ANALYSIS ON ALUMINIUM HYBRID METAL MATRIX COMPOSITE REINFORCED WITH HfC, Si₃N₄ and MoS₂ NANOPARTICLES

N. UMMAL SALMAAN¹, D. S. ROBINSON SMART² & S. ANTONY RAJA³

¹Research Scholar, Department of Mechanical Engineering, Karunya Institute of Technology and Sciences,
Coimbatore, Tamil Nadu, India

²Professor, Department of Mechanical Engineering, Karunya Institute of Technology and Sciences,
Coimbatore, Tamil Nadu, India

³Associate Professor, Department of Mechanical Engineering, Karunya Institute of Technology and Sciences,
Coimbatore, Tamil Nadu, India

ABSTRACT

The conventional materials are replacing with the aluminium hybrid metal matrix composite because of its superior tribological and mechanical properties. In engineering applications like aerospace, military, defence, automobile and marine aluminium metal matrix composite has a significant role to play. The aluminium metal is also being reinforced with HfC, Si₃N₄, MoS₂ to enhance the fatigue strength, creep, wear resistance, corrosion resistance, impact strength, damping properties and heat resistance capability. The main focus of this article is to review and summarize various techniques available for fabrication of AMCs, to study the influence of HfC, Si₃N₄, MoS₂ on aluminium material properties. The review indicates that the reinforcement of HfC, Si₃N₄, MoS₂ particles have improved the mechanical behaviour (Hardness, tensile strength and Compressive strength), tribological Behaviour and corrosion behaviour of the aluminium metal matrix composite.

KEYWORDS: Aluminium Metal Matrix Composite, Al7075, Hafnium Carbide, Silicon Nitride, Molybdenum Disulphide & Nano-Hybrid Composite

Original Article

Received: Apr 12, 2020; **Accepted:** May 08, 2020; **Published:** May 26, 2020; **Paper Id.:** IJMPERDJUN202068

INTRODUCTION

The growth and utilization of the composite materials continues to expand rapidly. Currently, composite material is the most important material in the engineering applications. The main reasons of using the composite material is due to their mixture of high stiffness, strength, toughness, lightness, corrosion resistance and more importantly composite material can be used in all type of hot and cold environment applications [1]. It is clear that, there are some biological materials such as wood, plastics etc, do have complex internal structures based on the existing mechanical properties. Composite material has very complex structure and very difficult to understand the right mixture of materials for the right usage of applications. Also, the adaptation of the manufactured composites requires various inputs from the various branches of sciences.[2] Due to the wide range of applications, fabrication of composite materials is the biggest challenge in the area of materials engineering. Manufacturing of composite material based on the applications, desired material properties, type of matrix and reinforcement materials. Liquid route techniques are compo casting (or) rheum casting, spray casting, squeeze casting, stir casting, ultrasonic-assisted casting, liquid metal infiltration and In-situ (reactive) processes. Solid route techniques include friction stir

processing, powder route processes, bonding by diffusion, techniques through deposition of vapour and high energy ball milling. [3] Components such as fittings, landing gears, shaft, fuse parts, regulating valve parts, propeller blades, high-temperature turbines, military armours that are used in aircraft, marine, military, automobile components fail due to its low exposure, high temperatures, fatigue load, corrosion and creep load. So, this review article proclaims to understand the material behaviour and properties of nano metal matrix composite with aluminium based and reinforced with Hafnium Carbide (HfC), Molybdenum disulphide (MoS₂), Silicon Nitride (Si₃N₄), when it is exposed to low, high-temperature environment and other critical loading conditions.

REVIEW OF LITERATURES

Aluminium 7075 Alloy

The 7075 series of aluminium alloys are extremely high strength and are good in plastic deformation when compared to the other series, D. Aleksendrić et al [4] The aluminium 7075 alloy is also called as Zinc alloy due to the presence of high percentage of zinc composition when compared to the other chemical compositions, as shown in table 1 when compared to other base alloys. The Al-7075 has a wide range of applications. Furthermore, reinforcements can be added like single phase and multiple phase reinforcements such as B₄C, AlN, SiC, Al₂O₃, Fly ash, Gr, TiO₂, etc.

