	10	microwave	flexural
13	13	13	1	1	15	conventional	tensile
14	14	14	1	1	15	conventional	hardness
15	15	15	1	1	15	conventional	flexural
16	16	16	1	1	15	microwave	tensile
17	17	17	1	1	15	microwave	hardness
18	18	18	1	1	15	microwave	flexural

Figure 3.4 factorial design with Minitab software

From the Minitab software result there will be 18 samples of specimens are needed for the tests which are fabricated in different weight fraction of reinforcement to matrix and also the heat treatment methods.

3.3.2. Volume Fraction of the Fiber and Matrix in the Composite

From the ASTM standard for the mechanical tests specimens, volume of pouring, the volume of a riser we can calculate the volume of composite to be produced. The mass of each component of the composite can be found by multiplying the density of the reinforcing materials with their volume and. The density of aluminum is 2.7 g/cm^3 and the density of alumina 3.95 g/cm^3. i.e

$V_{mold} = V_{composite}$ (but the volume of mold is without allowance and the volume of composite is with by adding the specimens allowance)

$V_{composite}$ = volume of total samples

Table.3.4. Number of sample needed for mechanical test

Test	Dimension (mm)	Composition percentage for *Al6061* and *Alumina (Al_2O_3)*					
		5 % Alumina (Al_2O_3)		*10 % Alumina (Al_2O_3)*		*15 % Alumina (Al_2O_3)*	
		Heat treatment					
		Conventional	*Microwave*	*conventional*	*microwave*	*conventional*	*microwave*
Tensile test	200*20*2.5 (with required futures)	1	1	1	1	1	1
Hardness test	15 *15*5	1	1	1	1	1	1
Flexural test	200*20*2.5	1	1	1	1	1	1

$V_{mold} = V_{composite} = 460cm^3$

$W_{composite} = V_{composite} * \rho_{composite}$ ………………………………………………………………. (3.1)

For sample 1 (5% Al_2O_3)

$\phi_{Al} = 0.95$

$\phi_{Al2O3} = 0.05$

$V_{Al} = \phi_{Al} * V_{composite}$ ………………………………………………………………………………. (3.2)

$V_{Al} = 0.95 * 460\ cm^3 = 437\ cm^3$

$V_{Al2O3} = 0.05 * 460\ cm^3 = 23\ cm^3$

$V_{composite} = V_{Al} + V_{Al2O3} = 460\ cm^3$

$\rho_{composite} = \rho_{Al}\ \phi_{Al} + V_{Al2O3}\ \phi_{Al2O3}$ ……………………………………………………………….. (3.3)

$= 2.7\ g/cm^3 * 0.95 + 3.95\ g/cm^3 * 0.05$

$= 2.7625\ g/cm^3$

$W_{composite} = \rho_{composite} * V_{composite}$

$W_{composite} = 2.7625\ g/cm^3 * 460\ cm^3$

$= 1270.75\ g$

$W_{Al2O3} = \rho_{Al2O3} * V_{Al2O3}$

$= 3.95\ g/cm^3 * 23\ cm^3$

$= 90.85\ g$

$W_{Al} = \rho_{Al} * V_{Al}$

$= 2.7\ g/cm^3 * 437\ cm^3$

$= 1179.9\ g$

Using the same method, for the weight fraction of Al_2O_3 10% and 15% is calculated and given in the table below:

Table.3.5. Volume Fraction of the Matrix and the Reinforcing particles.

Sample	ϕ_{Al}	ϕ_{Al2O3}	V_{Al}	V_{Al2O3}	$W_{composite}$	W_{Al2O3}	W_{Al}
2	0.9	0.1	414	46	1299.5	181.7	1117.8
3	0.85	0.15	391	69	1328.25	272.55	1055.7

3.3.3. Mold preparation

Sand casting is widely used because this process is simple, and almost any material can be cast, no limit to size, shape or weight, low tooling cost. The quality of the sand casting depends on the quality and uniformity of green sand material that is used for making the mold.

The main molding material in this study was 200–250 mesh silica sand. Additional binding elements were water, graphite powder, and molasses. On preparing the mold, 90% silica sand, 9% water and 1% molasses were added and mix well.

To prepare the sand casting first the patterns those are the specimens are prepared according to this ASTM standard dimension are prepared by wood including the allowance for shrinkage and light machining operation. Then parts of sand mold a cope and drag part are made. Put pattern from wood in sand to create mold cavity and do small hammering on the sand to make stability of the pattern then remove the pattern. [28].

Figure 3.5 preparation of sand molding

A) Silca sand mixed with molasses

B) test specimen pattern preparation

C) Ramming the mixed sand vigorously D) Removing the patterns

E) Clamping the cope over the drag F) Lubricating the cavities

3.3.4. Preheat the reinforcing material

Adding the Al_2O_3 particles directly into molten aluminum can cause thermal shock and particle agglomeration. Preheating reduces the temperature gradient and helps maintain particle dispersion also improving the composite's microstructure and properties.

The pretreatment is in general carried out in the temperature range of 100 to 300–500 °C, with a typical pretreatment starting at 100 °C to dehydrate the cell surface, and then ramping up in temperature to 300–500 °C to remove the chemically bound water. For items such as crucibles or linings which will come into direct contact with molten aluminum, the temperature treatment is commonly increased to 600–800°C to guarantee complete thermal stability [55], [56].

3.3.5. Casting and pouring

The aluminum is heated in a furnace to its melting point, which is approximately 680°C this is for full liquefaction.

But before placing the matrix in the furnace, the furnace is preheated at 350°C to 400 °C for about 15 min. The tiny chunks of Al6061 were then weighed and put in the charging medium graphite crucible's induction furnace. Consequently, a combination of Al_2O_3 was used to create particle reinforced AMCs with varying ratios of Al_2O_3 5, 10 and 15 wt %.

Al_2O_3 ceramic particles were initially heated in an electric furnace at 650 °C as part of this procedure.

Afterwards, the temperature of resistance furnace was increased above the melting temperature of Al near 700 °C to melt Al6061 completely. The addition of reinforcement particles in the Al matrix was done using stir casting. [30].

Since there is oxidation and slag layer at the top surface the slag skimmed off and the preheated Al_2O_3 particles were then added to the melt slowly. Stirring was carried out in a ceramic crucible for 10 min. After stirring vigorously the molten composite is heated at 700 °C for about 10 minute before pouring. During melting Sodium chloride is used as flux to prevent oxidation but there is oxidation and slag since we use stir casting.

The molten composite is poured through the pouring cup and fills the sand mold cavity then passing through down spur and gate. The riser is used as a reservoir for additional filling of mold cavity to compensate volumetric shrinkage during solidification.

Figure 3.6 processes of melting and casting the composite

A. Melting and stirring the Aluminum composite
C. Pouring into sand mould

B. Stirring the slurry
D. Removed cast parts

3.4. Heat treatment method

3.4.1. Conventional heat treatment

A heat treatment process designed to enhance its mechanical properties, particularly strength and hardness. Al6061 is primarily strengthened by precipitation hardening, where fine particles of a second phase (precipitates) form within the aluminum matrix.

The prepared specimens were solution treated at 540^{0}C for 6 hrs in a furnace and quenched in water at 60^{0}C. The temperature of the furnace was maintained within ± 5 ^{0}C of the set point by means of an automatic temperature controller.

Ageing treatment: The heat treated specimen were artificially aged at 4 hrs at a temperature of 200^{0}C and quenched in water at 60^{0}C [17] [25].

Figure 3.7 Heat treating the composite, Solution heat treatment, Quenching in water

3.4.2. Microwave heat treatment

Microwave heat treatment is a process that uses microwave radiation to heat and treat materials, Microwave heating can be applied to metal processing, such as heat treatment or alloy production, although its use is more challenging due to the way metals reflect microwave energy [1].

At room temperature microwaves are not absorbed by the metals; however, after reaching a particular temperature i.e. about 40% to 50% of melting point temperature, metals absorb microwaves. The specimen was kept inside the chamber, which is surrounded by two layers of elements, one is transparent to microwaves and other is absorber of microwaves [24].

The microwave oven which is found at Addis Ababa Science and Technology University is with 3 in1 watt power that is 900W, 1100W and 2500W.

In order to obtain T6 property of Al-6061 alloy, 1100W Microwave oven is used. Heat treatment was done over the material and it was heated up-to 520^0C in microwave oven. After reaching required temperature, the composite material was maintained for 6 minute at 520^0C.

Figure 3.8 Microwave heat treatmen with 1100W,holding for 6 minute

3.5. Mechanical Properties

The tensile strength, compressive strength, flexural strength, hardness and impact tests were carried out on both the heat treated & non heat treated composite material.

Universal testing machine

A Universal Testing Machine (UTM) is a versatile mechanical testing apparatus used to evaluate the mechanical properties of materials under various loading conditions. It can perform a range of tests including tensile, compressive, flexural (bending), and shear testing. The term "universal" signifies its ability to conduct multiple types of tests on different materials, such as metals, polymers, composites, and ceramics.

The UTM operates by applying a controlled force through hydraulic or electromechanical systems while simultaneously measuring deformation. It is equipped with load cells, extensometers, and digital control systems to capture data such as ultimate tensile strength, yield strength, elongation, Young’s modulus, and flexural strength with high accuracy [31].

In this study, the UTM was used to determine the tensile and flexural properties of Al 6061–Al_2O_3 composites. These measurements are crucial for understanding the material’s behavior under real-world mechanical loading.

3.5.1. Tensile test

A tensile strength test is a standard test among materials engineering and science to assess the tendency of a specific material to fail via tension. This test is important in order to characterize the mechanical properties of materials and is critical for functionality. In the tensile strength test, a sample material is pulled until it either deforms or breaks. The findings are significant in terms of the yield strength, ultimate tensile strength, elongation and reduction of area of the material and performing under load. This knowledge facilitates the selection of certain materials for given applications, which is important for safety, reliability and efficiency in product design and structure integrity.

The specimen is prepared as per ASTM E8M standard and follows the following procedure on universal test machine [18].

The prepared specimens (rectangular cross-section 57 x 2.5 mm & length 200 mm) were carried out utilizing Universal Testing Machine for the tensile test.

Figure 3.9 tensile test specimen test on the machine and specimen after test

3.5.2. Flexural strength test

The flexural test quantifies the response of a material to loading in simple bending. A flexural test applies a point load at designated locations on a sample until the sample bends or breaks. Following the ASTM A: 290 standard the specimen utilized was a square rod of dimension of 200x20 x 2.5 mm[19].

Figure 3.10 flexural test specimen tests on the machine and specimens after test

3.5.3. Hardness Test

Hardness testing measures the resistance of a material to deformation, usually permanent indentation. In hardness testing, a known force is applied to a standardized indenter that penetrates the surface of the material. The hardness value is obtained by measuring the depth, size, or area of the resultant indentation which is an indicator of the hardness, strength, wear resistance or durability of the material.

The sample is prepared as per ASTM E - 18 standard prepared in the size of 15 mm x 15 mm x 5 mm for hardness measurements. Hardness of specimens both for conventional and microwave heat treated will be carried out [12].

For each specimen, tests were taken at a different point, like two times the diameter of the other test point. The applied load was 100 kg, and the ball indenter used was 1/16' as the Aluminum Rockwell hardness test standard. Advantages of the Rockwell hardness method include the direct Rockwell hardness number display and fast testing time.

Figure 3.11 Rockwell hardness test specimen test on the machine and specimen after test

3.6. Specification of four wheeler control arm

3.6.1. Analytical data

By considering the structural and material properties needed four wheeler control arm is primarily selected for Al 6061 composite application area. Depending on this the Al

6061 composite four wheeler control arm is designed with SOLIDWORK 2021 software and imported to ANSYS 19.2 for analysis.

Suspension system serves purpose of providing stability to vehicle which results improving comfort ability of riding. It provides traction control and steering stability [32].

The automobile control arm is the primary safety mechanism in the chassis suspension system of an automobile. It is used to connect the body to the steering knuckle and to transmit the loads between the two. The design of the automobile control arm should be sufficiently strong and reliable. In the same time it is also needed to reduce weight and size in order to be lightweight, energy and emission saving. For this reason, understanding the trend and scheme of material selection in the control arm is highly relevant to vehicle chassis and overall safety.

The two predominant materials in automotive applications are aluminum alloys and steel, both with their own advantages and disadvantages. While compared to steel, aluminum alloy has the characteristics of lightweight and high formability, relatively lower strength and hardness of aluminum and aluminum alloy is somewhat limited for ensuring automobile safety [33].

A double A-arm wishbone design is far superior in strength and shock and vibration absorption, and therefore is the most widely adapted design used in double wishbone suspension systems [34].

For this research Toyota Hilux 2017 is selected because:-

The Toyota Hilux control arm has been chosen as the object of study as it plays a critical function in the vehicle’s suspension system, while also imposing demanding mechanical performance requirements. Plus, as a complex structural element that experiences bending and torsion loads, it is an ideal part to evaluate the implementation of aluminum matrix composites (AMCs) in the automotive industry. Several key factors support this selection:

1. **High stress application**: The control arm is put under high dynamic loads and would be an appropriate candidate to study the strength, stiffness and fatigue resistance of aluminum composites.

2. **Potential to Reduce Weight**: Elimination of the traditional steel control arm and substitution with an aluminum composite version is consistent with industry trends in reducing vehicle weight and improving fuel efficiency without sacrificing safety.

3. **Widespread Use of the Hilux**: The Toyota Hilux is a globally popular vehicle, particularly in markets that demand high durability and reliability. Improving its components with advanced materials has potential commercial relevance.

4. **Benchmarking Opportunity**: The existing performance data and material specifications of the Hilux control arm provide a solid benchmark against which the composite design can be compared.

This specific focus is intended to serve as a tool for establishing aluminum composites as a feasible solution for implementation in the field of automotive manufacturing, thereby playing a role in the advancement of lightweight, high performance materials for vehicles.

TOYOTA HILUX 2017 with double cab 4WD has double wishbone suspension type with double control arm made from steel.

Table.3.6. material properties of steel [35]

properties	Value	Unit
Density	7850	Kg/m^3
Young modulus	207	Gpa
Poisson’s ratio	0.3	-
Tensile yield strength	250	Mpa
Ultimate yield strength	460	Mpa
Hardness	61	HRC(Rockwell)

Table.3.7. dimensional specification of Double control arm for TOYOTA HILUX 2017 [60]

Specification	Value
Model	Double wishbone
Length	237mm
Width	288.5mm
Upper and lower bolt	24mm

3.6.2. 3D modeling of double control arm

Using SOLIDWORK 2017, the double control arm model was created. This software program is a 3D mechanical design tool for designing, visualizing, and simulating analyses in 3D prototypes. SOLIDWORK was used to represent a variety of industrial and mechanical design processes.

With the help of this software, the user may simply make modifications without having to start at the beginning and update every drawing. SOLIDWORK is a feature-rich parametric solid modeling program that is generally simple to use and has a wide range of expanded design and production applications.

For this research, based on the dimension given on table 3.7 3D modeling of double control arm is created with SOLIDWORK 2021 software.

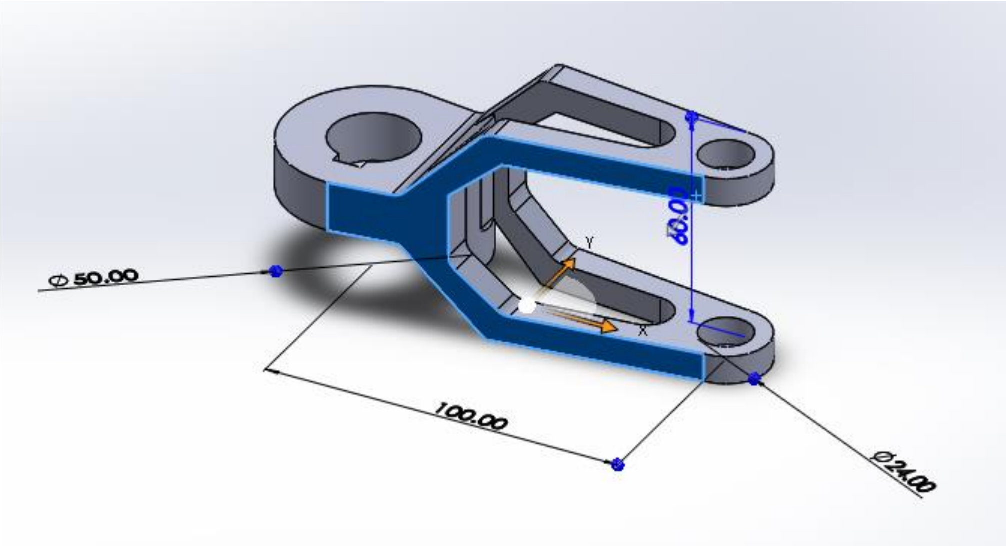


Figure 3.12 3D models for double control arm with SOLIDWORK2021 [60]

3.7. Finite element modeling and analysis

Finite element analysis (FEA) is a mathematical equation that is performed to form a simulation for providing a structural analysis of how a specific design would react under stress in the tangible world [36].

The consequences of continuous loading on a structure are investigated in detail in the field of ANSYS static structural analysis, which also evaluates stress, strain, and deformation under various loading scenarios. The incredibly flexible finite element analysis (FEA) program ANSYS 19.2 was used in this study.

3.7.1. Assumption for static structure analysis

Rigid arms: Control arms are often assumed to be rigid bodies in simplified models.

Fixed chassis: The vehicle frame (chassis) is often assumed to be fixed.

