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Effects of Voids Shape on Mechanical Properties of Sic Particles Reinforced Aluminium Matrix Composite

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GENERAL INTRODUCTION

General Introduction

A material has natural or artificial origin that man shapes to make objects. A material is therefore a basic material selected because of particular properties and implemented for a specific use. The chemical nature, the physical form, the surface state of the different raw materials which are the basis of the materials given to them with particular properties. Advanced materials are one of the classes of these materials: biomaterials, composites, smart materials, nanomaterials, active materials and functional materials [1-5].

A composite material is made up of different phases called reinforcements and matrix. The reinforcement is in the form of continuous and discontinuous fibers or particles, the role of the reinforcement is to ensure the function of mechanical resistance to forces [6-7]. The matrix ensures cohesion between the reinforcements so as to distribute the mechanical stresses. The arrangement of the fibers and their orientations make it possible to reinforce the mechanical properties of the structure.

Particle-reinforced composites were developed largely to fill the property gap between laminates (continuous fibers) used as primary structures by the aviation and aerospace industry and unreinforced materials used primarily in non-load-bearing applications. In some ways, discontinuous reinforcements combine the advantages of each of these materials [8]. Thus, particles have found their places in lightly loaded structures, in which stiffness dominates the design, but in which there must also be a noticeable increase in force on the unreinforced material [9]. Increasing the contact area can help compensate for the imperfect bonding between the particle-matrix interphase. Therefore, composite materials made of nanoparticles should offer higher strength than a conventional composite prepared with the same volume fraction [10]. A parametric study is carried out to discuss the effect of void volume fraction and void shape deviation on the mechanical behavior of UD composites. Considering the void volume fraction in high-quality composites should be limited within 5%, this value is set as 1 %, 3 % and 5 % [11].

General Introduction

The main objective of this work is to study the effect of porosity (1%, 2%, 3% 4% and 5%) on the mechanical behavior of a composite material with a Aluminium matrix reinforced by Sic (Silicon Carbide) particles. For this, we varied the porosity according to the volume fraction of the particles and this for three types of arrangement (square, hexagonal and random).

To do this, we began our work with a first chapter devoted to the different types of composite materials, as well as the techniques for their implementation based on particle-reinforced composites. Then, a second chapter devoted to a voids formation. The third and last chapter, we continued with the calculation of the dimensions of these particles to be able to be used in the numerical simulation software Castem, while using three shapes of voids (Circular, square and triangle) for different volume fraction of particles reinforcing a plate subjected to traction. Finally, we ended our study with a general conclusion.

CHAPTER I

Overview of Composite Materials

I.1 Introduction

The integrity of the composite relies on the strong interconnection between these phases, which ensures optimal performance under various conditions. The choice of reinforcement type, whether continuous or discontinuous, plays a crucial role in determining the mechanical properties and overall effectiveness of the composite material.

The function of reinforcement is to provide mechanical resistance against applied forces. The matrix plays a crucial role in maintaining cohesion among the reinforcements, facilitating the distribution of mechanical stresses. The configuration and orientation of the fibers enhance the mechanical characteristics of the structure. Structural components are constructed by layering materials, strategically optimizing the alignment of reinforcements in relation to the anticipated loads. The selection of resin or reinforcement type is determined based on the specific requirements of the intended application.

In this chapter, we explore the various categories of composite materials utilized in industrial applications. The mechanical properties of the interface between the fibers and the matrix play a crucial role in the formation of a composite structure. It is essential to ensure that there is no sliding or separation between the distinct phases of the structure in order to achieve optimal elastic mechanical properties [12].

I.2 Historical

The concept of integrating various elements to create composite materials with enhanced characteristics is not a recent development. Historical records indicate that as far back as 1500 BC, the Egyptians and early Mesopotamians utilized a blend of clay and straw to construct robust and enduring structures. Furthermore, in 1200 AD, the Mughals innovated the first compound bow, which was crafted from a combination of wood, bone, and animal glue. This design resulted in a weapon that was not only exceptionally strong but also remarkably precise and compact, making it the most formidable armament on land until the advent of gunpowder [13]. The concept of composite materials has existed in various iterations throughout human history; however, the development of modern composites began in the 18th century. During this period, the application of composite materials broadened significantly across numerous industrial sectors.

I.3 Definition of composite

A composite material is characterized as a combination of a minimum of two distinct materials, either on a macroscopic level or involving several immiscible substances that exhibit strong adhesion capabilities. The resulting assembly possesses enhanced properties that surpass those of the individual components. In contemporary terminology, "composite materials" often refer to configurations of fibers that are embedded within a matrix, which typically has significantly lower mechanical strength. The matrix plays a crucial role in maintaining the cohesion and alignment of the fibers, while also facilitating the transfer of stresses experienced by the components. Consequently, the materials produced through this process are notably heterogeneous and exhibit anisotropic characteristics [14].

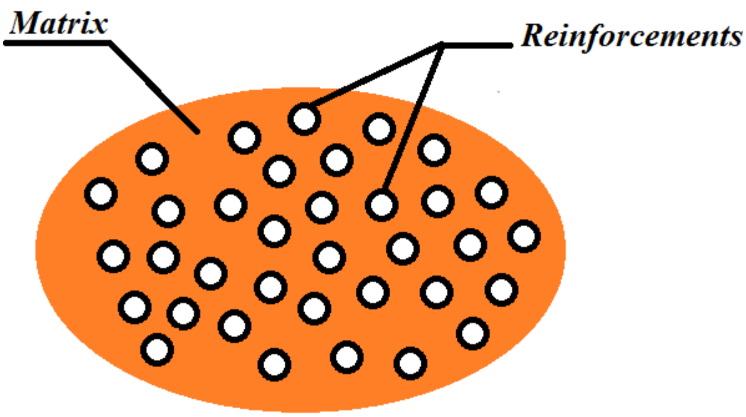


Figure I.1 *Schematic of reinforcements embedded in a matrix.*

I.4 Constituents of composite materials

Composite materials primarily consist of two key components: reinforcements and the matrix. Reinforcements can take various forms, including fibers that may be continuous or discontinuous, as well as skeletal structures. The primary function of the reinforcement is to provide mechanical strength, enabling the material to withstand tensile forces and maintain rigidity. Conversely, the matrix serves to bind the reinforcements together, facilitating the distribution of applied forces while also offering resistance to compression and bending, in addition to providing chemical protection [15].

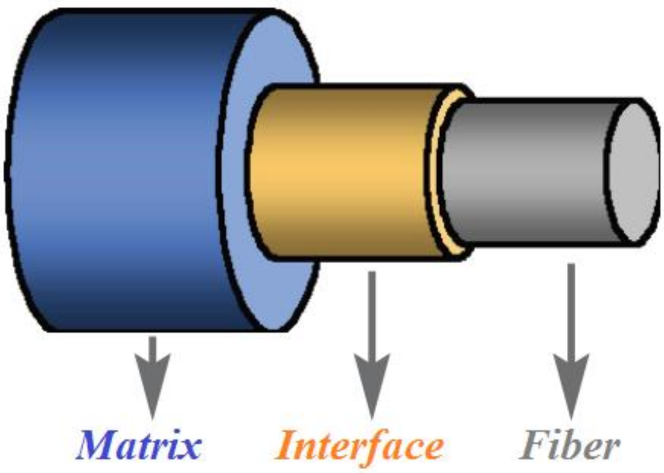


Figure I.2 *Constitution of a composite material.*

I.4.1 Matrix

In many instances, the matrix that forms the basis of composite materials is a polymer resin. There is a wide variety of polymer resins, each tailored for specific applications. For scenarios demanding exceptional resistance to elevated temperatures, composites utilizing a matrix of metal, ceramics, or carbon are preferred. Notably, carbon-based materials can withstand temperatures as high as 2,200°C. Presently, the predominant choice is thermosetting resins (TD) combined with long fibers; however, there is a significant increase in the adoption of thermoplastic polymers (TP) reinforced with short fibers.

The two categories of resins possess the ability to be molded or shaped, allowing for the creation of either finished or semi-finished products whose forms can be altered. Figure I.3 illustrates the classification of the matrix types that are frequently encountered [16].

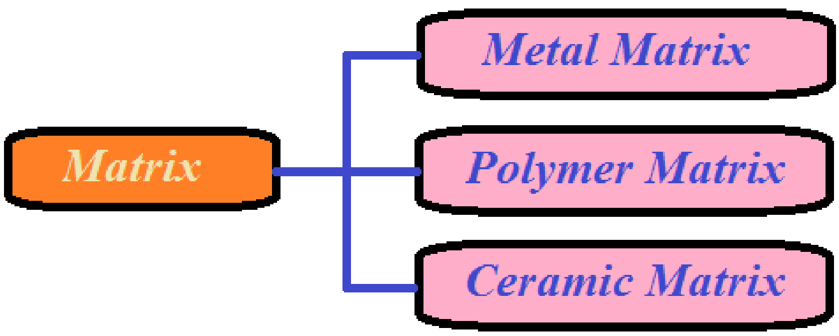


Figure I.3 *Different matrix classification.*

I.4.1.1 Polymer matrix

a) Thermoplastics

Thermoplastic matrix composites are becoming increasingly significant in various industries, particularly in aeronautics, due to their numerous advantages over thermoset materials. One of the key benefits of thermoplastic resins is their ability to be repeatedly softened through heating and solidified upon cooling, which enhances their moldability through viscoplastic behavior. This reversible transformation not only facilitates processing but also enables the recycling of the material. These thermoplastics are typically employed when temperatures approach their glass transition point for amorphous types, and can be utilized up to their melting point for semi-crystalline varieties. The application of these resins, whether reinforced with short or long fibers, is rapidly expanding, especially as a matrix in structural composite materials.

Table I.1 *Characteristics of thermoplastics [17]*

Resin Type	Density (Mg/m3)	Modulus (GPa)	Strength (MPa)
PEEK	1.26 – 1.32	3.2	93
PP	0.9	1.1 – 1.6	31 – 42
PPS	1.36	3.3	84
PAI	1.4	3.7 – 4.8	93 – 147

b) Thermoset

When specific polymers composed of organic or semi-organic materials are exposed to elevated temperatures, they undergo chemical reactions that lead to the combination of monomers, resulting in the formation of a rigid three-dimensional network. This process is known as crosslinking. The outcome of this polymerization is a solid, infusible material. Due to the irreversible nature of polymerization, these substances can only be molded a single time, rendering them non-recyclable. Typically, these resins exhibit low impact resistance and inadequate thermal stability. In the aerospace sector, four primary types of resins are frequently utilized: epoxies, bismaleimides, polyamides, and phenolics [18].

Thermosets are characterized as three-dimensional molecular networks that are interconnected by strong chemical bonds, specifically covalent bonds, which are formed irreversibly during the polymerization process.

Table I.2 *Characteristics of thermosets [19]*

Resin Type	Density (Mg/m3)	Modulus (GPa)	Strength (MPa)
Polyester	1.1 – 1.23	3.1 – 4.6	50 – 75
Epoxy	1.1 – 1.2	2.6 – 3.8	60 – 85
Vinyl Ester	1.12 – 1.13	3.1 – 3.3	60 – 90
Phenolic	1.0 – 1.25	3.0 – 4.0	60 – 80
Polyurethan	1.2	0.7	30 – 40
Bismaleimides	1.2 – 1.32	3.2 – 5.0	48 – 110

I.4.1.2 Ceramics

For applications involving elevated temperatures exceeding 800° C, ceramics are considered the most appropriate matrix materials. This is attributed to their remarkable refractoriness, elevated elastic moduli, significant hardness, and favorable chemical inertness, all of which are complemented by their relatively low densities in comparison to metals.

The integration of fibrous reinforcement within composites effectively addresses the primary drawback of ceramics, namely their brittleness. Consequently, ceramic matrix composites (CMCs) are increasingly regarded as viable options for producing components in thermal engines, spacecraft, and even in both civil and military nuclear sectors. The initial development of materials that combined reinforcements with ceramic matrices occurred in the 1960s, leading to the creation of carbon-carbon composites specifically designed for high-performance and high-temperature environments, such as military aviation and space exploration. These applications are characterized by their high costs, reflecting the substantial financial resources dedicated to these specialized fields. A significant advancement in CMC technology took place in 1969 when a company began utilizing these materials in contexts that had previously relied on superalloys, such as those made from cobalt or nickel, or on monolithic materials with inherent limitations, like the weight of tungsten or the fragility of graphite, all within the realm of high-cost applications. It was not until 1986 that CMCs were first employed in civil aviation, notably in the brake discs of the Airbus A310 [20].

I.4.1.3 Metal

Metal matrix composites have been engineered to enhance specific properties of metals while addressing some of the limitations associated with organic matrix composites, such as restricted temperature usage and susceptibility to aging. By incorporating fibers into metals and their alloys, these composites exhibit increased rigidity, mechanical strength, and fatigue resistance, not only at ambient temperatures—particularly for softer metals like lead—but also at elevated temperatures, as seen with aluminum and titanium [20].

The metals that are frequently utilized include aluminum, magnesium, and titanium, while cobalt, occasionally combined with nickel, is preferred for applications involving high temperatures. The incorporation of a metal matrix into composite materials imparts enhanced characteristics. Notable improvements include superior mechanical properties, increased fire and temperature resistance, enhanced electrical and thermal conductivity, as well as resistance to radiation and impermeability to gases and moisture. These advanced materials find applications across diverse sectors, ranging from drill bits made of tungsten to industries such as aerospace and automotive.

The primary constraint on the utilization of these materials is their elevated cost, which significantly surpasses that of traditional alternatives. Although research into these materials has only been conducted for approximately two decades, they have rapidly supplanted conventional materials in specific applications, particularly in the automotive sector (such as engines and brakes) and in aeronautics (including components like tails, landing gear, and turbines) [10].

I.4.2 Reinforcements

A composite material qualifies as a fiber composite when its reinforcement consists of fibers. These fibers can be categorized as either continuous or discontinuous, with the latter including staple and short fibers. The specific arrangement and orientation of these fibers allow for the tailored adjustment of the mechanical properties of the composite materials, enabling the production of materials that can vary from highly anisotropic to isotropic within a plane [21]. The various types of reinforcement that are frequently encountered are illustrated in Figure I.4.

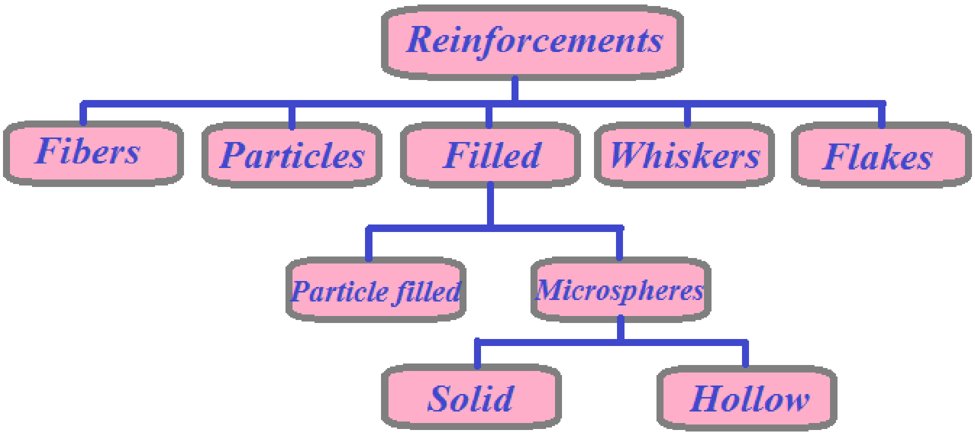


Figure I.4 *The different types of basic reinforcement.*

I.5 Matrix/reinforcement relationship

The effectiveness of a composite material is influenced by the inherent characteristics of its constituent components, as well as the critical role of adhesion, which is determined by the interactions between the reinforcement and the matrix. Various factors contribute to adhesion, originating from different sources, and can be categorized into three main groups: first, factors related to the reinforcement, including its nature, composition, and the effects of its size and distribution; second, factors pertaining to the matrix itself; and third, factors associated with the interface, which encompass aspects such as thickness, interfacial forces between the matrix and reinforcement, the wettability of the reinforcement by the matrix, and the impact of impurities.

The variety of parameters indicates that we do not establish a singular membership model; rather, we create multiple models, each tailored to specific scenarios. There are two categories of these models:

- Mechanical adhesion refers to the process by which a matrix securely attaches itself to the reinforcement through the interlocking of its material within the pores and surface irregularities.
- Specific membership enables the characterization of various membership types, allowing for the identification of distinct models. These include the electrostatic model, the interfacial diffusion model, the adsorption model, the chemical bond model, and the Bikerman model [16].

I.6 Additives

Incorporating various products into the resin can enhance its mechanical properties, particularly through the use of reinforcing fillers, such as hollow spherical fillers ranging from 5 to 150 µm in size. Additionally, non-reinforcing fillers may be utilized to lower the expenses associated with resin matrices. Furthermore, additives like coloring agents and mold release agents are commonly employed in the design of structures constructed from composite materials [15].

I.7 Substances

Filler refers to any inert substance, whether mineral or vegetable, that is incorporated into a base polymer to significantly alter its mechanical, electrical, or thermal characteristics, enhance its surface aesthetics, or simply reduce the production costs of the processed material. In contrast to thermoplastic materials, thermosetting materials have traditionally included a variety of fillers, often comprising up to 60% by mass. The selection of filler for a specific polymer is guided by the desired modifications for the final product, which may involve improving mechanical properties or facilitating processing. Generally, materials intended for use as fillers in plastic applications must satisfy a series of specific criteria: the compatibility with the foundational resin is essential, along with the ability to wet surfaces effectively. It is also important to ensure a consistent quality and uniform particle size throughout the material. Additionally, the material should exhibit minimal abrasive properties and be cost-effective [16].

I.8 Classification of composite materials

Composites can be categorized based on the configuration of their components, the characteristics of the materials involved, and the specific type of composite material utilized.

I.8.1 Classification according to constituents

I.8.1.1 Fiber composites

A composite material qualifies as a fiber composite when its reinforcement consists of fibers. These fibers can be categorized as either continuous or discontinuous, including staple fibers and short fibers, among others. The configuration and orientation of the fibers enable the customization of the composite's properties, allowing for the production of materials that vary from highly anisotropic to isotropic within a plane.

I.8.1.2 Particle composites

A composite material is classified as a particle composite when its reinforcement takes the form of particles. Unlike fibers, particles do not possess specific dimensions. Typically, particles are utilized to enhance various properties of materials or matrices, including rigidity, thermal resistance, abrasion resistance, and minimization of shrinkage, among others. In numerous instances, particles serve primarily as fillers to lower material costs without compromising their inherent characteristics. The selection of the appropriate matrix-particle combination is contingent upon the desired material properties. For instance, elastomer particles can be added to brittle polymer matrices to enhance their fracture and impact resistance, thereby decreasing their susceptibility to cracking [23].