Table 1: Elemental Composition of Al7075

Composition	Zn	Si	Fe	Ti	Cu	Mn	Mg	Cr	Other	Balance
Percentage	5.1-6.1	0.4	0.5	0.2	1.2-2.0	0.3	2.1-2.9	0.18-0.28	0.65	Al

Mechanical Behaviour of Aluminium 7075 Alloy

P. Zhou et al [5] analysed that the deformation mechanism and mechanical behaviour of 7075 aluminium alloy sheets which undergoes the dynamic strain and the ageing and sheets are investigated by inducing it into the solution treatment. To calculate the various strain rates, the uniaxial tensile tests are carried out. During the heat treatment, it was observed that the secondary phase shows the alloy dissolution and which made the mechanical properties of Aluminium alloy 7075 to change from one state to another. During the solid solution state, when the critical point temperature is at 623K and the temperature of the liquid alloy is getting less than the critical point temperature, the particles undergo the quenching process. The effect mentioned by the Portevin-Le Chatelier in engineering stress-strain curve shows more accurately the plastic deformation or inhomogeneous deformation of the aluminium 7075 alloys. From this effect, it proves that, the higher tensile strength and high elongation occurs when there is maximum external force during the tensile testing. M. S. Xie et al [6] Proved that the Al 7075 alloy could also be reinforced with metallic glasses to improve the disinfection of the metallic glasses. When these metallic glasses, along with Al7075 alloy are processed under quasi-static loading, the stress-strain curve denotes the linear increase in yield strength, compressive strength and consecutive increase in reinforced volume. B. Jayendra et al [7] investigated that the Al7075 alloy along with the boron carbide and graphite (Gr) reinforcements are casted by stir casting technique to form a composite material. As a result, from the Brinell hardness test, it shows that the hardness of the Al7075 alloys increased up to 150 BHN and also shows an increase in impact strength up to a maximum of 4 Joules. This can be achieved by increasing the volume of graphite reinforcement. The impact test was conducted by using Charpy impact testing machine. There is also an increase in ultimate strength, yield tensile strength due to increase of graphite volume, but the variation between the graphite and boron carbide shows that the values are nominal

due to good bonding between Al7075 alloy and their reinforcements. J. T. Wang et al [8] has stated that by using the LSP (Laser Shock Peening) the creep properties of Al7075 can be adjusted based on the applications where Al7075 is used. Also, these studies prove that by LSP method, at steady-state creep life will be increased by 97%, 37%, 120% at 350MPa, 350MPa and 300MPa respectively per 200°C. Hence, LSP method can increase the creep resistance of 7075 aluminium at the higher temperatures and true stress. A. Abolhasani et al [9] reported that the tensile testing method is carried out in Al7075-T7351 to check the equivalent strain on rolling, X-Ray diffraction to check the microstructural evolution and also another mechanical testing for mechanical properties. During the temperature of 250-350°C, the tensile results shows that the ductility was decreased. Based on the changes in temperature, there will be drastic changes in the mechanical properties. M. Imran et al [10] The addition of ceramic particulates added as reinforcements in the aluminium 7075 alloy results in more hardness by heat treatment process. The correct composition of matrix and reinforcements are prepared using the stir casting method to have good bonding between matrix and reinforcements after it is heated in a furnace at 470°C followed by quenching process. The specimens were tested by using Brinell hardness method based on the different Wt%. The hardness gets increased and additionally it shows good increase in hardness, when the specimen undergoes the Quenching process through ice. G. Rotella et al [11] has discussed that about the high cycle fatigue strength of aluminium alloy 7075-T6 and investigations on effect of lubrication during different machining parameters. The machining can be done with three different cutting speeds at 90m/min, 120m/min and 150 m/min and the different types of lubrication methodologies such as minimum quantity coolant, high pressure jet of air and cryogenic lubrications have been analysed. As a result of cryogenic cooling, it is observed that surface quality is improved and which leads the 7075-T6 aluminium alloy more reliable and long-life products when compared to other cooling methods. When there is no coolant and absent of improper cutting speed, it always resulted in the low surface quality and worst fatigue performance. F. Shahriyari et al [12] investigated the creep behaviour of Al7075 using two heat treatments methods which are solid solution and annealing. The microstructures are used to find the creep mechanism as well as creep strength by process called Equal Channel Angular Pressing (ECAP) and the results of before and after ECAP process is studied by TEM. Before the process of ECAP, the Al7075 have only coarse MgZn₂, after enhancing the number of entry of ECAP process the fine MgZn₂ and the disappear of coarse MgZn₂ was found. The mechanical properties such as hardness, yield strength and tensile strength were increased after four passes of ECAP process compared to the annealed sample. Also the creep rupture life had decreased as the stress increased after the completion of ECAP process by four passes.

