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Mechanical, tribological and microstructural characterization of stir cast Al-6061 metal/matrix composites—a comprehensive review

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Abstract. Aluminum 6061 is a heat-treated, extruded alloy used for various engineering and structural components such as wings and fuselage of aircraft, railings, window frames, driveshaft and valves, etc. Al-6061 is widely used amongst its 6000 aluminum series because of its outstanding properties like medium to high strength, excellent environmental resistance, low density, high elongation at break and superior machinability. This paper aims to review the mechanical, tribological and microstructural characterization of stir cast Al-6061 metal/matrix composites (MMCs). In this review article an attempt has been made to demonstrate the effect of different reinforcements on metallurgical behavior of Al-6061 MMC. The particulates reinforcements like SiC, Al_2O_3, Gr, B_4C, TiC, fly ash, bagasse ash and red mud were dispersed with Al-6061 alloy through stir casting route as single, dual and triple reinforcements. The experimental results showed significant improvement in tribological and mechanical properties of Al-6061 MMC as compared with Al-6061 alloy. The overall characterizations of Al-6061 MMC are summarized with key findings, which will provide a methodical approach for researchers in selecting optimized parameters for the fabrication of aluminum-based MMC.

Keywords. Al-6061; mechanical properties; metal/matrix composites; microstructural properties; stir casting; tribological properties.

1. Introduction

Al-6000 are heat-treatable wrought alloys also known as Mg/Si alloys and because of magnesium-silicate (Mg_2Si) the alloys retain their heat treatability [1]. The Al-6000 alloys found major applications in welding and structural components due to their excellent corrosion resistance, medium strength and good formability [2, 3]. From Al-6000 series, the commercial alloys used for the development of aluminum-based metal/matrix composite (MMC) are Al-6061, Al-6063, Al-6026 and Al-6082 and amongst them Al-6061 is reinforced maximum time with particulate reinforcements through stir casting process [4, 5].

Al-6061 is a precipitated hardening alloy containing magnesium (Mg), silicon (Si) and iron (Fe) as its chief alloying elements. It was developed in 1935, originally called "Alloy 61 S" and also known by the name "structural aluminum" [6, 7]. Al-6061 is the most versatile alloy used in the construction of marine fitting, yacht, chassis, bearing and scuba tanks, shipbuilding, transport along with aircraft structure and automobile components [8–10]. Al-6061 alloy possesses excellent combinations of properties like good strength at elevated temperature, high stiffness to weight ratio, superior weldability and castability [11, 12]. Al-6061 alloy is extensively used in engineering and structural applications because its strength can be enhanced through liquid heat treatment and age hardening techniques [13]. The elemental compositions of Al-6061 alloy are presented in table 1 [1]. The physical characteristics of Al-6061 are presented in table 2 [7, 14, 15]. The Al-6061 alloy is mostly available in different designations like annealed pre-tempered Al-6061(O), solution heat treatment and naturally aged Al-6061 (T4), and solution heat treatment and artificial aging Al-6061 (T6) [10]. The Al-6061 (T6) is commonly used for the construction of fly fishing reel, bicycle frames, hydraulic brake piston and bike frames [16]. The mechanical properties of different grades of Al-6061 alloy are presented in table 3 [17, 18].

The aluminum alloy possesses good combination of physical and mechanical properties, yet these alloys failed to perform under various high-performance and high-temperature applications. However, in those specific applications, aluminum particulates metal/matrix composites (Al-PMMC) become the most valuable alternatives for researchers [19, 20]. Though the usage of Al-PMMC is not limited to structural and functional applications, these composite materials have gained wide potential in aerospace, marine, defense and automobile sectors as multi-

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Table 1. Elemental composition of un-reinforced Al-6061 alloy by weight percentage [1].

Elements	Mg	Si	Fe	Cu	Zn	Mn	Ti	Cr	Al
Amount (wt%)	0.8/1.2	0.4/0.8	0.7	0.15/0.4	0.25	0.15	0.15	0.04/0.35	Bal.

Table 2. Physical properties of un-reinforced Al-6061 (T6) alloy [9, 14–16].

Alloy	Density (g/cm^3)	Melting point (°C)	Poisson's ratio	Elastic modulus (GPa)	Solutionized temperature (°C)	Aging temperature (°C)
Al-6061	2.7	582/652	0.33	68.9	529	177

Table 3. Mechanical properties of different grades of un-reinforced Al-6061 alloy [14, 15].