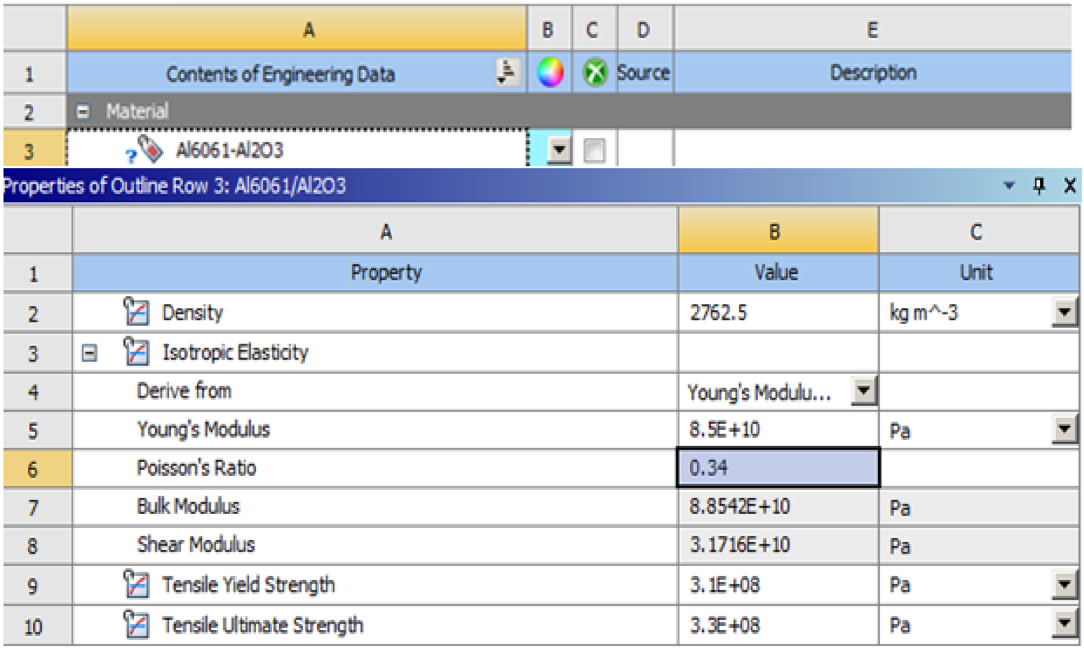
Linear elasticity: Unless analyzing failure or large deformation, materials are often assumed to behave linearly elastic

No wear/fatigue: short-term structural analysis often assumes any material fatigue or long-term degradation.

3.7.2. Finite element analysis procedure

I. Assign material and its properties

The mechanical properties of the material that is Al 6061 – Al_2O_3 composite can be entered with the aid of defining engineering data. Applying it involves selecting the Engineering Data from the ANSYS Workbench's analysis tab and entering the corresponding values. The experimental results are providing the fundamental equivalent values or material attributes.



	A	B	C	D	E
1	Contents of Engineering Data			Source	Description
2	Material				
3	Al6061-Al2O3		☐		

Properties of Outline Row 3: Al6061/Al2O3

	A	B	C
1	Property	Value	Unit
2	Density	2762.5	kg m^-3
3	Isotropic Elasticity		
4	Derive from	Young's Modulu...	
5	Young's Modulus	8.5E+10	Pa
6	Poisson's Ratio	0.34	
7	Bulk Modulus	8.8542E+10	Pa
8	Shear Modulus	3.1716E+10	Pa
9	Tensile Yield Strength	3.1E+08	Pa
10	Tensile Ultimate Strength	3.3E+08	Pa

Figure 3.13 Material properties of Al6061-Al2O3 composite represented on ANSYS

II. Import geometry

To perform an analysis, the 3D model created with SOLIDWORKS software and saved in IGS format was imported into the ANSYS program. Material qualities are assigned in order to precisely depict the components. The double control arm in this study is made of Al 6061 – Al_2O_3 composite.

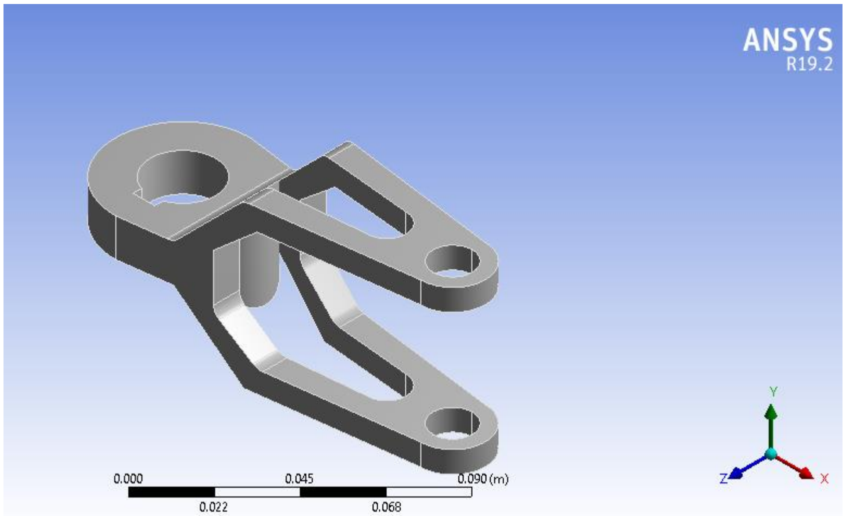


Figure 3.14 A 3D model of double control arm imported to ANSYS

III. Mesh generation

Analyzing the structure, which is an assemblage of discrete parts called elements joined at a finite number of places called nodes, is the fundamental idea behind FEA. The process of meshing, which creates a web between the features, breaks down the complex geometry model into manageable chunks in an otherwise unmanageable scenario. One component of the FEA is solid modeling. Therefore, Solid Modeling's only goal is to make the geometry's mesh as easily and effectively as feasible.

Using this setting, ANSYS constructs a mesh containing 27302 elements and 49120 nodes.

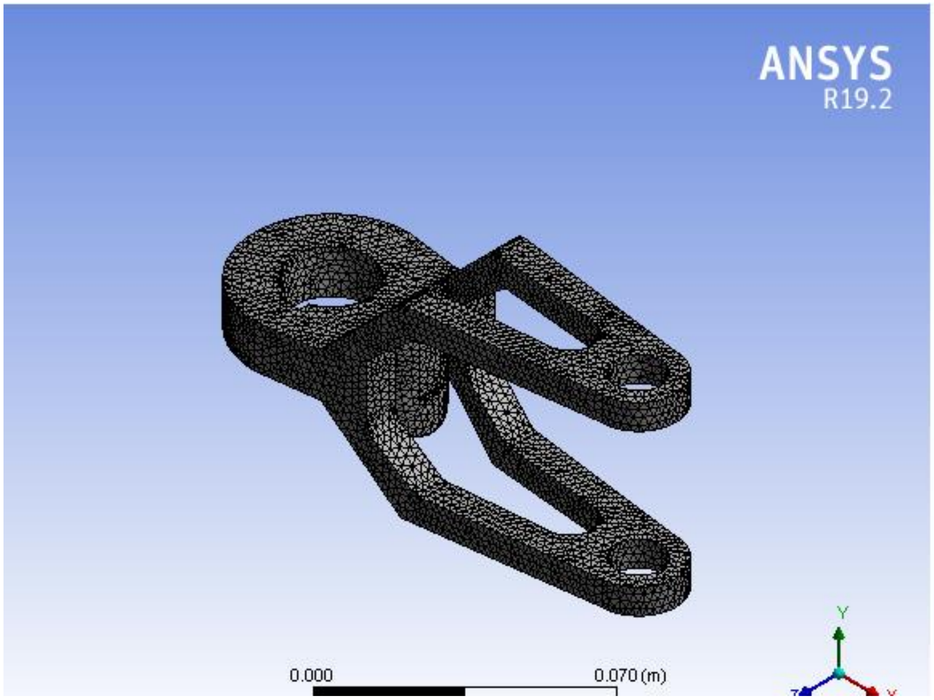


Figure 3.15 Mesh generation of the 3D model of control arm

IV. Boundary conditions for static analysis

Used a force and a fixed support as two boundary conditions in a static analysis. Similar to how a tire moves upward when a car passes through a pothole, a fixed support is applied to the bottom and higher portions of the chassis, and a force is applied upward to the knuckle joint.

Weight of the vehicle: 2000 kg

Weight distribution on suspension system: 67% at rear and 33% at front [34].

Gravitational force: 9.81

To find: F, Force on the vehicle

$$load = F \times \frac{weight\ distribution\ at\ the\ rare}{100} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \ (3.4)$$

With this including factor of safety we apply 20000N force.

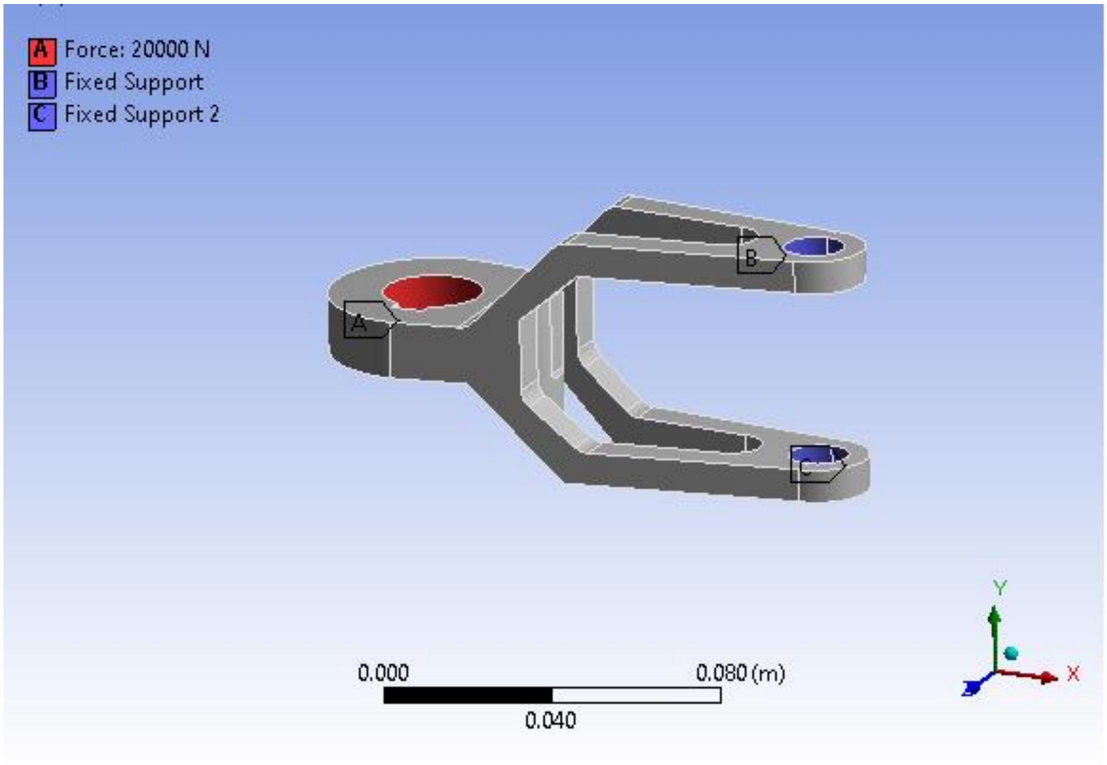


Figure 3.16 Boundary condition for double control arm

V. Generate solution

In this stage the solver carries out complex numerical calculations for quantities such as displacement and stresses. You can follow the progress of the solution from the solution information panel. Avoiding this procedure from being a trial and error process, a realistic set of boundary conditions, units and a good quality mesh, particularly in important regions of the geometry, must be maintained throughout to yield meaningful, accurate results.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Experimental Results

4.1.1 Tensile Test

For the tensile strength test three specimens are prepared for each Al 6061 - Al_2O_3 composition. The test was taken under ASTM E8/E8M standard. All specimens showed catastrophic collapse upon reaching their maximum value, followed by an abrupt drop in load. The specimens exhibited linear tendencies in brittle fracture to failure.