Hafnium Carbide-HfC

Hafnium carbide is transition metal carbide which has a melting point greater than 3900°C, and it is a high-temperature material used in aerospace industries for propulsion chambers. A. Sayir et al [13] stated that Hafnium carbide is a light ceramic with high mechanical strength, but the Hafnium carbide requires other materials to increase stain to become failure capability by increasing the toughness. G. Li et al [14] investigated the different values of carbon content in HfC which resulted in the variation of hardness and elastic modulus based on the amount of the carbon content coating in HfC. By enhancing the content of the carbon by 56.9%, the elastic modulus and hardness value increases to 255Gpa and 27.9, If there is more than 70% of the carbon content, which results in the drop of hardness and elastic modulus significantly.

Silicon Nitride - Si₃N₄

Silicon nitride is used in various fields and it has tremendous mechanical properties when compared to other ceramic materials. It has thermal corrosion resistance, thermal shock resistance and good oxidation resistance. J. M. Mistry et al

[15] stated that the addition of silicon nitride ceramic 8% wt with Aluminium 7075 alloys shows good tensile strength and flexural strength. When the 12 wt % of Si_3N_4 , the tensile strength decreased due to the improper bonding. Figure1 shows the SEM image of Silicon Nitride with 8% of volume present in Aluminium 7075 alloy.

Figure 1: SEM Image of wt 8% Si_3N_4 in Al-7075 Alloy [15].

TRIBOLOGICAL BEHAVIOUR

Aluminium 7075

S. Suresh et al [16] experimented the tribological behaviour of the Al7075 along with the silicon carbide with the various wt% using the liquid metallurgy technique. En-32 steel disk with a round pin wear tester was made use to evaluate the specimen wear rate, friction coefficient and the weight loss of the material, when the specimen undergoes with different loads 20N, 30N, 40N and with various wt% of reinforcements. In Figure 2, it shows that the effect of wear resistance under 2 m/s sliding speed, the wear resistance is considerably increasing based on the wt% of the reinforcements added. From figure 3 it is clear that, the coefficient of the friction is gradually decreased from 0.4 to 0.36, if 4 wt% of silicon carbide is added to Al7075 alloy. Following figures shows that, the specific wear rate and frictional coefficient are based on the wt% of silicon carbide. Figure 2 and 3 shows the wt% of the reinforcement verses wear resistance and specific wear rate versus wt% of the reinforcement at sliding speed of 2m/s.