Alloy	Yield strength (MPa)	Ultimate tensile strength (MPa)	Percentage elongation	Fatigue strength (MPa)	Hardness (BHN)	Shear strength (MPa)
Al-6061 (O)	55	124	25	62	30	80
Al-6061 (T4)	145	241	22	90	65	165
Al-6061 (T6)	276	310	12	96.5	95	207

functional materials [21, 22]. In particulates metal/matrix composites, mainly the harder reinforcement (nonmetallic material) is dispersed into softer matrix (metallic alloy) to obtain homogeneous distribution of reinforcing and matrix phase [4, 23]. The aim of PMMC is to get desired mechanical strength and hardness with improved physical and tribological properties. In recent years, the unique combination of ceramic and agro-industrial waste in the form of hybrid metal/matrix composite (HMMC) has also become a major area of research. The extensively used particulates ceramics reinforcements are SiC, B_4C, Al_2O_3, Gr and agro-industrial reinforcements such as bagasse ash (BA), bamboo leaf ash (BLA), fly ash (FA), red mud (RM) and rice husk ash (RHA) [19, 24, 25].

This review article provides a systematic case study on mechanical, tribological, microstructural and physical characterization of stir cast Al-6061 MMC. The effect of single, dual and triple reinforcements on overall properties has been reviewed and discussed. Comparative studies of Al-6061 alloy and Al-6061 MMC were also conducted and the outcomes of experimental results are presented in tabular form, bar charts, optical microscopy (OM) and scanning electron microscopy (SEM) graphs. Finally the experimental results of various characterizations are summarized in the form of key findings. The novelty of this article shows that no study has been carried out to demonstrate the overall metallurgical property of stir cast Al-6061 MMC with optimized process parameters. In future this review article will benefit academic researchers to choose the best permutation and combination of reinforcements and optimized process parameters to synthesize other aluminum-based alloys for achieving maximum metallurgical and functional properties. The basic structure of review article is illustrated in figure 1.

2. Stir casting

According to literature study on fabrication routes of aluminum-based composites, the liquid metallurgical mode (stir casting) was considered as one of the best and widely accepted technique amongst all the primary production methods [26, 27]. Stir casting technique possesses many advantages over other conventional methods such as low processing cost, good homogeneity among the particulates, less moisture absorptions, applicability to mass production and suitability to a wide range of shapes, sizes and volume fractions. However, wettability between matrix and

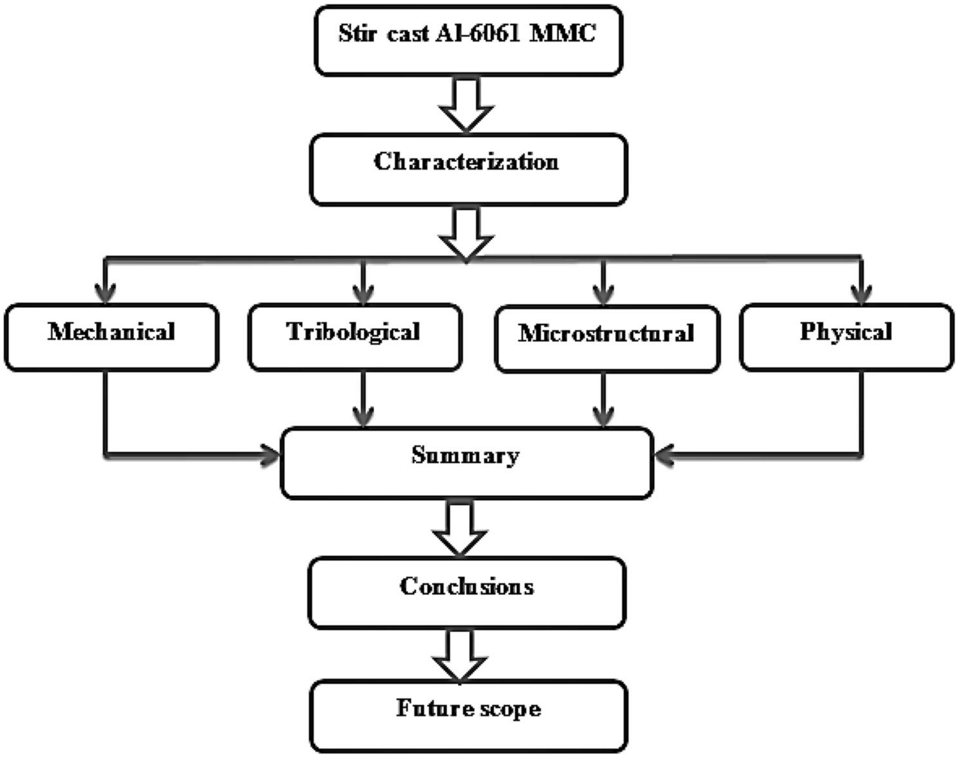


Figure 1. Schematic preview of review article (Al-6061 MMC).