Figure I.5 *Different particle shapes*

I.8.2 Classification according to the structure

I.8.2.1 Monolayer

Monolayer serves as the fundamental component of composite structures. Various types of monolayer are distinguished by the configuration of the reinforcement, which can include long fibers (either unidirectional or randomly distributed), woven fibers, and short fibers [24].

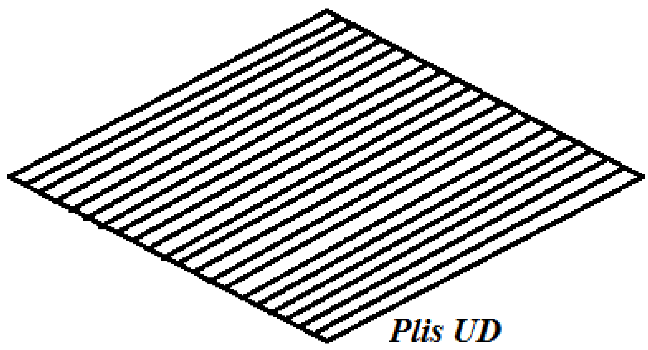


Figure I.6 *Monolayer composite.*

I.8.2.2 Woven composites

Numerous composite components are constructed utilizing fabrics. In these materials, the fibers are organized into threads and arranged into specific patterns. Upon completion of the final shaping, the matrix is evident at two distinct levels:

- Within the threads,
- Within the woven structure.

The weaving patterns employed in composite materials can exhibit a range of shapes, including:

- A single layer of threads;
- Thickness achieved by stitching multiple layers together;
- Layering to create a laminate structure.

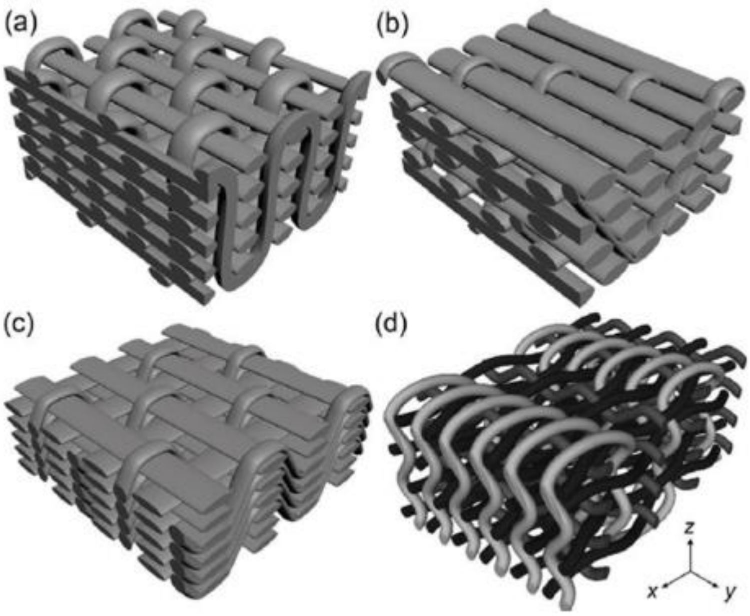


Figure I.7 *Examples of Common Planar Fabrics*

There exist additional three-dimensional fabrics characterized by threads arranged in various orientations. This weaving technique enables the creation of materials with varying thicknesses, enhancing their resistance to tearing; however, the manufacturing process is notably more intricate.

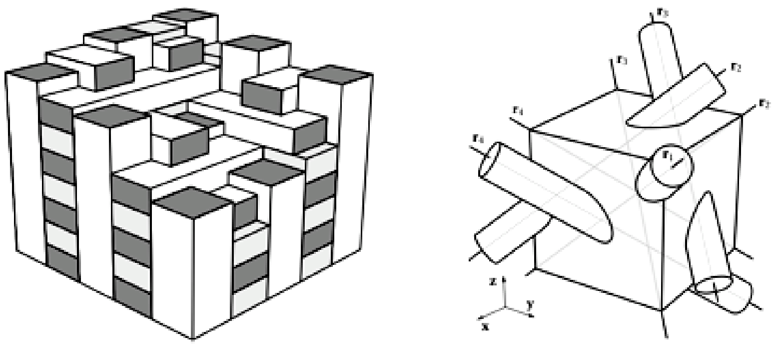


Figure I-8 *Examples of three-dimensional fabrics*

I.8.2.3 Laminates

A laminate consists of a series of monolayer, each oriented in relation to a shared frame of reference that applies to all layers, referred to as the laminate's frame of reference. The illustration below depicts a laminated composite material.

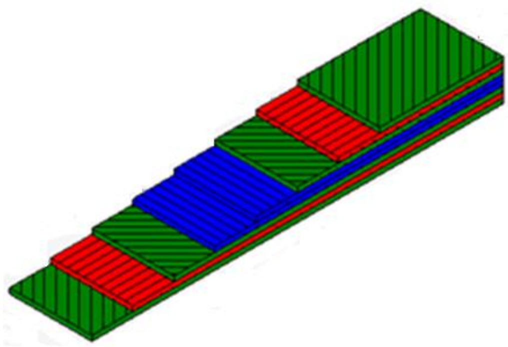


Figure I.9 *Laminate.*

The selection of stacking sequences, particularly the orientations, will yield distinct mechanical characteristics. A laminate configured as (0, +45, +90, -45)2s consists of four layers oriented at 0°, -45°, 90°, and +45°, with the 0° orientation aligning with the direction of one of the primary axes of the composite material. These layers will be symmetrically arranged concerning the central plane of the laminate. Various types of laminates could be designed in this manner:

- Balanced: laminate comprising as many layers oriented in the direction +θ as layers oriented in the direction-θ ;
- Symmetric: laminate comprising layers arranged symmetrically with respect to a mean plane;
- Orthogonal: laminate comprising as many layers at 0° as layers 90°.

I.8.2.4 Sandwich

Materials consisting of two rigid and thin outer layers encasing a thick and less resilient core create a structure that is remarkably lightweight. This sandwich material exhibits minimal bending weight and serves as an outstanding thermal insulator. The illustration below depicts a composite sandwich material [23].

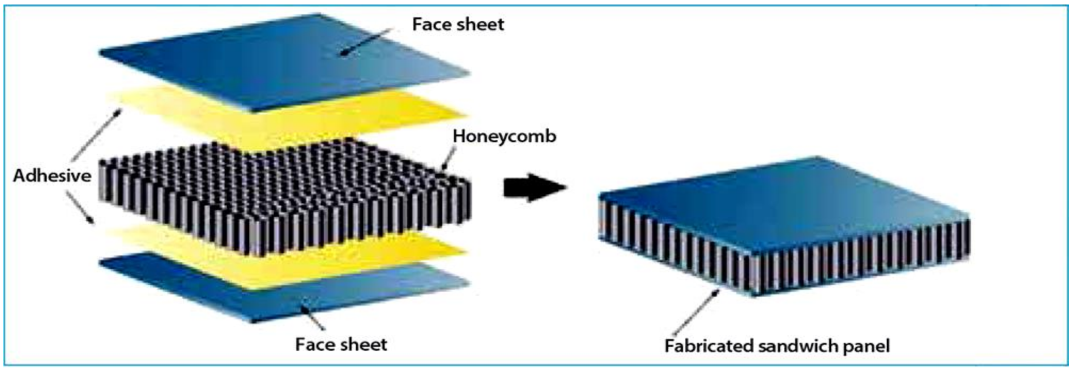


Figure I.10 *Sandwich.*

- **The core**: There are a large number of materials that can be used as a core. These materials are divided into three classes:
  - Solid low density materials: balsa and other types of wood;
  - High density materials increased in cellular form: honeycomb;
  - Enhanced high density materials in corrugated form: corrugated sheets.
- **Skin**: A wide variety of materials are used as skin, for example: metal sheets such as aluminum, titanium, etc. The choice of materials used as skin is important from the point of view of the working environment, because this part comes into direct contact with the latter [24].

I.8.3 Classification according to the type of composite material

There are two types of composites: large diffusion composites and high performance composites.

I.8.3.1 Widespread composite materials

Composite materials are widely recognized for their significant benefits, which include cost efficiency achieved through lower production costs, their formulation consisting of polyester combined with either long or short glass fibers (available as mats or fabrics), and the straightforward nature of their manufacturing processes, such as contact molding, sheet molding compound (SMC), and injection molding.

I.8.3.2 High performance composite materials

High-performance composite materials are employed in the aerospace industry, where the demand for superior performance is driven by significant added value. The reinforcements utilized are predominantly long fibers, with a reinforcement ratio exceeding 50%. The production of these composites involves several methods, including autoclave draping and filament winding, with many processes still being carried out manually [25,26].

I.9 Advantage of composite materials

- Favorable strength-to-weight ratio;
- Ability to form intricate components (based on molding principles);
- Excellent fatigue resistance;
- Minimal degradation due to moisture, heat, and corrosion (with the exception of interactions between aluminum and carbon fibers) [27].

I.10 Disadvantages of composite materials

- The effects of water and temperature on aging;
- Caution is advised when using paint strippers, as they can damage epoxy resins;
- Impact resistance is generally lower than that of metal alternatives;
- Costs can be excessively high due to the time and resources required for research and implementation, although savings are particularly significant for large-scale production [27].

I.11 Manufacturing composite materials

This section aims to outline the various techniques employed in the comprehensive implementation of composite materials and to clarify the specific contexts in which each method is applicable. The development and processing of composites can be categorized into several approaches:

The design of composite materials is influenced by the intended application and the nature of the loading, which contrasts significantly with traditional materials, where structural design is tailored to the properties of the constituent material. It is clear that the effectiveness and appropriateness of a composite material hinge on the selection of its two primary components—matrix and particles—based on the specific applications for which it is intended. Two critical objectives must be met:

- It is crucial that the liquid surrounding the particles during the composite formation process achieves spontaneous wetting, meaning that the adhesion energy from this interaction must exceed the cohesive energy of the matrix.
- The mechanical properties will be enhanced if the interface is characterized [28].

I.11.1 Stir casting

The stir casting technique involves the amalgamation of pure metals with a molten metal reservoir through mechanical agitation. In contemporary applications, this process has been enhanced by the incorporation of motorized stirring during the mixing phase. The material matrix is subjected to heating beyond its red-hot threshold, ensuring that the metal is entirely liquefied. Subsequently, the molten mixture is allowed to cool and maintained in a semi-solid state. At this juncture, preheated reinforcements are introduced into the molten pool and thoroughly blended. The semi-solid metal is then reheated to achieve the desired liquid state and mixed systematically. This effective methodological approach facilitates the disruption of the surrounding gas environment around the particles [29].

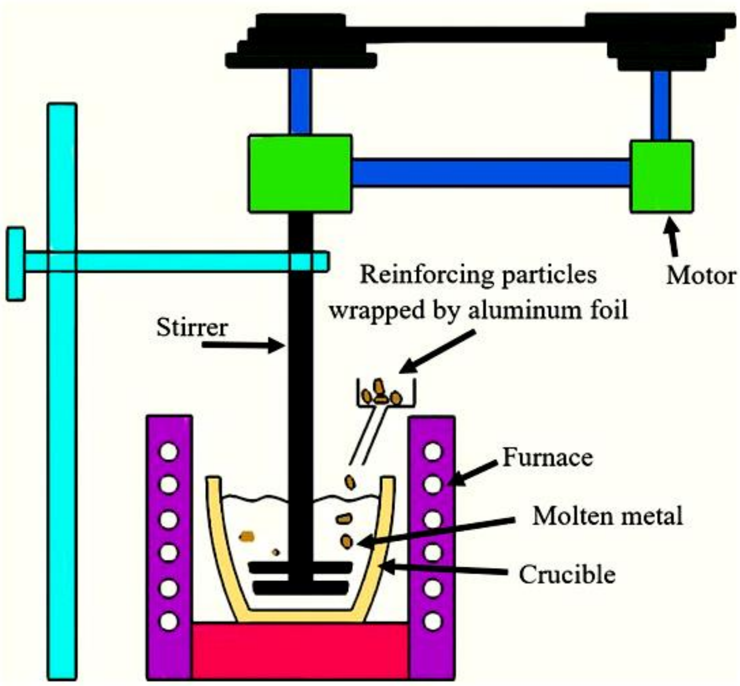


Figure I.11 *Stir casting technique [30].*

a) Stir casting process parameter

The fabrication of Metal Matrix Composites (MMCs) via stir casting necessitates careful consideration of several variable factors:

- ***Rotation Speed**:* The control of rotation speed is crucial, as it not only affects the conditions under which the casting is produced but also influences the final shape of the casting. When reinforcement is introduced into the matrix, an increase in rotation speed is required to achieve refinement; conversely, a reduction in speed can lead to instability within the liquid mass.
- ***Stirring speed**:* stirring speed is a critical parameter that impacts wettability, which is essential for the bonding quality between the reinforcement and the matrix. The stirring speed directly governs the flow pattern of the molten metal, and an increase in wettability correlates with a higher solidification rate.
- ***Stirring temperature**:* the stirring temperature is vital in aluminum fabrication due to its effect on viscosity; as the processing temperature rises, the viscosity of the molten metal decreases, facilitating better particle distribution within the MMCs [31].
- ***Pre-heat temperature of Reinforcement**:* pre-heating the reinforcement materials to 500°C for 30 minutes has been shown to eliminate unwanted moisture and gases, enhancing the overall quality of the composite.
- ***Stirring time**:* The duration of stirring also significantly influences the uniform circulation of reinforcement particles within the MMCs.
- ***Pouring temperature range**:* the pouring temperature range is critical to the solidification process, as it varies with the dimensions of the parts being produced; lower pouring temperatures tend to promote maximum grain refinement, while higher temperatures can lead to columnar growth in various alloys, although practical limitations often restrict the choices available.
- ***Temperature of the Mould**:* To prevent issues such as tearing or die expansion, it is essential to maintain the mould at an appropriate temperature through preheating. Typically, the mould's temperature should not be excessively low or excessively high.

b) Compo-casting technique

The compo-casting technique is a liquid-phase process wherein reinforcing particles are introduced into a molten metal pool while undergoing vigorous agitation. Research indicates that the primary solid particles, which are initially formed in semi-solid phase slurry, can be incorporated with the reinforcing particles to prevent gravitational segregation and minimize clustering.

c) Squeeze casting

Squeeze casting, also referred to as liquid forging, is a metal forming technique that integrates fixed mold casting with die forging. The process begins with the pouring of a predetermined quantity of molten metal alloy into a preheated, lubricated die, followed by the application of pressure to facilitate the forging and solidification processes.

d) Spray Deposition

Spray deposition, commonly known as spray forming or spray casting, is a method that produces near-net-shape metal matrix composites (MMCs) with consistent microstructures through the deposition of partially solidified sprayed droplets. This technique typically involves the winding of foil-coated fiber coils from a drum, onto which a metal pool is sprayed to create a mono tape [29].

I.11.2 Reinforcement materials

The properties of metal matrix composites (MMCs) are significantly influenced by the physical characteristics of the reinforcement materials, such as fibers or granular particles, which include their type, size, and weight fraction. These factors enhance the overall performance of the MMCs, while the chemical nature of the reinforcement interacts with the matrix material, thereby affecting their physical attributes, including microstructure. During the fabrication of MMCs, establishing robust chemical bonds between the matrix and the reinforcement is crucial for ensuring effective wetting of the reinforcement within the molten matrix. However, poor wettability can lead to the formation of oxide films on the surface of the reinforcement in the molten metal, which can adversely impact the composite's properties due to the adsorption of contaminants. To improve the wettability between the reinforcement and the matrix, it is essential to apply heat treatment to metallic coatings, such as calcium, titanium, and magnesium, before introducing the particles into the metal pool. Additionally, ceramic reinforcements, including carbides, oxides, and borides like Al_2O_3, TiB2, TiO_2, SiC, TiC, and B_4C, are commonly utilized in aluminum matrix composites (AMCs). This review highlights the various processes involved in the fabrication of metal matrix composites, with a particular emphasis on the significant role of mixing casting, which is vital due to its superior specifications. In this method, the reinforcing particles are systematically added to the liquid pool and stirred to achieve a uniform distribution within the MMCs [31].

I.12Application areas

The remarkable mechanical properties of fiber-resin composite materials, characterized by specific attributes, render them highly appealing for structural applications. Furthermore, the anisotropic nature of these materials can be easily manipulated by designers, allowing for tailored adjustments in rigidity and strength in response to external forces. A significant advantage of composite materials is their capacity for optimization in accordance with specific applications, enabling reinforcement to be strategically positioned where it is most needed. This optimization leads to exceptional performance, often making these materials the lightest option available for a given level of mechanical strength. Nevertheless, the high manufacturing costs limit their use to certain sectors, including:

- Electricity and electronics;
- Construction and civil engineering;
- Transportation across road, rail, maritime, aerospace, and military domains;
- Healthcare, particularly in medical instrumentation ;
- Sports and recreational activities, such as skiing, tennis, windsurfing, surfing, golf, and rowing.

Consequently, it is evident that composite materials are predominantly employed in scenarios where superior performance is essential, and cost considerations are secondary [32].

