Asian Journal of Applied Science and Technology
Volume 7, Issue 4, Pages 156-175, October-December 2023

Mechanical Properties Improvements of the Materials Used in Manufacturing of Food Processing Equipment's and Containers Using Different Techniques

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DOI: https://doi.org/10.38177/ajast.2023.7416

Article Received: 26 October 2023 *Article Accepted: 29 December 2023* *Article Published: 30 December 2023*

ABSTRACT

The selection of construction materials is typically based on various factors such as cost, availability, ease of fabrication, strength, toughness, elasticity, sensitivity to corrosion and wear resistance. However, when it comes to materials used in food processing equipment and services, the primary focus is also on preventing food contamination from dirt, chemicals, microorganisms, and physical substances during the limited time that the product and equipment surfaces come into contact. In the production of machinery and equipment for food processing, storage, and transportation, a variety of metals are utilized, including aluminum, copper, tin, titanium, and notably stainless steel (SS). These metals are chosen for their mechanical qualities. To further enhance the mechanical strength, ease of forming fabrication, and health-friendly features of metallic materials, this study aims to explore the development of an expanded range of such materials using advanced scientific and technological applications.

Keywords: Ferrous materials; Composite materials; Non-ferrous materials; Mechanical properties; Food industry; Heat treatment; Ceramic particles; Food processing equipment.

1. Introduction

Whenever materials come into direct contact with food, they must adhere to the rules, laws, regulations, standards, and guidelines established by national and international legislative and standardization bodies. However, these regulations are primarily focused on "packaging materials" rather than "construction materials for food processing equipment and services" [1-4]. When selecting building materials, considerations such as cost, availability, ease of fabrication, elasticity, strength and fatigue resistance are typically taken into account. However, in the case of materials used in the manufacturing of food processing equipment, the primary concern is to prevent food contamination from dirt, chemicals, microorganisms, and physical matters during the limited period of contact between equipment and product surface [5-11].

Metals and alloys are commonly employed in materials that come into contact with food, including equipment used in the food industry. Consequently, they have the potential to contaminate food. It is crucial that no substances from materials in contact with food migrate into the food in amounts that could pose a risk to human health. For materials composed of metals and alloys that come into contact with food, the release of metals, both the main constituents and anticipated impurities, is of great significance. Corrosion of the metal material releases metals. Release is a better term to use when discussing metal materials than migration because the two terms have different mechanisms. Metals and alloys are commonly coated on their surfaces. If these food-contact materials are not coated, the metal will corrode and release metal ions into the food. The health of individuals may be harmed if there is an overall level of metals in food that exceeds the limits set by health guidelines. Although they are utilized in many materials that come into contact with food, metals and alloys are most frequently found in process equipment found in both private residences and the food industry. Process equipment encompasses a wide range of items such as storage bins, spray dryers, boilers, kitchen knives, pipes, pots, pans, silverware, and various equipment utilized in industrial food production. Metals and alloys find diverse applications in this domain, including their use as layers in multilayer materials, foils, and cans, such as incorporating a metal layer in plastic packaging [12-14].

Aluminum alloys are commonly employed in the fabrication of containers, drink jars, cookware, and cooking utensils. The 5xxx and 6xxx series are known for being the strongest and most corrosion-resistant alloys used in wrought aluminum products [15]. Additionally, a range of casting alloys exhibit robust corrosion resistance, making them popular choices for cooking utensils and food processing equipment [16]. These aluminum alloys offer a combination of good corrosion resistance, strong mechanical properties, and weldability [17,18]. Copper and copper alloys are broadly utilized in several industrial applications. Their exceptional thermal and electrical conductivity, corrosion resistance, appealing appearance make these materials highly suitable for use in the food industry [19-21]. Cu is frequently utilized in pipelines for residential and commercial water utilities that contain seawater, as well as heating and cooling systems [22].

Furthermore, steel is a type of metal that is used in a wide range of products, including food equipment, household appliances, and automobiles, making it an indispensable part of modern life. Because mild steel has good mechanical qualities, including strength, ductility, and weldability, it was used to make food equipment [23-27]. Many studies have been conducted with the goal of improving mechanical properties of metallic materials. Consequently, a greater variety of materials with improved mechanical strength, simpler forming and fabrication, and health-friendly qualities will be covered in this article along with previous research on these materials.

2. Effect of grain refiner

For traditional aluminum alloys, coarse grains after casting and solidification present a challenge. The mechanical properties of aluminum alloy are significantly influenced by grain size. Defects like shrinkage cavities, cracks, and composition segregation are often caused by them [28]. As a result, research has shifted to the addition of grain refinement to Al alloys in order to enhance their microstructure and mechanical properties [29]. As shown in Figure 1, Zhang et al. [30] state that it is evident that the Al3Ti phase forms when a small amount of titanium is added to the alloy Al–Mg–Si–Zn. Moreover, this alloy's mechanical properties improved, as seen in Figure 2.