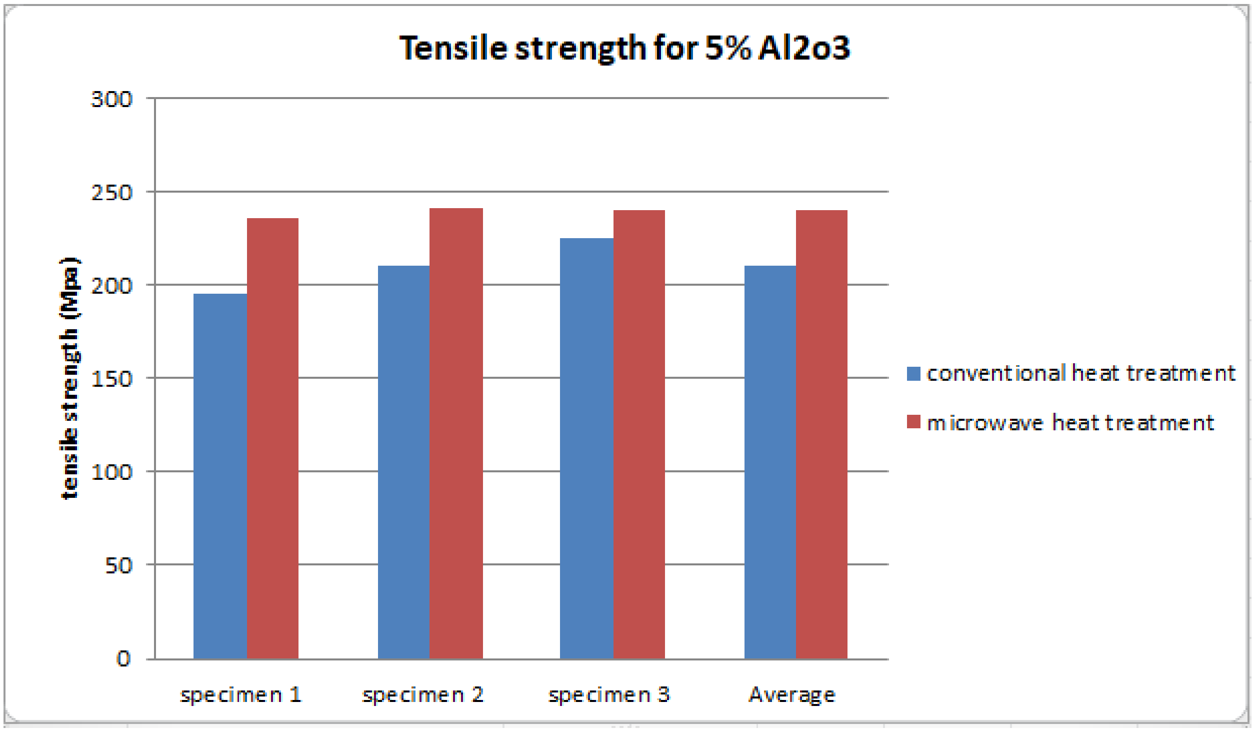


Figure 4.1 Tensile test results for 5% of Al_2O_3

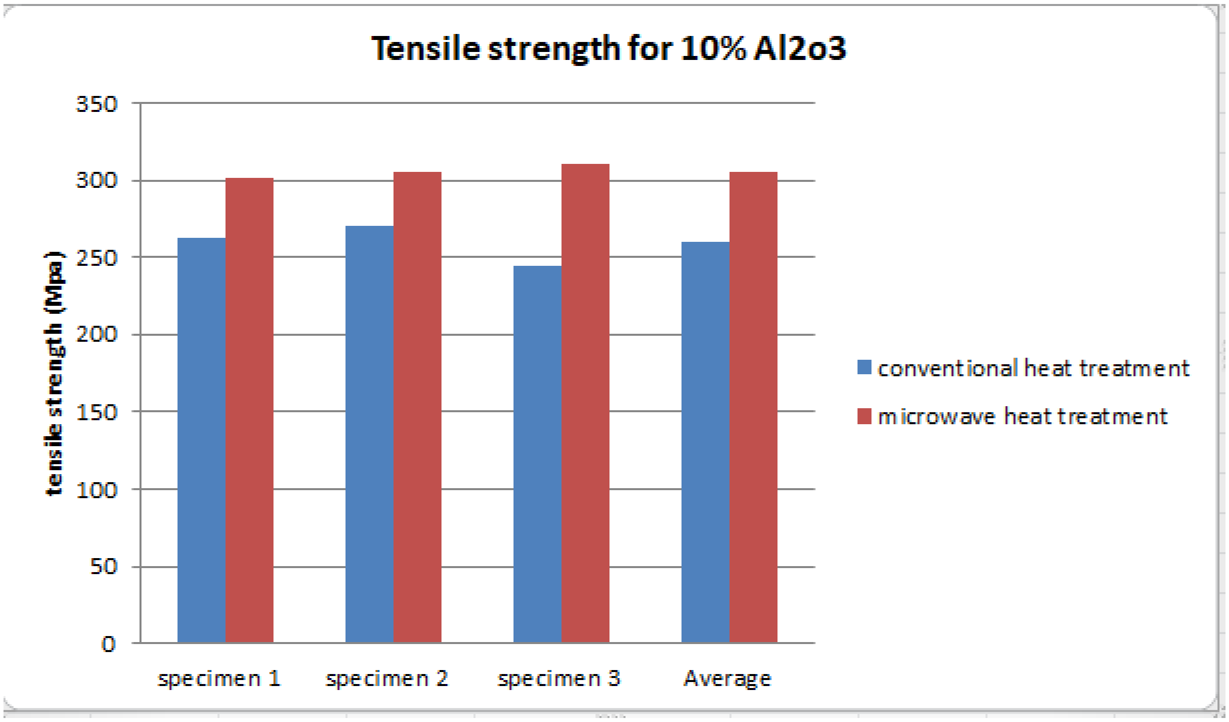


Figure 4.2 Tensile test results for 10% of Al_2O_3

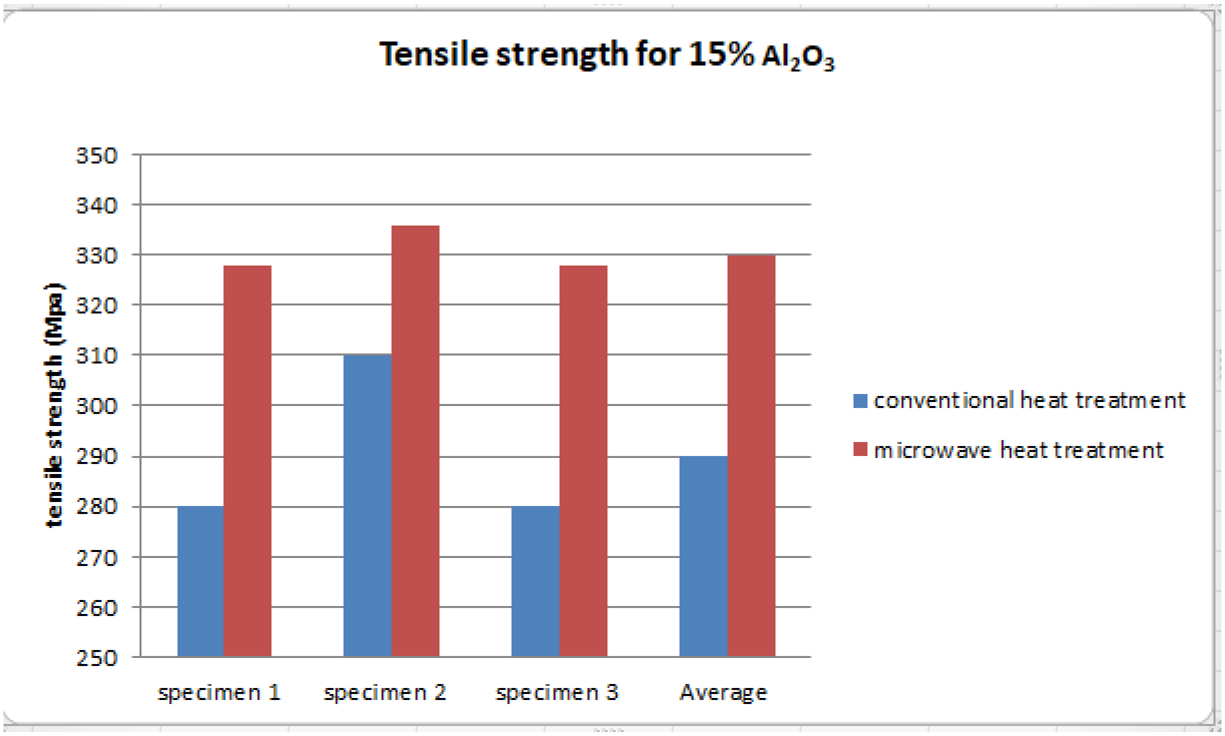


Figure 4.3 Tensile test results for 15% of Al_2O_3

4.1.1.1 Tensile test discussion

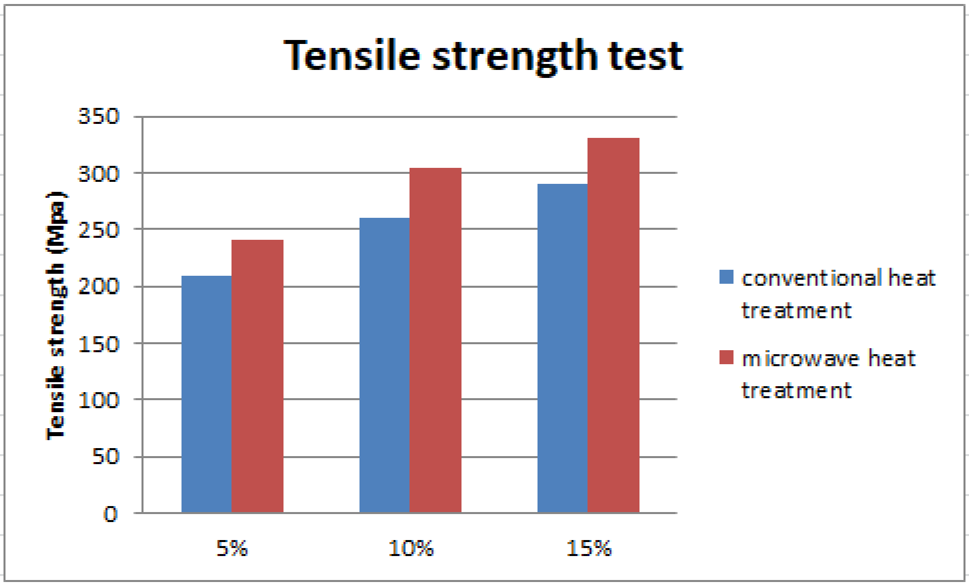


Figure 4.4 Tensile test results for all composition of Al_2O_3

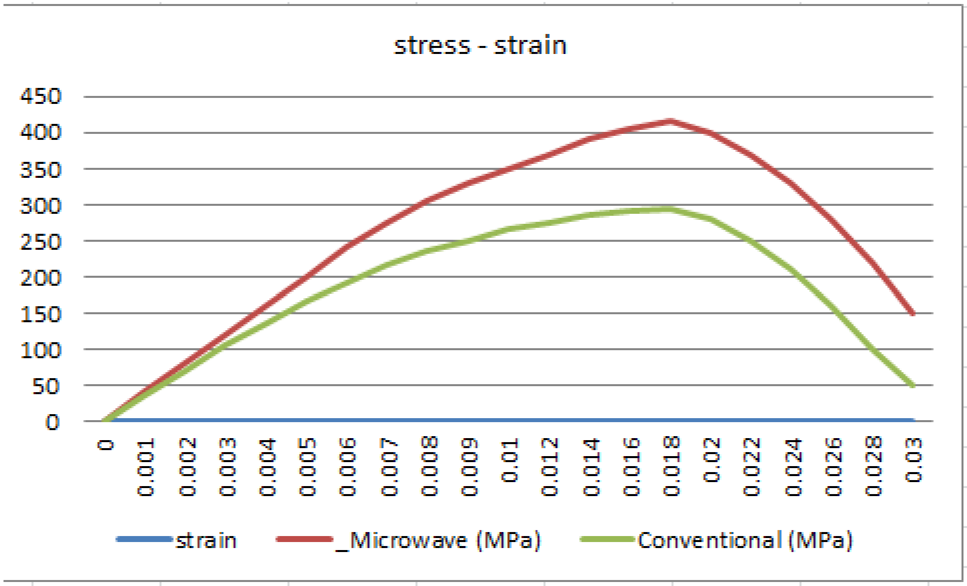


Figure 4.5 stress – strain comparison for microwave and conventional heat treatment

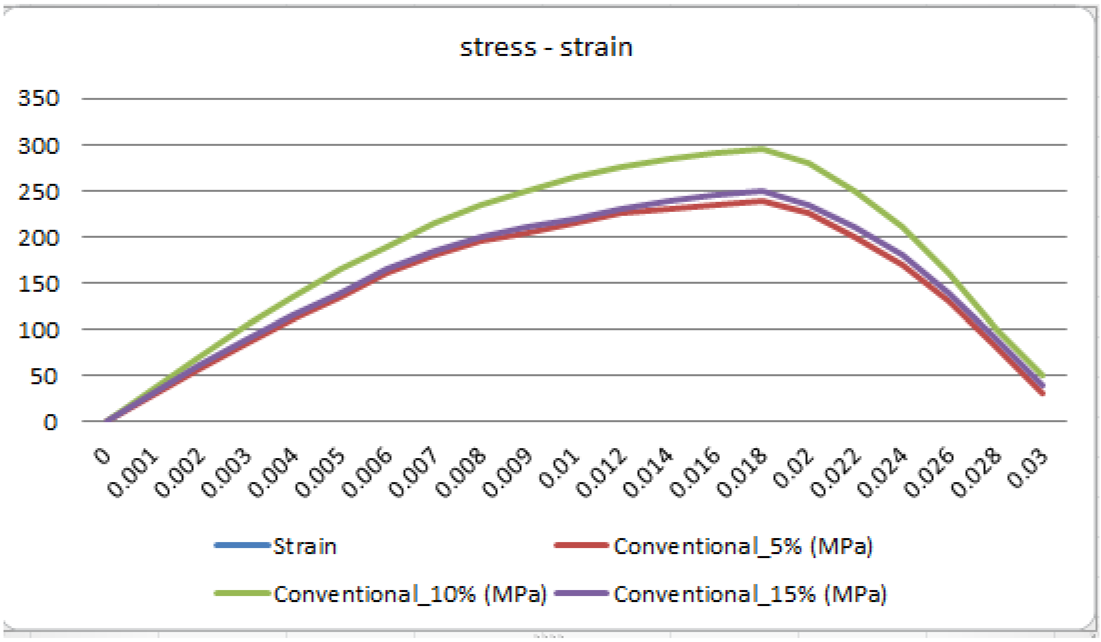


Figure 4.6 stress – strain comparison for conventional heat treatment

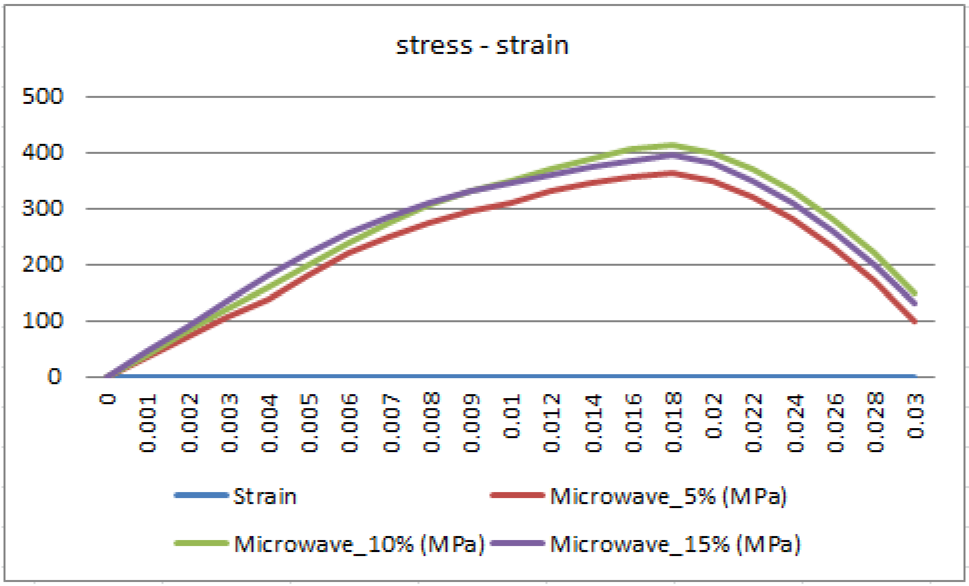


Figure 4.7 stress – strain comparison for microwave

The effect of Al_2O_3 reinforcement content on tensile strength and strain hardening is discussed below

For 5 % Al_2O_3 have moderate strength with highest elongation percentage, for 10% Al_2O_3 have optimal strength with slightly reduced elongation and for 15 % Al_2O_3 gain highest strength but further reduced elongation.

So higher Al_2O_3 improve the strength but reduce elongation percentage due to the brittleness of the reinforcement material but microwave treated composites outperform in both strength and elongation percentage at all levels because microwave heat treatment yields finer microstructures due to uniform rapid heating. This improves strength and energy absorption capacity.

4.1.2 Hardness Test

For the hardness test three specimens were prepared for each reinforcement loading. Hardness test Rockwell Scale B, with ball indenter 1/16 is performed.

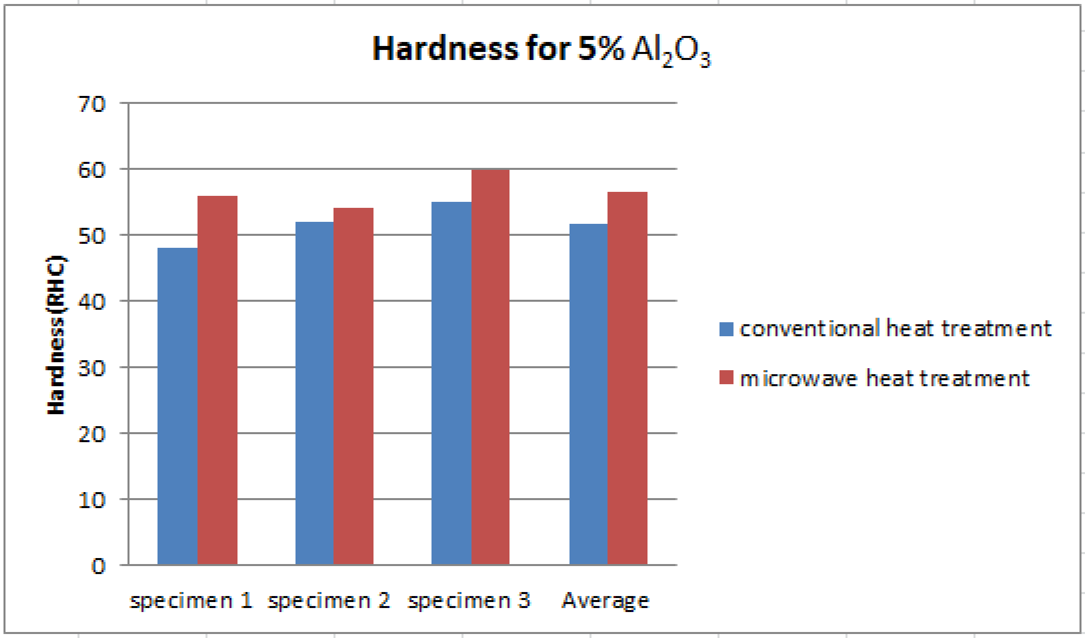


Figure 4.8 Hardness test results for 5% of Al_2O_3

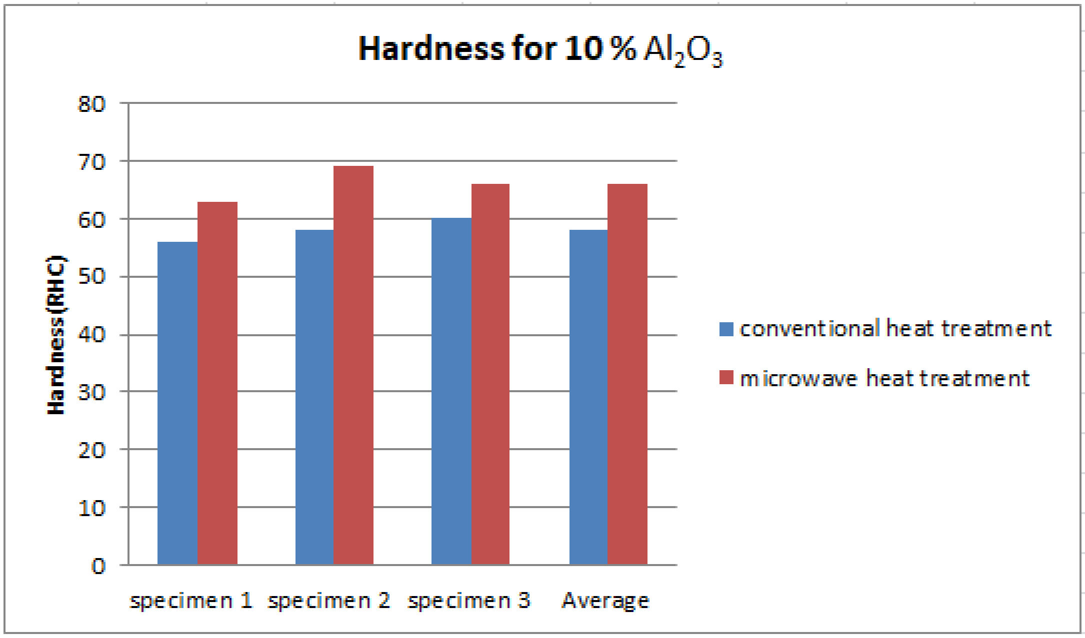


Figure 4.9 Hardness test results for 10% of Al_2O_3

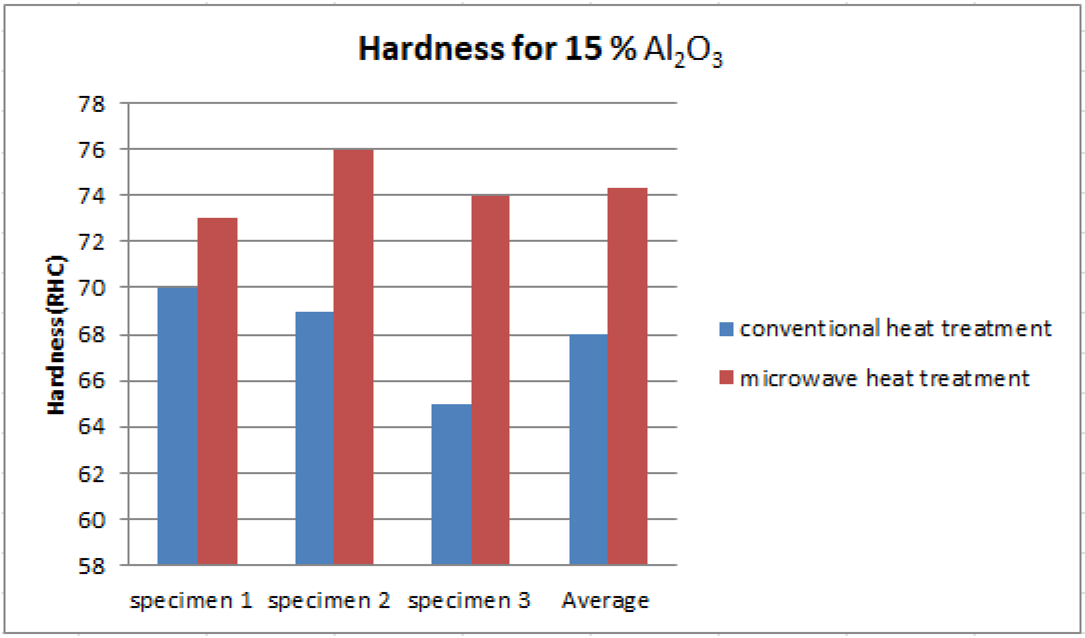


Figure 4.10 Hardness test results for 15% of Al_2O_3

4.1.2.1 Hardness test discussion

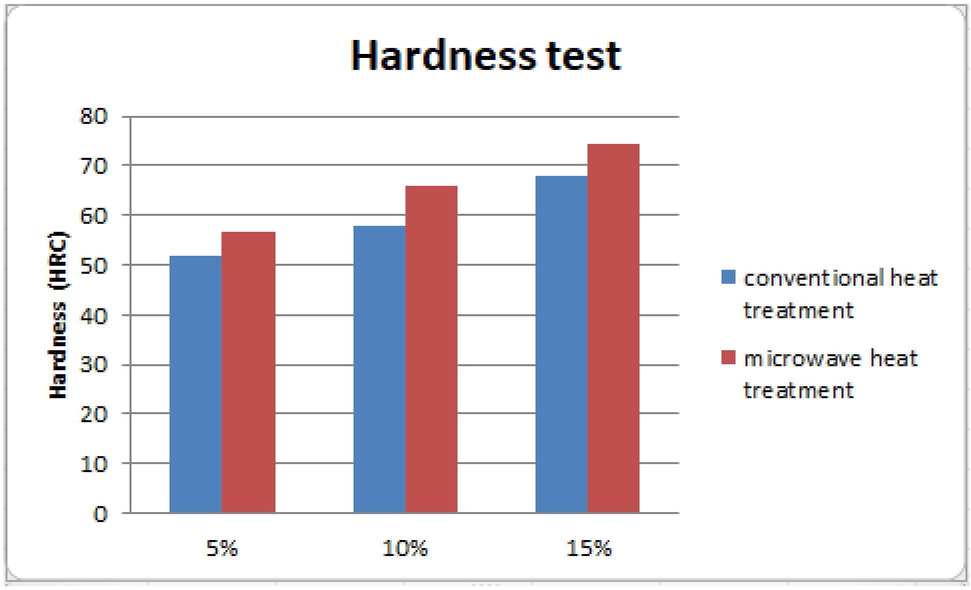


Figure 4.11 Hardness test results for all composition of Al_2O_3

According to the Rockwell hardness test indenter scale for soft and aluminum-type materials, the output force is 100 kg based on the average hardness specimen values, with the highest hardness value being 74.3 (HRB) and the minimum value being 51.66 (HRB). The matrix's hardness characteristics increase with the addition of reinforcement.