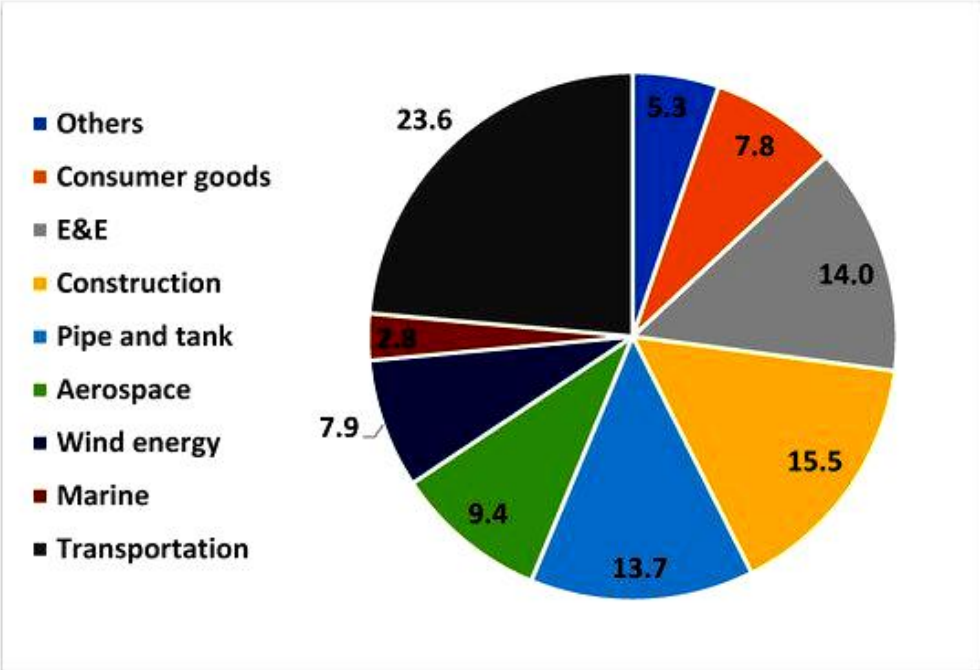


Figure I.12 *Global composite materials by application, in 2020 [33]*

CHAPTER II

Voids Formation in Particulate Composite

II.1 Introduction

The production of composite materials presents significant complexities, primarily due to the multitude of control parameters that must be managed, alongside substantial capital and time investments. Various defects, including voids, contamination, and delamination, can be introduced during the manufacturing process, adversely affecting the mechanical properties of the composites. Among the various types of defects that can arise, voids are particularly critical, as they are more frequently encountered than other defects, thereby posing a greater risk to the integrity of the final product [34].

II.2 Voids in composites

Voids are typically understood as areas within the laminate that have been removed and substituted with air pockets, which justifies their representation as inclusions in modeling. These voids are prevalent in nearly all composite materials, regardless of whether they are produced through autoclave processes, liquid composite molding, or alternative methods. The development of voids is influenced by a variety of manufacturing factors, including vacuum pressure, curing temperature, autoclave pressure, and resin viscosity, among others.

II.3 Void characteristics

Microvoids, are usually generated through two ways: evaporation of contaminants at elevated temperatures during curing, and air entrapment in highly viscous resins. The generated microvoids exist in composites as either interparticles voids or matrix voids. The former are caused by highly viscous resin not flowing between particles, and the latter are completely enclosed within the matrix [35]. Voids in composite are most often characterized by the void volume fraction, commonly referred to as void content.

II.4 Void formation, causes, and control

One of the most frequent manufacturing-induced flaws is voids, which show that there is air in the matrix [36]. Different thermodynamic and rheological events occur during different production techniques, the formation and evolution of voids during the processing of particles-reinforced composites vary [37].

II.4.1 Formation of voids

Void formation is a common issue, and it can be caused by factors such as:

- Mechanical air entrapment during resin flow,
- Gas formation due to chemical reactions during cure,
- The nucleation of dissolved gases in the resin.

The presence of air pockets is primarily caused by the uneven distribution of particles within the material, leading to inconsistent permeability of the particle preform. This inconsistency results in varying resin flow rates in different areas [37].

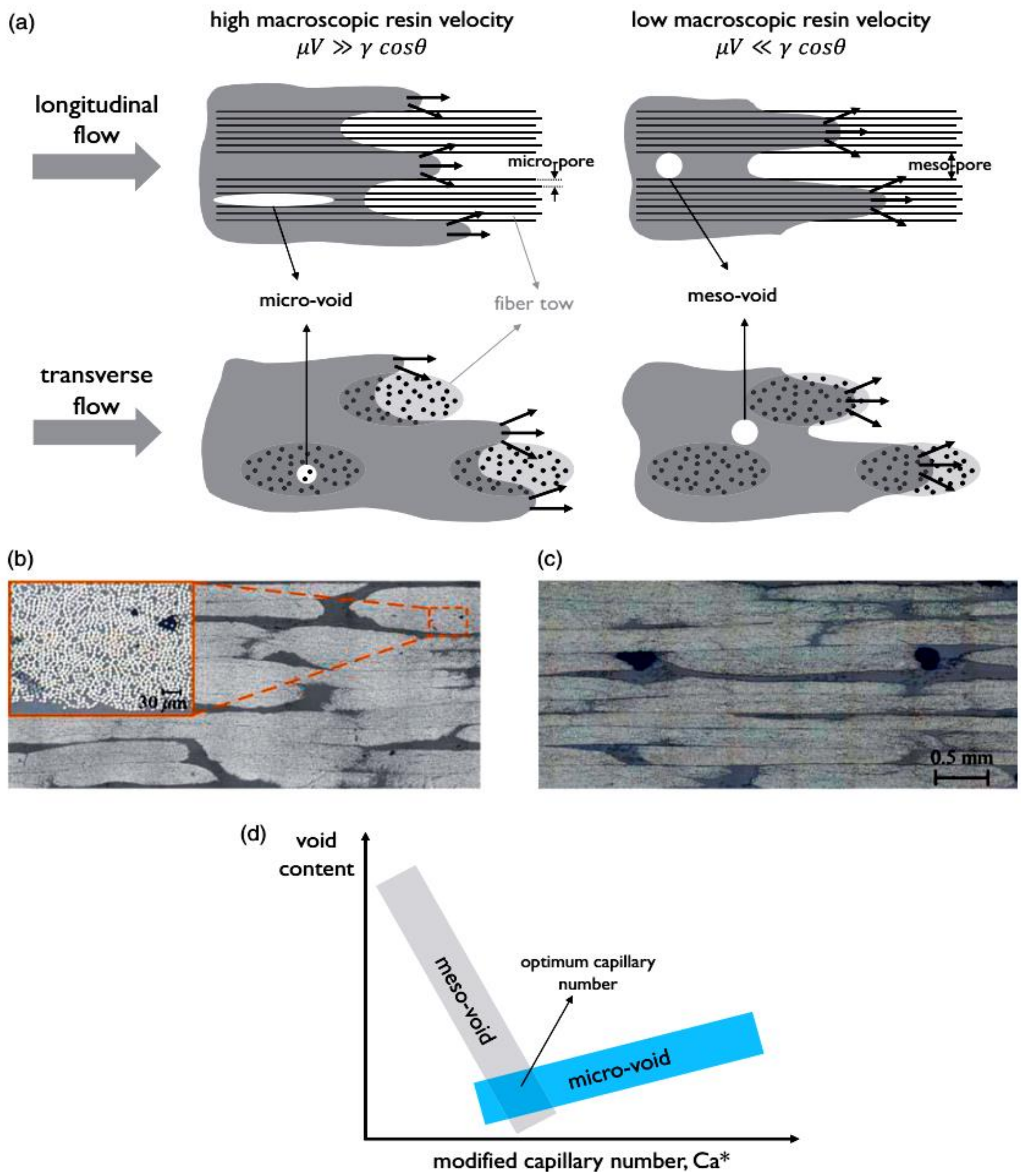


Figure II-1. *Schematic of void formation*

Figure II-1. (a) illustrate the process of void creation in the course of longitudinal and transverse flow within liquid composite molding of a dual-scale fibrous preform, highlighting the interplay between viscous flow and capillary flow - diagonal arrows indicate the transverse saturation of the fiber bundle; microscopic images exhibit (b) micro- and (c) meso-voids within and amidst fiber bundles, correspondingly; (d) diagrammatic representation of the correlation between void volume and the adjusted capillary number, illustrating an optimal capillary number for attaining the least amount of voids..

The formation of voids in particles reinforced composites occurs at three distinct scales, namely macro, meso, and micro, owing to their multi-scale nature.

- Micro-voids are formed in between the particles in a tow,
- Meso-voids in between the tows,
- Macro-voids in a larger zone of the preform (observable with the naked eye).

a) Formation of macro-voids

A macro-void refers to an area that has not yet been filled with the macroscopic resin flow, despite the resin flow front reaching the vent. These voids are visible to the naked eye and are typically caused by irregular flow patterns due to:

- The preform's uneven permeability,
- Incorrect injection points,
- The inclusion of inserts,
- Ribs,
- Cores in the mold.

b) Formation of micro- and meso-voids

The voids exhibit more complex physics in their development compared to macro-voids, prompting extensive research in this field that advocates for a dual-scale approach to studying voids. This dual-scale voidage is a defining feature of tow-based composites, which are textile composites made of yarns and exclude unidirectional plies, random mats, and short fiber composites.

II.4.2 Void motion

Voids can either remain stationary or move along with the resin flow, especially in axial flows where void formation takes place at the flow front. The movement of voids is determined by the balance between the drag caused by the pressure gradient across the void and the adhesion due to surface tension. The mobility of voids is typically described by two dimensionless parameters: the capillary number and the ratio of void size to the inter-tow or inter-fiber spacing. A high resin velocity, indicating a high capillary number, results in increased void mobility. There exists a critical capillary number, beyond which the void starts to move.

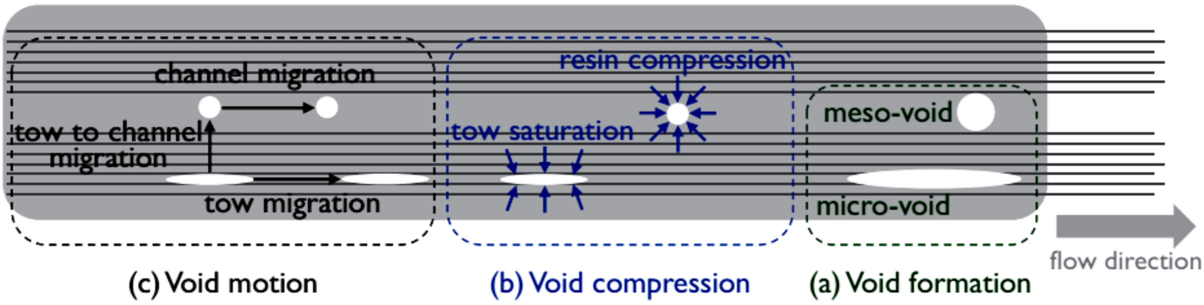


Figure II-2 *Stages of void life during resin impregnation through a resin transfer molding process*

The resin transfer molding process involves three distinct stages in the life of voids: (a) the creation of micro- and meso-voids within and between the tows, (b) the compression of meso-voids caused by the rise in resin pressure and the compression of micro-voids due to tow saturation, and (c) the movement of meso-voids in the channels between tows or the movement of micro-voids within the tows or towards the intertow channels. These stages have been deduced from various sources in the literature [38].

II.5 Composite arrangement

In the theoretical analysis, the particles are assumed to have uniform arrangements; each particle has a circular shape and the same diameter [39]. As for short fiber reinforced composites, the arrangements used are square and hexagonal (shown in Figure II-3)

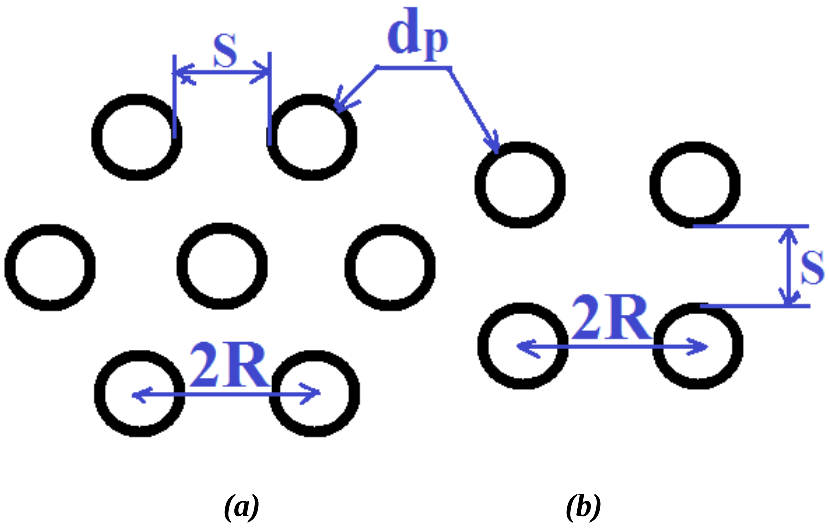


Figure II-3 *Particles packing, (a) hexagonal and (b) square*

dp: represent the particle diameter;

s: distance between particles;

2R: distance from center to center of particles.

a) Hexagonal packing

The particle arrangement of this type of arrangement is shown schematically in Figure II-3(a), assume that there are ***N*** particles in the composite. Considering the hexagonal element and according to the definition of the particle volume fraction of a composite, in this case the maximum particle volume fraction is calculated as follows:

$$V_{fmh} = \frac{\pi}{2\sqrt{3}}\left(\frac{r}{R_{\min}}\right)^2 \quad \text{(II.1)}$$

b) Square packing

The particle arrangement in this case is shown in Figure II-.3(b), and we have accordingly:

$$V_{fms} = \frac{\pi}{4}\left(\frac{r}{R_{\min}}\right)^2 \quad \text{(II.2)}$$

Rearranged the equations Eq II.1 and Eq II.2 we will have the distance ***s*** between the particles in the two ideal arrangements:

$$s = 2\left[\left(\frac{\pi}{2\sqrt{3}V_f}\right)^{1/2} - 1\right]r \qquad \text{(Hexagonal)} \qquad \text{(II.3)}$$

$$s = 2\left[\left(\frac{\pi}{4V_f}\right)^{1/2} - 1\right]r \qquad \text{(Square)} \qquad \text{(II.4)}$$

These ideal arrangements are generally used to develop micromechanical models due to their simplicity. However, they are not observed in the real composites except in a few localized regions. One of the main consequences of non-uniformity of arrangement is the difficulty in obtaining volume fractions above 0.7, which is considered the practical limit for commercial materials.

The development of micromechanical equations for particulate composites follows the same lines as those for continuous fiber reinforced composites. In case of particle reinforced composites, particles are uniformly dispersed in the matrix material and they are supposed to be arranged in a regular lattice pattern like a square or hexagon [40].

The following assumptions have been made in the current micromechanics of particulate composites:

1. The composite is composed of two phases - particles and matrix.
2. Each phase of the composite can be described by continuous mechanics. Therefore, the input parameters are the moduli, Poisson's ratios, thermal expansion coefficients and thermal conductivities of the individual phases.
3. La Micromechanics is characterized by average values of composite properties and average stresses of the constituents over a certain region.
4. The interface between the particle and the binder was assumed to be a perfect bond.
5. The interface between the particle and the binder was assumed to be a perfect bond.
6. Properties of individual phases are assumed to be isotropic [41].

In the case of a composite with voids, respecting the constraints following geometric shapes:

1. The particles have the same size (diameter).
2. Voids have the same size.
3. Particles must not overlap with each other.

4. Voids should not overlap with each other.
5. Particles and voids must not touch each other.
6. Particles and voids should not touch the cell walls.

The mechanical properties of a particle reinforced matrix depend on factors such as volume fraction, particle shape and spatial distribution within the matrix; the properties of the matrix also influence the behavior of the composite [38].

II.6 Dimension calculation

II.6.1 Dimensions of composite reinforced with circle voids

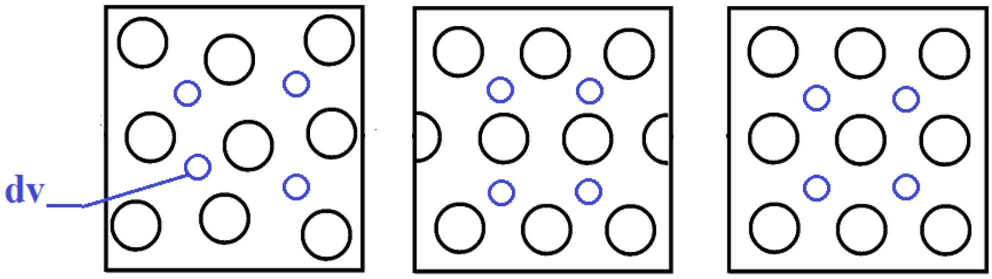


Figure II-4 *Circle voids*

$$V_{fVoid}=\frac{V_{Void}}{V_{total}}=\frac{N_{Void}\left(\frac{\pi d_{Void}{}^{2}}{4}\right)}{l_m^2} \qquad \text{(II.5)}$$

$$d_{Void}=\sqrt{\frac{4V_{fVoid}l_m^2}{N_{Void}\pi}} \qquad \text{(II.6)}$$

Dans le premier cas, on supposer avoir des pores de forme circulaire, utilisant l'équation (II.6) pour le calcul des diamètres en fonction de la fraction volumique des pores.

The results found are grouped in the Table II-1

Table II-1 *Voids diameter in function of volume fraction for circle shape*

$V_{f\,void}$	0.01	0.02	0.03	0.04	0.05
$d_{Void}(\mu m)$	11.28	15.96	19.54	22.57	25.23

II.6.2 Dimensions of composite reinforced with square voids

Lc: represent of the length of the square.

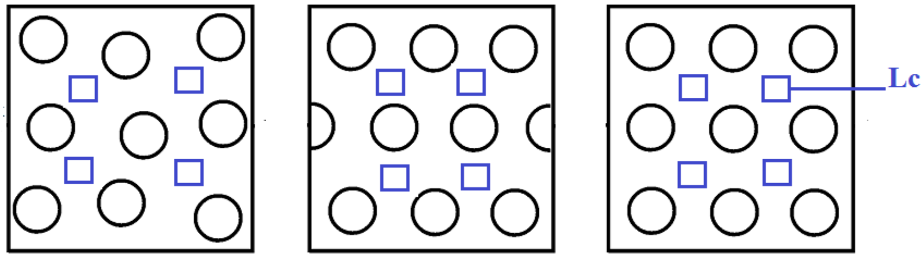


Figure II-5 *Square Voids*

$$V_{fVoid} = \frac{V_{Void}}{V_{total}} = \frac{N_{Void} \times L_C^2}{l_m^2} \quad \text{(II.7)}$$

$$L_C = \sqrt{\frac{V_{fVoid} \times l_m^2}{N_{Void}}} \quad \text{(II.8)}$$

The results found are grouped in the Table II-2

Table II-2 *Voids length in function of volume fraction for square shape*

$V_{f\,void}$	0.01	0.02	0.03	0.04	0.05
$LC_{Void}(\mu m)$	10.00	14.14	17.32	20.00	22.35

II.6.3 Dimensions of composite reinforced with triangle voids

Lt: represent of the length of the triangle (we supposed that the triangle is equilateral).