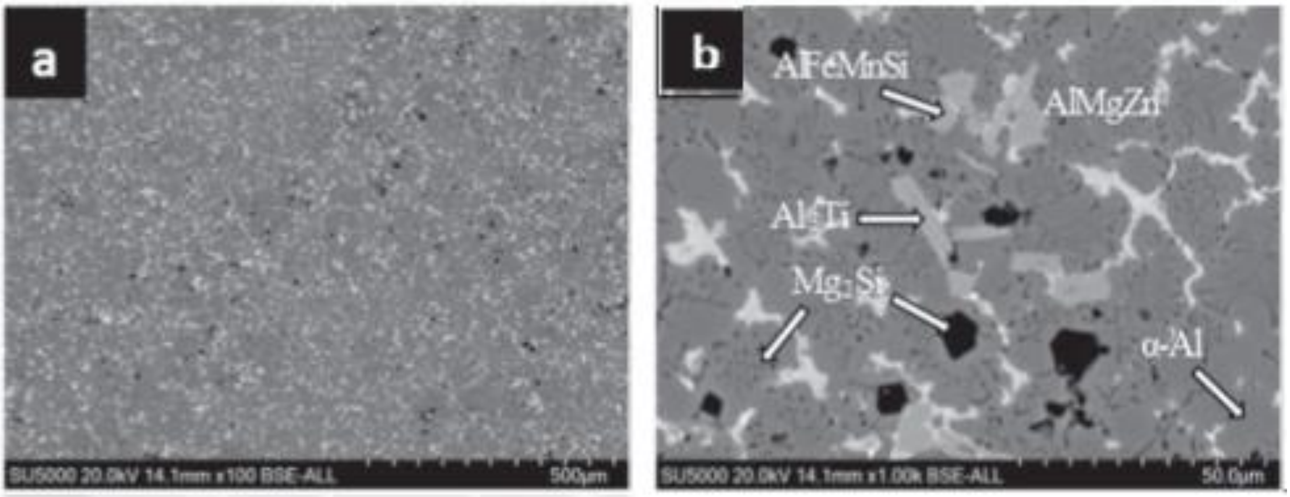

Figure 1. Microstructure of the Al–Mg–Si–Zn alloy containing 0.2 wt.% Ti

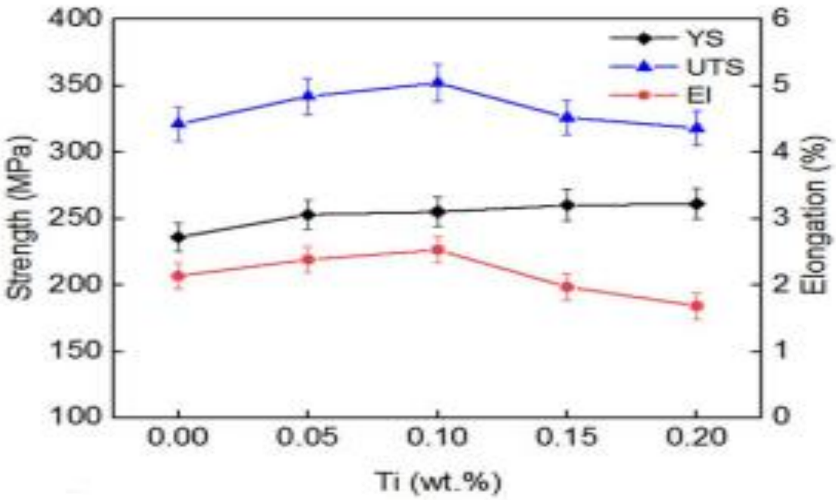

Figure 2. The mechanical properties of the Al–Mg–Si–Zn alloy with different Ti additions

In a study by Kodetova´ et al. [31], it was found that the Sc and Zr addition to hot-rolled alloys helps stabilize and refine the grain structure. Hot-rolled alloys of AlZnMgCuFe had grain sizes of approximately 1000 mm, whereas the addition of Sc and Zr resulted in grain sizes of 20 mm in AlZnMgCuFeScZr alloys. Another investigation by Abd El-Aziz et al. [32] focused on the impact of adding different ratios (0-3 wt.%) of Al-5Ti alloy on the mechanical properties and microstructure of AlSiMgMn alloy. When 2 weight percent of Al-5Ti was added, the ultimate strength of the alloy increased from 165 to 208 MPa, and the yield strength increased from 125 to 160 MPa. However, as depicted in Figure 3, no significant improvements in these properties were observed with a 3 weight percent addition of Al-5Ti master alloy.

Ding et al. [33] examined the influence of different types of Al-5Ti master alloys with varying microstructures, sizes, and amounts of TiAl3 intermetallic on grain refinement in commercial Al. They concluded that the microstructural characteristics of Al-5Ti alloys, such as size, morphology, and the presence of TiAl3 intermetallic, played a role in achieving the desired grain refinement characteristics with the appropriate holding time.

Furthermore, Pio et al. [34] investigated the effects of adding Al-5Ti-B alloy on the mechanical properties of LM6 Al-Si alloy. Since LM6 Al alloy with its 10-13 weight percent Si content typically exhibits coarse grain sizes upon solidification, the addition of 0.5 weight percent of Al-5Ti-B master alloy resulted in improved mechanical properties. However, further significant advancements were not observed even with an increase in the amount of grain refiners used.

3. Effect of Reinforcement addition

Recent material science research has been focused on developing innovative lightweight materials with enhanced specific strength, stiffness, fatigue, creep, and wear resistance [35]. Among the various options, metal matrix composites (MMCs) reinforced with nano-sized or micro-sized particles have shown great promise in achieving improved mechanical properties. Although the reinforcement leads to improvements in strength and hardness, there is a slight reduction in ductility [36, 37]. The creation of MMCs involves different methods such as squeeze casting, powder metallurgy, and melt techniques, as depicted in Figures 4-6.

