Characterization of Metal Matrix Composites reinforced with suitable reinforcement agents – A Comprehensive Review

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Abstract. Invention of new materials is always essential for the growing industries. The materials which are newly invented or developed are expected to be of improved strength, light weight, simple preparation methods and lesser cost. Composite materials are found as better choices to be tested for satisfying the researchers’ expectations for different structural applications. Various research works are being performed with metal matrix composites (MMC) by incorporating suitable reinforcing agents with them in order to achieve better desirable properties. The current paper presents the researcher works so far carried out on distinct metal matrix composites, the incorporated reinforcement agents, the amount of reinforcement agents added, the preparation methods of MMCs and the details of mechanical characteristics which got improved out of the reinforcement. This cumulative work will surely be helpful for the researchers in this field in selecting suitable reinforcing agent for preparing their composites.

Keywords: Metal Matrix Composites; Reinforcement Agent; Characterization; Mechanical characterization.

1. Introduction
In general, composite materials are prepared by combining at least two distinct materials with different characteristics. Since there is a demand for materials with higher strength to weight ratio, composite materials are concentrated more in many industrial sectors and automobile sectors. Based on the matrix medium, composite materials are categorised as metal matrix, ceramic matrix and polymer matrix composites. Though several works are going on with polymer matrix [1–5] and ceramic matrix composites, MMCs are concentrated more because of their better mechanical characteristics. In the present study, a detailed review work has been presented on the fabrication process, inclusion of reinforcement agents and the improvement achieved on various mechanical characteristics of recently addressed metal matrix composites.

1.1. Fabrication of Metal Matrix Composites
For the fabrication of MMCs, different techniques are generally used such as stir casting process, powder metallurgy, infiltration technique etc., [6] Among them, most of the researchers have followed stir casting technique for mass production because of its simple procedure and better results. In stir casting process, the metal and reinforcement agents are mixed at molten stage with the help of a mechanical stirrer. The metal and reinforcement particles are taken in a crucible and kept inside a hot furnace for melting. After stirring the metal and reinforcement particles at molten state for required time in order to get uniform distribution of the particles in the parent metal, the molten mixture will be
transferred to a designed mould for casting; and then will be cooled at atmospheric condition to get the finished metal matrix composite [7]. In powder metallurgy process, the metal and the reinforcement agents are initially powderized using any one of the techniques like ball milling and ultrasonic concussion. Then the evenly distributed powder mixture is sintered in a spark plasma sintering system by applying compressive pressure at vacuum atmosphere [8]. Copper based metal matrix composites prepared using powder metallurgy technique were reported to have improved thermal conductivity and wear resistance properties [9].

1.2. Inclusion of reinforcement agents with MMCs
The inclusion of Aluminium Nitride (AlN) particles enhances the thermal conductivity property in aluminium based metal matrix composites in turn AlN added MMCs are suggested to used for electronic packages and in the fabrication of heat dissipation devices [10]. The inclusion of Magnesium – Ceramic particles improves the mechanical properties in magnesium based MMCs like stiffness and abrasive wear resistance. The addition of Silicon Carbide particles with Aluminium based MMCs shows improved ultimate tensile strength property [11]. Aluminium based MMCs added with Boron Nitride nanoparticles gain better tensile properties in comparison with that of the parent material. Also the inclusion of Carbon nanotubes and graphene shows better tensile characteristics in the aluminium based MMCs [12]. The increase in the addition of volume percentage of Silicon Nitride particles leads to reduction in the bending strength of the Al based metal matrix composites. The nano sized alumina particles incorporated aluminium 6061 composites were reported in the literature that they exhibited better tensile properties with more volume percentage of alumina particles reinforcement [13]. The addition of Titanium Carbide and Molybdenum disulfide particles helps to achieve improved wear resistance in magnesium based composite materials. Also, it was observed by referring several literatures in the relevant area that the effect of adding reinforcement agents and their sizes on the wear resistance characteristics changes metal to metal [14]. The uniform distribution of Zirconium silicate and Titanium diboride micro particles in the aluminium metal matrix composites results in achieving better tensile strength and hardness properties [15]. Tensile strength and hardness values can be improved in aluminium MMCs by adding coconut shell ash particles [16]. In the field of MMC characterization, recent research works are focusing on developing high strength Fiber Metal Laminates by incorporating suitable reinforcement agents [31].