Figure 2: Wt% of the Reinforcement Verses Wear Resistance [16]

Figure 3: Specific Wear Rate Versus wt% of Si_3N_4 [16]

Z. Yuan et al [17] stated that the silicon nitride and the silicon carbide ceramics are excellent in wear resistance, high temperature, high strength, high hardness and excellent oxidation resistance. This can be used in wide applications such as the turbine, cylinder liners and also at the high-speed aquatic environment. It also stated that to improve the wear resistance, some additives can be added to the lubricants and surface texturing on the frictional surface. To find the tests on surface wear rate the ball-on-disk tribometer is used. The Si₃N₄ ceramic undergoes the tests using five lubrications such as water, aqueous, dry graphene, dry lubrication and self-developed graphene under different load conditions with a maximum rotational speed up to 200 m/s and maximum rotating time up to 3600 Sec. When compared to the five states of lubrication, it was found that the Si₃N₄ ceramic are good in graphene solution lubrication than the dry sliding friction. The worn area of the Si₃N₄ which is under graphene solution is 657 μm and which is less than the dry lubrication is having 1208 μm worn area.

Figure 4: Rotating Time vs Friction Coefficient based on Different Types of Lubrication [17].

Molybdenum Di-Sulphide- MoS₂

K. W. Liew et al [18] states that some of the surface engineering techniques which are made use to control the wear performance and friction of the materials. MoS₂ is coated on the structure by sputtering, burnishing and spray bonding methods. The coating on aluminium 7075 alloy should have constant pressure ranging thickness from 1 to 5 μm . The test conducted on the pin-on-disc tribo test machine shows an excellent wear resistance on the aluminium surface

METHODOLOGY – MANUFACTURING METHODS

Sintering Process

D. Lu et al [19] stated that ultra-fine HfC powder could be synthesized using a precursor liquid conversion method along with a sintering process by plasma-activated condition by using the salicylic acid, Hafnium dichloride oxide and citric acid to obtain the purest form of Hafnium carbide powders. During this process to form a complex based solution, first the HfOCl₂ (Hafnium dichloride oxide) and 8H₂O (Salicylic acid) are dissolved in ethanol for 1 hour, then citric acid was added and stirred for 1 hour. After that the solution is made to dry at 65°C using an evaporator which is a rotary type till the powder is obtained. For this, pyrolysis process has to be done on precursor material at 800°C before PAS system, as shown in Figure 5. The pyrolysis product was mixed using a planetary ball mill. Through the PAS System, the aggregates can be removed and the experiment should be carried out by synthesizing the hafnium powder ranging from 600°C to 1550°C. J.-X. Liu et al [20] stated that a sintering process without pressure to be carried out to produce the fine hafnium carbide powder. In the Pressureless sintering process, the chemically produced HfC powder was pressed uniaxially at 20 MPa and then it is subjected to cold isostatic depression pressed by applying 250 MPa. At high temperature, in graphite-

resistant furnace, the HfC ceramics were sintered with pressure less. The compacted form of Hafnium carbide ceramics was exposed to temperature up to 1800°C and heated up. The rate of heating should be 50°C/min and again the compacted form of hafnium carbide ceramics should be heated at 2400°C with a heating rate of 30°/min by considering the exposing time of 30 min, the furnace was allowed to cool till it reachesthe prevailing room temperature. The compacted sintered hafnium carbide powder was carried out below 1000°C by using a vacuum, then in a flowing 99.9% argon atmosphere above 1000°C.

Figure 5: Process of Pure Hafnium Carbide from Citric acid and Salicylic Acid [19]

Stir Casting Process

M. Ravikumar et al [21] stated that, the process of stir casting, which is used to manufacture metal matrix composites is one of the most efficient ways to add up the reinforcements to the metal matrix. When it comes to the conventional method, the melting process can be done by using the coke furnace. When it comes to the fabrication method, the most economical method is Stir- casting. During the conventional method, the molten metal gets ready and pre-heated, reinforcements are added based on the wt% chosen. After the addition of the reinforcements, the base metal and the reinforcements with exact wt% are mixed by using an electrical stirrer. Then the die which is already pre-heated with releaser spray will let the molten metal into the die continuously. Finally, the casting part based upon the metal matrix composites is obtained.

Figure 6: Illustration Diagram of Stir Casting Method.