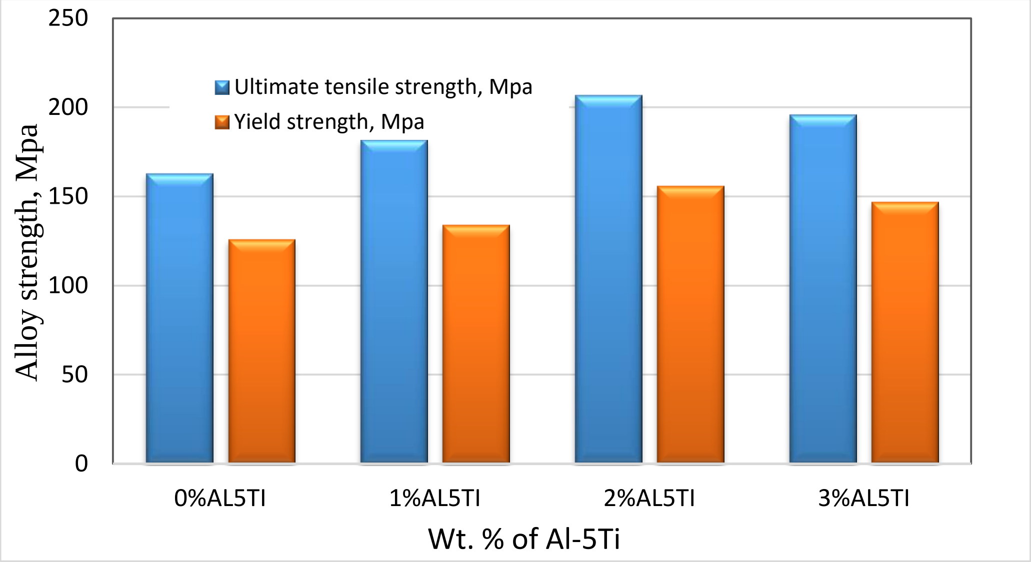

Figure 3. Mechanical properties of the AlSiMgMn alloy with different wt.% of Al-5Ti master alloy

To enhance the resistance of MMCs, hard particles like SiC and Al2O3 are typically embedded within soft aluminum-based alloys. These MMCs find significant applications in industries such as aerospace and automotive, particularly in components where tribological properties are crucial. Examples include cylinder heads, disc brake rotors, connecting rods, and pistons. The use of MMCs based on Al-alloy reinforced with SiC or Al2O3 particles continues to grow in these applications [38].

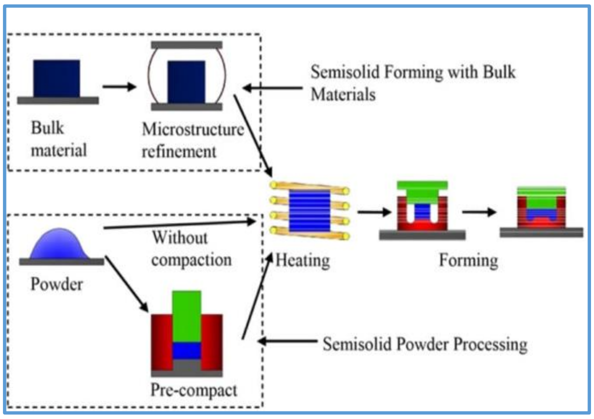

Figure 4. Semisolid powder Processing

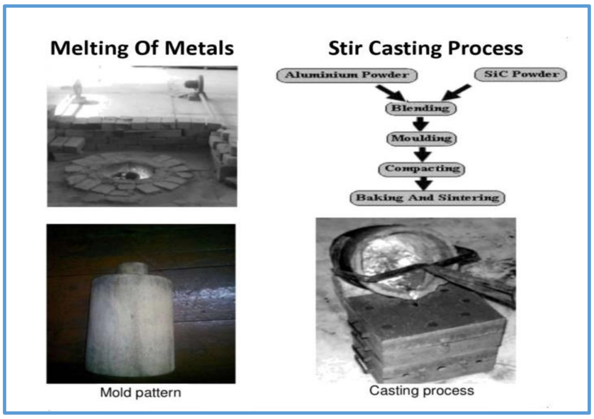

Figure 5. Casting Processing

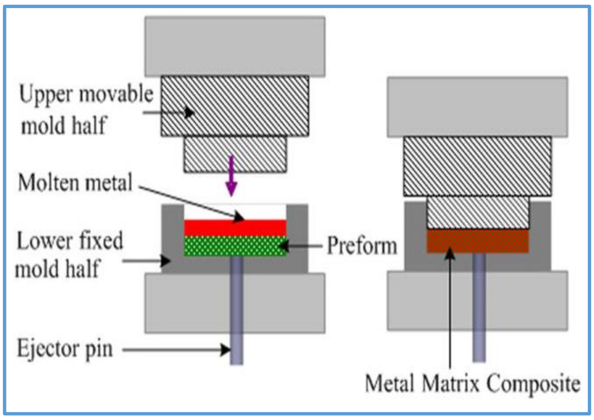

Figure 6. Squeeze Casting Infiltration Processing

Additionally, these MMC have a lower volume to weight ratio, which results in improved fuel efficiency. Furthermore, because particulates are less expensive than fiber, MMC reinforced with them is more affordable than MMC reinforced with fiber [39]. In a study by Mazahery et al. [40], it was found that the presence of nano-Al2O3 reinforcement significantly improved hardness, 0.2% yield strength, tensile strength (UTS) and ductility. Aigbodion et al. [41] observed that increasing the weight fraction of alumino-silicate reinforcement in the alloy resulted in increased hardness values and compressive strength, while decreasing impact energy. Corrochano et al. [42] demonstrated that Al 6061 alloy reinforced with Al2O3 whiskers exhibited exceptionally high mechanical properties. Another research by Hassan and Aigbodion [43] revealed that the addition of SiC particles to Al-Si-Fe alloy increased yield strength, tensile strength and hardness with a decrease in impact energy. Pankaj Jadhav et al. [44] investigated the effects of adding 4 weight percent B4C and Gr to A356/B4C and A356/Gr metal matrix composites on their mechanical characteristics and microstructure. Compared to the base alloy, they observed a 13.3% improvement in hardness and an 11.4% enhancement in UTS. Numerical analysis conducted by Ali Mazahery and Mohsen Ostad Shabani [45] on the A356/Al2O3 composite indicated that its tensile strength, elastic modulus, and hardness surpassed those of the monolithic alloys.