1.3. Optimization techniques used in MMCs characterization study
Researchers have used various optimization techniques suitably in the characterization study of different MMCs. For the optimization study on the wear behavior of MMCs, sliding distance, normal load, sliding speed, vol./wt.% of the reinforcement are usually considered as the significant input parameters. Distinct optimization techniques carried out for the wear behavior study on MMCs are detailed in Table 1.

| S. No. | Base Metal | Reinforcement | Objective | Optimization Technique | Result |
|-------|------------|---------------|-----------|------------------------|--------|
| 1.    | Copper     | MWCNTs        | To optimize the wear loss | Taguchi’s technique | Wear loss decreases with increasing the volume fraction of MWCNT up to the level of 3% [9] |
| 2.    | Al−Si alloy| Gr and Si₃N₄ | To optimize the wear rate and CoF | Taguchi’s technique | 25% decrement in wear rate for Al−Gr−Si₃N₄ hybrid composites than Al−Si₃N₄ nanocomposite for 1 km sliding distance; |
3. Pure magnesium (CRT panel glass and BN) To optimize the wear rate and coefficient of friction Taguchi based Grey Relational Analysis

4. Aluminium (ISO 99.0Cu) Coconut shell ash To optimize the wear rate and coefficient of friction Grey–Fuzzy approach & Desirability function approach

5. AA6061 and AA7075 B_4C and Graphite To optimize the wear rate Response Surface Methodology

6. AA6061 Si_3N_4 and Graphite To optimize the wear rate and coefficient of friction Grey Relational Analysis

65% decrement in wear rate for Al–Gr–Si3N4 hybrid composite for the loads of 20 and 30 N [13].

20μm CRT panel glass at 10 wt%, 10N of applied load, 1 m/s sliding velocity and 500m sliding distance was found to be the optimal combination [14].

10N applied load, 15 vol.% of reinforcement & 2000km sliding distance was the optimal combination [16].

Wear rate was minimum at 10 N applied load, 0.8 m/s sliding speed & 2000 m sliding distance [17].

1m/s sliding speed, 10N normal load & 4 wt.% of Si3N4 was found to be the optimal combination [18].

2. Extensive Literature Survey

The base metal, reinforcement agent and method of fabrication of several MMCs, the mechanical property study and significant results of MMCs study have been referred through various literatures and collectively presented in Table 2.