When the content of Al_2O_3 increases, the hardness of the composite material also increases in both heat treatment methods. This is because Al_2O_3 particles' natural hardness prevents dislocation motion in the aluminum matrix, increasing resistance to indentation.

Table.4.1. Conventional vs. microwave heat treatment for hardness increment

Al_2O_3 loading	Conventional heat treated	Microwave heat treated	% increase
5 %	51.66	56.6	8.7
10 %	58	66	12.12
15 %	68	74.3	8.45

The microwave treatment's quick, consistent heating improves the connection between Al6061 and Al_2O_3. Because of their enhanced strength, the composites can disperse loads more efficiently.

4.1.3 Flexural strength test result

Three specimens are prepared for each reinforcement loading and heat treatment method. The flexural strength is calculated as

$$\sigma bf = \frac{3LP}{2(bd)} \qquad (4.1)$$

Where

σbf = Stress on the outer surface at midpoint (Mpa)

L = supported span (mm)

P = load at given point (N)

b = width of the test beam (mm)

d = thickness of the beam (mm)

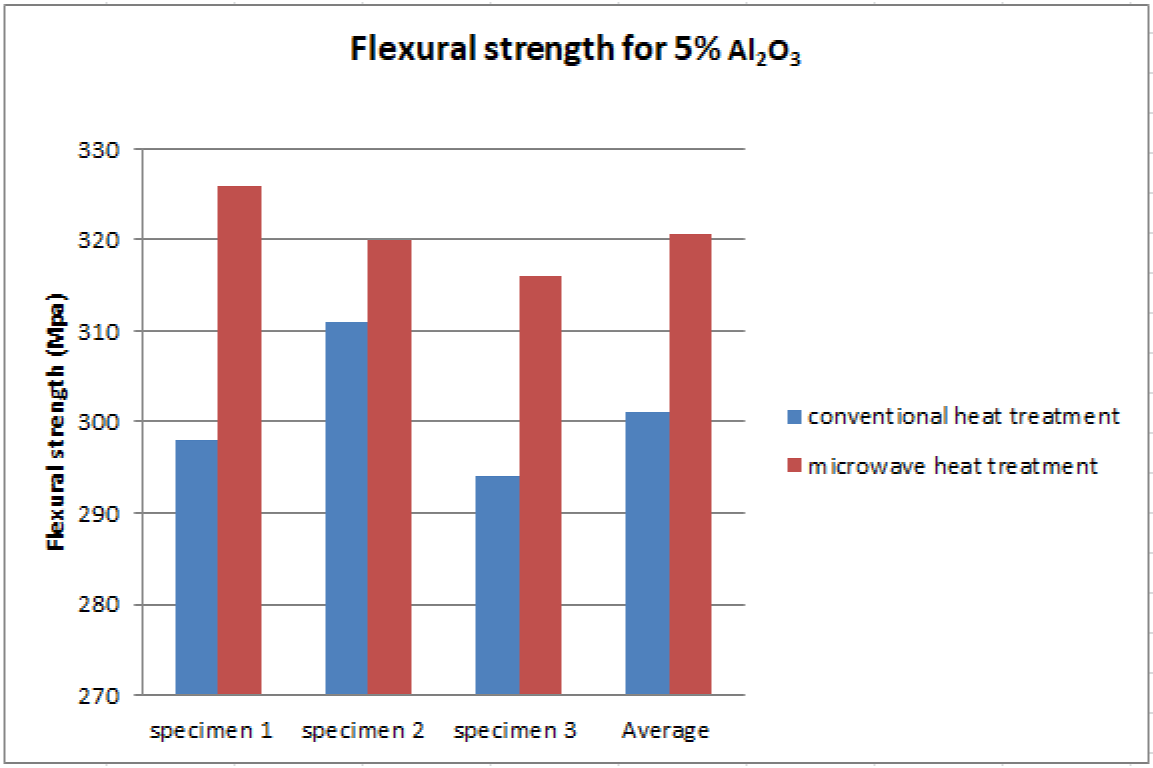


Figure 4.12 Flexural strength test results for 5% of Al_2O_3

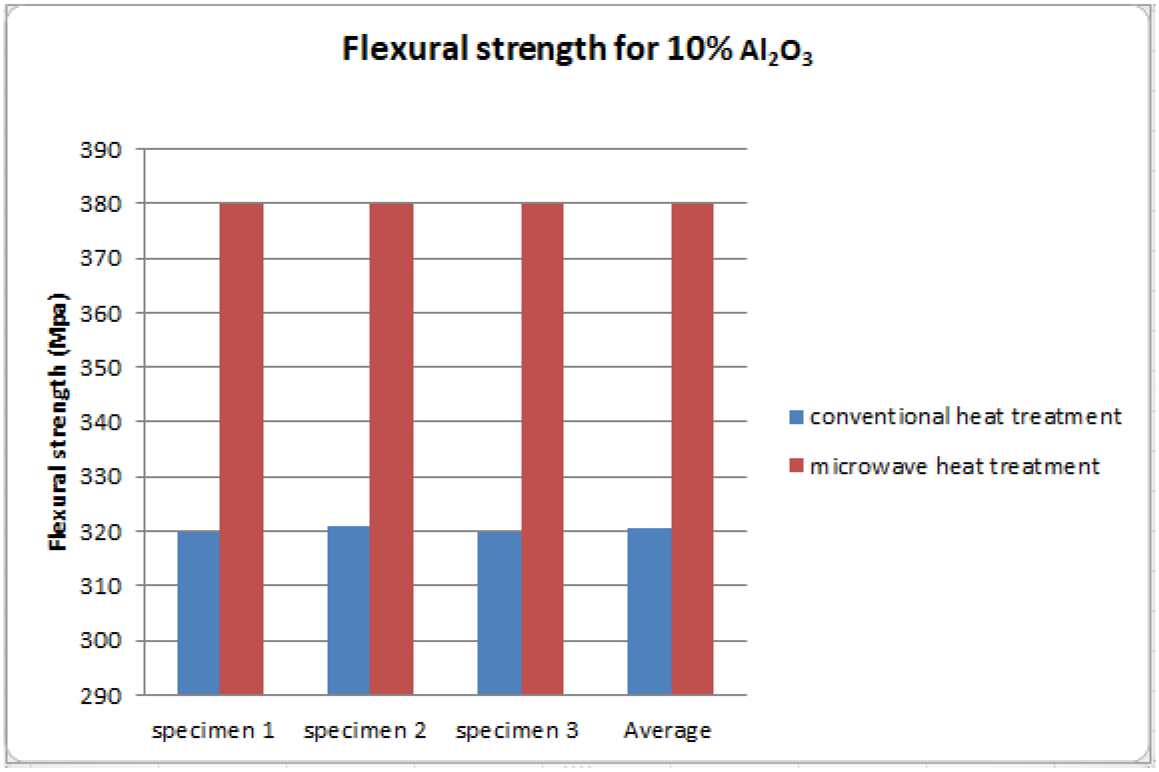


Figure 4.13 Flexural strength test results for 10% of Al_2O_3

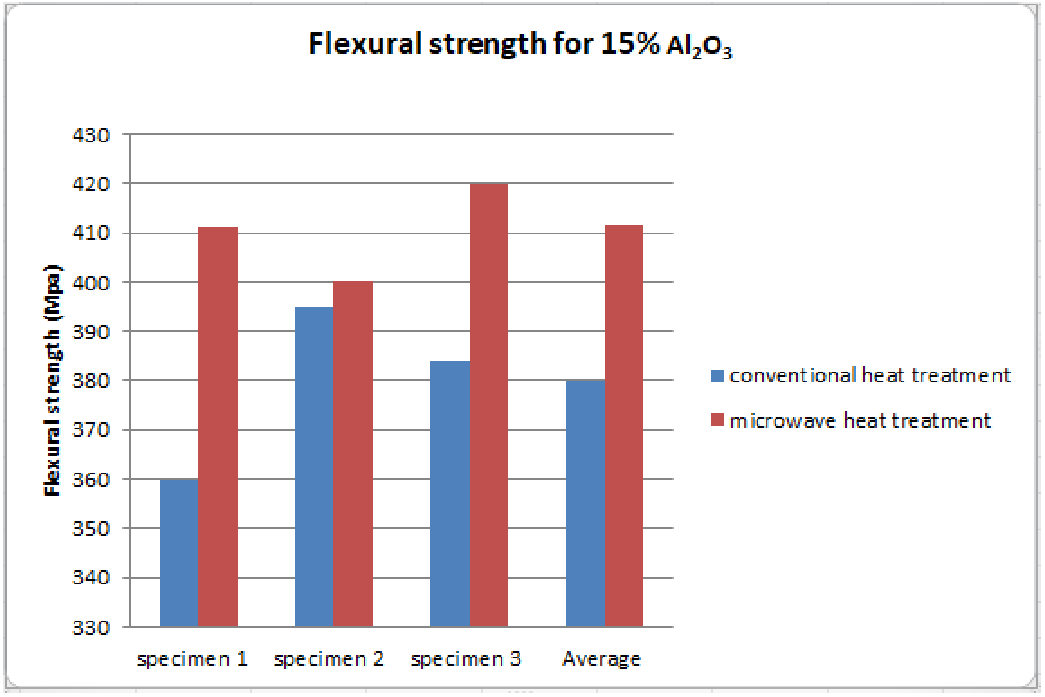


Figure 4.14 Flexural strength test results for 15% of Al_2O_3

4.1.3.1 Flexural test discussion

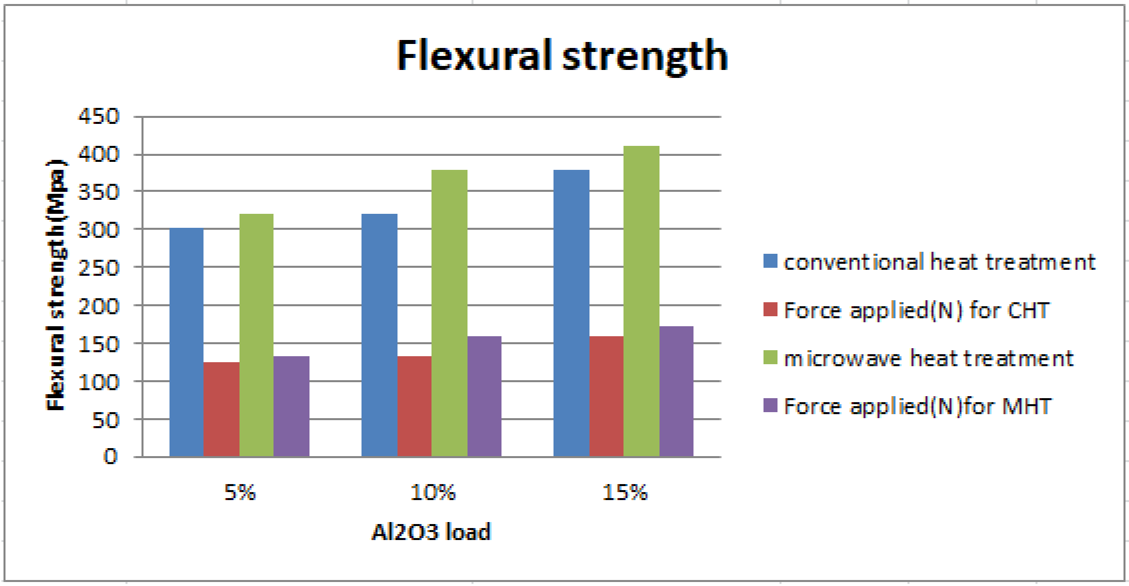


Figure 4.15 Flexural strength test results for all composition of Al_2O_3

Both treatments exhibit an increasing trend in force with reinforcement loading, typical of materials under bending stress.

The maximum flexural strength value of 411.3 MPa and the maximum output force of 171.4 N are derived from the average values of flexural specimens; these values represent a 26.76 % improvement from the minimum value of test which is 5% Al_2O_3 with conventional heat treatment.

The composite loses its ability to limit the specimens' plastic flow as the volume fraction rises. Similar findings showed that when the weight percentage of the particles increases, so does the composite's flexural strength.

This indicates that in comparison to the non-treated material, microwave pre-heat treatment greatly enhances the flexural properties of the material at the various force values. In high mechanical properties applications, this method may be preferred over traditional heat treating.

4.2 Interacting effect of the mechanical tests with factors

Tensile strength

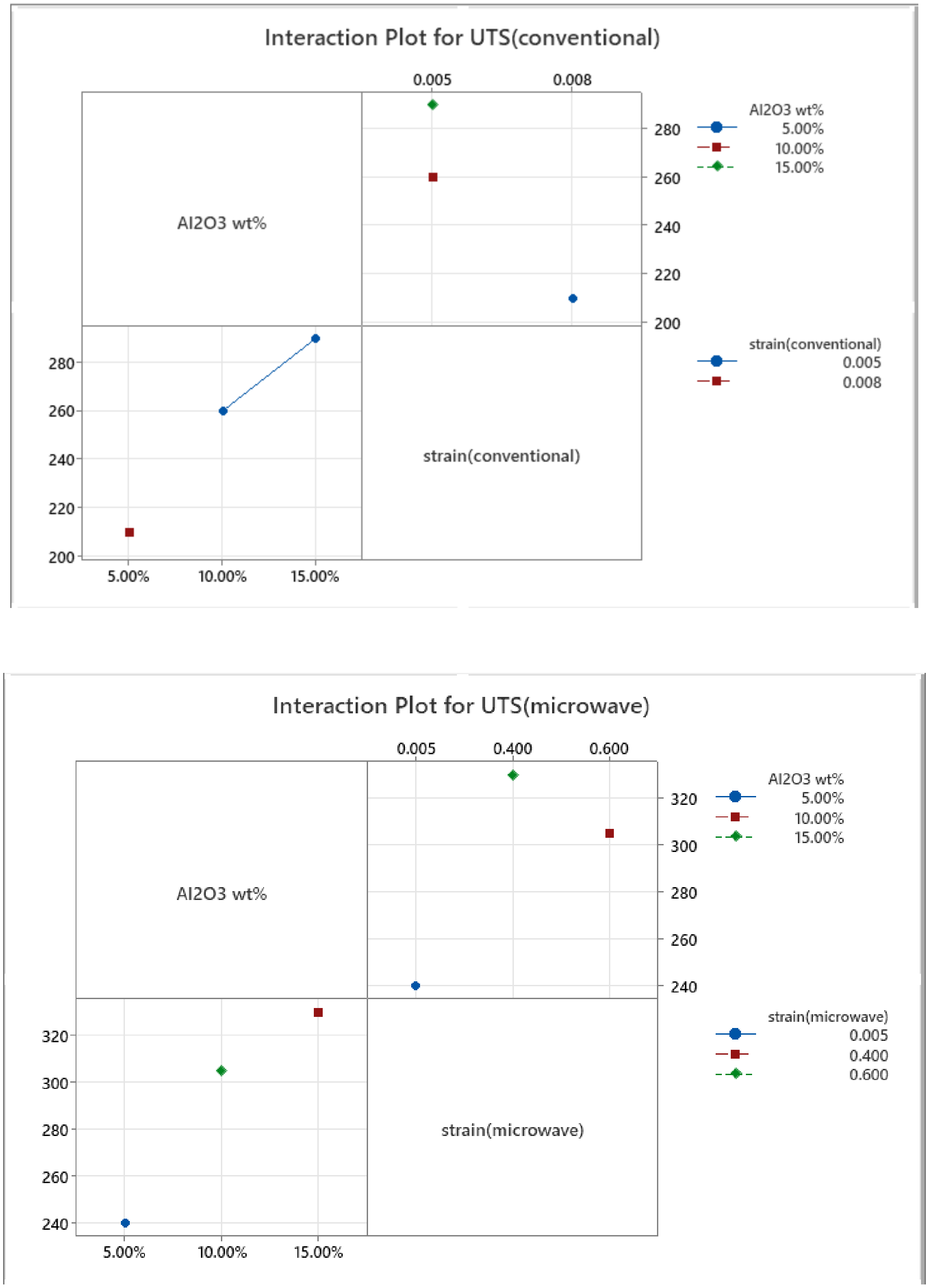


Figure4.16 interacting effect of tensile test with heat treatment, Al_2O_3 *content and strain*