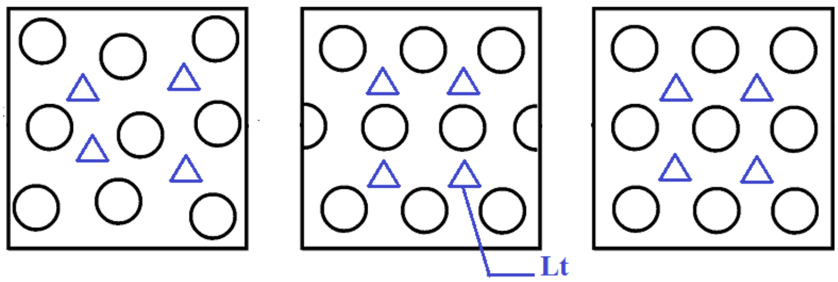


Figure II-6 *Triangle voids*

$$V_{fVoid} = \frac{V_{Void}}{V_{total}} = \frac{N_{Void} \times 0.5 L_T^2}{l_m^2} \quad \text{(II.9)}$$

$$L_T = \sqrt{\frac{V_{fVoid} l_m^2}{N_{Void} \times 0.5}} \tag{II.10}$$

The results found are grouped in the Table II-3

Table II-3 *Voids length in function of volume fraction for equilateral triangle shape*

$V_{f\,void}$	0.01	0.02	0.03	0.04	0.05
$LT_{Void}(\mu m)$	14.14	20.00	24.49	28.28	31.62

CHAPTER III

Results and Discussion

Chapter III: Results and Discussion

III.1 Introduction

This research focuses on a composite material that incorporates a thermoplastic matrix. Organic matrix composites are limited to applications where temperatures remain below 200 to 300°C. In this study, we examined a multi-reinforcement composite model that is enhanced with particles, analyzing its behavior under tensile loading and considering various forms of voids [42].

III.2 Composite material

Ceramic inclusions within metal-matrix composites significantly enhance their mechanical properties, including strength and hardness, as well as their chemical and thermal stability. These advanced materials exhibit excellent resistance to high temperatures, making them suitable for applications such as thermal barrier coatings, turbine engines, and other essential components and assemblies. The reinforcing agents typically consist of oxides or carbides, with alumina (Al2O3), silicon carbide (SiC), and graphite being the most commonly utilized in various forms. Generally, the manufacturing process involves casting techniques followed by additional processing to achieve the desired shape. Alternatively, powder metallurgy methods can be employed, allowing for the desired composition to be attained through the simple mixing of the constituent materials. This study focuses on a composite material that features an aluminum matrix reinforced with SiC particles [43].

III.2.1 Sic particles as reinforcements

Silicon carbide (SiC) in its particulate form has been utilized for an extended period. It is relatively inexpensive and is widely employed in applications such as abrasives, refractories, and various chemical processes. The production of particulate SiC involves a reaction between silica, typically sourced from sand, and carbon, usually derived from coke, at a temperature of 2,400 degrees Celsius within an electric furnace. The resultant SiC is initially formed into large granules, which are then ground to achieve the desired particle size. There are two distinct types of SiC particulate reinforcement characterized by their morphology: angular and rounded [44]. The type of SiC discussed herein serves as the reinforcing material for the composite material under examination in this research. Relevant parameter values are detailed in Table III-1.

Table III-1 *The mechanical properties of silicon carbide (SiC) particles [45]*

Properties of Sic particles	
Density	$3.20x10^3$ Kg/m^3
Poisson's ratio	0.2
Young Module	485 Gpa
Thermal conductivity	81 $W.m^{-1}.K^{-1}$
Thermal expansion	$4.90x10^{-9}$ K^{-1}

III.2.2 Aluminium Matrix

Aluminum matrix composites (AMC) have garnered significant attention from designers and engineers due to their advantageous properties, including ease of casting, low melting temperatures, enhanced thermal conductivity, reduced weight, elevated specific strength and stiffness, minimal thermal expansion coefficients, and superior resistance to abrasion and wear, as well as improved damping characteristics. These composites have established applications across various industries, including defense, mining, aerospace, automotive, and thermal management, among others. For a comprehensive overview of the properties of Aluminum matrix composites, please refer to Table III-2:

Table III-2 *Aluminum matrix material parameters [45]*

Properties of Aluminium substrate	
Density	$2.70x10^3$ Kg/m^3
Poisson's ratio	0.33
Young Module	68.9 Gpa
Thermal conductivity	193 $W.m^{-1}.K^{-1}$
Thermal expansion	$2.18x10^{-5}$ K^{-1}
Formatting temperature	260-325°C

III.3 Finite element modeling

The CASTEM software [47] serves as a tool for finite element analysis. To investigate the elastic response of a composite material when subjected to a straightforward tensile load, a model comprising particles embedded within a surrounding matrix was utilized, as illustrated in Figure III-1. The composite experiences a consistent tensile stress denoted as σ. The volume fraction of the reinforcements is varied from 0.05 to 0.40, while the volume fraction of the pores ranges from 0.01 to 0.05.

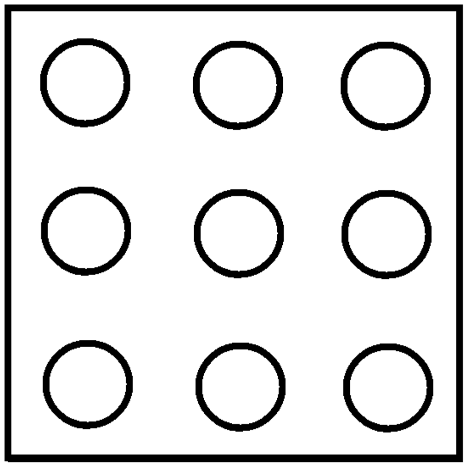
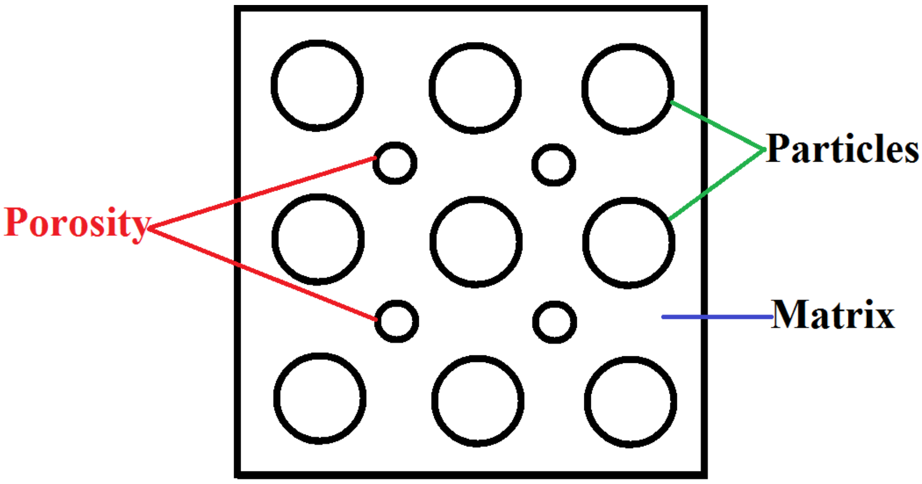
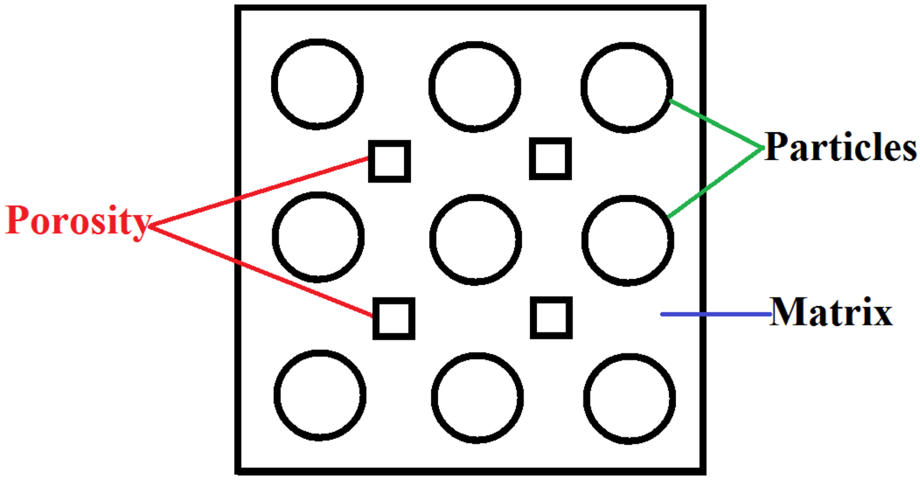


Figure III-1*Model for a particle-reinforced composite*

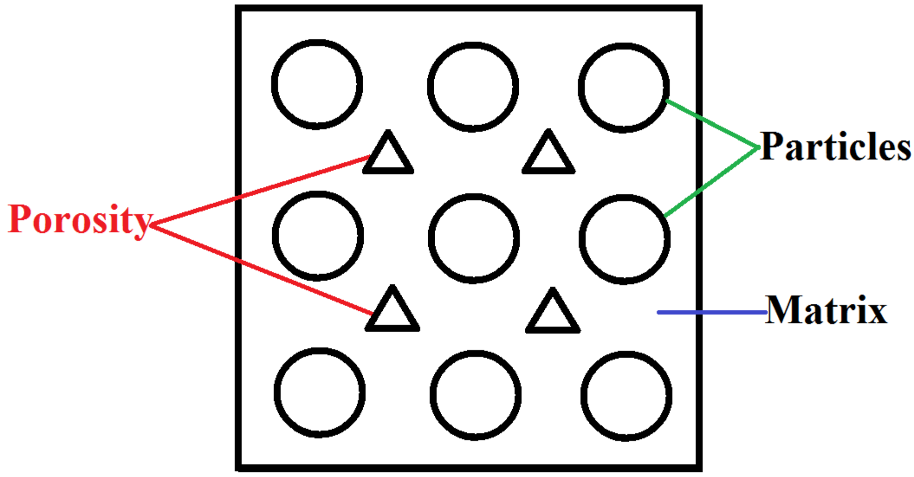
In the subsequent sections, we will examine how porosity influences the mechanical properties of the composite material, as illustrated in Figure III.2.



(a)



(b)



(c)

Figure III-2 *Model for a particle-reinforced composite with voids, (a) circle, (b) square and (c) triangle*

III.3.1 Composite property

The model's compact size necessitated the use of a fine mesh of elements [48]. For the sake of simplicity, we assume uniform dimensions for all particles [49, 50]. Given the axisymmetrical nature of the sample, it can be treated as a two-dimensional elastic body. The parameters listed below are consistently applied across all calculations [51]**:**

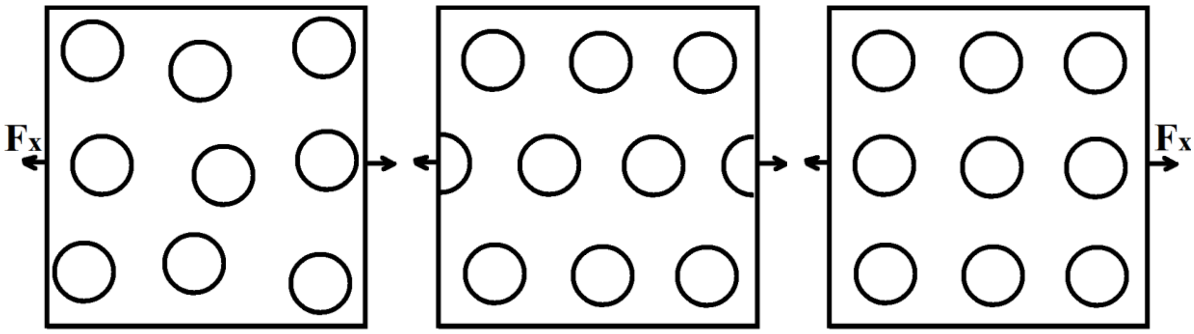
1. Sic Particles: Young module E_p= 485 *GPa*. Poisson ratio v_p = 0,2 and density ρ_p= 3,20 *g / cc*.

2. Aluminium matrix: Young module E_m = 68.9 *GPa*. Poisson ratio v_m = 0,33 and density ρ_m= 2,70 g / *cc*.

The composite material was designed and discretized using triangular elements to achieve optimal convergence and accuracy in the results. It is subjected to a uniform tensile stress denoted as σ. For the sake of simplicity, we consider that all particles possess an identical diameter, d_p [52,53].

III.3.2 Boundary condition

The boundary conditions that characterize the application of a tensile load to a particle-reinforced composite are defined at X=0, as illustrated in Figure III-4. In this context, the X-axis aligns with the direction of the applied force. A constraint of $F_x = 5.65e\text{-}8\ N/\mu m^2$ was imposed on the end faces of the matrix [54], i.e. X = 0 and X = l_m.



(a) (b) (c)

Figure III-3 *Boundary conditions for a composite reinforced with 9 square particles*

(a) Square layout, (b) Hexagonal layout, (c) Random layout

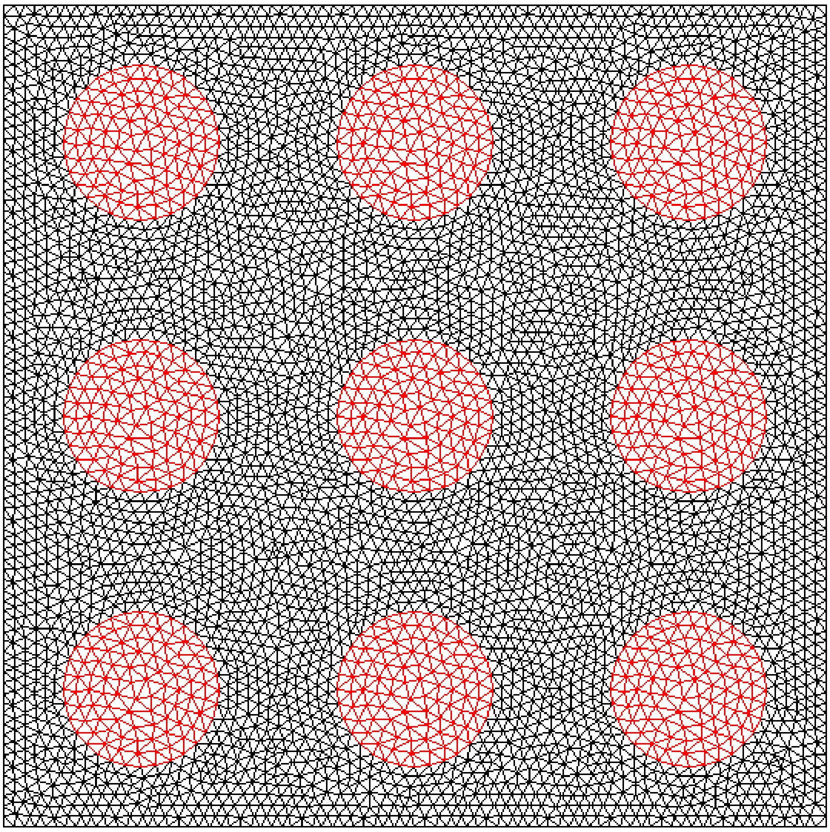


Figure III-4 *Composite mesh of composite without voids*

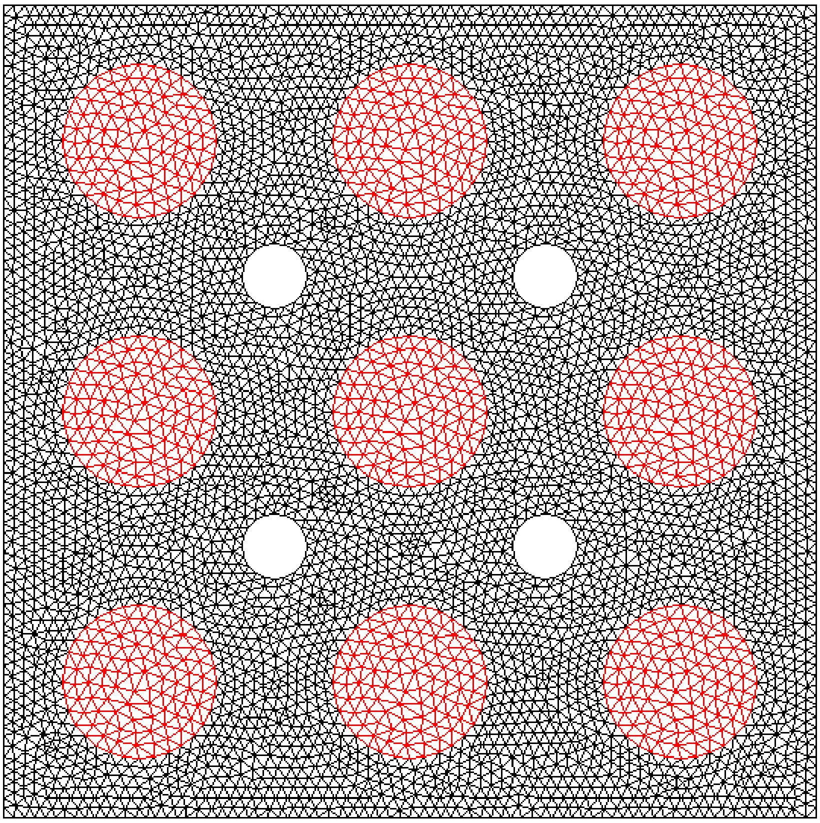
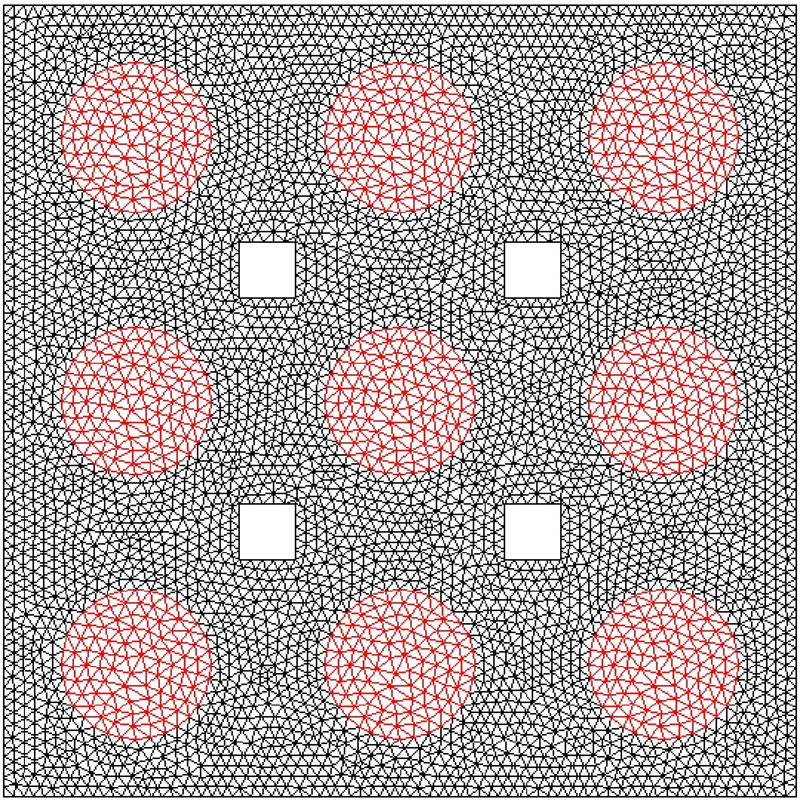
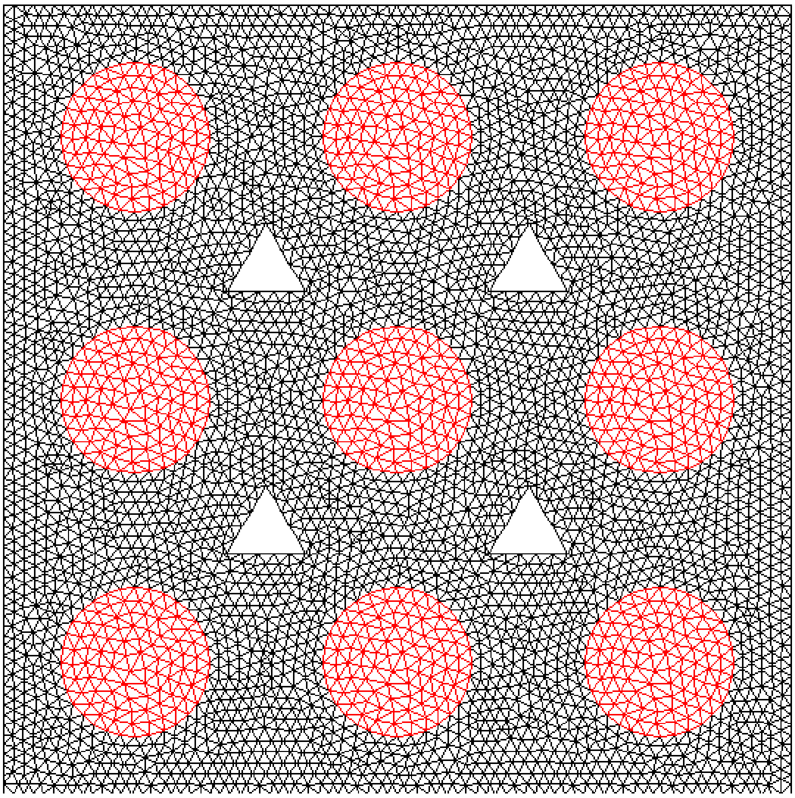