Conversely, pure copper has low wear resistance, low strength under tensile load, and low hardness. Because of this, adding various particles as reinforcement and creating copper matrix composites are two possible remedies for these weaknesses [46]. As the greatest replacement for conventional materials, metal matrix composites are currently creating a lot of interest in future [47-49]. It is now commonly known that appropriate reinforcement selection can result in improved properties for copper metal matrix composites. As reinforcement particles in the copper matrix, a variety of ceramic materials, including SiC, Al2O3, ZrB2, ZrO2, TiO2, and TiB2, have been employed. Researchers have reported that the mechanical properties of copper have improved as a consequence of the addition of these reinforcements [50-62]. According to Elmahdy et al. [46], microhardness (146.5 HV) was attained by adding 10% weight percentage ZrO2 to Cu-. ZrB2 reinforced copper-matrix composites with a hardness of greater than 120 HV have been prepared by Zhang et al. [56]. ZrB2 reinforced copper-matrix composites with a hardness of greater than 100 HV were prepared by Wang et al. [57]. According to Sreedharan et al. [58], adding more B4C nanoparticles increased the hardness of copper. Fathy et al.'s research [59] revealed that adding more Al2O3 nanoparticles to copper increased its hardness. According to Efe et al.'s research [60], adding more SiC nanoparticles made copper harder. Moghanian et al.'s research [50] examined the impact of adding 1-3 weight percent of TiO2 to copper. They discovered that adding more TiO2 to the Cu/TiO2 nanocomposite increased its hardness. According to Sorkhe et al. [62], adding more nanoparticles up to 5 weight percent TiO2 enhanced the hardness of the Cu/TiO2 nanocomposite.

In recent years, metal matrix composites (MMCs) reinforced by ceramic particles, whiskers, and short fibers have shown excellent performance in the frictional and wear regions, thanks to their exceptional strength and superior wear resistance [63]. The wear performance of MMCs is crucial in applications involving relative motion, such as internal combustion engine pistons or automobile brake discs. Vencl et al. [64, 65] conducted research revealing that wear properties of composite materials was primarily influenced by the presence of 3 weight percent Al_2O_3 particles, up to certain loads of up to 1 MPa. The wear rate of composites with percentage of 10% Al_2O_3 was nearly two orders of magnitude lower than that of the base alloy. According to Jun. et al. [66], the critical transition load into severe wear condition in the 12 vol.% Al2O3/Al-12Si composites improved to a range between 196 and 245N, compared to 147 to 196N for the monolithic Al-12Si alloy. Hong and Seo [67] investigated the wear performance and damage in an Al-Mg-Si alloy matrix composite reinforced by 10 vol.% Al2O3 as a function of wear factors such as applied load and sliding speed. To gain a better understanding of the relationship between microstructural variables and wear behavior in Al alloy base-matrix composites, the correlation between wear characteristics and microstructural evolution was investigated in an Al-Mg-Si alloy base-matrix composite reinforced by 10 vol.% Al2O3, as shown in Figures 7, 8.

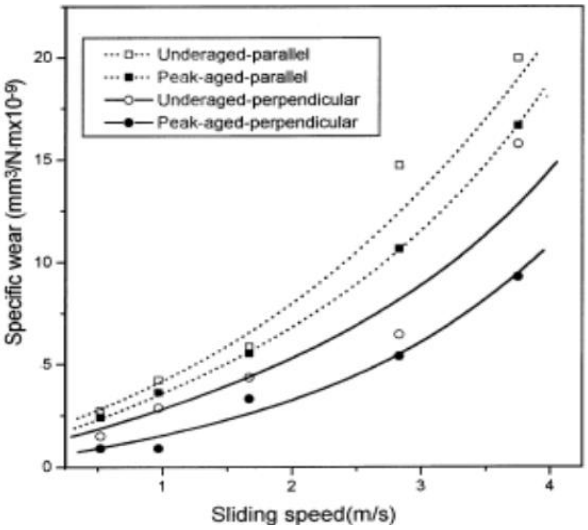

Figure 7. The specific wear variation of planes perpendicular and parallel to extrusion direction as a function of sliding speed

According to research conducted by Atta et al. [35], the influence of Al2O3 percentage in the Al-Si matrix diminishes as the applied load increases. Increasing the applied load results in a 20% reduction in the specific wear rate for a 25% Al2O3 content. However, the applied load leads to a slight increase in the specific wear rate with a minor rise at 25% Al2O3. Al-Qutub et al. [68] found that the wear resistance of metal matrix composites (MMCs) improves when the volume percentage of alumina particles in 6160 Al Alloy is increased to 30%. Tang et al. [69] observed that the wear rate of Al-Si alloy exhibits a higher growth rate at various rotational speeds compared to Al-Si alloy matrix composites with a 10% weight percent carbon content (Figure 9). They also demonstrated that as the rotational speed increases, the wear mechanisms of the Al-Si alloy and two Al-Si/CF composites transition from abrasive wear to delamination wear. Additionally, the carbon fibers (CF) can impede microcrack propagation and delay crack initiation, as depicted in Figure 10. Ning et al. [50] stated that the wear performance of Cu/TiO2 composite coated layers are superior in case of uniformly dispersed reinforcements throughout the matrix. Warrier and Rohatgi [51] made the dispersions of reinforcement particles publicly available, highlighting the potential of TiO2 to enhance the mechanical properties of Cu. Akarapu [52] found that Cu/TiO2 composite coated layers exhibit greater wear resistance compared to Cu-Al2O3 composite coated layers. Moghanian et al. [47] discovered that in Cu/TiO2 nanocomposites, a low content of TiO2 particles results in an increase in the rate of wear volume loss with increasing sliding distance. Conversely, Saber et al. [63] observed that the weight loss of copper nanocomposites due to wear decreases with an increase in the quantity of TiO2 nanoparticles. However, both pure copper and nanocomposites experience an increase in weight loss with higher applied loads and sliding distances.