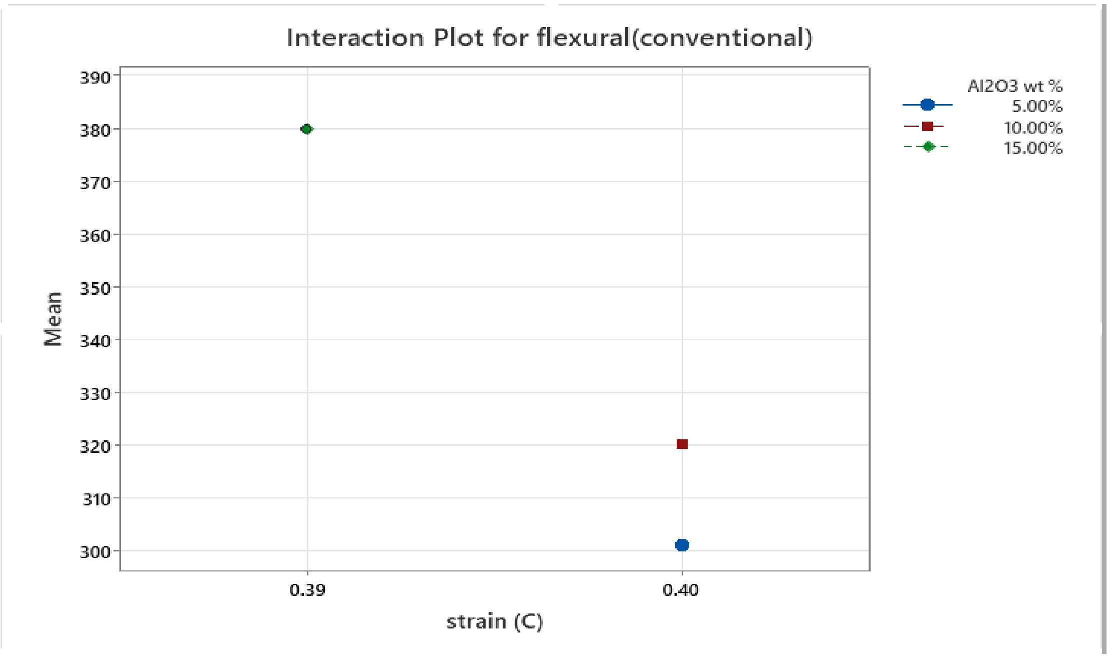
Microwave heat treatment demonstrates enhanced tensile properties compared to conventional heat treatment. Increasing the Al_2O_3 content generally improves the composite's strength due to better load transfer and grain refinement; however, excessive reinforcement (beyond 15 wt%) can lead to particle reduced ductility. Strain value also plays a critical role microwave-treated samples exhibit higher strain to failure, indicating improved ductility under certain compositions. The interactive effect shows that optimal tensile performance is achieved at a moderate Al_2O_3 content (typically 10–15 wt%) combined with microwave heat treatment, where both strength and ductility are balanced.

Hardness test

Figure 4.17 Interacting effect of Rockwell hardness test with heat treatment and Al_2O_3 content

Increasing Al_2O_3 content enhances hardness by introducing harder ceramic phases, though excessive reinforcement may lead to brittleness. The interaction with strain shows that while hardness generally increases with Al_2O_3 content and microwave treatment, it may decrease slightly under high strain due to micro crack formation. Overall, optimal hardness is achieved with microwave treatment and moderate Al_2O_3 content.

Flexural strength



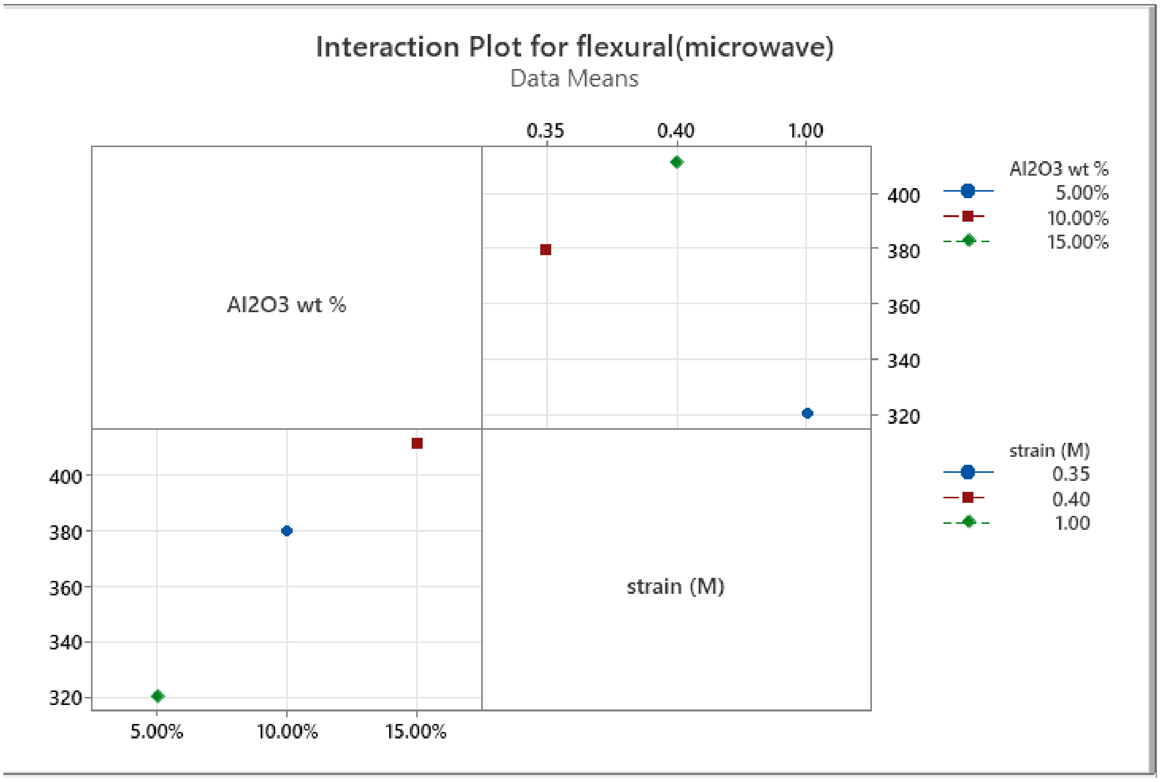
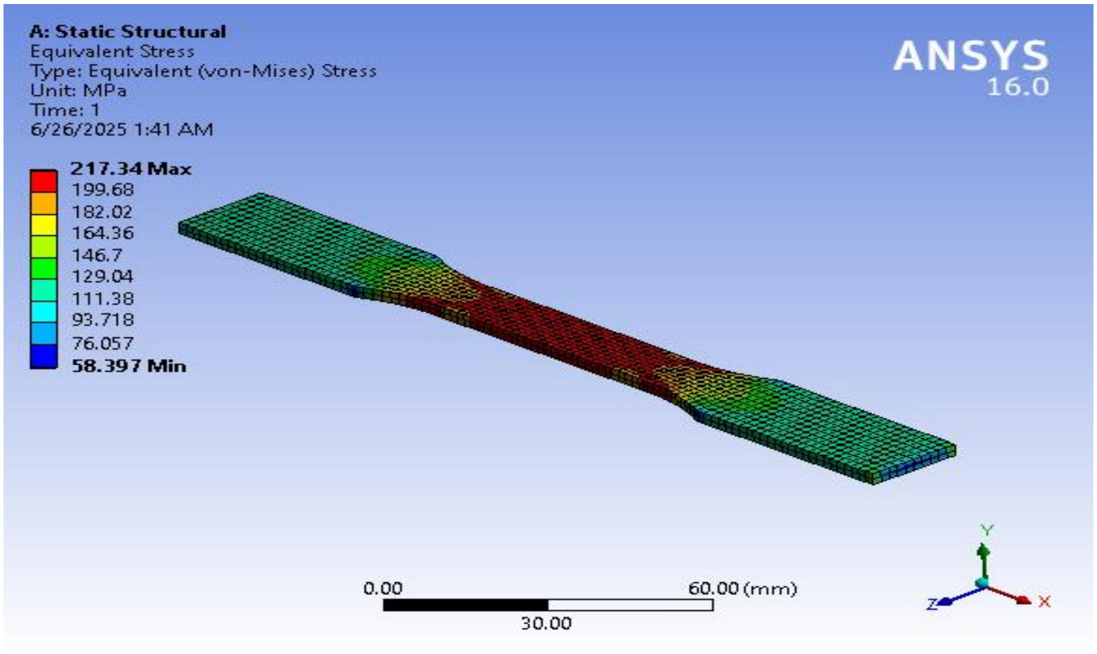


Figure 4.18 Interacting effect of flexural strength with heat treatment, Al_2O_3 content and strain

Microwave heat treatment enhances flexural strength more effectively than conventional treatment due to improved bonding and uniform microstructure. An increase in Al_2O_3 content generally improves flexural performance by reinforcing the matrix, but excessive content may cause particle clustering and reduce toughness. Strain influences the flexural response, where higher strain may lead to micro-cracking, especially in over-reinforced or conventionally treated samples.

4.3 Validation of experimental result with FEA

Tensile test result



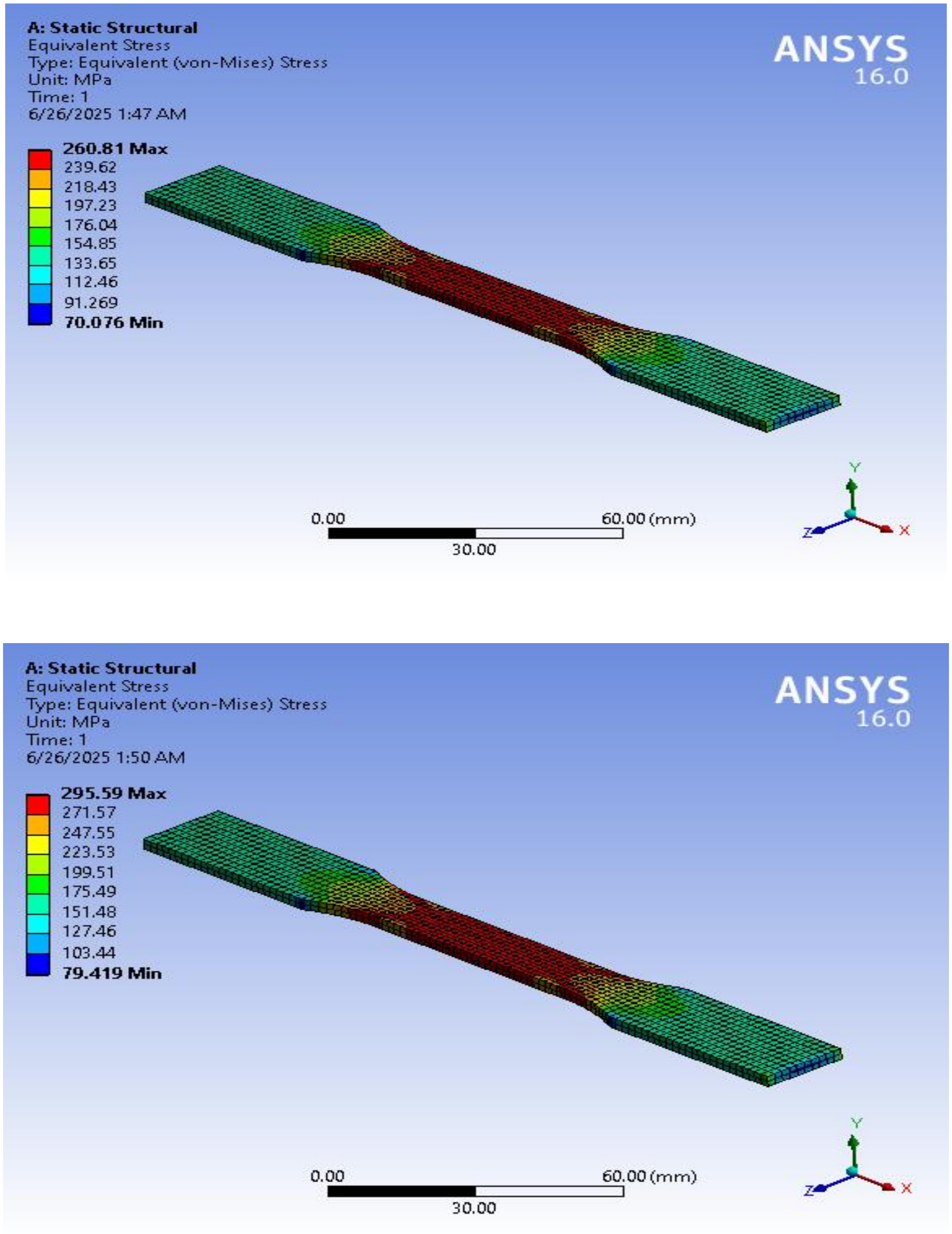
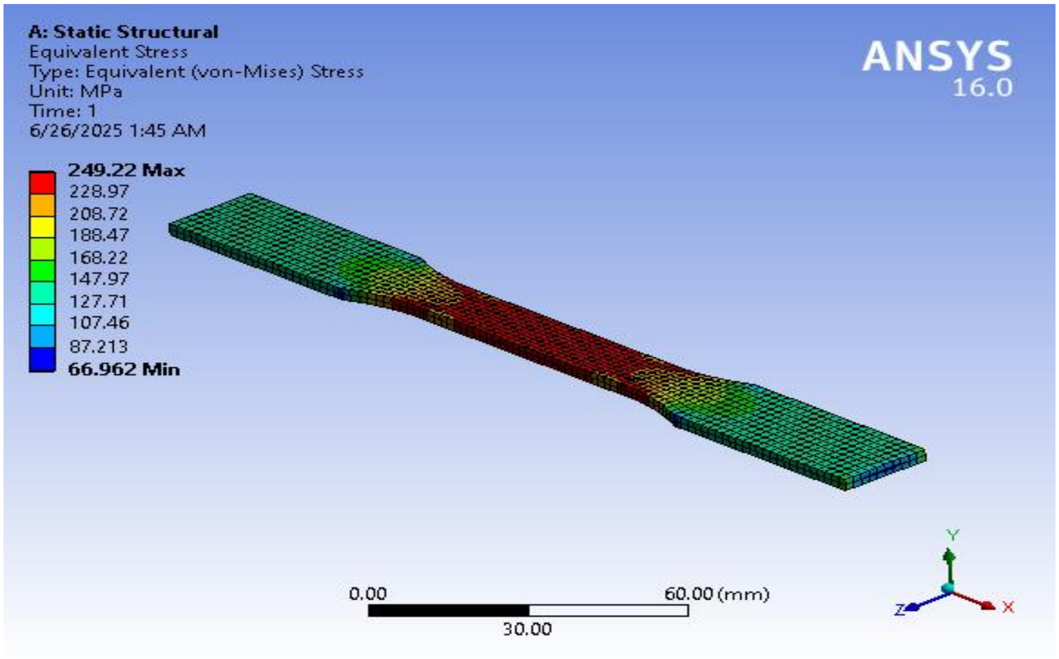
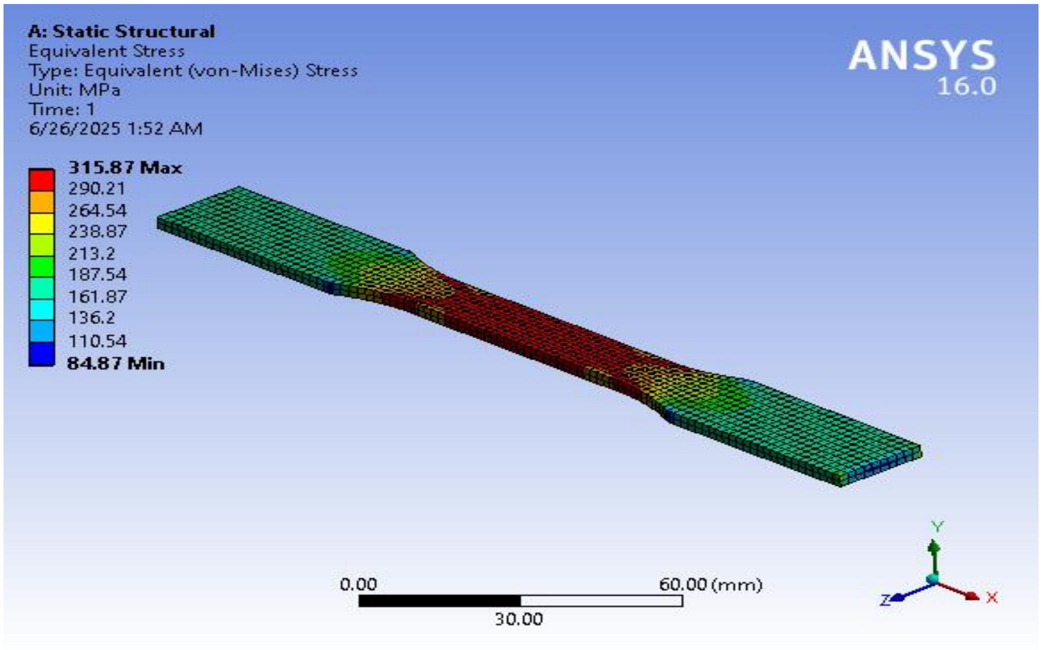


Figure 4.19 simulation results for tensile strength with conventional heat treatment and with 5,10 and 15% Al2O3 content


A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
6/26/2025 1:45 AM
249.22 Max
228.97
208.72
188.47
168.22
147.97
127.71
107.46
87.213
66.962 Min
ANSYS
16.0
0.00
30.00
60.00 (mm)
Y
Z
X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Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
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6/26/2025 1:52 AM
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238.87
213.2
187.54
161.87
136.2
110.54
84.87 Min
ANSYS
16.0
0.00
30.00
60.00 (mm)
Y
Z
X

