A Comprehensive Review on the Mechanical and Tribological Properties of Al 7075-Based Metal Matrix Composites

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Abstract. This review paper examines the most recent development in the mechanical and physical properties of metal matrix composites (MMCs) taking Al 7075 as main metal. In order to increase the Mechanical Properties, Physical properties as well as tribological properties of AL7075 lot of reinforcement like SiC, Al_2O_3, TiC, B_4C, graphene, MoS_2, Nano mg and even some hybrid combinations are used. This paper cover various manufacturing techniques, different parameter that are used during manufacturing, optimization techniques and important findings from recent research. It also examines the performance improvements made possible by adding reinforcement and using secondary techniques that are advantageous in fascinating potential uses of these composites in areas including civil engineering, automotive, and aerospace.

Keywords: Al 7075, Metal Matrix Composites, Tribology, Mechanical Properties, Stir Casting, Friction Stir Processing, Reinforcement.

1. Introduction

AL 7075 is a high-strength aluminum alloy primarily alloyed with zinc (Zn). It is mainly used in civil engineering, defense, automobile and aerospace sector due to its high strength. It has a high strength-to-weight ratio, good fatigue and corrosion resistance. It has limitations in using it in extreme conditions due to its tribological properties, like wear resistance and friction resistance [1].

To overcome these limitations, researchers use metal matrix composites (MMCs) based on Al7075. The merger of ceramic reinforcements like SiC, Al_2O_3, B_4C, TiC, TiB_2, or ZrO_2 has significantly improved the hardness, tensile strength, and wear resistance [2]. These ceramics reinforcements increase the load capacity and create a strong bond with the aluminum matrix by acting as a barrier against movement and displacement.

Moreover, to enhance the electrical and thermal conductivity without compromising with mechanical integrity, metal reinforcements like Ni, Cu, and Ag are used [3]. In recent years, hybrid composites that are reinforced with ceramics, metals, and carbon-based materials such as graphite, graphene, or MoS_2 have become

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more and more popular due to their higher resistance, flexibility, self-lubrication, and corrosion protection [4].

The performance of composite depends upon processing technique used. Traditional method, like stir casting is cost effective and suitable for mass production, while advance methods like friction stir processing, ultrasonic-assisted casting, cryogenic FSP, and molten salt processing—gives better control over microstructure, porosity, and particle distribution [4-5].

In the past ten years, lot of research work is done on AL7075 MMCs to improve the performance through experimentation, modeling and optimization. Researcher investigate the type of reinforcement, its size, volume fraction, processing techniques, and post-processing treatments. The best combination of parameters has been determined to improve strength, wear resistance and corrosion performance by using optimization techniques such as Taguchi, ANOVA, RSM, and ANN [6-7]

This review paper gives a detailed overview of AL 7075 Metal Matrix Composites (MMCs), including synthesis methods, the impact of reinforcement, mechanical characteristics, tribological behaviour, and future research directions. This review paper states about the current growth in aluminium composite that help engineers and researchers to work efficiently on aluminium composite [8].

2. Fabrication techniques for AMCs

Fabrication techniques play an important role in fabrication of good quality aluminum matrix composites (AMCs). Factors like Particle distribution, bonding strength, microstructural integrity, porosity levels, and overall mechanical performance depends upon the fabrication method selected. In this section, the manufacturing methods that covered are conventional and advance manufacturing.

• **Stir Casting:** It is an old and economical liquid processing method. This method is widely used for fabrication of aluminium metal matrix composites (MMCs) due to its economic perspective. In this fabrication method, firstly the base material i.e. AL7075 is melted, after that reinforcements are added slowly. The stirring is done mechanically for even dispersal of particles before solidification. This method is used on large scale for fabrication because of its easiness, scalability, and cost effectiveness. But still there are some challenges like maintain even dispersion of reinforcement, and porosity free fabrication. Soluble agents like magnesium can be used for increasing solubility and bonding quality. Preheating of reinforcement can also be enhance bonding [9].

• **Friction Stir Processing (FSP):** The friction stir processing (FSP) is a solid-state technique that is derived from friction stir welding. In this technique, when a rotating tool is injected into the material, plastic deformation and frictional heat are produced, redistribution of reinforcement particles into the matrix. The reinforcements can be located on the surface or in holes that have already been drilled. Because FSP occurs below the melting temperature, it improves the microstructure, eliminates porosity and avoids solidification issues. Investigation shows that FSP improves AL 7075 composites tensile strength, microhardness, and wear resistance [10].

• **Ultrasonic-Assisted Stir Casting:** It is a process in which high-frequency ultrasonic waves (about 20 kHz) are supplied to the molten metal through ultrasonic probe to ensure proper mixing of base material and reinforcement by avoiding cluster of particles, get rid of gas bubbles, and improve wettability. This provides a close grain structure that help to reduced porosity, increased mechanical and tribological properties, and improved dispersion, especially for nano sized reinforcements [11].