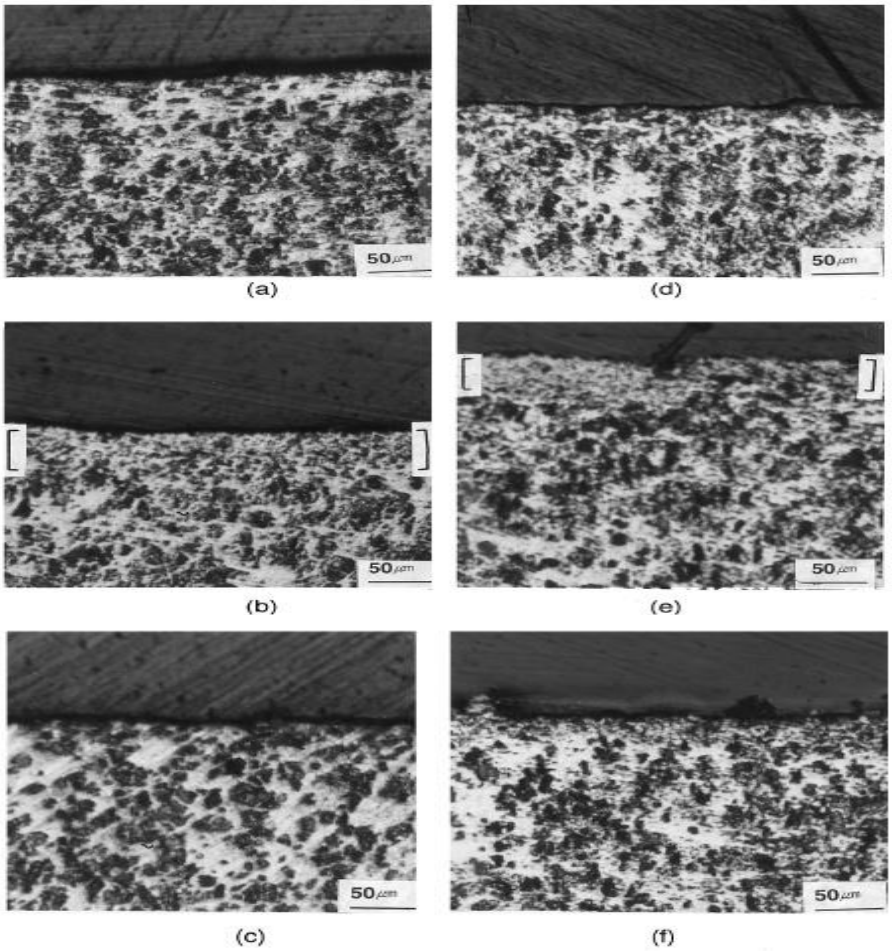

Figure 8. The sectioned profile under-aged (a–c) and peak-aged (d–f) Al alloy matrix composites in which the worn surface is perpendicular to the extrusion direction

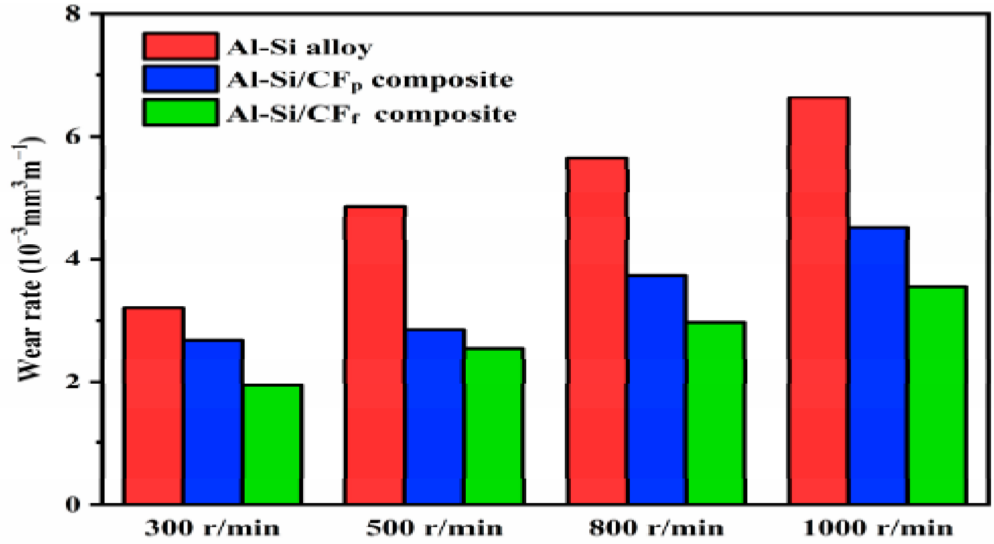

Figure 9. The effect of rotational speeds on Wear performance of Al-Si alloy and Al-Si/CFp, Al-Si/CFf composites