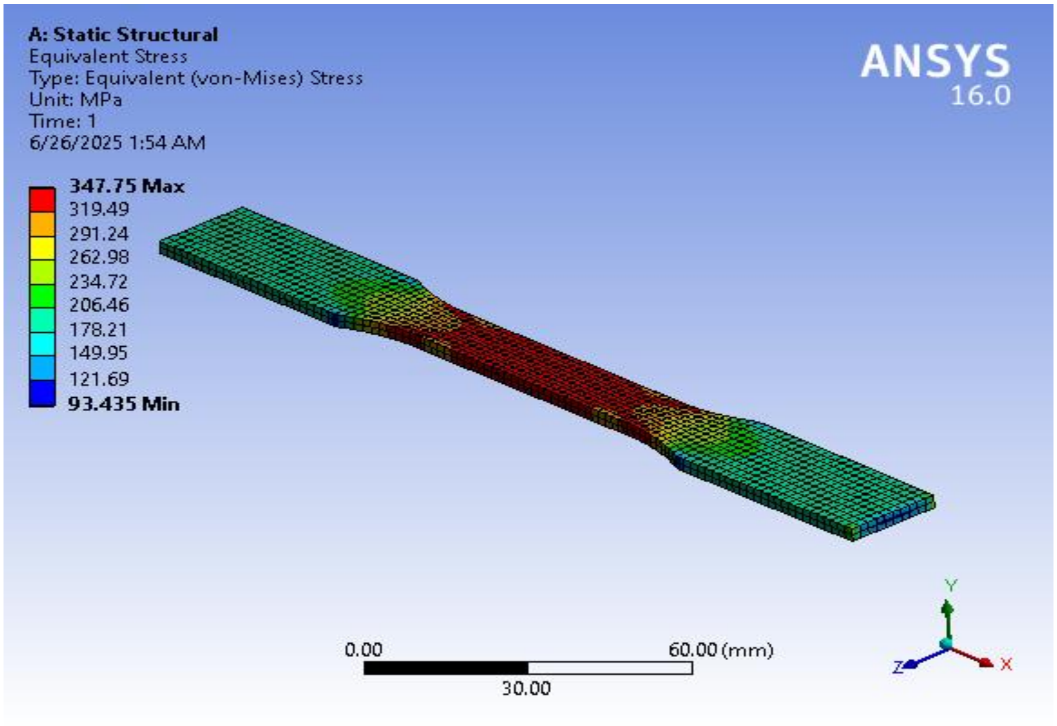


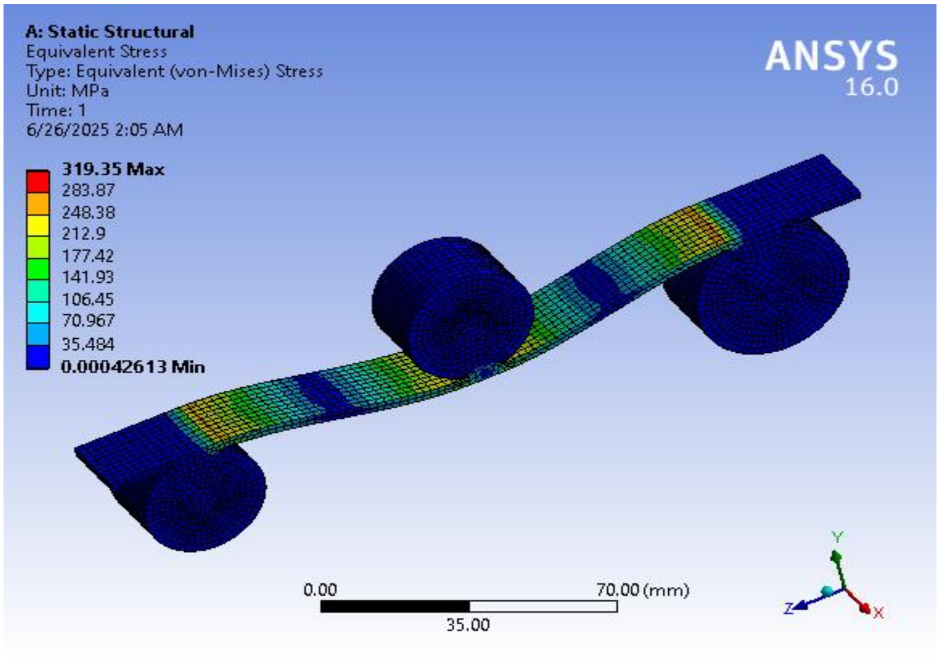
Figure 4.20 simulation result for tensile strength with microwave heat treatment and with 5,10 and 15% Al2O3 content

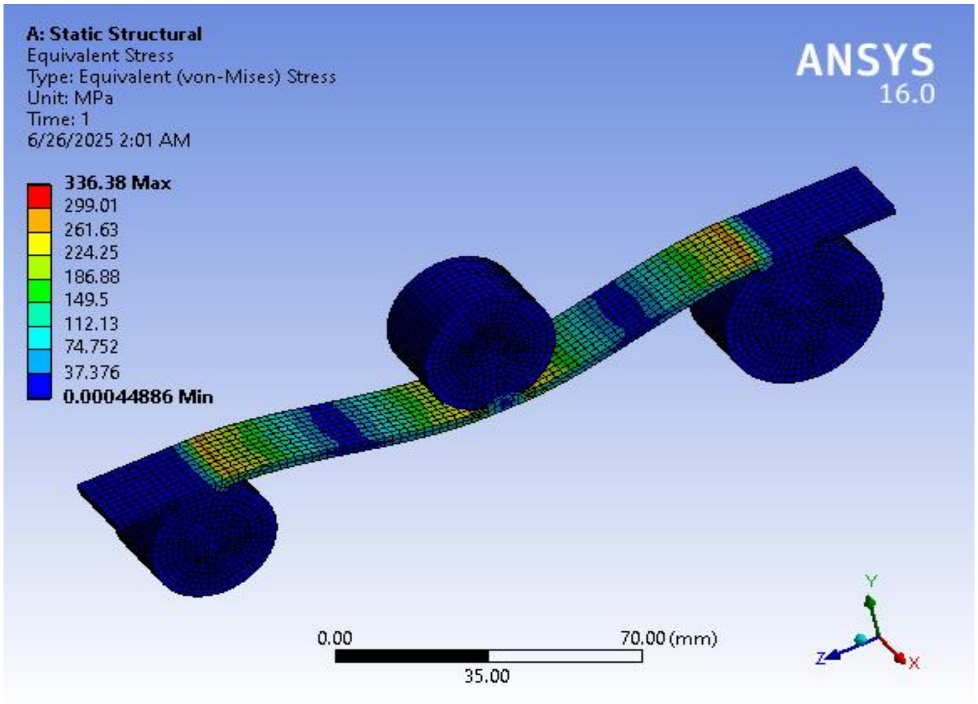
Table 4.2. Comparison table for tensile test result

Al_2O_3 content and heat treatment	Experimental result (Mpa)	ANSYS result (Mpa)	% Error
5% Al_2O_3 (conventional)	210	217.34	3.5 %
10% Al_2O_3 (conventional)	260	260.81	0.3 %
15% Al_2O_3 (conventional)	290	295.59	1.93 %
5% Al_2O_3 (microwave)	240	249.22	3.84 %
10% Al_2O_3 (microwave)	305	315.87	3.56 %
15% Al_2O_3 (microwave)	330	347	5.15 %

The comparison between experimental and ANSYS results shows a strong correlation in tensile strength across all Al_2O_3 compositions and heat treatment methods, with percentage errors remaining below 6%. The highest strength was observed at 15% Al_2O_3 with microwave treatment (330 MPa), confirming the positive impact of increased reinforcement and advanced heat treatment. The low error margins also validate the accuracy of the simulation results.

Flexural test result





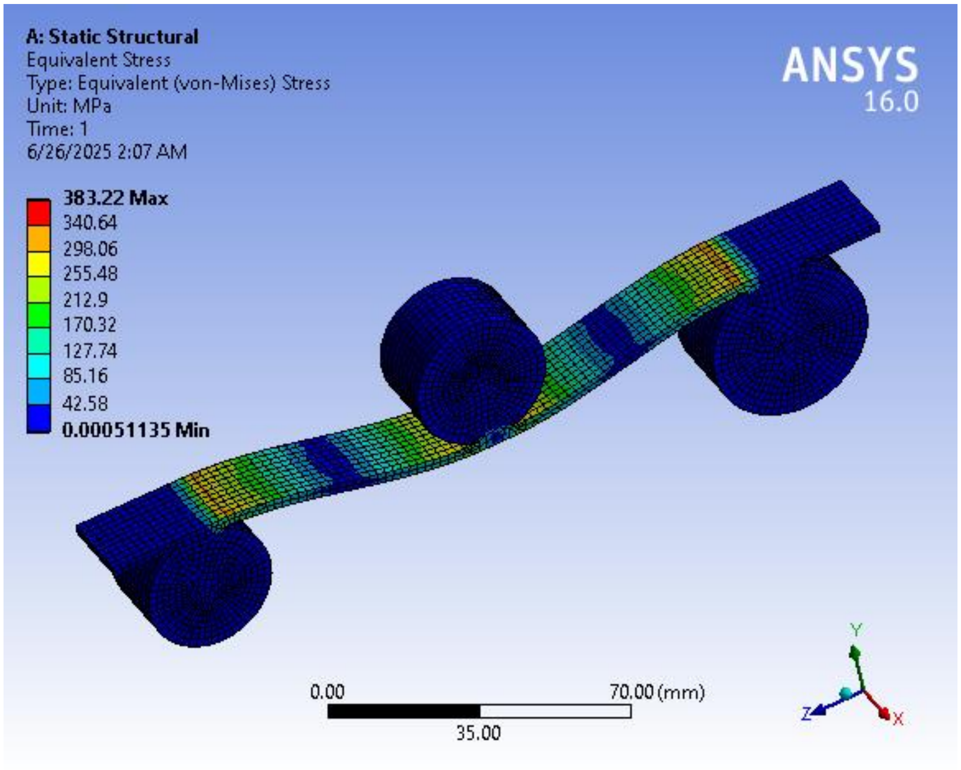
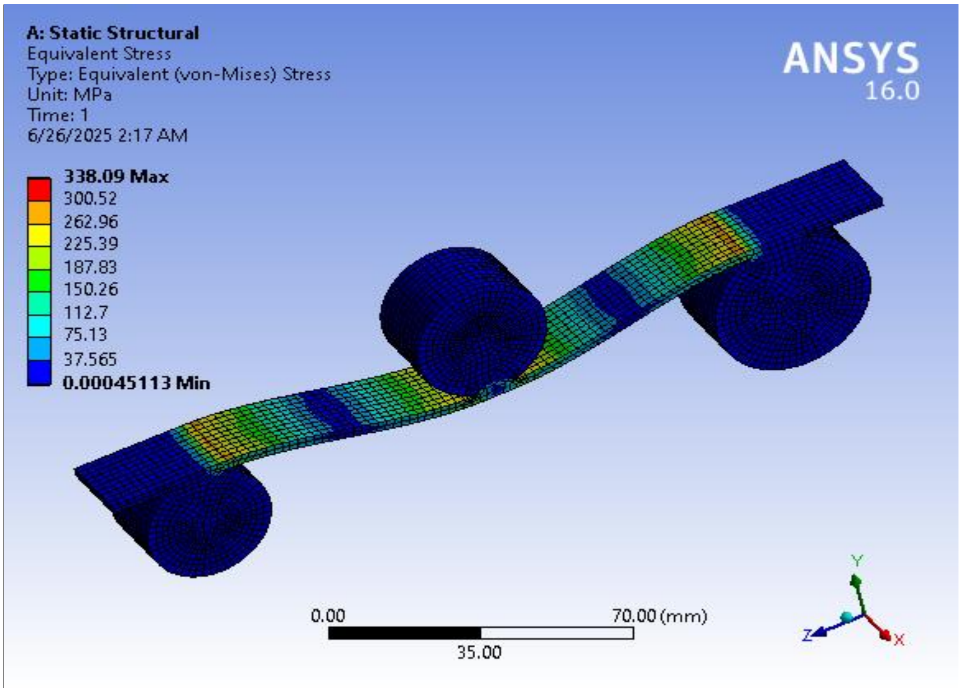
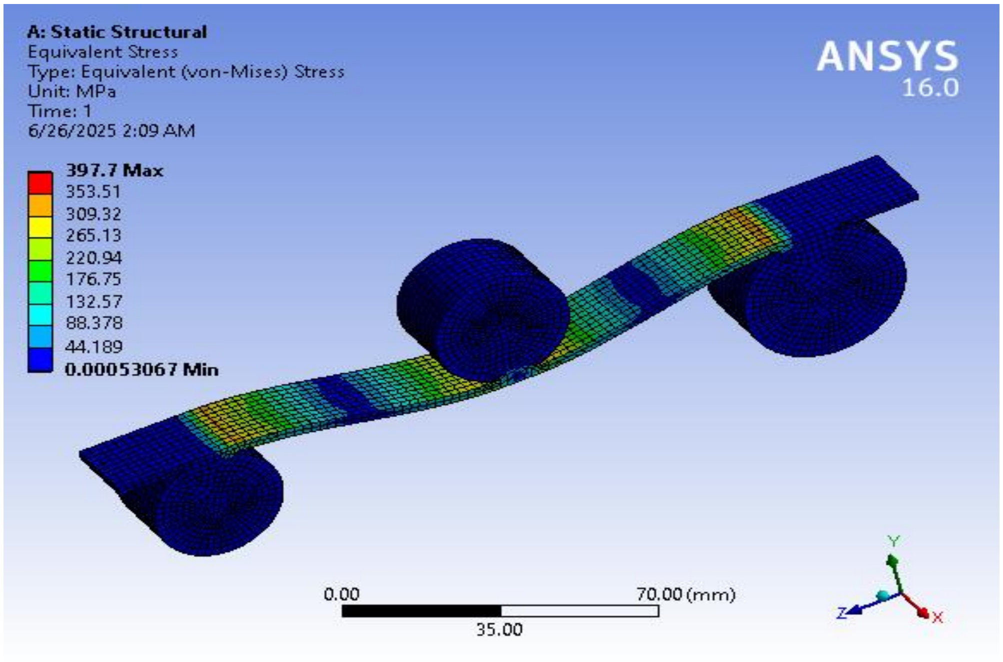


Figure 4.21 simulation result for flexural strength with conventional heat treatment and with 5,10 and 15% Al2O3 content





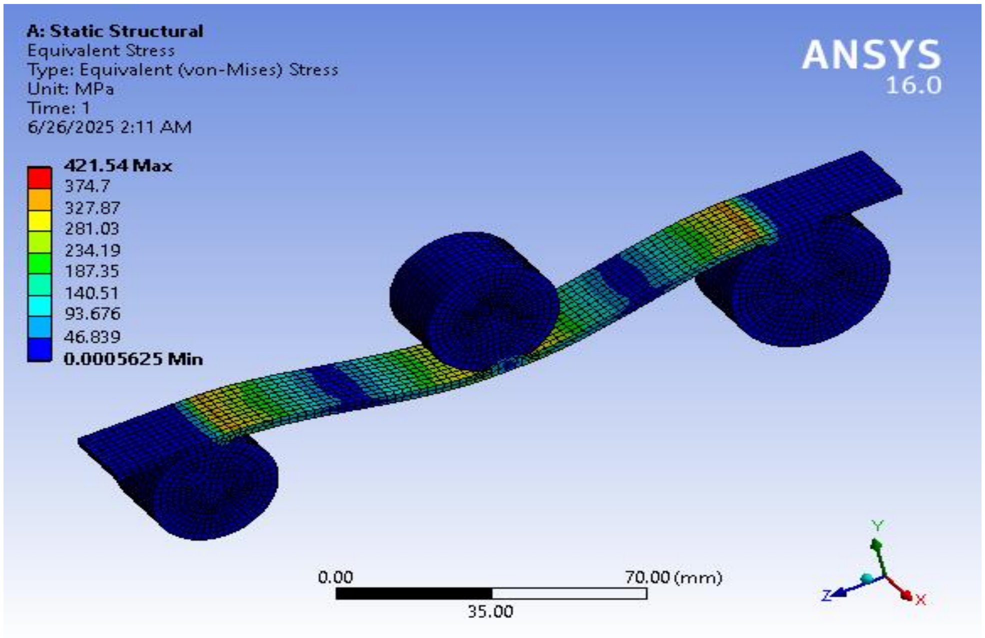


Figure 4.22 simulation results for flexural strength with microwave heat treatment and with 5,10 and 15% Al_2O_3 content

Table 4.3. Comparison table for flexural test result

Al_2O_3 content and heat treatment	Experimental result (Mpa)	ANSYS result (Mpa)	% Error
5% Al_2O_3 (conventional)	301	319.35	5.98 %
10% Al_2O_3 (conventional)	320.3	336.38	5.02 %
15% Al_2O_3 (conventional)	380	383.22	0.85 %
5% Al_2O_3 (microwave)	320.6	338.09	5.45 %
10% Al_2O_3 (microwave)	380	397.7	4.66 %
15% Al_2O_3 (microwave)	411.3	421.54	2.5 %

The table shows a close agreement between experimental and ANSYS flexural strength results, with error percentages ranging from 0.85 % to 5.98 %, confirming the reliability of simulation. The highest strength (411.3 MPa) was recorded at 15% Al_2O_3 with microwave treatment, demonstrating that both increased reinforcement and advanced heat treatment synergistically improve flexural performance.

4.4 The static structural analysis result

4.4.1. Equivalent Stress (Von - Miss)

The composite material used for a double control arm yields a maximum von Miss stress of 173.76 Mpa and minimum of 1.08 Mpa, which is lower than the yield stress of 295 MPa.