• **Cryogenic Friction Stir Processing (Cryo-FSP):** Cryo-FSP is a solid-state material processing method in which processing is carried out at very low temperature by using liquid nitrogen gas. The very low temperature restricts grain growth which results in increasing hardness, strength and fatigue resistance due to nano sized structure. This processing method is mainly used for high performance structural applications where wear and corrosion play an important role while maintaining ductility [12-13].

3. Reinforcement materials and their effects

Reinforcement plays a vital role during manufacturing of AL7075 based composited by improving their mechanical and tribological properties. The reinforcements contribute in composites by improving hardness, wear resistance and whole strength. The widely used reinforcements are SiC, Al2O3, B—C, TiC, TiB_2, and ZrO_2 [14-15].

The metal reinforcement like Ni, Ag, and Cu are used to increase the electrical and thermal conductivity, as well as to improve ductility and impact toughness while maintaining mechanical strength and corrosive resistance [16].

Now a days, hybrid reinforcement such as SiC–Graphite, Al_2O_3–TiO_2, and MoS_2–TiB_2 are mostly used. These reinforcements have great contribution to increase hardness and self-lubrication properties [17]. They improve mechanical and tribological performance by reducing coefficient of friction and improving wear resistance [18]. Additionally, hybrid reinforcement also increases hardness while maintaining ductility and toughness that making composites suitable for automobile and aerospace applications [19-20].

The type, size and weight proportion of reinforcement also play a vital role in microstructure and mechanical characteristics of composites. By use of finer particle reinforcement, it is easy to get improved wear resistance and better hardness [21-22]. However, excess use of reinforcement in composite may lead to increase brittleness which Vise-versa reduces ductility [23-25].

4. Mechanical and tribological properties of Al7075

Hardness and Strength Improvements - According to previous research, addition of reinforcement significantly increased the strength and hardness of Al7075

metal matrix composites. The combination of ceramic reinforcement such as SiC, Al_2O3, and B_2C with aluminium matrix stops movement of dislocation that can increase microhardness of Al 7075 by up to 50% when compared to the base alloy [26-28].

Additionally, hybrid reinforcement like SiC–Graphite and Al_2O_3–TiO_2 improve the hardness and strength [29-30]. For the applications that require high wear and impact resistance as well as required more tensile and compressive strength, AL7075 with reinforcement like TiB_2 and TiC is used [31,32]. For better refining of grain structure that results less grain size and better hardness fine reinforcements are used [33-34].

For uniform reinforcement distribution with less porosity and better microstructure, friction stir processing (FSP) and ultrasonic-assisted casting techniques are used that also help to increase harness and strength of Al 7075 composites [35-36]. It is very important to understand that excess use of reinforcement in composite also make it weak by decreasing its ductility and making it brittle because of clustering [37-38].

In summary, it is important to carefully selection of type, size and volume fraction of reinforcement for creating balance between hardness and strength. This assures the perfect use of Al 7075 MMCs for high-performance in automobile and aerospace [39].

Wear Resistance - In automobile and aerospace industries, wear resistance of Al 7075 metal matrix composites (MMCs) is a main performance feature. Reinforcement like SiC, Al_2O_3, and B_4C significantly improve wear resistance by reducing the deterioration of material and minimize the direct metal-to-metal contact during sliding [40-41]. Furthermore, they also bear the applied loads which results reducing in wear damage and helps avoid localized stress accumulation [42-43]. Hybrid reinforcement like SiC-Graphite creates a balance between hardness and self-lubrication to reduce wear rate and coefficient of friction (COF) [44].

Additionally, in hybrid composites, solid lubricants such as MoS_2 and hBN create a lubricating layer at the contact surface that results in reducing loss of material due to wear and friction [45-46]. Researcher also confirmed that use of finer particles size reinforcement and processing techniques like friction stir processing (FSP) are major contributor because they can also improve wear performance by improving microstructure and reducing boundary sliding when compared to those fabricated with conventional methods [47-48]. Additionally, also confirmed that ultrasonic-assisted casting reduce porosity and strengthening the matrix-reinforcement bond, which improves wear resistance [49].

Corrosion Behavior - In areas like aerospace, marine, and automotive where the work is done frequently in harsh environments, it is important that AL7075 have ability to withstand corrosion. Addition of ceramic reinforcements as Al2O3, SiC, and TiB2 significantly increase the Corrosion resistance [50-51].

Moreover, it has been found that hybrid reinforcement that contain ceramic and metallic particles improve corrosion resistance. For example, by modifying

microstructural irregularities and creating a more even passive oxide layer on the surface of the composite, adding TiC and B_4C can reduce the possibility of galvanic corrosion [52]. Furthermore, reinforcements such as MoS_2 and hBN increase corrosion resistance by reducing frictional wear, which else result to expose metal surface in harsh conditions [53].

According to research, Al7075 MMC's corrosion resistance is significantly increased by modifying the amount of reinforcement and the processing parameter used [54].