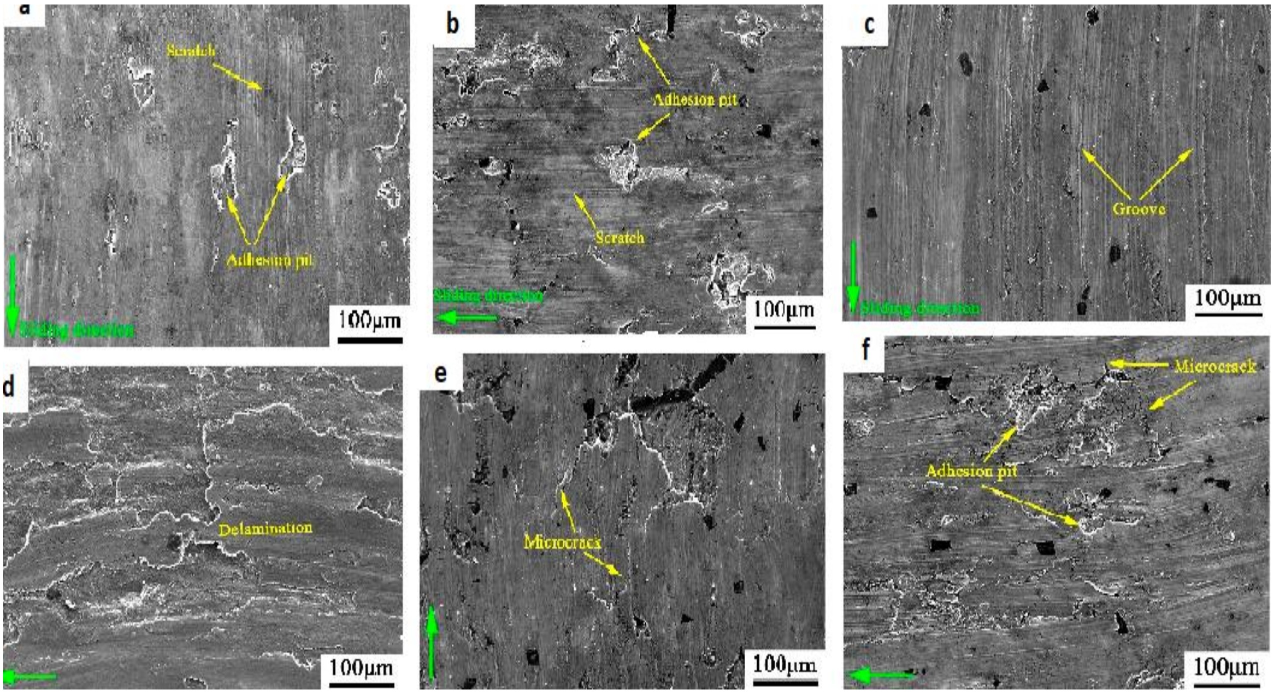

Figure 10. SEM images of the worn surface morphologiesat at rotational speed 300 r/min and 800 r/min of (a),(d) Al-Si (b),(e) Al-Si/CFp composites (c),(f) Al-Si/CFf composites

4. Effect of Heat-Treatment

In order to modify mechanical performance of the materials (i.e. yield strength, ultimate tensile strength, hardness, Young's modulus, elongation percentage), heat treatment operations involve carefully heating and cooling the material. By changing some specific manufacturing goals, heat treatment can also be used to increase a material's strength, particularly after it has undergone significant stress from welding and forging. The most significant heat treatments that are frequently applied to alter the mechanical characteristics and microstructure of engineering materials, especially steels, are annealing, normalizing, hardening, and tempering. When a significant degree of tensile strength and elongation are needed in engineering materials, annealing is the heat treatment type that is most commonly used to soften the materials and refine its grains because of the formation of ferrite-pearlite microstructure [70,71]. In their study, Thameer and Abbas [72] examine how the heat treatment processes of isothermal annealing, full annealing, and normalizing affect the ingot 30CrMoV9 steel's microstructure, fracture section, and a few specific mechanical properties like toughness, hardness, percentage reduction, and elongation. They demonstrated how different heat treatments can alter and enhance the mechanical properties of ingot 30CrMoV9 steel for a specific use, as shown in Table 1.

Table 1. Mechanical Properties of 30CrMoV9 steel before and after heat treatment

Specimen	ultimate Tensile Strength (N/(mm)^2)	Yield Stress N/(mm)^2 0.2%	E%	R%	Toughness (J)	Hardness HV)(
As forged	500	460	3	5	50	394
Normalizing	362	210	18	18	65	323
Full annealing	780	492	65	65	102	140
Isothermal annealing	603	390	60	60	100	160

Furthermore, the mechanical and tribological properties of MMCs can be further enhanced through appropriate heat treatment. The importance of heat treatment is to modify the microstructure of the metal matrix, thereby improving the toughness, hardness, and tensile strength of both the alloy and MMC reinforced with hard particles. Heat treatment has been found to enhance the wear resistance of alloys and MMCs, as indicated by studies on sliding wear behavior [73-78].

In the case of bimetallic composite plates, heat treatment is a commonly employed process to optimize their characteristics for various applications [79-81]. It is well known that heat treatment procedures can influence the carbon elements diffusion, thereby impacting the mechanical strength and corrosion resistance of the composite plates [82]. Abd Elaziz et al. [70] investigated the effect of heat treatment on the flexural behavior, hardness, and microstructure of bimetal beams composed of AISI4140 steel, known for its ductility, and high-Cr WI, renowned for its wear resistance. The two halves of the bimetal castings were joined using dovetail joints and/or connector pins. The study revealed that heat treatment of the bimetal casting beams significantly improved the flexural strength and hardness of high-Cr WI and AISI4140 steel, as illustrated in Figure 11. Ren et al. [83] examined the impact of annealing temperature on the Cu/304 composite plates. They found that as the annealing temperature increased, the diffusion distance of elements also increased, resulting in improved ductility but a decrease in overall hardness and strength. Jin et al. [84] investigated the influence of heat treatment on the properties of 316L/Q345R composite plates. The microstructure after quenching is primarily consisted of martensite, which exhibited reduced ductility but increased strength. Ma et al. [85] observed that a thin carburized layer was found near the bonding interface of the 304/Q235 at 1100°C quenching, and the carbon diffusion distance decreased with increasing quenching temperature. Hyojin [86] investigated the influence of normalizing and tempering procedures on the properties of S32750 steel-EH40 composite plates for hull structures. The tempered state was found to be more effective in increasing the yield and tensile strengths compared to the normalized state.