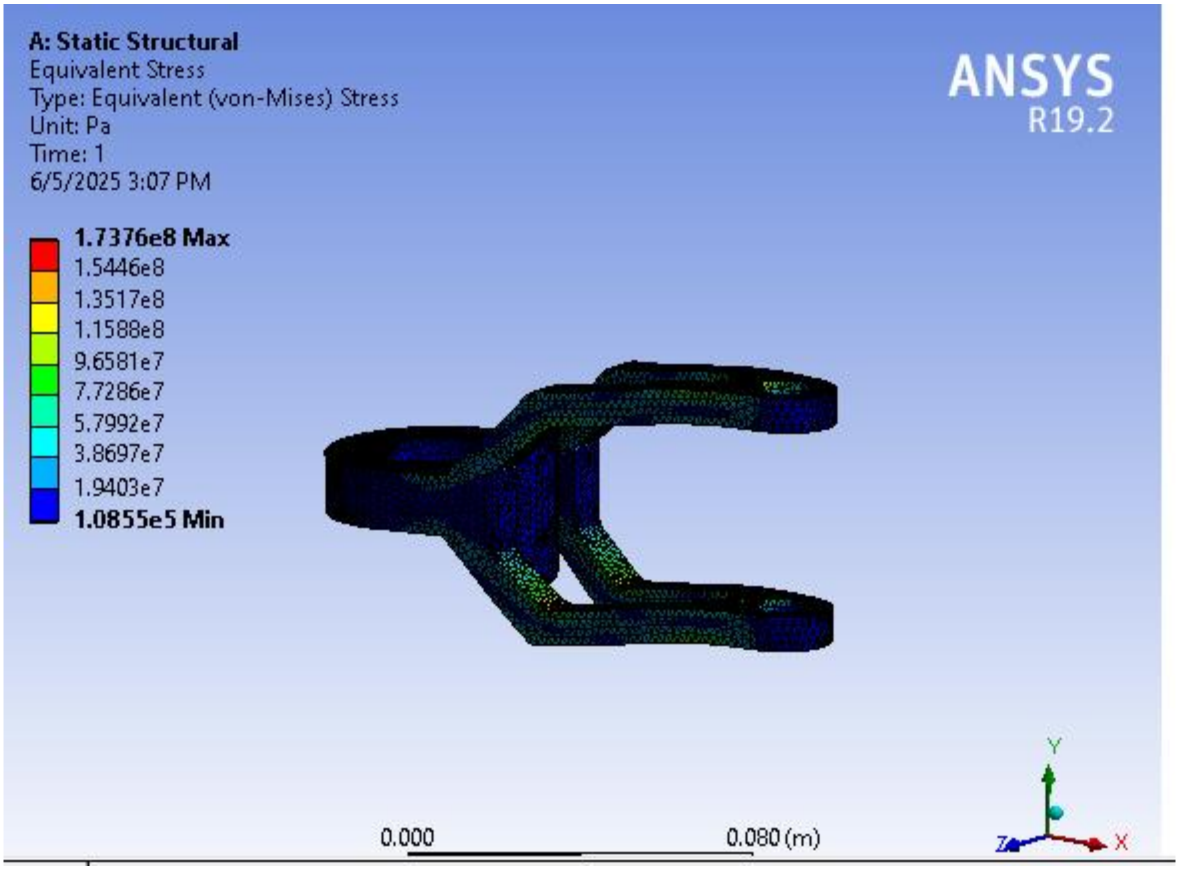


Figure 4.23 Von –Mises stress analysis result

4.4.2. Total Deformation

When used as a double control arm, the Al 6061/Al_2O_3 composite achieved a maximum total deformation of 0.138 mm and a minimum deformation of 0 mm. The deformation values form ANSYS R19.2 is shown on the figure below.

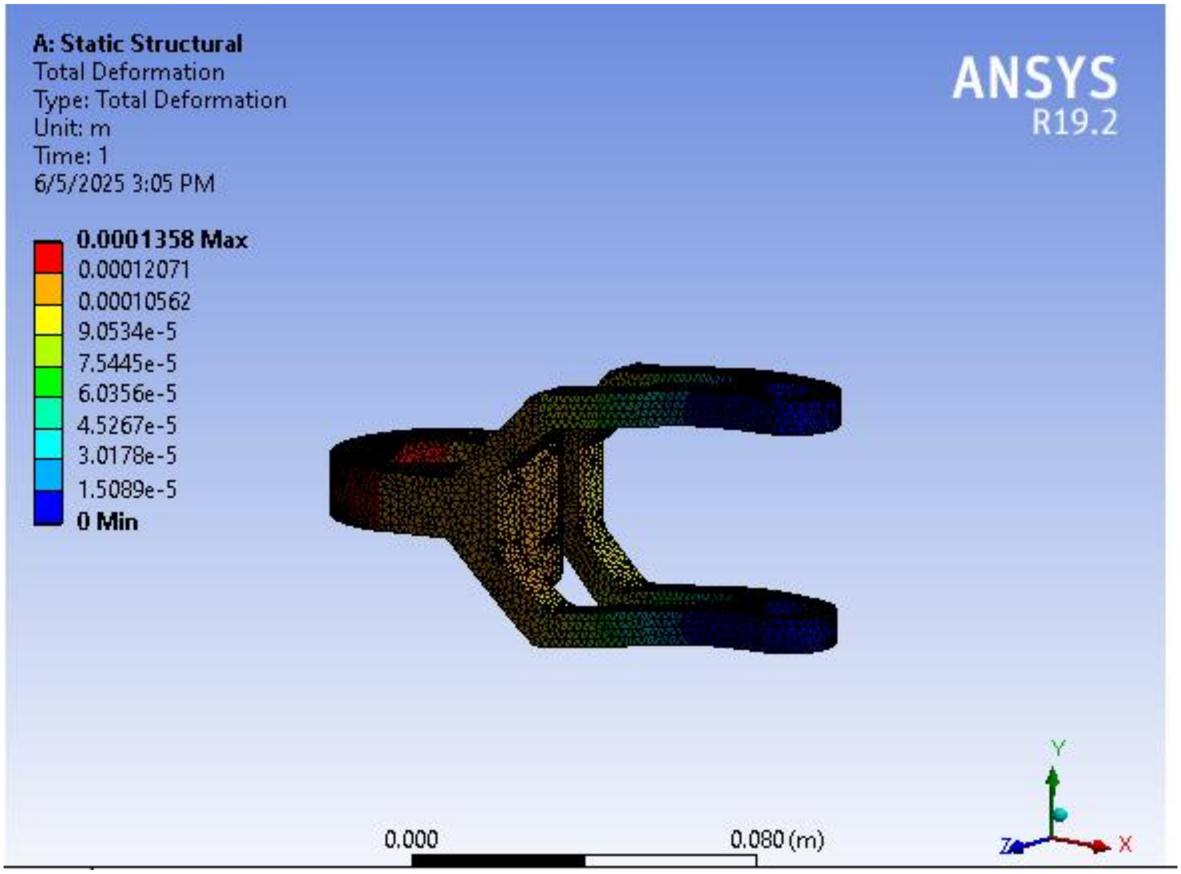


Figure 4.24 Total deformation analysis result

Based on mechanical testing and FEA results, the Al6061/Al_2O_3 composite with 15% reinforcement and microwave treated exhibited superior mechanical properties compared to conventional treated and meet the stress and stiffness of double control arm. It's better corrosion resistance and lower density also one of its advantage. Since the factor of safety for automotive parts must be above 1.5 [37] and composite structure demonstrates satisfactory performance. The stress level is at safe limit, indicating that the design is mechanically safe for specified loading condition.

CHAPTER FIVE

5. Conclusion and Recommendation

5.1. Conclusion

On this current study, the stir casting process has been used successfully in manufacturing the Al 6061–Al_2O_3 metal matrix composites in which the weight % of the alumina was taken as 5%, 10% and 15%. Since the focus was in understanding how the microwave heat treatment influenced the mechanical performance of the composites, hardness, tensile strength, and flexural strength were looked at in this study.

The experimental results showed that Al_2O_3 particles improved considerably the mechanical behavior of the aluminum matrix. This proportionate increase in hardness, tensile strength and flexural strength observed with increasing reinforcement content indicates that alumina particles act as reinforcing agents. In addition, these mechanical properties were also enhanced by microwave heat treatment.

Both the percentage of alumina reinforcement as well as microwave heat treatment played significant role in enhancing the mechanical properties of Al 6061–Al_2O_3 composites. The findings indicate that these composites are a very promising option for application in engineering areas that require lightweight materials that maintain strength and durability.

The tensile strength tended to increase with higher Al_2O_3 contents and samples treated in microwave exhibited higher tensile strength values than conventionally heat treated samples. The increase is attributed to even heating, as well as rapid heating, associated with microwave processing.

The hardness of microwave treated composites was 12% higher when compared to standard cured composites, showing that it had increased resistance to surface wear.

Flexural strength followed a similar trend, also presenting the best performance at 15% Al_2O_3.

The validation results demonstrate a strong correlation between experimental and ANSYS simulation outcomes for flexural strength across all Al_2O_3 compositions and heat treatment methods. The percentage error remains consistently low within 4% indicating that the finite element model reliably predicts the mechanical response of Al6061/Al_2O_3 composites.

It is concluded that Microwave heat treatment can be more efficient in consolidation of Al6061 - Al_2O_3 composite in improving its mechanical properties. Similarly, the ideal combination of strength and hardness that can be achieved with 15% Al_2O_3 when produced by microwave process makes it suitable for high performance applications like automotive industries.

5.2. Recommendation

It is observed that the microwave processed Al6061/Al2O3 composites have superior tensile, hardness and wear properties as compared to the conventional processed composites. These improvements are as a result of the even and rapid heating associated with the microwave processing which is conducive to fine, evenly dispersed Al_2O_3 reinforcement, and reduced thermal shock.

Taking these superior attributes into account, microwave heat-treated Al6061/Al_2O_3 composites are recommended for application in automotive suspension parts like the double control arm which require high load bearing capacity, low weight and superior fatigue as well as wear resistant components. Being lightweight but strong, the composite contributes to overall vehicle performance such as improved handling, fuel economy, and increased component life.

Thus implementing microwave heat treatment while manufacturing Al6061/Al_2O_3 based double control arms can be a very promising approach towards lightweight and high performing suspension systems.

For future, it needs to conduct Amore simulation analysis in regarding to impact strength and thermal properties to increase the efficiency of the product and other application areas.

5.3. Future work

To further improve composite performance, future research may examine

- Evaluate alternatives thermal treatments similarly focus on the optimization of power level and time for microwave heat treatment.
- Modeling and simulating thermal distribution and predict mechanical behavior under different heat treatments.
- Perform advanced microstructural analysis to explore interfacial bonding, particle distribution, and phase transformation caused by both microwave and artificial aging heat treatments using SEM, TEM, and XRD
- Investigate the incorporation of secondary reinforcements such as SiC, graphite, or CNTs in addition to Al_2O_3 to create hybrid composites and assess the ability to further enhance the mechanical properties.

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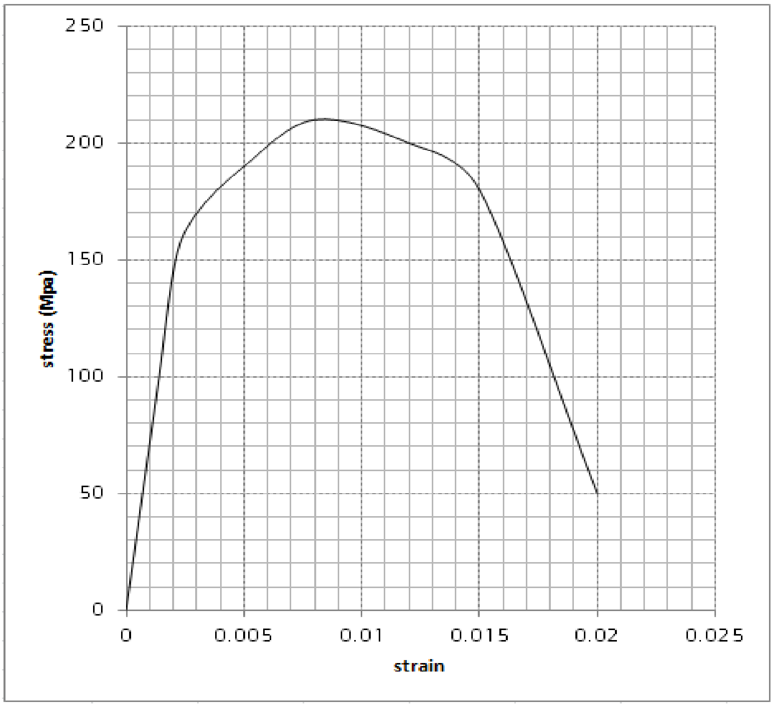
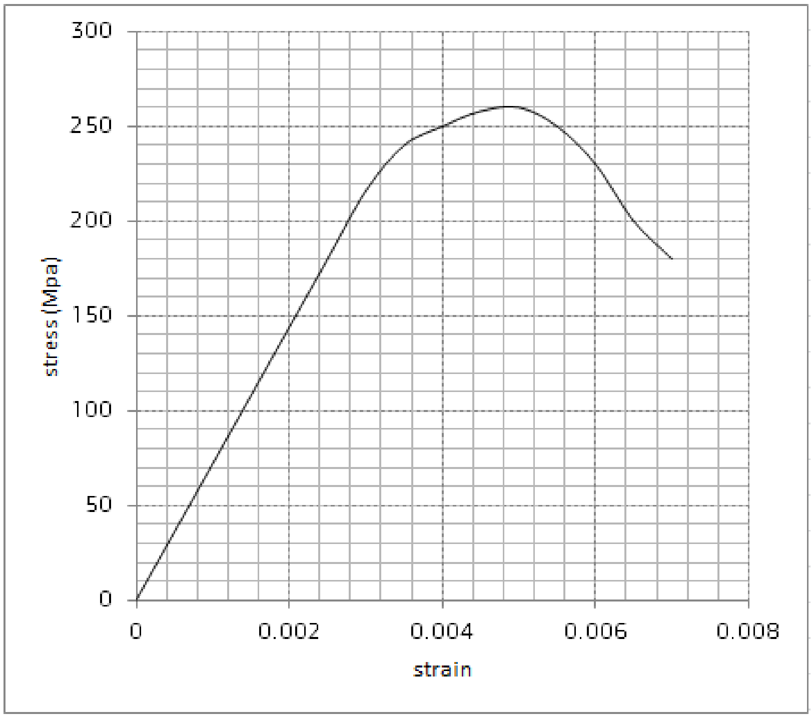
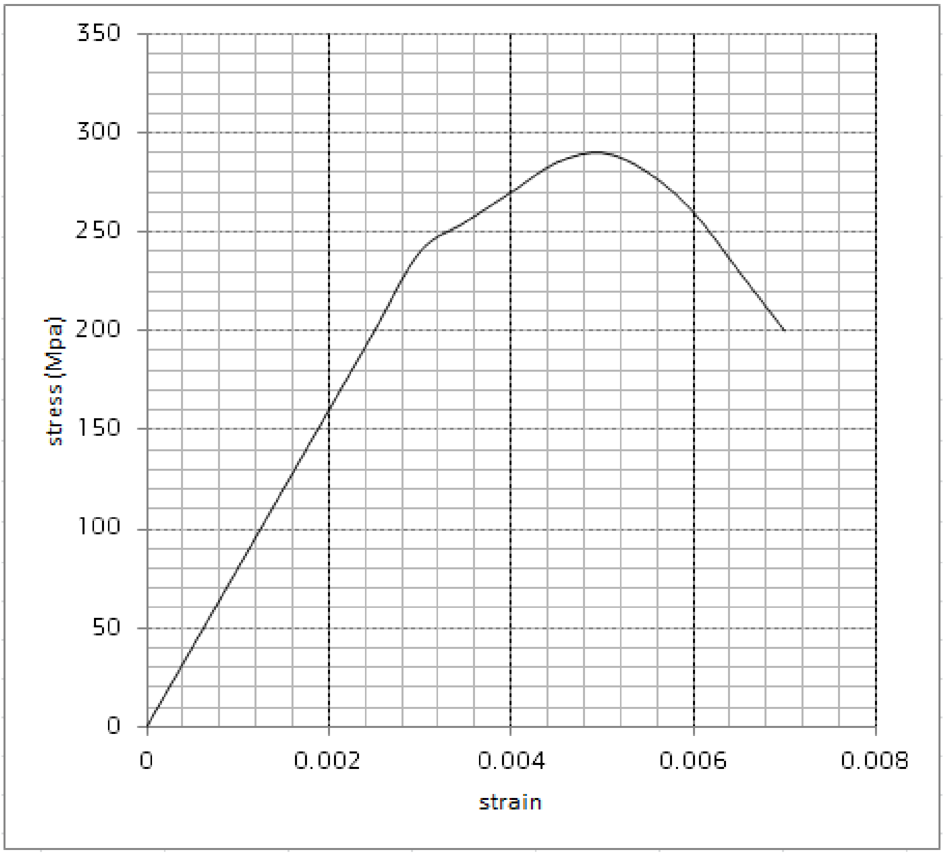
APPENDEX