Figure III-5 *Composite mesh of composite with circle voids*



(a)



(b)

Figure III-6 *Composite mesh with voids; (a) square, (b) triangle*

Figure III-4 illustrates a triangular mesh employed in the simulation of a composite reinforced by nine particles devoid of porosities, while Figures III-5 and III-6 depict the same triangular mesh in scenarios where the composite exhibits porosities in the forms of circular, square, or triangular shapes.

III.4 Calculation of the composite dimensions

To simplify the calculations, we assumed to have a composite of a square-shaped matrix of length $l_m = 200\ \mu m$ reinforced by nine particles of the same diameter.

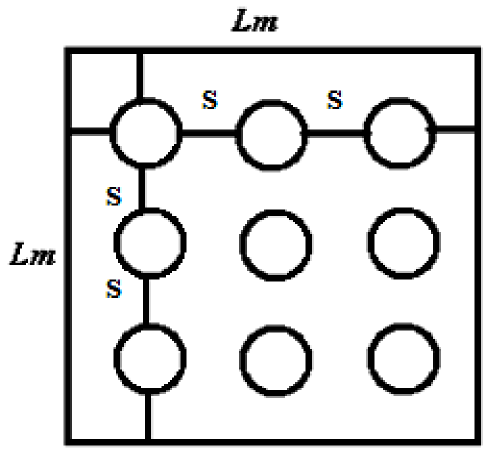


Figure III-7 *Composite reinforced with nine circular particles*

III.4.1Particle size

In the case of circular reinforcements, we seek to calculate the diameter of these particles, using formula (III.1), we will have:

$$V_f = \frac{V_{particle}}{V_{total}} = \frac{N_p\left(\pi d_p^2/4\right)}{l_m l_m} \Rightarrow d_p = \sqrt{\frac{4V_f l_m^{\ 2}}{N_p \pi}} \tag{III.1}$$

To calculate the distance between particles, we use the formula (III.2).

$$s = \frac{(l_m - (3\times d_p))}{3} \tag{III.2}$$

The results found are grouped in the Table III-3

Table III-3 *Particles size*

V_f	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
d_p	16.82	23.79	29.14	33.65	37.62	41.21	44.51	47.58
s	49.84	42.87	37.52	33.01	29.04	25.45	22.15	19.16

III.5 Results and discussion

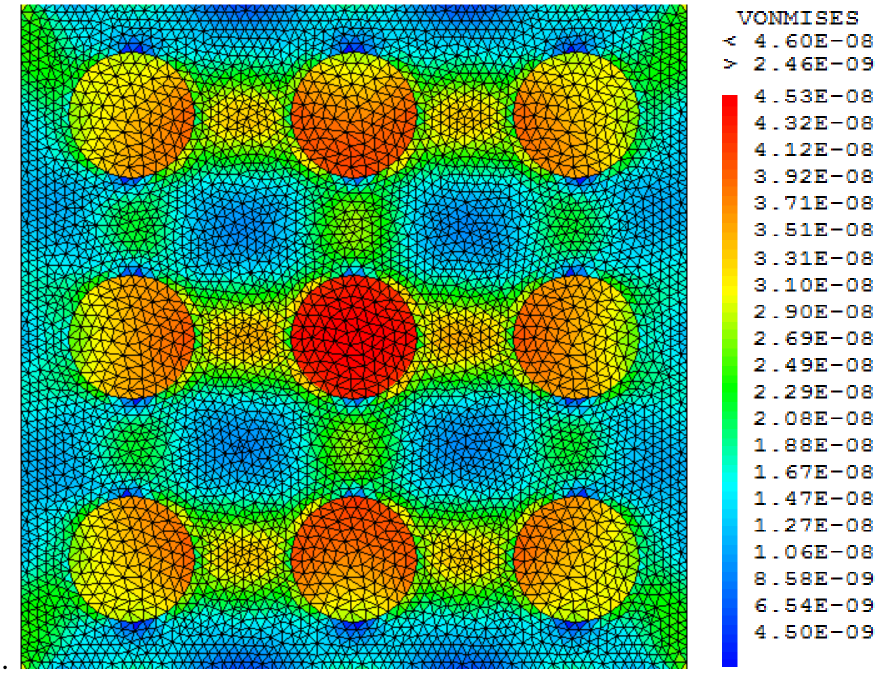


Figure III-8 *Von Mises stress distribution V_f = 25% (square arrangement)*

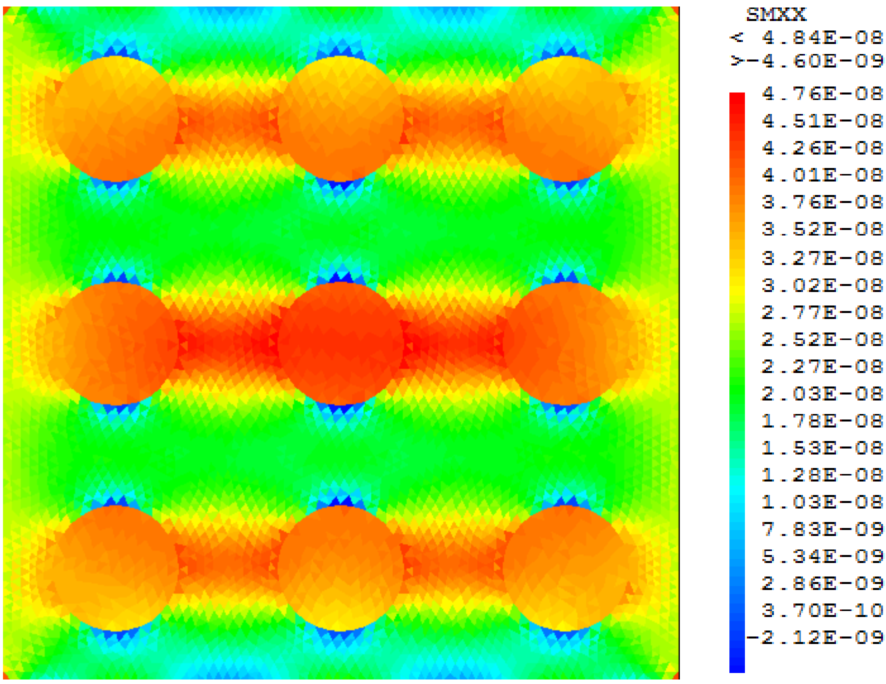


Figure III-9 *Longitudinal stress distribution V_f = 25% (square arrangement)*

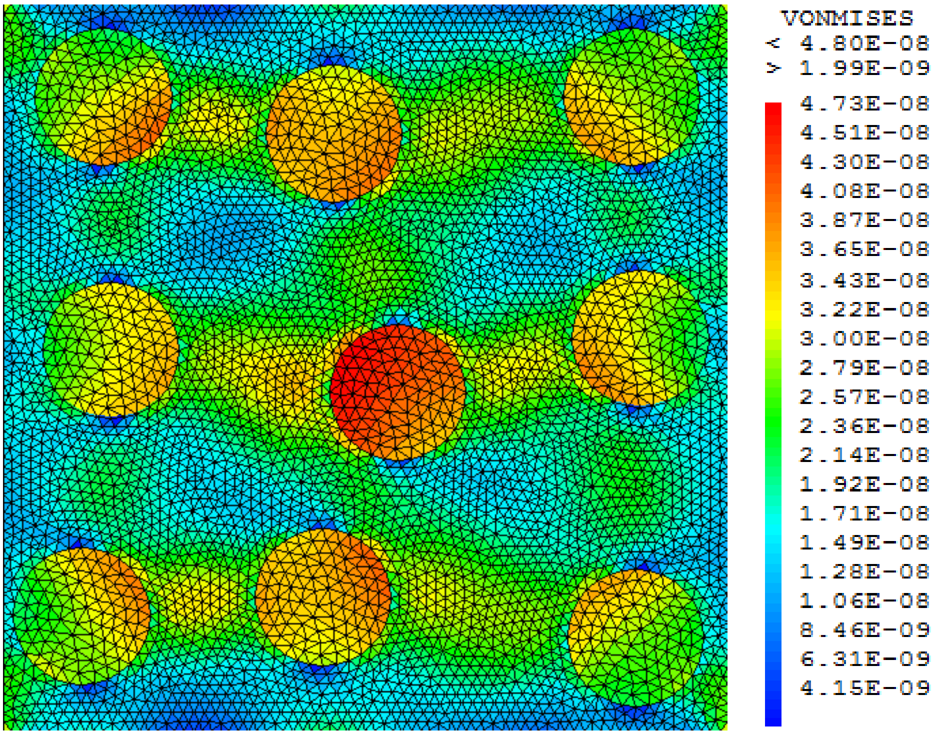


Figure III-10 *Von Mises stress distribution V_f = 25% (Random arrangement)*

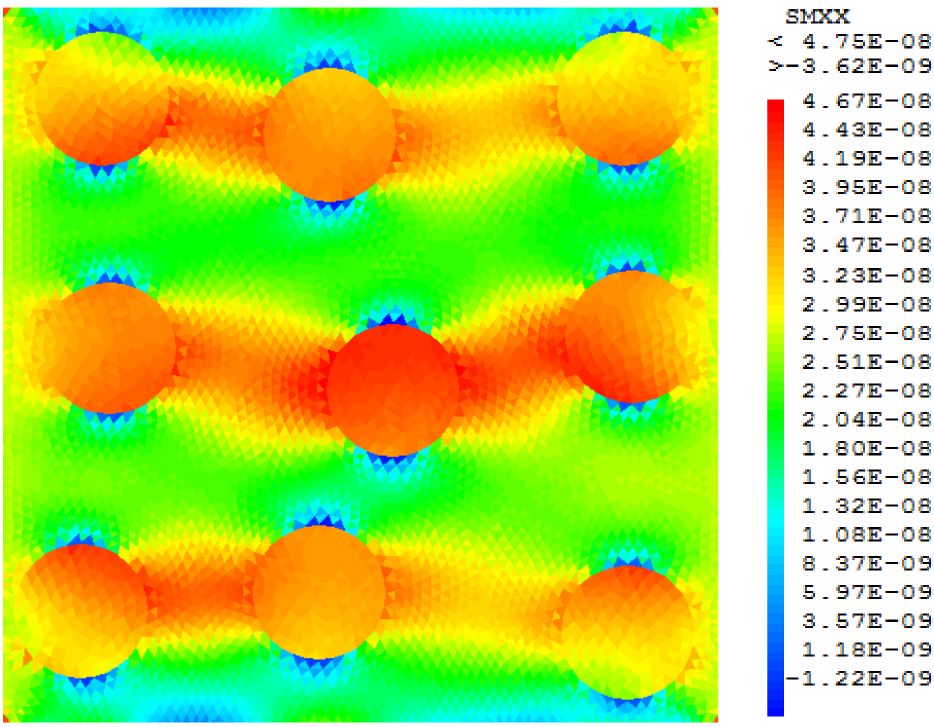


Figure III.11 *Longitudinal stress distribution V_f= 25% (Random arrangement)*

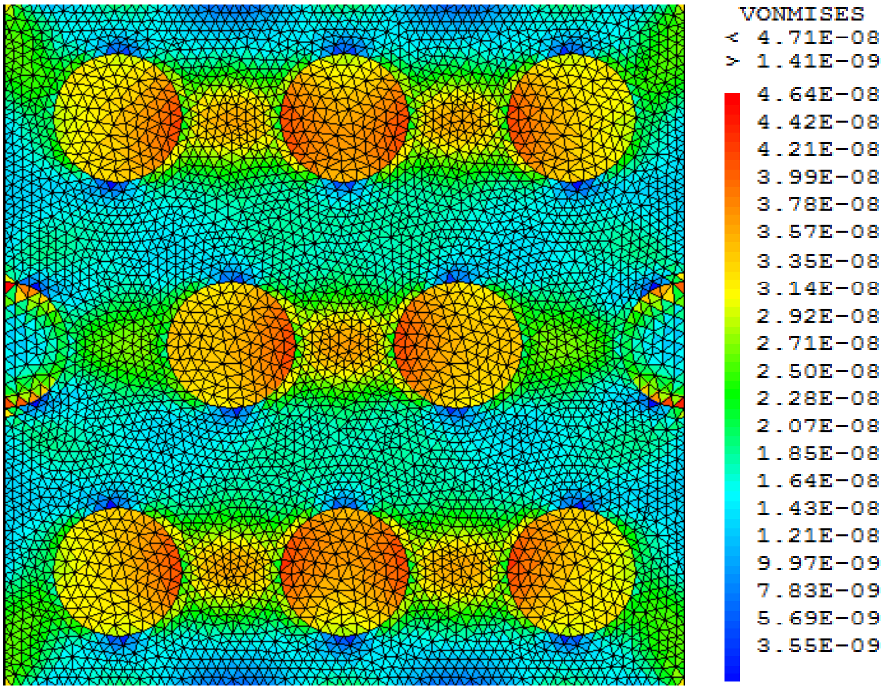


Figure III-12 *Von Mises stress distribution V_f = 25% (Hexagonal arrangement)*

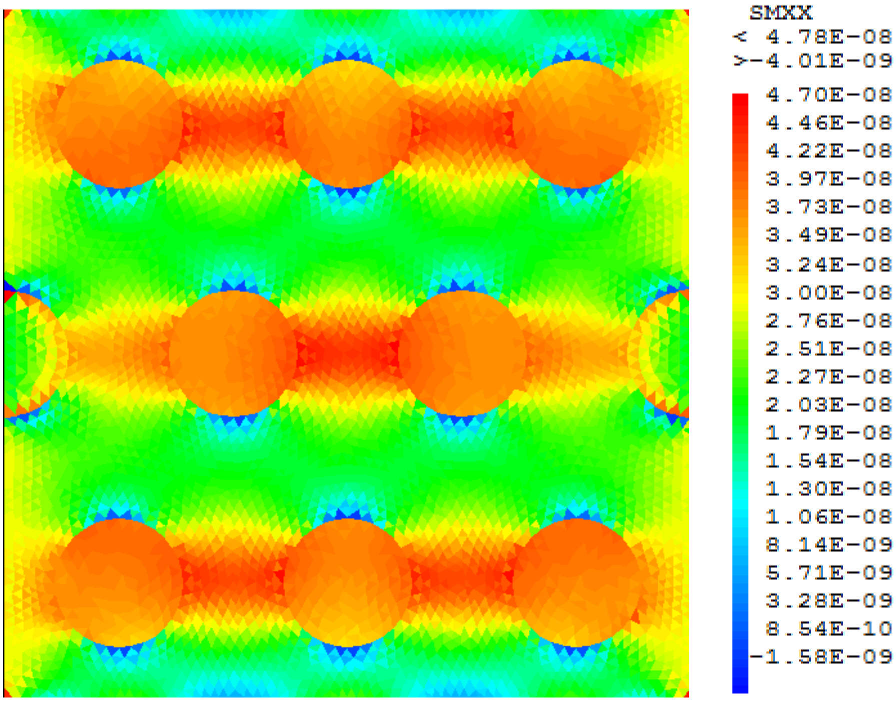


Figure III-13 *Longitudinal stress distribution V_f = 25% (Hexagonal arrangement)*

Figures III-8, III-10, and III-12 illustrate the distribution of Von Mises stresses within a composite material reinforced with nine particles at a volume fraction of V_f= 25%, showcasing three distinct arrangements. It is observed that the stresses are predominantly concentrated in the Sic reinforcements. Similar observations can be made regarding the longitudinal stresses, as depicted in Figures III-9, III-11, and III-13.