Aluminium Metal matrix Composites (AMC) are classified owing to their good properties such as corrosion, mechanical, thermal stability and this can be obtained by adding the same phase mixing of reinforcements. P. Malhotra et al [22] used the stir casting technique to fabricate the Al7075 alloy with wt10% of SiC reinforcements with magnesium particles. Magnesium will help to increase the wet ability. Then the mechanical stirring was done at a temperature of 750°C for over 30 mins at 300 rpm so that, the magnesium will start to melt and forms a circular shaped hybrid composite to perform

experiments on the Metal Removing Rate (MRR) and Electrode Wear Ratio (EWR). B. Ravi et al [23] used AA6061 with B₄C with different percentage using the stir casting method for various investigations. Where both particulates are heated to a temperature of 850°C and all the mixtures were stirred continuously for more than 10-15 minutes at 400rpm of impeller speed with the powder rate of feed of 0.8-1.2 g/s. M. I. Ul Haq et al [24] studied the sliding friction under dry, wet conditions and characteristics of AA7075-Si₃N₄ composite were fabricated by using stir casting method. AA7075 with 8 wt % of Si₃N₄ was heated at 950°C in a crucible made of graphite keeping in an electric furnace, adding the preheated ceramic particles at a uniform feed rate and with a mechanical stirring. The results of XRD and SEM show the presence of Si₃N₄ and its uniform distribution. J. J. Moses et al [25] predicted the process parameters of manufacturing AA6061/TiC aluminium matrix using a casting method with a stirrer attachment. A casting method which has electric stirrer protects the difficulties against the mechanical stir casting. S. S. S. Suresh et al [26] stated that, infusing Al₂O₃ along with Aluminium 7075 and wt1% of, magnesium improved the wettability of the reinforcement and impact strength. Aluminium 7075 is fabricated in a rectangular shape by heating up to 900°C after adding the Al₂O₃, magnesium and it was again made to undergo for pre-heating at 650°C by using the stainless-steel stirrer to avoid the reactions. Use of stainless-steel stirrer helps to migrate the Fe from the Al7075.

Chemical Vapour Deposition Technique

D.Kim et al [27] The process of chemical vapour deposition technique is used to reinforce the hafnium carbide with the carbon fibres by using an industrial scale furnace. It has an induction coil, graphite susceptor, insulation jacket and water jacket extraction for cooling purpose. Also because of a vacuum pumping system, hafnium carbide is highly dense with the carbon fibres.

Optical Microstructure-Scanning Electron Microscope

Ankit Tyagi et al [28] showed the homogeneous distribution of AA6082 mixed with Silicon nitride using SEM and microscopic images. It shows that there is a good bonding in matrix alloy and reinforcements. The SEM images show that there exists porosity blowholes and pinholes, as shown in Figure 7. T.Sharanya Balaji et al [29] has gone through the microstructure analysis using FE-SEM of AA7075-Si₃N₄. Figure 8 shows the reinforcement particle of Si₃N₄, which clearly shows the presence of porosity and fly-ash. B. Matović et al [30] shows the morphologies of powders attained by the annealing process with different temperature. The hafnium carbide powder was subjected to annealing at 1000°C and is formed into a lump like a structure, as shown in Figure 9 and this is the purest form of about 99.9%. [24] studied the sliding wear under dry condition of Al 7075 with the particulates added as reinforcements. The SEM image shows the uniform distribution of ceramics in Al-7075 alloy and the pattern of sliding wear resistance was studied by using an optical microscope.