APPENDIX A: TENSILE TEST RESULT



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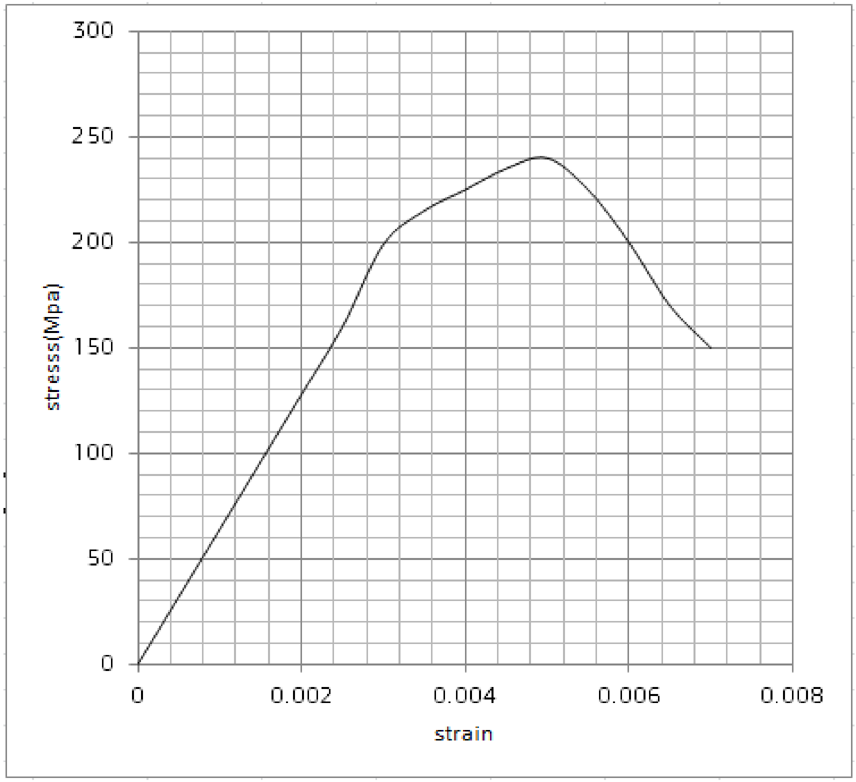
0.006
0.008
strain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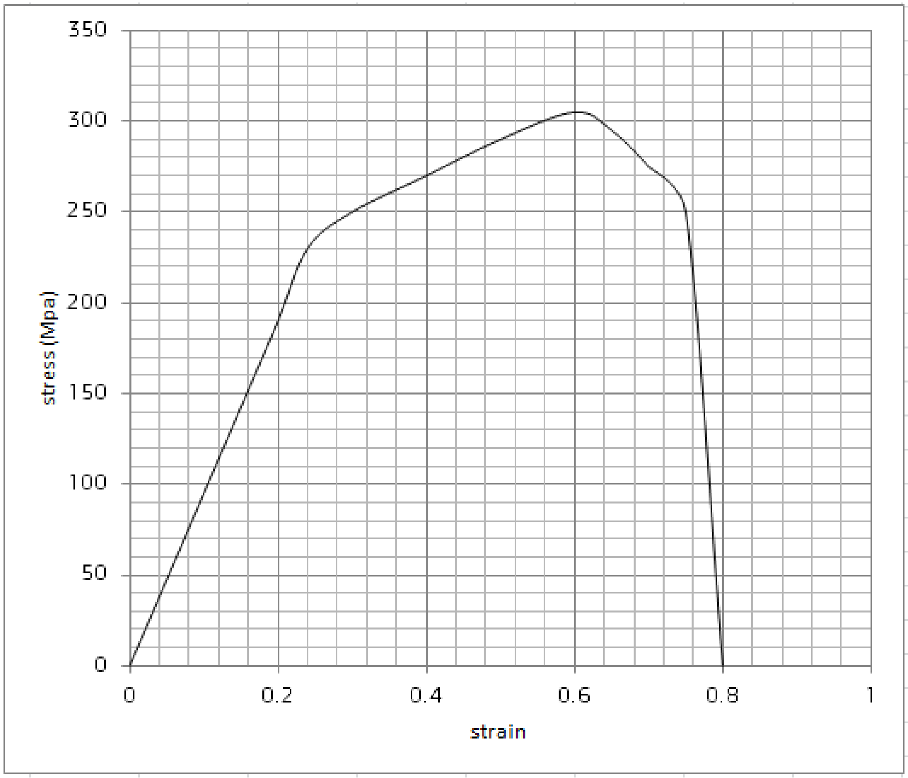
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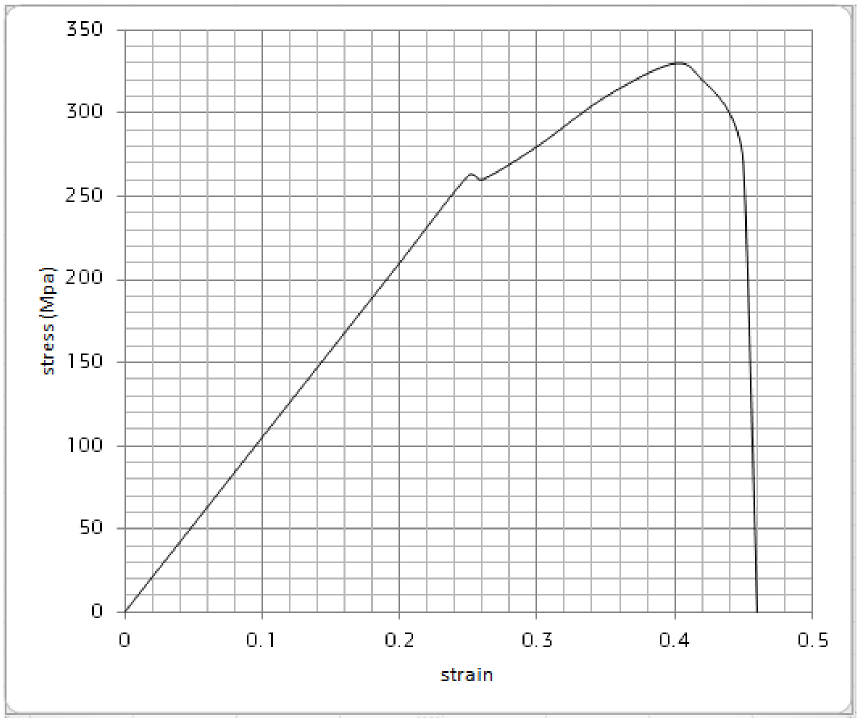
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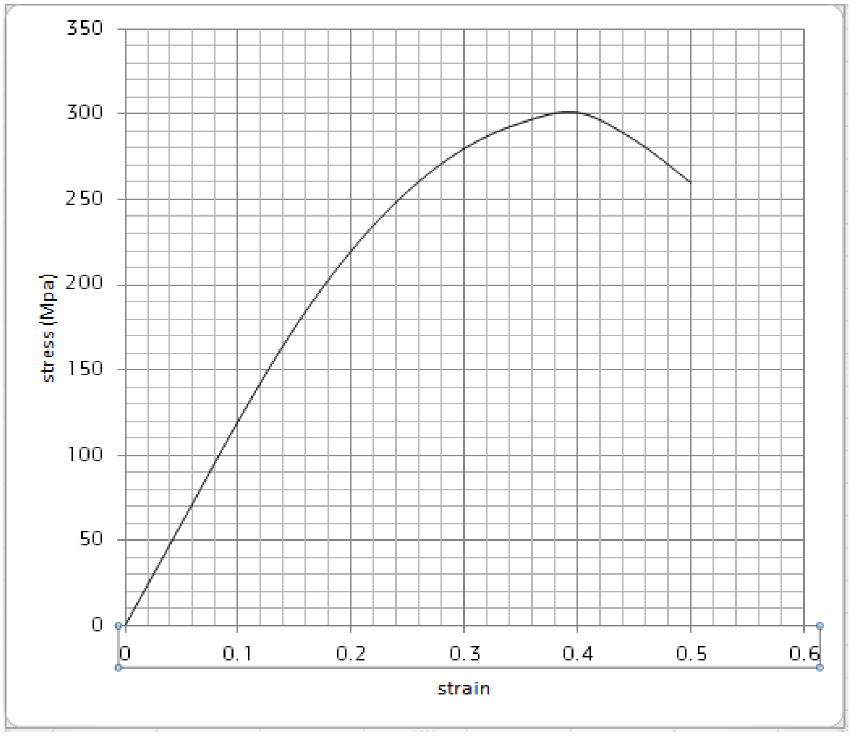
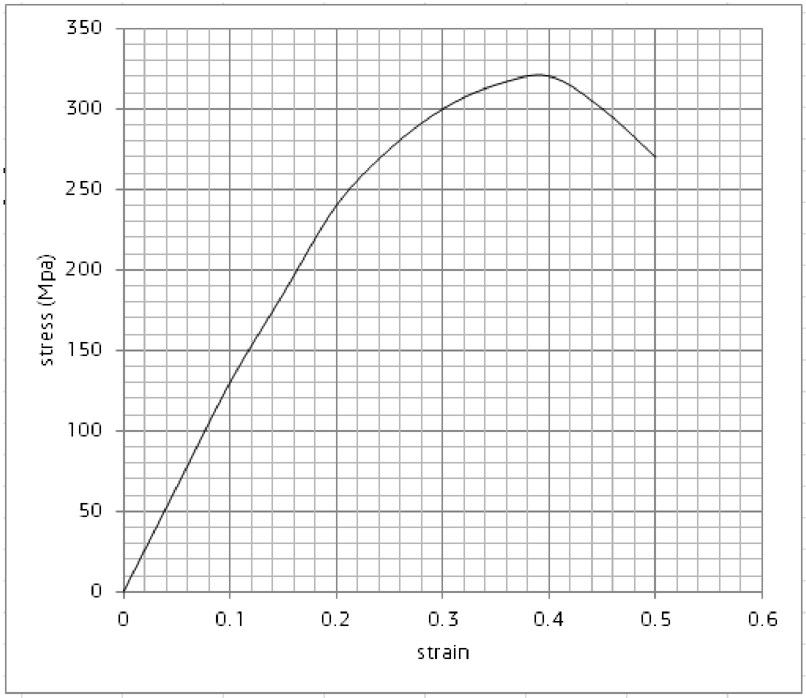
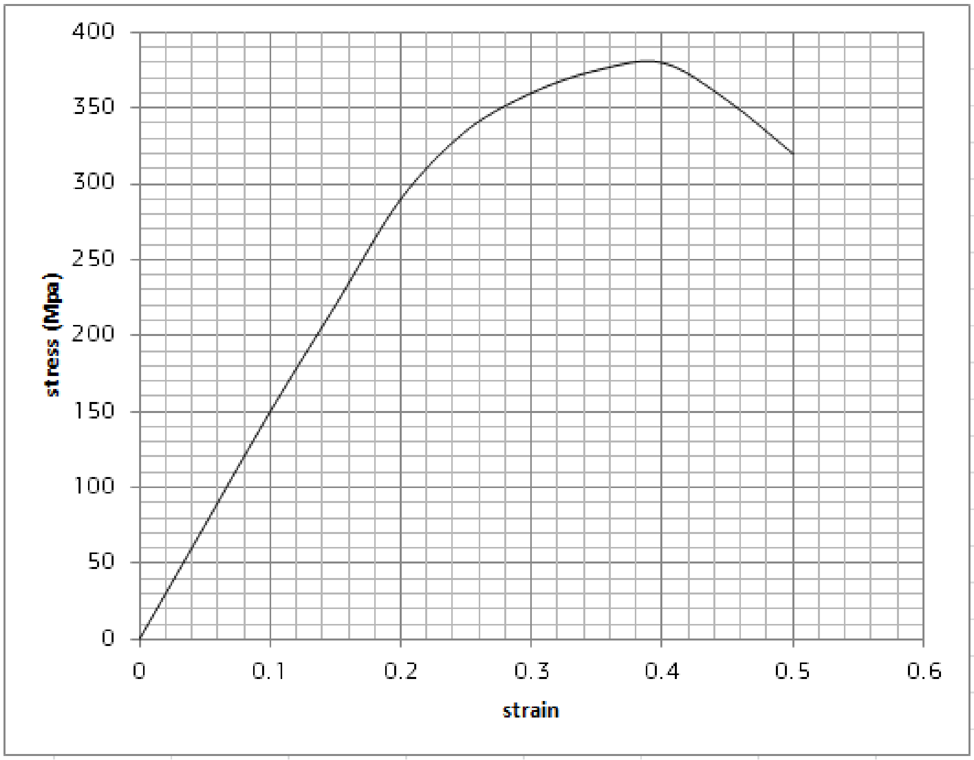
strain

APPENDIX B: FLEXURAL TEST RESULT



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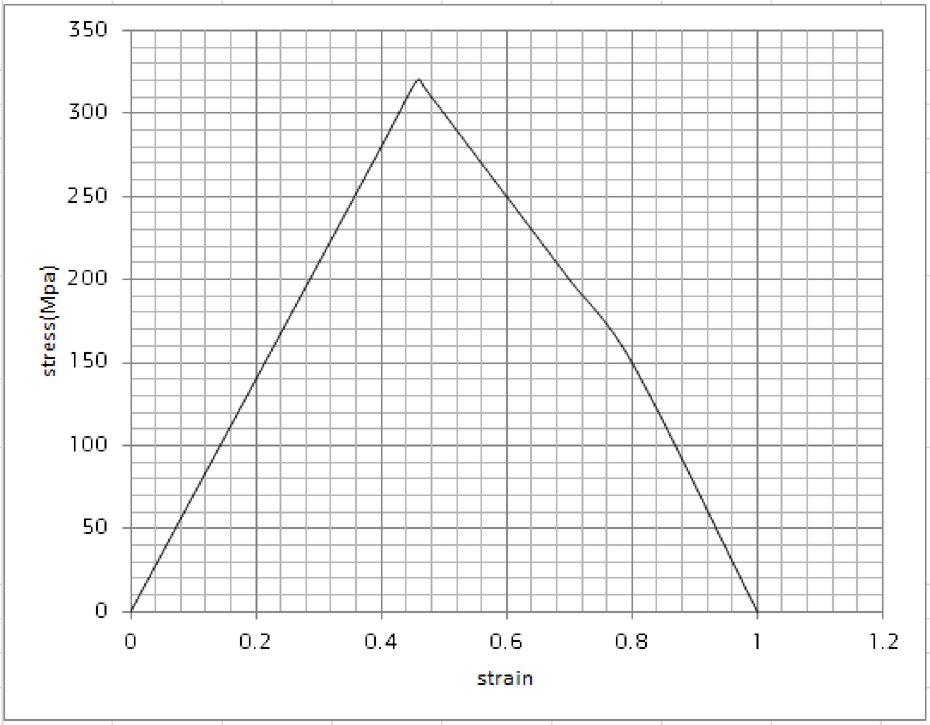
0.6
strain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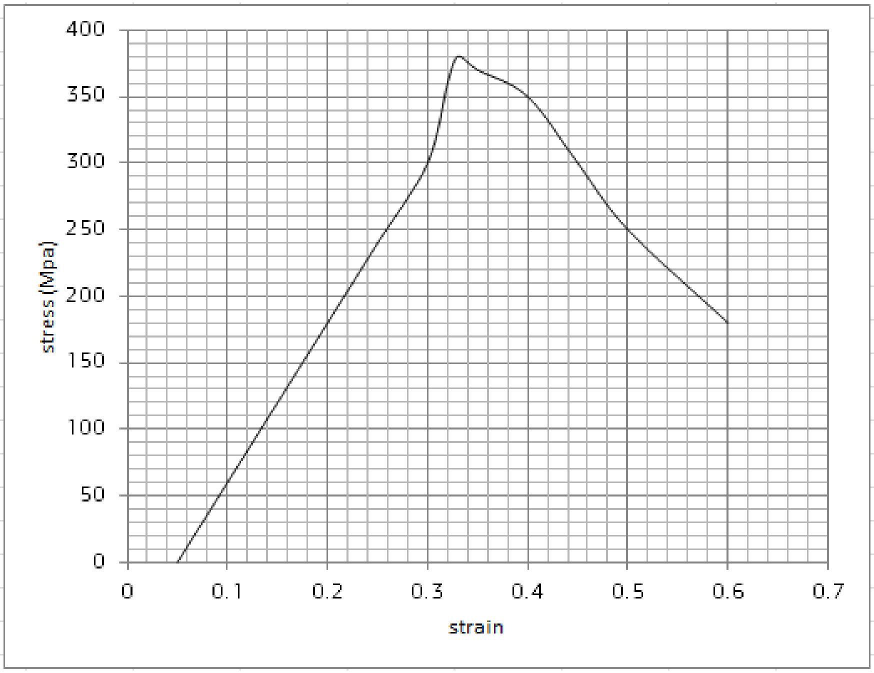
strain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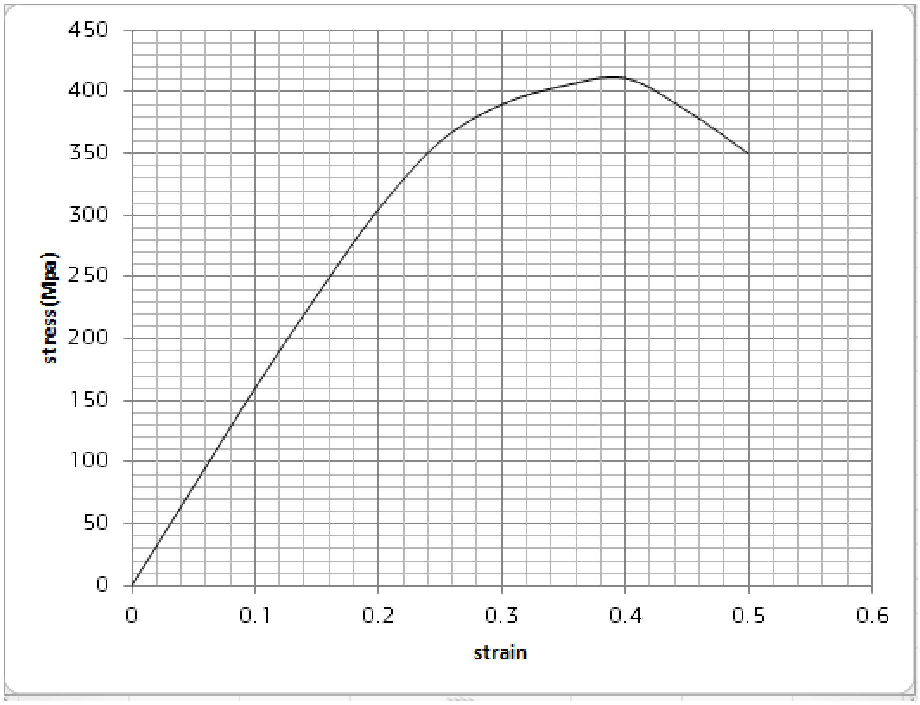
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0.6
strain