5. Parameter optimization techniques

By adjusting process parameters, we will improve the mechanical, tribological, and corrosion properties of Al 7075 metal matrix composites (MMCs). For this purpose, many statistical and computational modelling strategies have been used to find ideal reinforcement content, processing conditions, and post-processing treatments. To find the best process parameters for improved hardness, better wear and corrosion resistance the analysis techniques such as Taguchi analysis, response surface methodology (RSM), and artificial neural networks (ANN) are used [55].

Statistical Optimization Methods

To find the effective inputs or parameters to improve manufacturing process we must use following analysis tools.

Taguchi Method - Taguchi method is an analysis tool that is used to observe the effects of various input variables like reinforcement weight fraction, stirring speed and time, and tool speed on outcomes like hardness, tensile strength, and wear resistance. In this method, orthogonal array is used to make experimental process simpler and effective. Furthermore, to identify powerful characteristics with nominal changeability signal-to-noise (S/N) ratios helps effectively [55].

Analysis of Variance (ANOVA) - ANOVA is another analysis tool that is commonly used with other Design of Experiments (DOE) methods to find how effectively each parameter is important for contribution to overall properties of the composite statistically. In the design and processing of composites, ANOVA helps us make right decision by measuring the effect and relationship between each variable [56].

Response Surface Methodology (RSM) - Response surface methodology is also an advanced analysis technique in which the relationship between various parameters is found by using surface plots and regression modelling. For best tribological or mechanical performance, it developed rational model and helped to find the best processing variables [57].

ANNs – In today's scenario of optimization techniques, artificial neural networks (ANNs) and machine learning algorithms play a great role. These optimization techniques include data-driven models that create relations between input and output responses.

To analyze the difficult, nonlinear relations between input variables and the outputs an artificial neural network is used effectively. It helps us to forecast the nature of fabricated composites under different settings of different parameters after training [58].

Finite Element Analysis (FEA) and Simulation Techniques – To analyze the stress distribution and wear under various conditions for AL7075, Finite Element Analysis (FEA) is an excellent analysis tool because of simulation. It also talks about if there is any change in size, shape and distribution of reinforcement [59].

Multi-Response Optimization - It is an analysis technique in which analysis is done by using desire function analysis and grey rational analysis (GRA) [60].

6. CONCLUSIONS

After a detailed study of Al 7075-based metal matrix composites, we found the mechanical and tribological properties of Al 7075-based metal matrix composites (MMCs) are improved by adding ceramic, metallic, and hybrid reinforcements with base metal.

Some important results after detailed study are:

- **Mechanical Performance:** After the study it is found that with the use of reinforcements like SiC, Al_2O_3, TiC, B_4C, and TiB_2, the hardness, tensile as well as compressive strength, and impact strength significantly increased.
- **Tribological Performance:** In the study it is also found that the hybrid composites like SiC–Graphite, Al_2O_3–TiO_2, and MoS_2–TiB_2 etc. play an important role in decreasing wear rate and friction. Also, if we kept in view the sharing of loads and the creation of lubricating tribofilms between surfaces, hybrid composites like graphite, MoS_2, and hBN with ceramics would play a vital role.
- **Corrosion Resistance:** During the study we found that by adding ceramic particles the corrosion resistance increases, as there is a layer of even passive coating that acts as a barrier. Additionally, it is found that advanced methods of stir casting, like ultrasonic-assisted casting and friction stir processing (FSP) help to reduce porosity and interfacial errors, both of which are necessary for reducing corrosion.
- **Fabrication Techniques:** As per study, it is clear that for microstructure improvement and even dispersion of particles, methods like Friction Stir Processing (FSP), Cryo-FSP, and ultrasonic-assisted stir casting are better than conventional stir casting.
- **Optimization Strategies:** As per research done, it clearly shows that for evaluating the best processing parameters, predicting material performance, and reducing experimentation, the statistical and computational methods that are effectively used are Taguchi design, ANOVA, response surface methodology (RSM), artificial neural networks (ANNs), and finite element analysis.

7. FUTURE SCOPE

After reviewing, we found that a lot of research is done on the fabrication of AL7075 MMCs, but still we also find some gaps in research that can be filled by further research.

- **Amalgamation of Nano-Reinforcement**: There is limited study focused on nano-reinforcements like Nano Cu, Nano Mg, Graphene, and Nano-Al_2O_3 that can be added to base material, AL7075, to significantly improve its mechanical, physical, and tribological properties without compromising much with its overall weight.
- **Hybrid Reinforcement Design**: Also, there is limited research done on hybrid composites, e.g., combining SiC, Al_2O_3, TiC, Nano Cu, Nano Mg, ZnO, and natural additives like aloe vera ash dust. While hybrid composites have a lot of advantages, we still don't know how reinforcement actually reacts with base material.
- **Advanced Processing Techniques**: This review clearly shows that there is insufficient research done on advanced processing techniques like spark plasma sintering, laser-assisted casting, and cryogenic friction stir processing. Advanced processing methods play an important role in increasing the uniformity of reinforcements in AL7075.

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