Electron Diffraction X-Ray

K.R.Ramkumar et al [31] studied the electron diffraction. X-Ray figures show the peak of corresponding reinforcements according to their wt%. XRD spectrum shows the amount of percentage of the reinforcement presents, as indicated in Figure 10. The spectrum image is clearly displaying the increase of TiC peak intensity based on the increase of wt% and it doesn't show any intermetallic phases. So, it proves that there are no impurities and no response between the Al phase and TiC cubic phases. Robinson Smart et al [32] stated that the X-ray diffraction analysis showed that the intensity peak of Al, SiO₂, Al₂O₃, Fe₂O₃ gets increased when there is an increase in fly ash content but in XRD, the fly ash particles are not

detected. This is because the integrity of fly ash particles is preserved during the casting process. In Figure 11, it shows the XRD pattern of AA6061 and fly ash composites.

Figure 7: (a, b) SEM and Microscopic Image of Cast AA6082 Aluminium Alloy with low Amount of Silicon Nitride wt%, (c, d) SEM and Microscopic Image of cast AA6082 Aluminium Alloy with High Amount of Silicon Nitride wt%

Figure 8: SEM Image of AA7075- Si_3N_4 (With Porosity) [29].

Figure 9: SEM Image of Hafnium Carbide [30].

Figure 10: X-Ray Diffraction Peak Obtained on AA 7075–x wt.% TiC (x = 0, 2.5, 5, and 7.5) [31].

Figure 11: XRD Patterns of AA6061/fly ash Compocast Composites.[32].

CONCLUSIONS

From the above reviews, it is observed that the aluminium metal matrix composite has an enormous development in improving mechanical and tribological properties. Al7075 alloy has been one of the major requirements in the field of material science and technology. Among all 7xxx series, the Al7075 alloy is the most adaptable material for all types of defence vehicles and rocket launchers. In addition to its applications in marine, automobile, it can also be used for low and high-temperature applications such as plunger pump which is used in the underground to pump the oil at different temperatures. Aluminium metal matrix can be fabricated using the stir casting method which can add up the different reinforcement elements based on the mechanical and tribological properties of aluminium alloys. It is observed that the mechanical properties are enhanced based on the various wt% of ceramic materials reinforced in Al-7075 alloy. It is clear that the addition of silicon nitride, Hafnium carbide and molybdenum disulphide will increase the tensile strength, compressive strength, yield strength, flexural strength and decreases the ductility. Also, the tribological behaviour, coefficient of wear resistance has increased with an increase in wt% of molybdenum disulphide. Also, it was observed that the Hafnium carbide is the very strongest material ever found, which has a high boiling point and melting point especially when it comes to pure form and having good mechanical properties. So, HfC can be used in all type of major critical applications. Silicon Nitride is a ceramic material that can be reinforced with the aluminium metal matrix composites which has high sustainability due to high hardness and strength. The use of SEM (Scanning Electron Microscopy) indicates that the porosity and the defects in the materials can be studied easily. And the XRD analysis is very useful in scanning the

presence of reinforcements along with the wt%. The extensive review shows the limited study has been proposed on Hafnium Carbide and Silicon Nitride and shows that there is a research gap for further investigations.