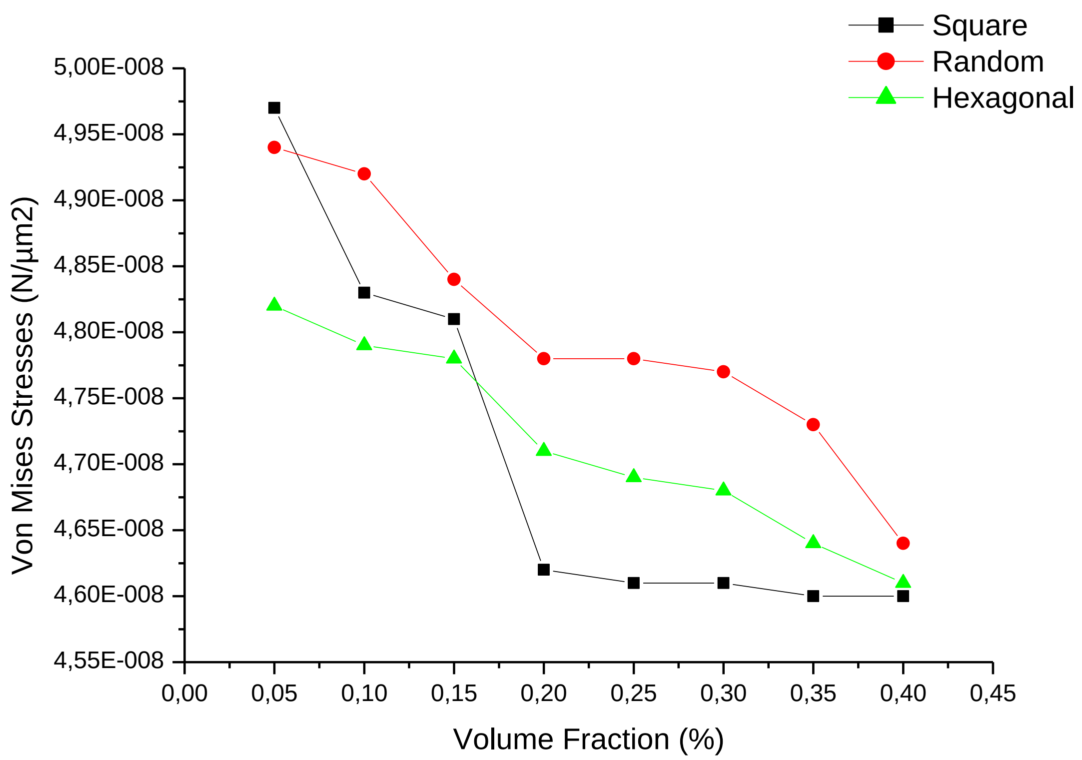


Figure III-14 *Evolution of Von Mises stresses as a function of the volume fraction of the circle particles for the different arrangements*

Figure III-14 illustrates the progression of Von Mises stresses in function of volume fraction of particles across various configurations. It is observed that the stress values in the random arrangement surpass those of the other arrangements. Furthermore, it is evident that an increase in the volume fraction of reinforcements leads to a reduction in Von Mises stresses, indicating that the presence of glass particles enhances the strength of the composite material in comparison to its unreinforced counterpart.

The main objective of this study is to explore the impact of porosity on the mechanical characteristics of composite materials. To begin, we performed an analysis on a composite devoid of pores, examining volume fractions that varied from V_f = 5% to V_f = 40%.

In the subsequent sections, we will focus on a reinforcement volume fraction of V_f=25% while systematically varying the porosity levels (V_{fVoids} = 1% up to V_{fVoids}= 5%).

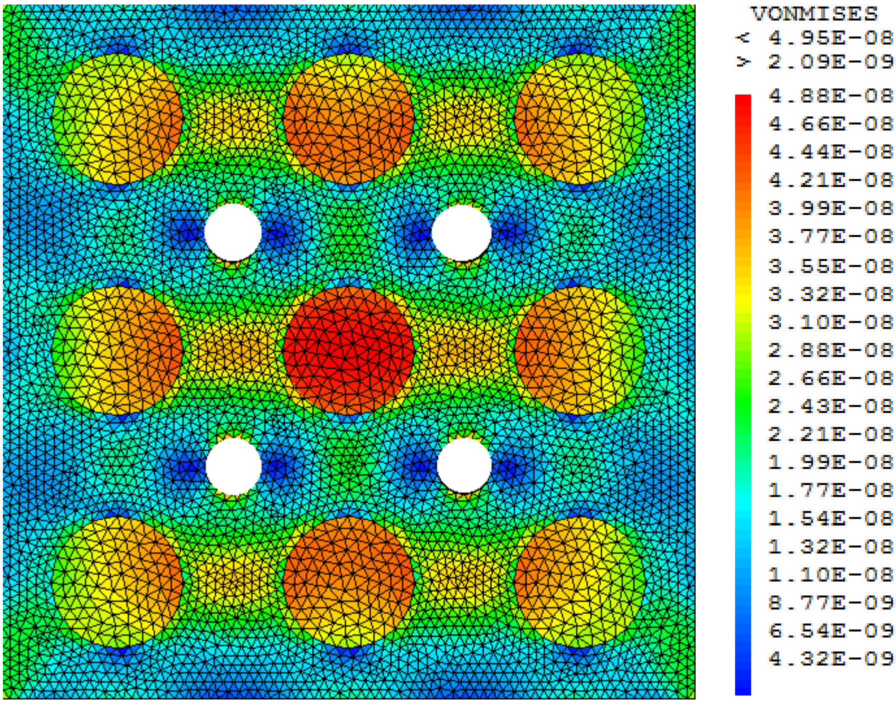


Figure III-15 *Von Mises stress distribution V_f= 25% of particles and for a circle porosity of 2% (Square arrangement)*

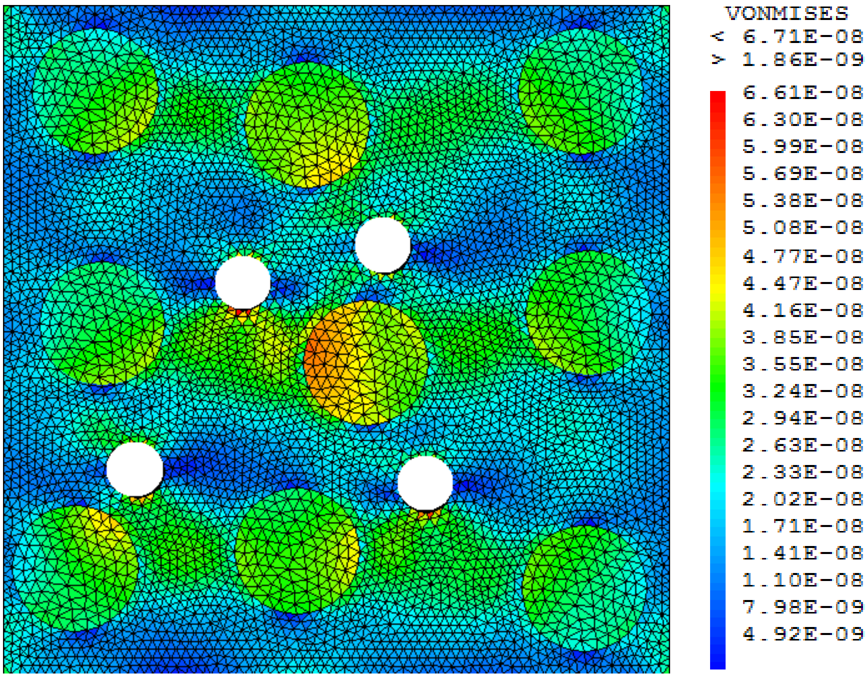


Figure III-16 *Von Mises stress distribution V_f = 25% of particles and for a circle porosity of 2% (Random arrangement)*

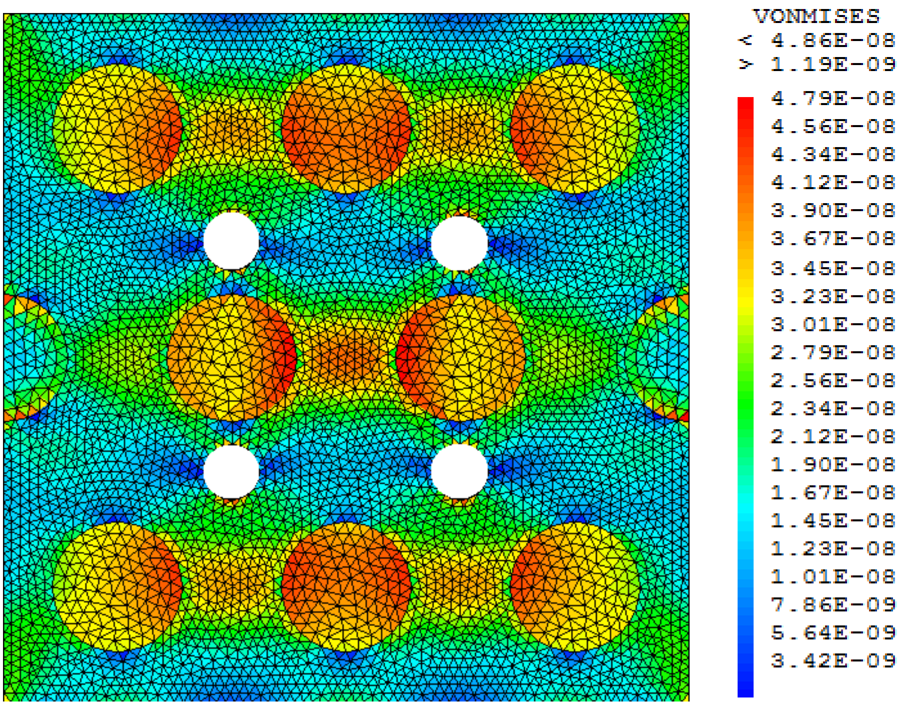


Figure III-17 *Von Mises stress distribution V_f = 25% of particles and for a circle porosity of 2% (Hexagonal arrangement)*

Figures III-15, III-16, and III-17 illustrate the distribution of Von Mises stresses within a composite material reinforced with nine particles at a volume fraction of V_f= 25% in presence of circle voids of 2% volume fraction, showcasing three distinct arrangements. It is observed that the stresses are still concentrated in the glass reinforcements and surrounding porosity.

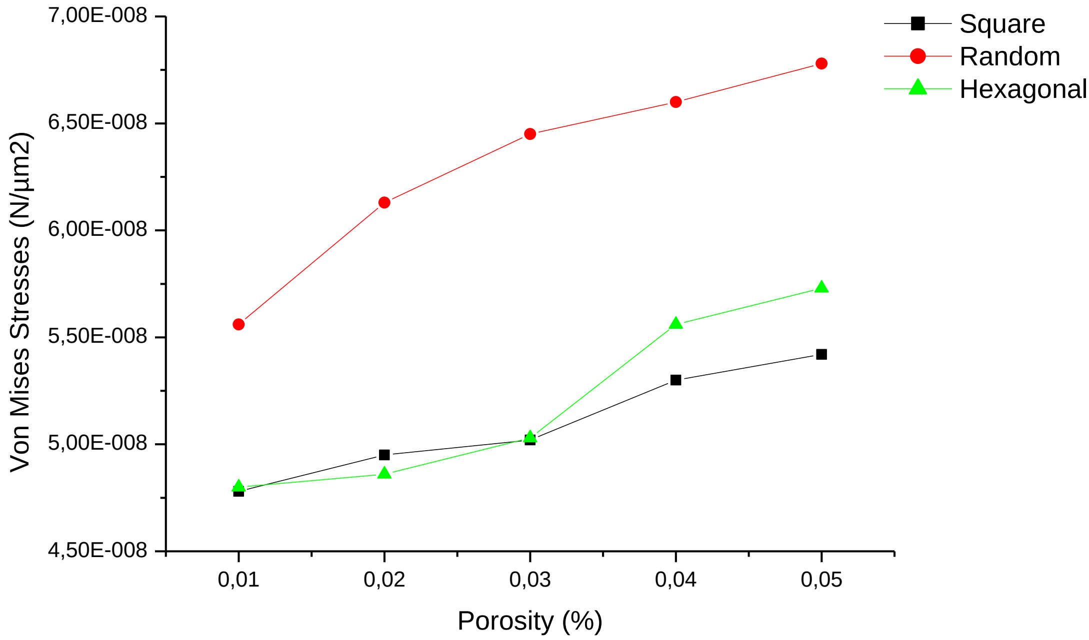


Figure III-18 *Evolution of Von Mises stresses as a function of porosity for the different arrangements (circle voids)*

Figures III-18 depicts the progression of Von Mises stresses in relation to porosity for the various arrangements (square, random, and hexagonal). Notably, the random arrangement exhibits higher stress levels compared to the other configurations. Additionally, an increase in porosity correlates with an elevation in stress, which subsequently impacts the composite's performance. This analysis suggests that Sic particles enhance the strength of composite materials, whereas the presence of voids adversely affects their structural integrity.

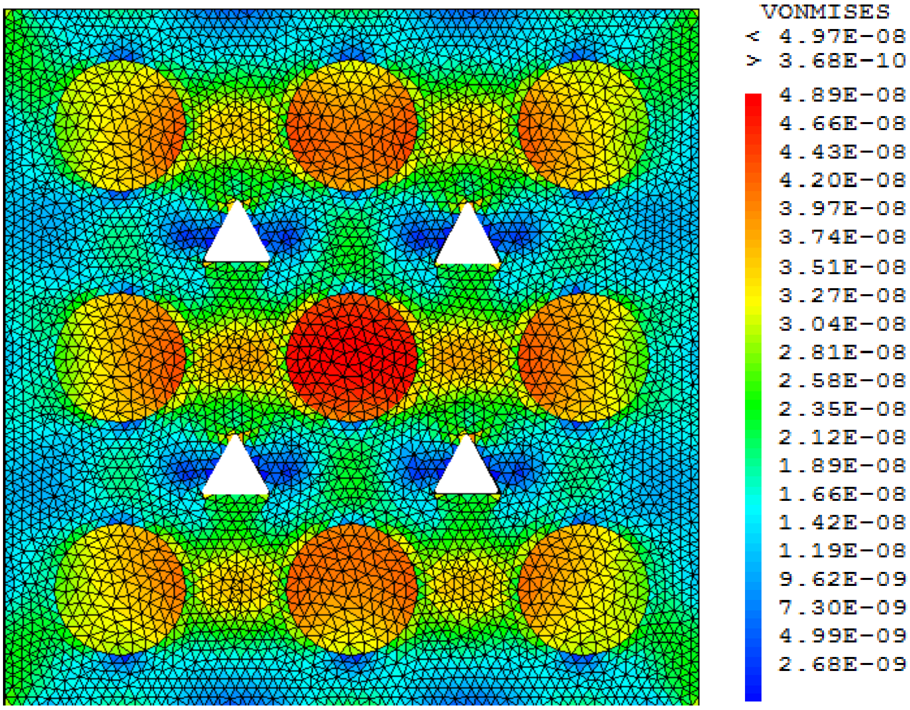


Figure III-19 *Von Mises stress distribution V_f = 25% of particles and for a triangle porosity of 2% (Square arrangement)*

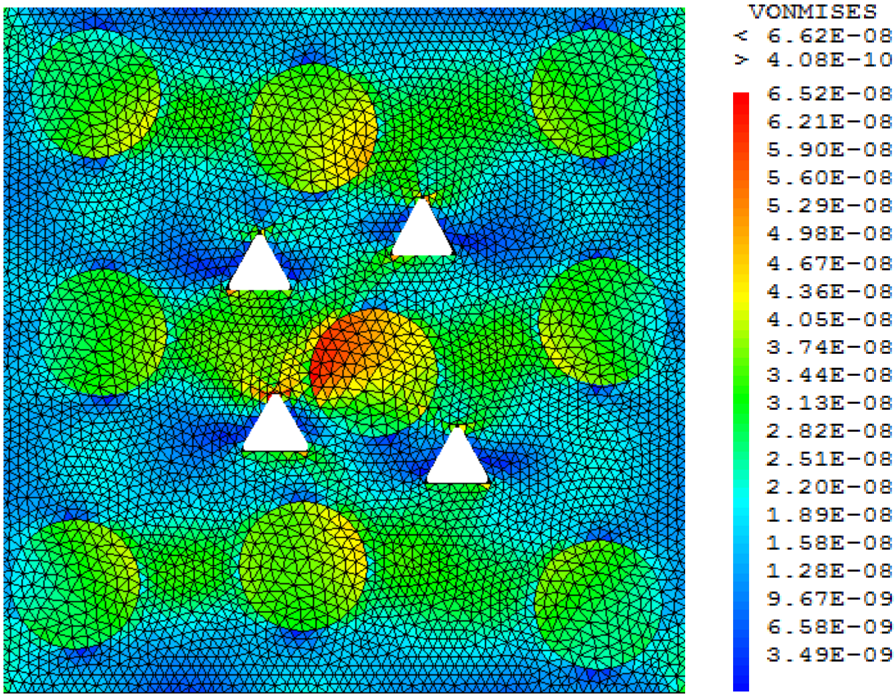


Figure III-20 *Von Mises stress distribution V_f = 25% of particles and for a triangle porosity of 2% (Random arrangement)*

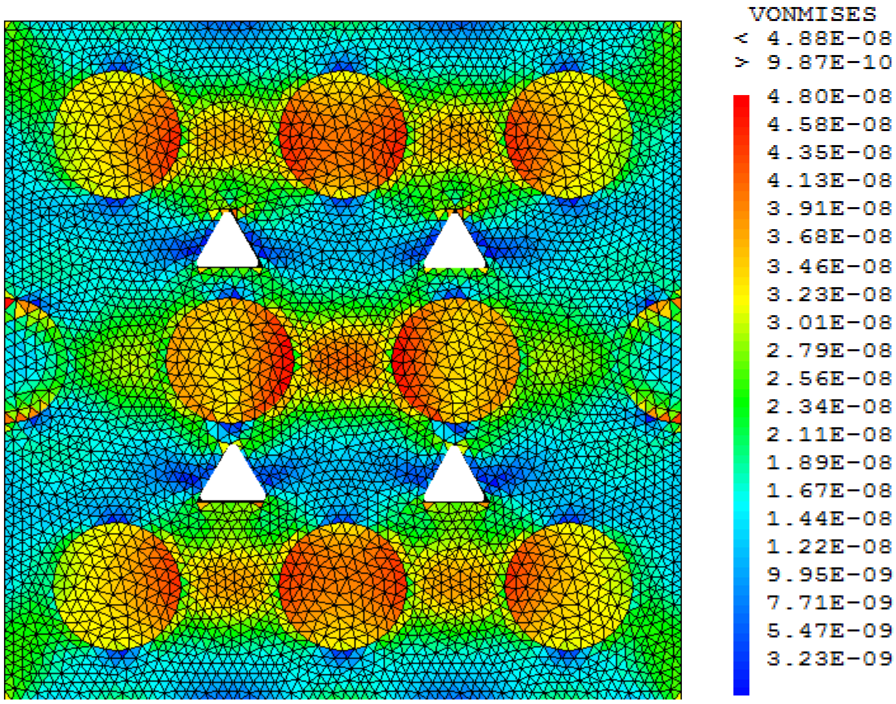


***Figure III-21** Von Mises stress distribution V_f = 25% of particles and for a triangle porosity of 2% (Hexagonal arrangement)*