| S. No. | Base Metal | Reinforcement | Composition | Method of fabrication | Reported results |
|-------|------------|---------------|-------------|-----------------------|------------------|
| 1.    | Aluminium alloy -17Si | ZrSiO_4 and Graphite | 3, 6, 9 & 12 wt.% of ZrSiO_4 & 2 wt.% of Gr | Stir casting process | • Wear rate decreased for all the loading conditions when compared to the base material when the wt.% of ZrSiO_4 reinforcement increases  
• 12%ZrSiO_4+2%Gr of reinforcement will have better wear resistance properties compared to all other percentage of reinforcement  
• 6% ZrSiO_4+2%Gr reinforcement will give the |
| Nr. | Material System | Additional Component(s) | Reinforcement Content | Processing Method | Additional Information |
|-----|-----------------|------------------------|-----------------------|-------------------|------------------------|
| 2.  | Al-17Si         | ZrSiO$_4$              | 3, 6, 9 & 12 wt.%     | Stir casting process | Better hardness property [19] |
|     |                 |                        |                       |                   | - Tensile strength of the composite increased with ZrSiO$_4$ particles till 3% and thereafter started to decrease. The reason behind that is Zirconium has higher hardness than Al matrix [20] |
|     |                 |                        |                       |                   | - Hardness values of Al-TiB$_2$ & Al-B$_4$C composites were higher than Al-ZrSiO$_4$ composites in equal amounts of reinforcements [15] |
| 3.  | Aluminium Alloy 356 | B$_4$C, TiB$_2$ and ZrSiO$_4$ separately | 5, 10 & 15 vol.% | Stir casting process | - Considerable improvement in the fracture toughness with the combinations: 6% SiC+2% ZrSiO$_4$ & 4% SiC+4%ZrSiO$_4$ |
|     |                 |                        |                       |                   | - The compositions 0%SiC+8%ZrSiO$_4$ & 2%SiC+6%ZrSiO$_4$ had high compression strength [21] |
| 4.  | AA356           | SiC & ZrSiO$_4$        | 0%SiC+8%ZrSiO$_4$    | Stir casting process | - Tensile strength increases with the increase in the wt.% of Al$_2$O$_3$ |
|     |                 |                        | 6%SiC+2%ZrSiO$_4$    |                   | - Electromagnetic stirring action helped MMC getting composed with smaller grain size and good interface bonding [22] |
|     |                 |                        | 2%SiC+6%ZrSiO$_4$    |                   | - Tensile properties got enhanced with 0.3 wt% of graphene. Increasing the graphene content beyond 0.3 wt% resulted in cluster formation [23] |
|     |                 |                        | 4%SiC+4%ZrSiO$_4$    |                   | - Hardness increases with increasing reinforcement content up to 1 wt.% Al$_2$O$_3$ but thereafter the hardness decreases. This is due to the heterogeneous distribution of nanoparticles and high porosity |
| 5.  | A359            | Al$_2$O$_3$            | 2, 4, 6 & 8 wt.%     | Electromagnetic stir casting method | |
| 6.  | AA7050          | Graphene               | 0.3, 0.5 & 0.7 wt.%  | Stir casting method | |
| 7.  | AA6061          | Nano Al$_2$O$_3$       | 0.5, 1 & 1.5 wt.%    | Stir casting method | |
| No. | Alloy   | Reinforcement                  | Volume % | Method                          |
|-----|---------|--------------------------------|----------|---------------------------------|
| 8.  | Al–4.5 wt.% Cu | Zircon sand and alumina particles | 15 vol.% | Stir casting method              |
| 9.  | AA356   | Nano SiC                        | 0, 0.5, 1.5, 2.5, 3.5 & 4.5 vol.% | Stir casting method              |
| 10. | AA356   | palm kernel shell ash nano particles | 1, 2, 3 & 4 wt.% | double layer feeding-stir casting method |
| 11. | AA356   | Aloe vera powder                | 10 wt.%  | Stir casting process             |
| 12. | AA (AlSi10Mg) | Rice husk ash                  | 3, 6, 9 & 12 wt.% | Stir casting process             |
| 13. | AA356   | AlN/MWCNT/AlN/MWCNT – 0.5,      |          | Stir casting process             |

- Yield strength increases with increasing the inclusion of Al$_2$O$_3$ particles [24]
- Wear resistance properties of Al–4.5 wt.% Cu alloy improved significantly with the addition of Al$_2$O$_3$ and zircon particles [25]
- Yield and ultimate tensile strength values & elastic modulus got improved with the inclusion of nano particles although some reduction in ductility was observed.
- The highest yield strength & ultimate tensile strength were obtained with the addition of 3.5% SiC nano particles [26]
- Improvement of 30.47%, 41.91%, 49.52%, 40.9% and 65.09% were obtained for hardness, tensile strength, yield strength, % of elongation & impact energy at 4 wt% addition of reinforcement [27]
- BHN was higher than that of pure Al
- Aloe vera powder increased the ultimate tensile strength 55.62% [28]
- Hardness of the composite linearly increased with the increase in wt.% of the rice husk ash particles. This occurred due to the increase in surface area of the matrix & thus the grain sizes got reduced.
- Rice husk ash increased the tensile & compressive strength of the prepared MMC [29]
- The optimal vol% of reinforcements were
Graphite 0.75, 1 & 2 vol.\% & Graphite – 0.5 vol.\% identified as 1% for MWCNT and 0.75% for AlN for mechanical properties [30]

3. Conclusion
This comprehensive study presents the cumulative details regarding the synthesis and characterization studies carried out on different metal matrix composites. Among the various available synthesis techniques, stir casting method was found to be the economical and effective technique for the preparation of MMCs. Few optimization techniques used for optimizing the wear study parameters on MMCs have been addressed. Further, the significant points taken from the characterization study results on MMCs have been presented. In which, the base metal selection, reinforcement agent consideration, preparation technique for the MMCs, composition of reinforcement inclusion, objectives of the study and the significant improvements in the mechanical, thermal and wear resistance properties of some aluminium based metal matrix composites have been detailed. This review work will definitely be helpful for the new researchers in the field of processing metal matrix composites.

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