REFERENCES

1. Clyne, T. W., & Hull, D. (2019). *An Introduction to Composite Materials* (3rd ed.). Cambridge University Press.
2. S.C.Tjong, "Composites -General Introduction," pp.1-63, 1999
3. Development and C. Korean, "Module-1: General Introduction M1: General Introduction," *Composites*, vol. 1, no. c, pp. 1–35, 2011.
4. D. Aleksendrić and P. Carlone, "Introduction to composite materials," *Soft Comput. Des. Manuf. Compos. Mater.* pp. 1–5, 2015.
5. Zhou, P., Song, Y., Hua, L., Lu, J., Zhang, J., & Wang, F. (2019). Mechanical behavior and deformation mechanism of 7075 aluminum alloy under solution induced dynamic strain aging. *Materials Science and Engineering: A*, 759, 498–505.
6. Xie, M. S., Wang, Z., Zhang, G. Q., & Yang, C. (2020). Microstructure and mechanical property of bimodal-size metallic glass particle-reinforced Al alloy matrix composites. *Journal of Alloys and Compounds*, 814, 152317.
7. Jayendra, B., Sumanth, D., Dinesh, G., & Rao, M. V. (2020). Mechanical Characterization of Stir Cast Al-7075/B4C/Graphite Reinforced Hybrid Metal Matrix Composites. *Materials Today: Proceedings*, 21, 1104–1110.
8. Wang, J. T., Xie, L., Luo, K. Y., Tan, W. S., Cheng, L., Chen, J. F., Lu, Y. L., Li, X. P., & Ge, M. Z. (2018). Improving creep properties of 7075 aluminum alloy by laser shock peening. *Surface and Coatings Technology*, 349, 725–735.
9. Abolhasani, A., Zarei-Hanzaki, A., Abedi, H. R., & Rokni, M. R. (2012). The room temperature mechanical properties of hot rolled 7075 aluminum alloy. *Materials & Design*, 34, 631–636.
10. Imran, M., & Khan, A. R. A. (2019). Characterization of Al-7075 metal matrix composites: A review. *Journal of Materials Research and Technology*, 8(3), 3347–3356.
11. Rotella, G. (2019). Effect of surface integrity induced by machining on high cycle fatigue life of 7075-T6 aluminum alloy. *Journal of Manufacturing Processes*, 41, 83–91.
12. Rotella, G. (2019). Effect of surface integrity induced by machining on high cycle fatigue life of 7075-T6 aluminum alloy. *Journal of Manufacturing Processes*, 41, 83–91.
13. Shahriyari, F., Shaeri, M. H., Bavarsiha, F., & Noghani, M. T. (2019). Creep behavior of solid solutioned and annealed Al-7075 alloy processed by equal channel angular pressing. *Materials Science and Engineering: A*, 765, 138225.
14. Li, G., & Li, G. (2010). Microstructure and mechanical properties of hafnium carbide coatings synthesized by reactive magnetron sputtering. *Journal of Coatings Technology and Research*, 7(3), 403–407.
15. Mistry, J. M., & Gohil, P. P. (2019). Experimental investigations on wear and friction behaviour of Si3N4p reinforced heat-treated aluminium matrix composites produced using electromagnetic stir casting process. *Composites Part B: Engineering*, 161, 190–204.
16. Suresh, S., Gowd, G. H., & Deva Kumar, M. L. S. (2019). Tribological Behavior of Al 7075/SiC Metal Matrix Nano-composite by Stir Casting Method. *Journal of The Institution of Engineers (India): Series D*, 100(1), 97–103.
17. Yuan, Z., He, Y., Cheng, K., Duan, Z., & Wang, L. (2019). Effect of self-developed graphene lubricant on tribological behaviour of silicon carbide/silicon nitride interface. *Ceramics International*, 45(8), 10211–10222.