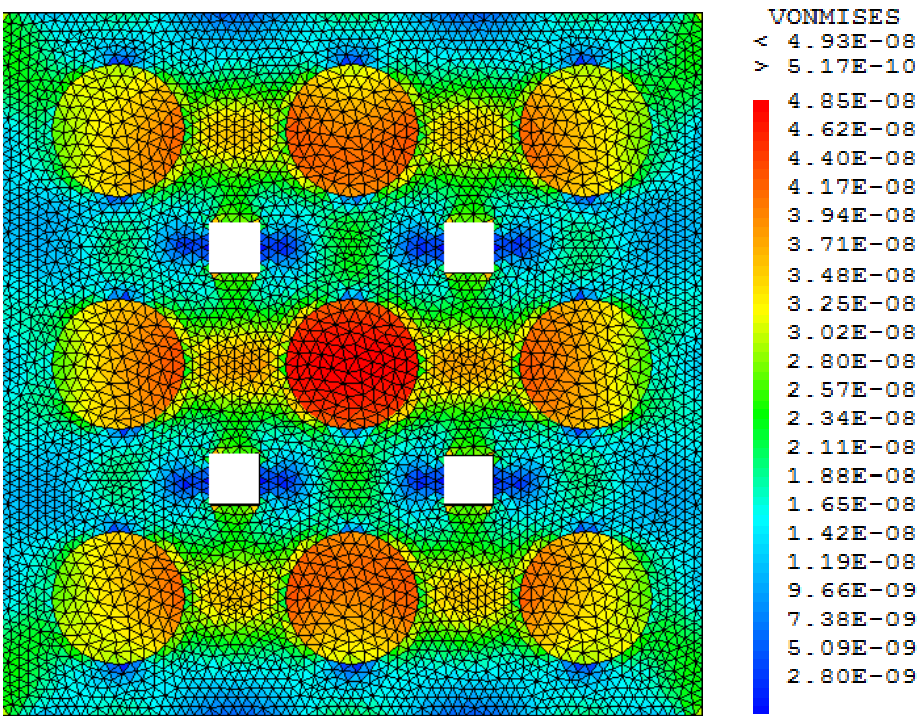


***Figure III-22** Von Mises stress distribution V_f = 25% of particles and for a square porosity of 2% (Square arrangement)*

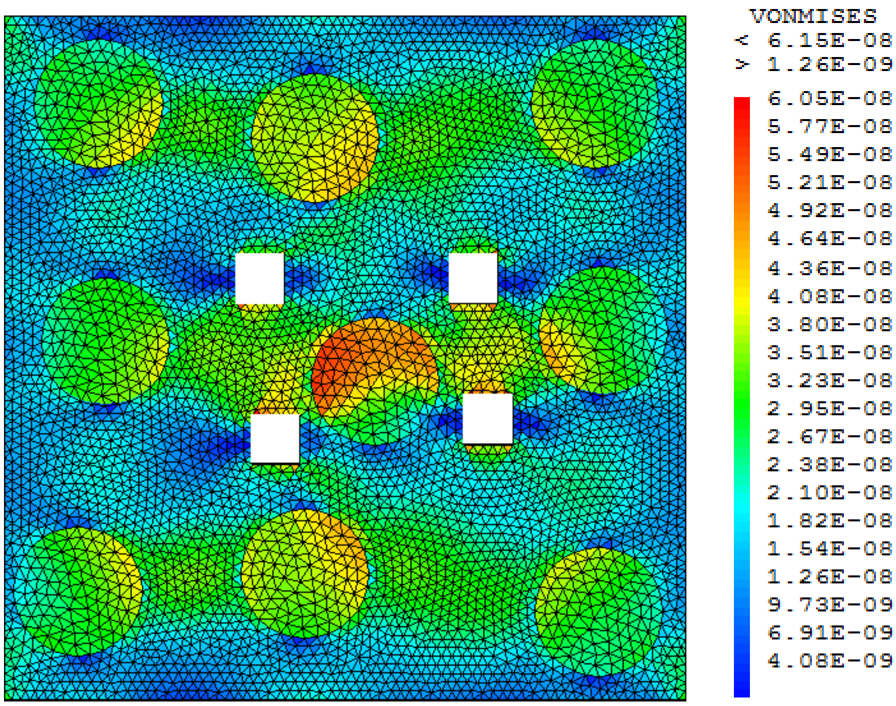


Figure III-23 *Von Mises stress distribution V_f = 25% of particles and for a square porosity of 2% (Random arrangement)*

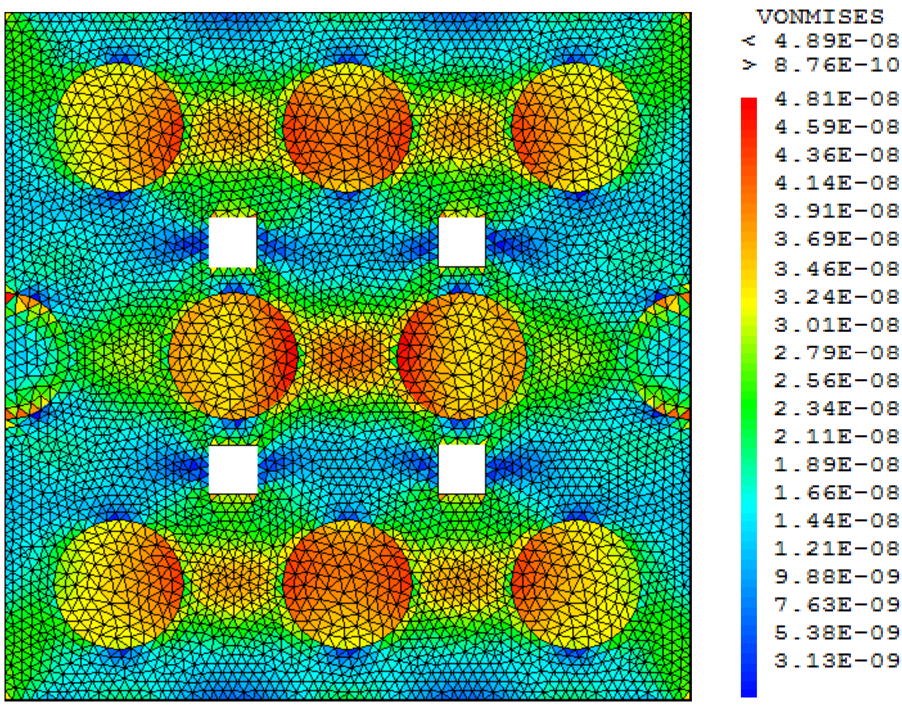


Figure III-24 *Von Mises stress distribution V_f = 25% of particles and for a square porosity of 2% (Hexagonal arrangement)*

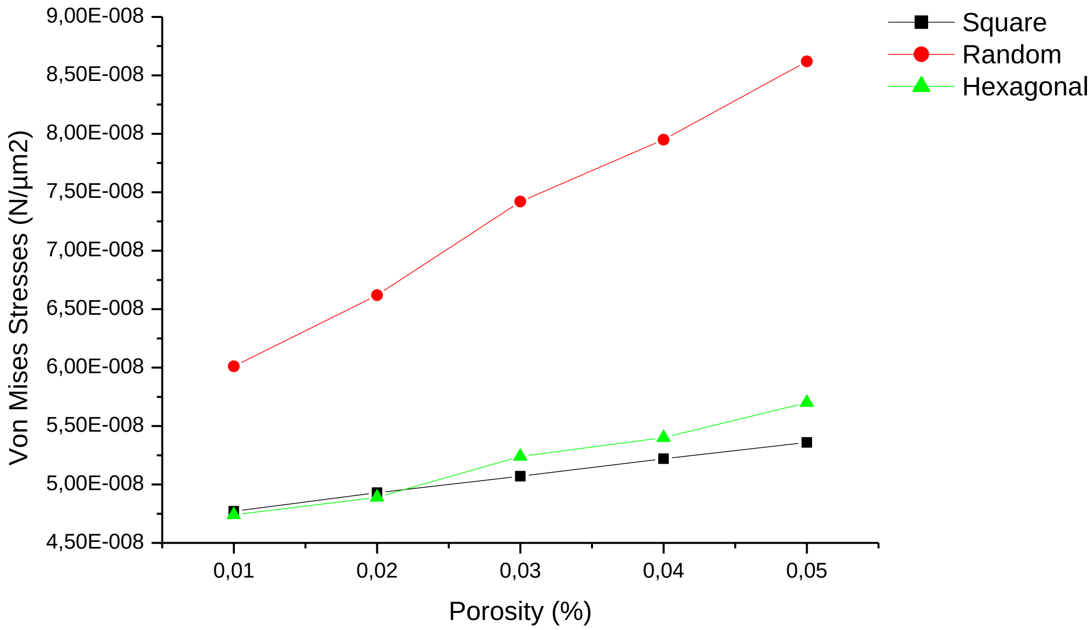


Figure III-25 *Evolution of Von Mises stresses as a function of porosity for the different arrangements (square voids)*

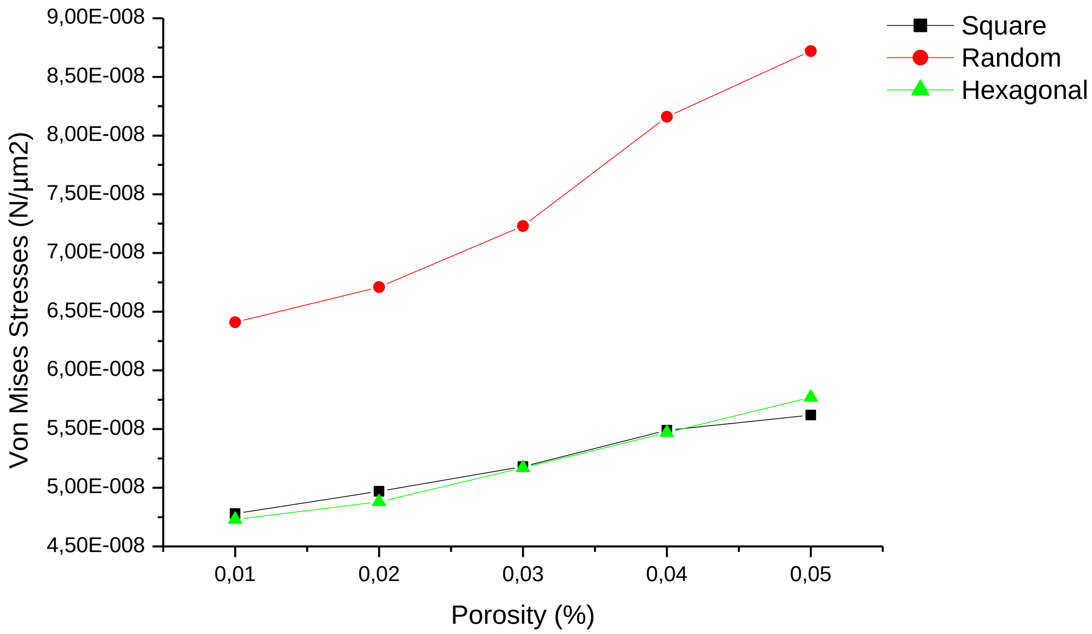


Figure III-26 *Evolution of Von Mises stresses as a function of porosity for the different arrangements (Triangle voids)*

The same remark is observed in cases where the porosity shape has been changed to triangle and square, the stress concentrations are still located on the reinforcements and in the surroundings of the pores.

In Figures III-24 and III-25, we notice that the evolution of the stresses in the random arrangement is more important than in the other two arrangements (square and hexagonal), this is due to the fact that in the random arrangement the particles get closer to each other and get closer to the pores which leads to the absence of the matrix which causes stress concentrations.

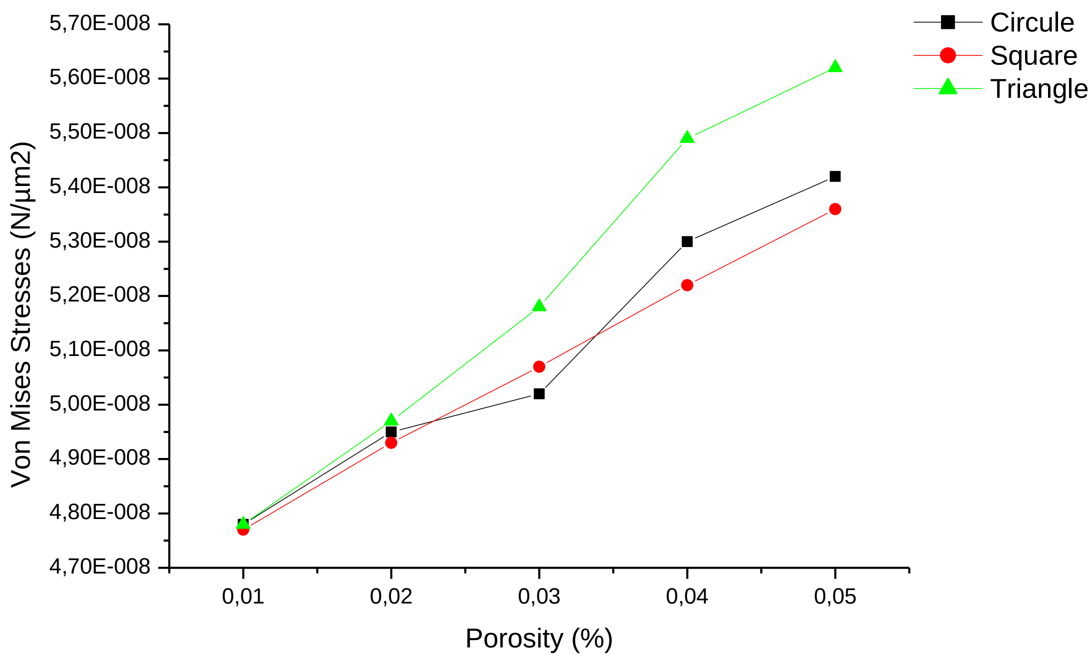


Figure III-27 *Evolution of Von Mises stresses as a function of porosity for the different shapes (Square arrangement)*

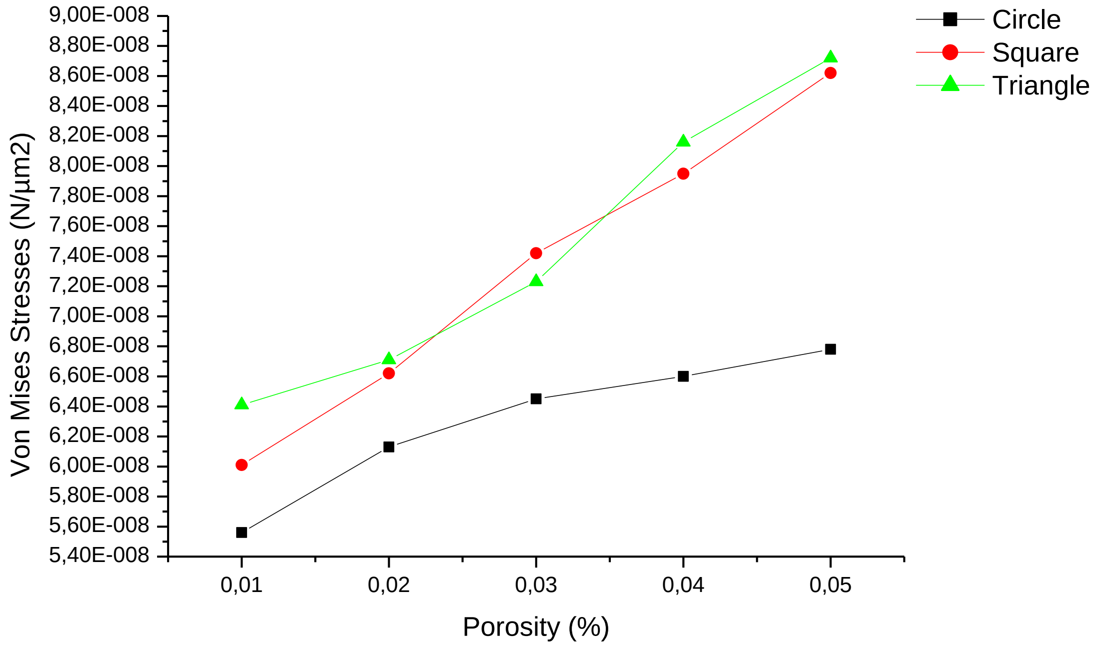


Figure III-28 *Evolution of Von Mises stresses as a function of porosity for the different shapes (Random arrangement)*

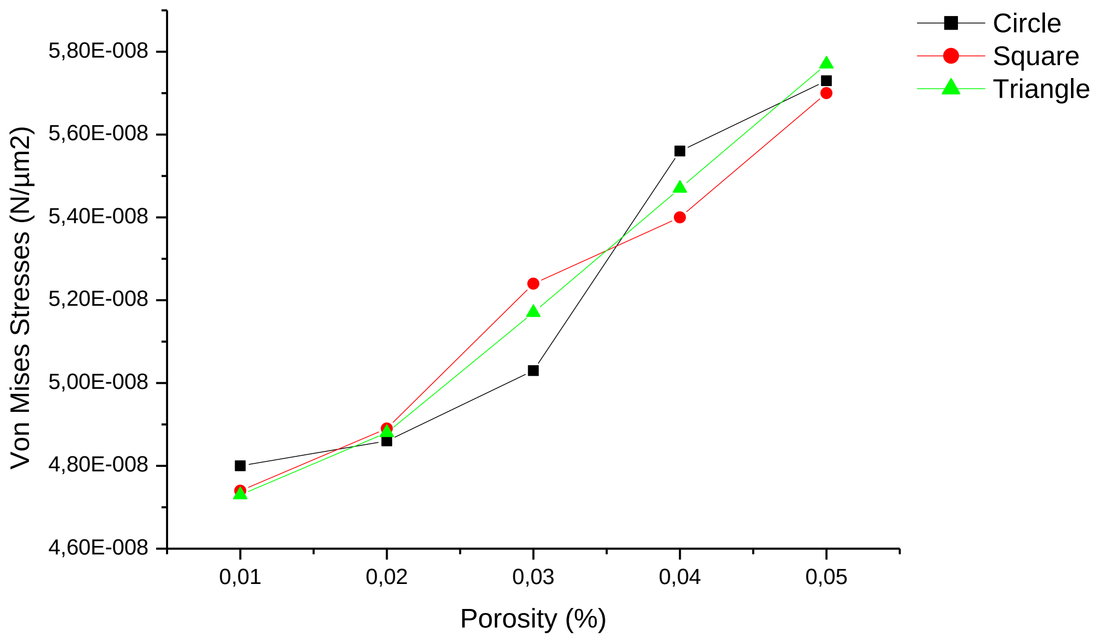


Figure III-29 *Evolution of Von Mises stresses as a function of porosity for the different shapes (Hexagonal arrangement)*

Figure III.27 illustrates the progression of Von Mises stresses for the square configuration in relation to porosity levels. It is observed that these stresses increase in a nearly linear manner, reaching peak values in the triangular configuration. This phenomenon can be attributed to the occurrence of stress concentrations at the angular geometries (triangular and square), whereas the stresses are significantly lower in the presence of circular pores. Similar observations can be made in Figures III.28 and III.29.