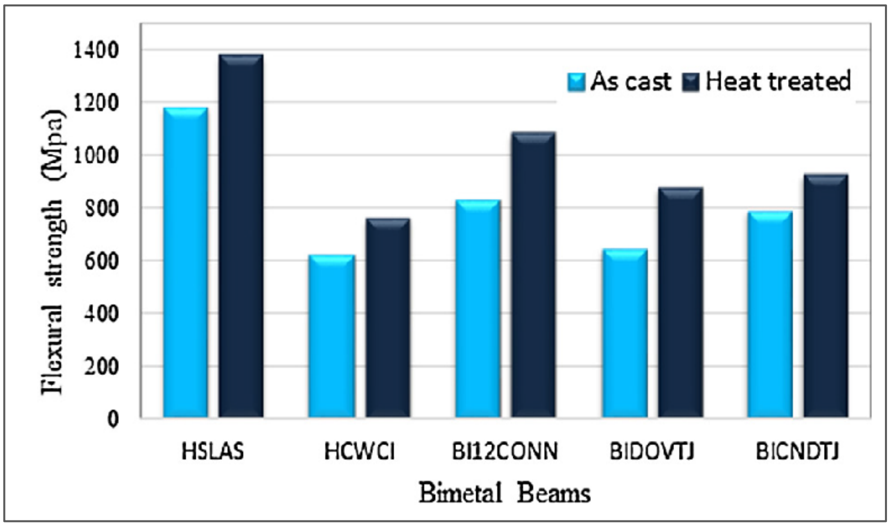

Figure 11. Flexural strengths of plain and bimetal casting specimens with the different mechanical joints in different conditions

Das et al. [87] reported that heat-treated composites exhibited superior wear properties compared to both the matrix alloy and composites in their as-cast state. Li and Tandon [88] found that heat treatment had no significant effect on the wear characteristics of Al-Si alloys reinforced with 20 vol% SiC particles, but it nearly doubled the hardness. Mozammil et al. [89] stated that the T6 heat treatment significantly influenced the final tensile strength and hardness of engineered or synthesized aluminum alloy composites, as well as the chosen aluminum alloy. Lakshmikanthan et al. [90] investigated the mechanical and tribological characteristics of A357 composites reinforced by dual particle size SiC (DPS A357) and found that T6 treatment improved wear resistance, hardness, yield strength, and tensile strength. Gandhi et al. [91] demonstrated that the addition of up to 0.5% multi-walled carbon nanotubes improved hardness and tensile properties of the composite, with a linear increase in tensile properties through heat treatment but no significant increase in hardness properties. Karuppusamy et al. [92] pointed out that heat-treated Al6061-10% SiC-10% graphite exhibited improved hardness and wear resistance compared to Al6061 alloy. Hussein et al. [93] found that heat treatment could enhance the mechanical and dynamic properties of aluminum alloys by up to 20%, yielding satisfactory results. Rawat et al. [94] reported that heat treatment or tempering improved the yield strength by 13.49% and ultimate tensile strength by approximately 15.58%.

In addition to heat treatment and eutectic silicon modification, H.R. Lashgari et al. [95] suggested that hard ceramic particles (SiC, $Al2O3$, $B4C$) can be used to reinforce Al-Si-Mg alloys, resulting in greater hardness and wear resistance compared to monolithic alloys. Li X et al. [96] demonstrated that the Al5Si1Cu0.5Mg matrix alloy and its composite exhibited higher microhardness, ultimate tensile strength, and elongation after undergoing T6 heat treatment compared to the as-cast condition. Furthermore, as illustrated in Figure 12, a significant portion of the cleavage plane in the Al5Si1Cu0.5Mg matrix alloy and its composite is replaced by a significant number of dimples, and the tearing ridges thicken.

Rajaram et al. [97] found that aging at 250°C provided the maximum tensile strength and increased the Brinell hardness by 37.1% and 50.5%, respectively, in comparison to non-aged Al7075-WC composites. The maximum impact energy observed was 92.2% for composites aged at 450°C. The strength properties of the Al7075+WC composite decreased at 350°C aging temperature. During aging, the mechanical properties of the Al7075+WC composite was improved from 150°C to 250°C and decreased from 250°C to 350°C. The wear resistance of the composite specimens increased with aging. Mehan et al. [98] reported that heat treatment reduced internal stresses in the aluminum alloy matrix and improved bonding between the ceramic reinforcement, resulting in a 15.58% increase in ultimate tensile strength and a 10.25% increase in impact strength, while hardness decreased by 6.5%.

Table 2. Mechanical properties of Al7075+WC composite

Specification	Average Tensile Strength (MPa)	Average Brinell Hardness Number	Average Impact Energy Observed (Joules)
Non-aged	91.35	83.43	2.06
Aged at 150 °C	99.63	107.63	2.46
Aged at 250 °C	125.25	125.57	3.66
Aged at 350 °C	95.71	119.86	2.93
Aged at 450 °C	109.66	121.56	3.96

5. Summary

A variety of metals, such as aluminum, copper, tin, titanium, and stainless steel (SS), find applications in the manufacturing of machinery and equipment utilized in food processing, storage, and transportation. These metals are chosen for their favorable mechanical properties. Aluminum alloys are extensively employed in the production of cookware, cooking utensils, containers, and beverage cans, thereby significantly contributing to the overall aluminum consumption. The 5xxx and 6xxx series alloys are particularly preferred for their excellent combination of corrosion resistance and strength, making them ideal for wrought aluminum products.