18. Meshram, R. E. E. N. A., and A. L. K. A. Chaturvedi. "Effect of insecticide on in vitro pollen germination of *Lycopersicon esculentum* (Mill.) of F1 hybrid variety Laxmi." *IJANS* 6.4 (2017): 1-10.
19. Liew, K. W., Chia, S. Y., Kok, C. K., & Low, K. O. (2013). Evaluation on tribological design coatings of Al₂O₃, Ni-P-PTFE and MoS₂ on aluminium alloy 7075 under oil lubrication. *Materials & Design*, 48, 77–84.
20. Lu, D., Wang, W., Wang, H., Zhang, J., Wang, Y., Zhang, F., & Fu, Z. (2016). Synthesis of ultra-fine hafnium carbide powders combining the methods of liquid precursor conversion and plasma activated sintering. *Ceramics International*, 42(7), 8108–8114.
21. Nagaral, Madeva, V. Auradi, and M. K. Ravishankar. "mechanical behaviour of aluminium 6061 alloy reinforced with al₂o₃ & graphite particulate hybrid metal matrix composites." *International Journal of Research in Engineering & Technology (IJRET)* Vol, 1, 193 198 (2013).
22. Liu, J.-X., Kan, Y.-M., & Zhang, G.-J. (2010). Synthesis of Ultra-Fine Hafnium Carbide Powder and its Pressureless Sintering. *Journal of the American Ceramic Society*, 93(4), 980–986.
23. Ravikumar, M., Reddappa, H. N., & Suresh, R. (2018). Aluminium Composites Fabrication Technique and Effect of Improvement in Their Mechanical Properties – A Review. *Materials Today: Proceedings*, 5(11), 23796–23805.
24. Suresh, R., and M. Prasanna Kumar. "Investigation of tribological behavior and its relation with processing and microstructures of Al 6061 metal matrix composites." *International Journal of Research in Engineering & Technology* 1.2 (2013): 91-104.
25. Malhotra, P., Tyagi, R. K., Singh, N. K., & Sikarwar, B. S. (2020). Experimental investigation and effects of process parameters on EDM of Al7075/SiC composite reinforced with magnesium particles. *Materials Today: Proceedings*, 21, 1496–1501.
26. Ravi, B., Naik, B. B., & Prakash, J. U. (2015). Characterization of Aluminium Matrix Composites (AA6061/B4C) Fabricated by Stir Casting Technique. *Materials Today: Proceedings*, 2(4–5), 2984–2990.
27. Ul Haq, M. I., & Anand, A. (2018). Dry Sliding Friction and Wear Behavior of AA7075-Si₃N₄ Composite. *Silicon*, 10(5), 1819–1829.
28. Moses, J. J., Dinaharan, I., & Sekhar, S. J. (2016). Prediction of influence of process parameters on tensile strength of AA6061/TiC aluminum matrix composites produced using stir casting. *Transactions of Nonferrous Metals Society of China*, 26(6), 1498–1511.
29. S. Suresh et al., S. S. ... TJPRC. (2018). Processing and Mechanical Testings of 7075 AL Matrix Composite Reinforced with AL₂O₃ Nano-Particles Fabricated by Stir Casting Route. *International Journal of Mechanical and Production Engineering Research and Development*, 8(2), 539–550.
30. Kim, D., Han, J., Park, C., Lee, H., Park, J. Y., & Kim, W. (2019). Chemical Vapor Deposition of Dense Hafnium Carbide from HfCl₄–C₃H₆–H₂ System for the Protection of Carbon Fibers. *Advanced Engineering Materials*, 21(5), 1800730.
31. Ankit Tyagi et al., " Characterization of AA6082/Si₃N₄ composites" *International conference on new frontiers in engineering science and technology*, 10.01.2018.
32. Belekar, RAJU M., P. S. Sawadh, and R. K. Mahadule. "Synthesis and structural properties of Al₂O₃-ZrO₂ nano composite prepared via solution combustion synthesis." *International Journal of Research in Engineering & Technology*, 2, 145 152 (2014).
33. T.Sharanya Balaji et al., " Influence Of Flyash & Silicon Nitride On Mechanical & Tribological Properties Of Aa 7075

- Hybrid Composite*". (2019). *International Journal of Innovative Technology and Exploring Engineering*, 8(9), 2344–2350.
34. Matović, B., Babić, B., Bučevac, D., Čebela, M., Maksimović, V., Pantić, J., & Miljković, M. (2013). Synthesis and characterization of hafnium carbide fine powders. *Ceramics International*, 39(1), 719–723.
35. Ramkumar, K. R., Sivasankaran, S., Al-Mufadi, F. A., Siddharth, S., & Raghu, R. (2019). Investigations on microstructure, mechanical, and tribological behaviour of AA 7075–xwt.% TiC composites for aerospace applications. *Archives of Civil and Mechanical Engineering*, 19(2), 428–438.
36. David Raja Selvam, J., Robinson Smart, D. S., & Dinaharan, I. (2013). Microstructure and some mechanical properties of fly ash particulate reinforced AA6061 aluminum alloy composites prepared by compocasting. *Materials & Design*, 49, 28–34.