GENERAL CONCLUSION

General conclusion

Particle-reinforced composites were primarily developed to bridge the performance gap between laminates, which utilize continuous fibers in critical structural applications within the aviation and aerospace sectors, and unreinforced materials that are typically employed in non-load-bearing contexts. These composites leverage the benefits of both material types, making them suitable for lightly loaded structures where stiffness is a key design consideration, while also necessitating a significant enhancement in the load-bearing capacity of the unreinforced components.

This research focuses on examining how the geometry of voids influences the mechanical properties of a particle-reinforced composite, specifically an Aluminium matrix augmented with Sic particles. Given the substantial disparity in elastic moduli between the particles and the matrix, it is essential to recognize that stress distribution varies across the materials, with the reinforcement generally experiencing higher stress due to its superior modulus of elasticity.

The findings indicate that particle-reinforced Aluminium composites are increasingly being adopted in industrial applications, and this study highlights the critical role of porosity in the composite's performance; the presence of voids correlates with elevated Von Mises stress levels for equivalent volume fractions. The simulation reveal that the Von Mises stress values for the porous model exceed those of the non-porous variant, suggesting that voids adversely affect the mechanical properties of the composites. Furthermore, the research underscores the significant impact of porosity shapes on the overall behavior and characteristics of these materials; it has been changed to triangle and square, the stress concentrations are still located on the reinforcements and in the surroundings of the pores.

As particle-reinforced composites continue to advance in the industry due to their favorable shaping capabilities and cost-effectiveness, the emergence of nanocomposites is also noted. To further this investigation, we propose an analysis of composite behavior when reinforced with particles exhibiting porosity shapes with non uniformed dimensions.

BIBLIOGRAPHIC REFERENCE

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[1] Messas, T., et al. "Analyzing vibration behavior of nano FGM (Si3N4/SUS304) plates: impact of homogenization models and nano parameters." (2023).

[2] Rebai, B., Mansouri, K., Chitour, M., Berkia, A., Messas, T., Khadraoui, F., & Litouche, B. (2023). Effect of idealization models on deflection of functionally graded material (FGM) plate. *Journal Of Nano- And Electronic Physics*, *15*(1), 01022(5pp),
DOI: 10.21272/jnep.15(1).01022

[3] Mourad, C., Rebai, B., Mansouri, K., Khadraoui, F., Berkia, A., & Messas, T. (2024). Investigating the influence of material composition on bending analysis of functionally graded beams using a 2D refined theory. *Journal of Computational Applied Mechanics*, *55*(1), 62-76.

[4] Berkia, A., Rebai, B., Litouche, B., Abbas, S., & Mansouri, K. (2023). Investigating parametric homogenization models for natural frequency of FGM nano beams. *AIMS Materials Science*, *10*(5).
DOI: 10.3934/matersci.2023048.

[5] Berkia, A., Benguediab, M., Bouhadra, A., Mansouri, K., Tounsi, A., & Chitour, M. (2022). Influence of Mechanical and Geometric Characteristics on Thermal Buckling of Functionally Graded Sandwich Plates. *Journal Of Nano- And Electronic Physics*, *14*(3), 03031(6pp), (2022), DOI: 10.21272/jnep.14(3).03031.

[6] Samir, B., Belkacem, M., & Brahim, G. (2020). Numerical Modeling of the Effects of Fiber Packing and Reinforcement Volume Ratio on the Transverse Elasticity Modulus of a Unidirectional Composite Material Glass/Epoxy. *Journal of Composite & Advanced Materials/Revue des Composites et des Matériaux Avancés*, *30*.
DOI: https://doi.org/10.18280/rcma.305-602

[7] Samir, B. (2016). Modélisation numérique de la propagation de l'endommagement et de la rupture dans les matériaux composites stratifiés sous sollicitations thermomécaniques et cycliques. Doctorat thesis,(2012) Université de Batna 2.

[8] Mansouri, K., Djebaili, H., & Brioua, M. (2017). The influence of fiber arrangement on the mechanical properties of short fiber reinforced thermoplastic matrix composite. *REVUE DES COMPOSITES ET DES MATERIAUX AVANCES-JOURNAL OF COMPOSITE AND ADVANCED MATERIALS*, *27*(3-4), 261-273.
DOI :10.3166/rcma.2017.00027.

[9] Kardos, J. L. (1985). Critical issues in achieving desirable mechanical properties for short fiber composites. *Pure and applied chemistry*, *57*(11), 1651-1657.

[10] Berthelot J. M. (2012), ***Matériaux composites-comportement mécanique et analyse des structures,*** 5 édition, lavoisier, Paris.

[11] Li, M., Zhang, H., Li, S., Zhu, W., & Ke, Y. (2022). Machine learning and materials informatics approaches for predicting transverse mechanical properties of unidirectional CFRP composites with microvoids. *Materials & Design*, *224*, 111340.

https://doi.org/10.1016/j.matdes.2022.111340.

[12] Gornet, L. (2008). Généralités sur les matériaux composites.

[13] Zahi, T., Noureddine, B. and Abdelghani, L. Etude des propriétés thermiques d'un matériau composite à matrice polymère, (2019-2020).

[14] LYNDA, H., NOURA, A., SAID, B.M. MATERIAUXCOMPOSITES Homogénéisation des matériaux composites a deux phases, (2019 /2020).

[15] BILLEL, S. Etude et simulation d'un composite Aéronautique à basede fibre decarbone et matrice époxy, (2019).

[16] H. Said, B. Ahmed, B.M. Noureddine and E.Mokhtar, ***ETUDE DE LA DIFFUSION D'UN MATERIAU COMPOSITE « résine époxy***»,(2014/2015).

[17] Ragoubi, M. (2010). *Contribution à l'amélioration de la compatiblilité interfaciale fibres naturelles/matrice thermoplastique via un traitement sous décharge couronne* (Doctoral dissertation, Université Henri Poincaré-Nancy 1).

[18] Zahera, Z. M. B. (2013). *Optimisation par algorithme génétique de l'écart entre fibres d'un matériau composite pour l'estimation de l'endommagement d'interface* (Doctoral dissertation, Université Mohamed Boudiaf des sciences et de la technologi).

[19] GLOSSAIRE DES MATERIAUX COMPOSITES – CARMA –Actualisation octobre 2006.

[20] Ledain, O. (2014). *Elaboration de matrices céramiques par un nouveau procédé hybride: imprégnation de poudres et CVI réactive* (Doctoral dissertation, Université de Bordeaux).

[21] TUMI, W. (2019). 'Optimisation de la configuration des tubes en matériaux composites sous pression. *Mémoire de master, université de Mohamed Khider. Biskra. Algérie*.

[22] A. SADOK, A. HEBBAR, R. ZENASNI and D. OUINAS, ***ETUDE DEL'ENDOMMAGEMENT DANS UN COMPOSITE STRATIFIE***, (2011/2012).

[23] SOUDANI, A., & HADJOUDJ, Y. *Résistance aux chocs de matériaux composite renforcé par des déchets plastique* (Doctoral dissertation).

[24] HADDADI, M. (2011). Etude numérique avec comparaison expérimentale des propriétés thermophysiques des matériaux composites à matrice polymère. *Mémoire de fin de cycle de Mater en physique. Université EL Hadj Lakhdar BATNA*.

[25] B. ABDALLAH and M. YOUBA, ***MATERIAUX COMPOSITES Homogénéisation des matériaux composites a deux phases***, (2010 /2011).

[26] Khaldoun, A. (2015). Effet des paramètres d'élaboration sur le comportement mécanique d'un bio-composites. *Université de M'sila*, *1016*.

[27] ELGHARBI, A. (2010). *Analyse Du Comportement Dynamique Des Plaques Stratifiées Rectangulaires Minces Symétriques en Matériaux Composites* (Doctoral dissertation, Université Mohamed Khider Biskra).

[28] El Hadji Babacar, L. Y. (2008). Nouveaux matériaux composites thermoformables à base de fibres de cellulose. *Institut National Polytechnique de Grenoble*.

[29] Saikrupa, C., Reddy, G. C. M., & Venkatesh, S. (2021, February). Aluminium metal matrix composites and effect of reinforcements–A Review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1057, No. 1, p. 012098). IOP Publishing.

[30] Badran, A. H., Alamro, T., Bazuhair, R. W., El-Mawla, A. A. G., El-Adben, S. Z., & Fouly, A. (2022). Investigation of the mechanical behavior of synthesized Al6061/TiO2 microcomposites using an innovative stir casting method. *Nanomaterials*, *12*(10), 1646.

https:// doi.org/10.3390/nano12101646

[31] Bhandare, R. G., & Sonawane, P. M. (2013). Preparation of aluminium matrix composite by using stir casting method. *International Journal of Engineering and Advanced Technology (IJEAT)*, *3*(3), 61-65.

[32] Abderraouf, A. *L'effet De La Temperature De Mercerisation Sur Les Proprietes Du Composite (Tissus De Jute / Polyester)*, (2017/2018).

[33] Amaechi, C. V., Agbomerie, C. O., Orok, E. O., & Ye, J. (2020). Economic aspects of fiber reinforced polymer composite recycling. *Encycl. Renew. Sustain. Mater. 2*, 377–397.

[34] Xueshu, L. I. U., & Fei, C. H. E. N. (2016). A review of void formation and its effects on the mechanical performance of carbon fiber reinforced plastic. *Engineering Transactions*, *64*(1), 33-51.

[35] Hyde, A., He, J., Cui, X., Lua, J., & Liu, L. (2020). Effects of microvoids on strength of unidirectional fiber-reinforced composite materials. *Composites Part B: Engineering*, *187*, 107844.
https://doi.org/10.1016/j.compositesb.2020.107844

[36] Strong, A. B. (2008). *Fundamentals of composites manufacturing: materials, methods and applications*. Society of manufacturing engineers.

[37] Mehdikhani, M., Gorbatikh, L., Verpoest, I., & Lomov, S. V. (2019). Voids in fiber-reinforced polymer composites: A review on their formation, characteristics, and effects on mechanical performance. *Journal of Composite Materials*, *53*(12), 1579-1669.
DOI: 10.1177/0021998318772152.

[38] Benghellab, H. and R. Belkhiri, R. (2024). *Effects of porosity on mechanical property of glass particles reinforced polyamide matrix composite*, End of studies Dissertation *Presented for graduation of Master (L.M.D),* Abbes Laghrour University.

[39] Mansouri, K., Chitour, M., Berkia, A., Rebai, B., Khadraoui, F., & Djebaili, H. (2023). Effect of Broken Glass Particle on Stress Transfer of Nylon Matrix Composite. *Journal Of Nano- And Electronic Physics, 15*(5).

DOI: 10.21272/jnep.15(5).05007.

[40] Del Rey, R., Serrat, R., Alba, J., Perez, I., Mutje, P., & Espinach, F. X. (2017). Effect of sodium hydroxide treatments on the tensile strength and the interphase quality of hemp core fiber-reinforced polypropylene composites. *Polymers*, *9*(8), 377.

[41] Kulkarni, A., Aswini, N., Dandekar, C. R., & Makhe, S. (2012, September). Modeling of short fiber reinforced injection moulded composite. In *IOP Conference Series: Materials Science and Engineering* (Vol. 40, No. 1, p. 012025). IOP Publishing.

[42] Mansouri, K., Djebaili, H., & Brioua, M. (2020). Mechanical Behavior of Particle Reinforced Thermoplastic Matrix Composites Using Finite Element Modeling. *Journal Of Nano- And Electronic Physics*, *12***(**5).
DOI: 10.21272/jnep.12(5).05004

[43] Rybin, V. V., Solovyev, A. A., & Zuev, A. D. (2022). Thermal and mechanical properties of a metal-matrix composite with ceramic inclusions. *Научно-технические ведомости Санкт-Петербургского государственного политехнического университета. Физико-математические науки*, *15*(S3. 3), 27-30.
https://doi.org/10.18721/ JPM.153.305

[44] Nikhilesh Chawla and Krishan K. Chawla, ***Metal Matrix Composites***, Second Edition, ISBN 978-1-4614-9548-2 (eBook), DOI 10.1007/978-1-4614-9548-2, Springer New York Heidelberg Dordrecht London, (2013).

[45] Laghari, R. A., Li, J., & Wu, Y. (2020). Study of machining process of SiCp/Al particle reinforced metal matrix composite using finite element analysis and experimental verification. *Materials*, *13*(23), 5524.
doi:10.3390/ma13235524

[46] Priyadarshi, D., & Sharma, R. K. (2016). Porosity in aluminium matrix composites: cause, effect and defence. *Mater Sci: Ind J*, *14*(4), 119-129.

[47] Castem, http://www-cast3m.cea.fr

[48] Houshyar, S., Shanks, R. A., & Hodzic, A. (2009). Modelling of polypropylene fibre-matrix composites using finite element analysis. *Express Polym Lett*, *3*(1), 2-12.

[49] Lei, H. F., Zhang, Z. Q., & Liu, B. (2012). Effect of fiber arrangement on mechanical properties of short fiber reinforced composites. *Composites Science and Technology*, *72*(4), 506-514.

[50] Mansouri, K., Chermime, B., Saoudi, A., Djebaili, H., Litim, A., & Kabouche, Z. (2021). Effect of reinforcing particle shape on the behavior of composites materials. *Journal Of Nano- And Electronic Physics,13***(**6). DOI: 10.21272/jnep.13(6).06018.

[51] O'Gara, J. F., Novak, G. E., & Wyzgoski, M. G. (2010, September). Predicting the tensile strength of short glass fiber reinforced injection molded plastics. In *Proceedings of the 10th-Annual SPE® Automotive Composites Conference & Exhibition (ACCE), Troy, MI, USA* (pp. 15-16).

[52] Khadraoui, F., Mansouri1, K., Sid, N., Hannachi1, B., Chitour1, M., Berkia, A., Rebai3, B., Himeur, N. (2024). Effect of Particle Shape and Size on Behavior of Composite Material

Using Finite Element Method. *Journal Of Nano- And Electronic Physics, 16*(5). DOI: 10.21272/jnep.16(5).05029

[53] Chitour, M., Khadraoui, F., Mansouri, K., Rebai, B., Menasria, A., Zemmouri, A., ... & Boumediri, H. (2024). A novel high order theory for static bending of functionally graded (FG) beams subjected to various mechanical loads. *Research on Engineering Structures and Materials*, *10*. http://dx.doi.org/10.17515/resm2024.141me0104rs

[54] Mansouri, K., Touati, S., Boumediri, H., Djebaili, H., Chitour, M., Zemmouri, A., Khadraoui, F., & Berkia, A. (2025). Numerical Modeling and Optimization of Mechanical Properties in Porous Aluminum Matrix Composites Reinforced with SiC Particles. *Materials Research*, *28*, e20240474. DOI: https://doi.org/10.1590/1980-5373-MR-2024-0474

RESUME

Dans ce mémoire, l'effet de la porosité et la forme des pores sur le comportement mécanique du composite renforcés par particules de Sic est évalué. Les petites particules adhèrent fortement a Aluminium, ce qui conduit à un fort effet de renforcement. Lorsque la surface totale de contact augmentait, davantage de charges étaient transférées aux particules de renforcement. L'objectif principal de ce travail est d'étudier l'effet de la porosité (1%, 2%, 3% 4% et 5%) sur le comportement mécanique d'un matériau composite à matrice métallique en Aluminium renforcée par des particules de Sic. Pour cela, nous avons fait varier la porosité en fonction de la fraction volumique des particules et ce pour trois types d'arrangement (carré, hexagonal et aléatoire) sous chargement de traction unidirectionnelle par la méthode des éléments finis. Les résultats obtenus dans ce travail montrent que le taux de porosité et la forme des pores ont un effet significatif sur les propriétés et le comportement du composite.

Mots-clés : Particules de Sic, Aluminium, Composite, Porosité, Forme de pore, Élément fini.

ABSTRACT.

In this thesis, the effect of porosity and voids shape on the mechanical behavior of the composite reinforced with Sic particles is evaluated. The small particles adhere strongly to the Aluminum, which leads to a strong reinforcing effect. As the total contact area increased, more charges were transferred to the reinforcing particles. The main objective of this work is to study the effect of porosity (1%, 2%, 3% 4% and 5%) on the mechanical behavior of a composite material with a metal Aluminium matrix reinforced by Sic particles. For this, we varied the porosity according to the volume fraction of the particles and this for three types of arrangement (square, hexagonal and random) under unidirectional tensile loading by the finite element method. The results obtained in this work show that porosity rate and voids shape have a significant effect on the properties and behavior of composites.

Keywords: Sic Particles, Aluminium, Composite, Porosity, Voids shape, Finite Element.

ملخص

في هذه المذكرة، يتم تقييم تأثير المسامات و شكلها على السلوك الميكانيكي للمركب المقوى بجزيئات Sic. تلتصق الجزيئات الصغيرة بقوة بالألومنيوم، مما يؤدي إلى تأثير تقويضي قوي. مع زيادة مساحة التلامس الإجمالية، تم نقل المزيد من الشحنات إلى جزيئات التسليح. الهدف الرئيسي من هذا العمل هو دراسة تأثير المسامية (1%، 2%، 3%، 4%، 5%) على السلوك الميكانيكي لمادة مركبة تحتوي على مادة معدنية من الألومنيوم معززة بجزيئات Sic. لهذا قمنا بتنويع المسامية حسب الجزء الحجمي للجسيمات وذلك لثلاثة أنواع من الترتيب (المربع، السداسي والعشوائي) تحت تحميل شد أحادي الاتجاه بطريقة العناصر المحدودة. أظهرت النتائج التي تم الحصول عليها في هذا العمل أن معدل المسامية و شكل المسامات لهما تأثير كبير على خصائص وسلوك المركب.

الكلمات المفتاحية: جسيمات Sic، ألومنيوم، المركب،المسامات، شكل المسامات، العنصر المحدود.