Certain casting alloys also possess high corrosion resistance, making them popular choices for food processing equipment and cooking utensils. Copper and copper alloys are usually utilized in many industrial applications. Cu finds widespread use in heating and cooling systems, pipelines for domestic and industrial water supply, including those exposed to seawater. Steel is an essential metal used in a wide array of products, including food equipment, household appliances, and automobiles, playing a vital role in modern life. Mild steel, known for its favorable mechanical properties such as strength, ductility, and weldability, has been traditionally employed in the manufacturing of food equipment.

The mechanical characteristics of aluminum alloys are significantly influenced by grain size. Larger grains can lead to defects like shrinkage cavities, cracks, and composition segregation. Grain refinement plays an important role in improving the mechanical attributes of wrought and as-cast aluminum alloys. Grain refiners (GR), typically in the form of master alloys like Al-Ti and Al-Ti-B, are commonly used to achieve grain refinement. The nucleation and growth processes of aluminum alloy grains during solidification are directly linked to grain refinement, making it a critical step in the casting process. Heterogeneous nucleation, facilitated by commercial master alloys and inoculant techniques, is employed to refine the grain. The optimal contact time is necessary to achieve the desired grain size when the grain refiner is added to the molten metal. Introducing inoculant particles into the molten metal is an effective means of obtaining small, regularly distributed equiaxed grains, which results in improved yield strength, toughness, formability, and machinability.

Metal matrix composites (MMC) are highly promising materials for enhancing mechanical properties such as tensile strength, flexural strength, and tribological properties. These composites consist of reinforcement particles, either nano- or micro-sized, embedded in a matrix. While reinforcements enhance strength and hardness, they may reduce ductility. Metal matrix composites are gaining attention as a viable alternative to conventional materials, and various ceramic materials, including SiC, Al2O3, ZrB2, ZrO2, TiO2, and TiB2, have been used as reinforcement particles in metal matrices. The incorporation of these reinforcements has significantly improved the mechanical properties of metals. Heat treatment processes involve carefully manipulating the heating and cooling of materials to modify their mechanical performance, such as yield strength, ultimate tensile strength, hardness, toughness, Young's modulus, percentage elongation.

Heat treatment is commonly employed to enhance the strength of materials, particularly after processes like welding and forging that subject the material to significant stress. Annealing, normalizing, hardening, and tempering are essential heat treatment methods used to alter the mechanical characteristics and microstructure of engineering materials, especially steels. Annealing, which softens materials and refines their grains through a ferrite-pearlite microstructure, is frequently utilized when engineering materials require elongation and substantial tensile strength.

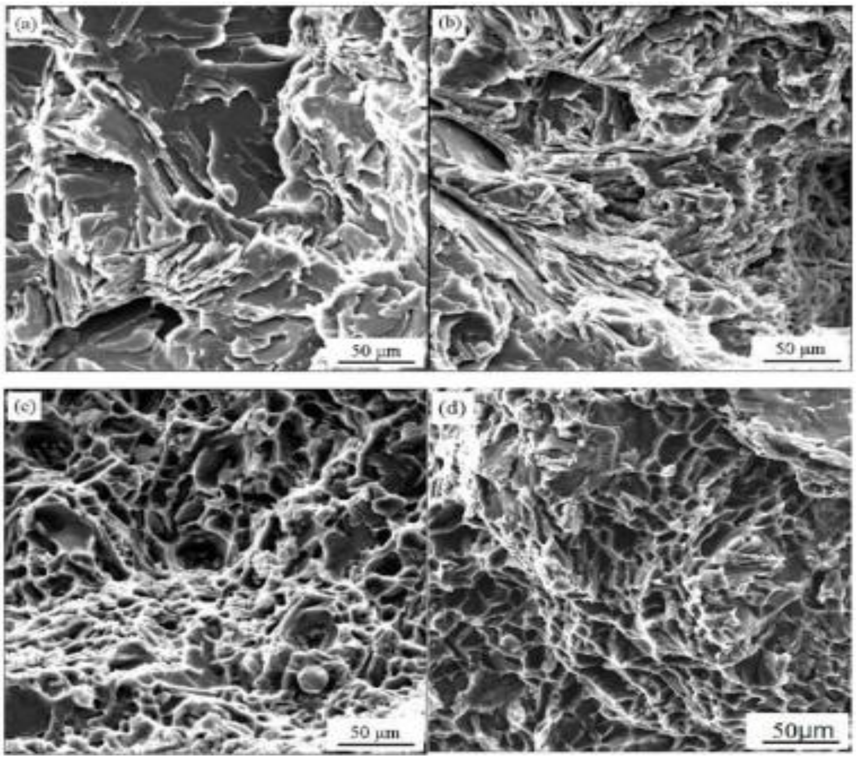

Figure 12. The fracture surfaces after tensile: (a) SEM image before and (c) after T6 for Al5Si1Cu0.5Mg matrix alloy; (b) SEM image before and (d) after T6 for the composite

Declarations

Source of Funding

This study did not receive any grant from funding agencies in the public or not-for-profit sectors.

Competing Interests Statement

The author declares that there are no competing interests.

Consent for Publication

The author declares that he consented to the publication of her original research work.

Authors’ Contributions

Author’s independent contribution.

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