reinforcing phase, agglomeration and porosity is the key limitation of this process [28–30]. The greatest benefit of stir casting procedure lies in its principle to fabricate materials in conventional manners like gravity casting using a bottom pouring furnace, which makes this process much simpler than other processes; however, the saving in manufacturing cost through this process is also one-third to one-tenth [31, 32]. The systematic stir casting setup with basic components is illustrated in figure 2. The overall characteristics of stir cast MMC and distribution of reinforcing particles inside a molten matrix were depend upon various process parameters as illustrated in figure 3. The right choice of these parameters significantly affects the overall performance of composite materials in terms of enhanced mechanical, tribological and microstructural properties [23, 33, 34]. The process parameters used by various researchers on Al-6061 MMC through stir casting technique are presented in table 4.

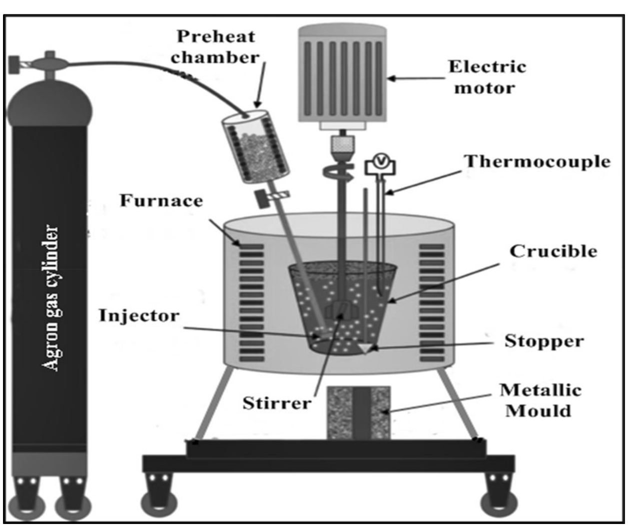


Figure 2. Schematic description of stir casting set-up.

3. Literature review

3.1 *Mechanical characterization of stir cast Al-6061 MMC*

A review on mechanical properties like ultimate tensile strength (UTS), microhardness, yield strength (YS), percentage elongation, ultimate compressive strength (UCS) and impact strength of as-cast Al-6061 MMC were discussed and compared to those of Al-6061 alloy. The results of various mechanical properties of Al-6061 MMC with sample compositions are presented in table 5. The specimens for mechanical characterization are prepared according to American Society for Testing and Materials

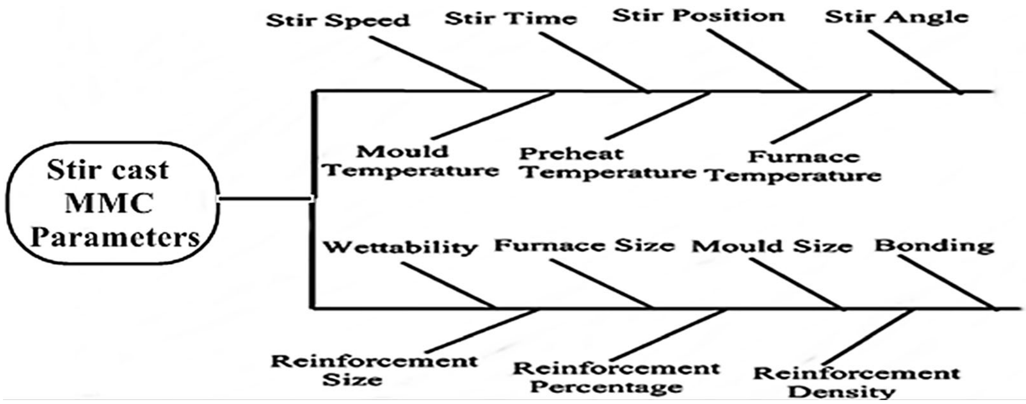


Figure 3. Stir cast MMC process parameters.

(ASTM) standards as illustrated in figure 4 [39, 41, 49, 51, 109]. The UTS, YS, percentage elongation and UCS of fabricated composites were assessed via a Universal Testing Machine (UTS). The macrohardness of cast specimens was determined using a Rockwell and Brinell hardness tester whereas microhardness was calculated using a Vicker hardness testing machine.

Hillary *et al* [35] studied the mechanical behavior of Al-6061 MMC reinforced with silicon carbide (SiC) and titanium diboride (TiB_2). The composite was fabricated using 5 wt% SiC and 2/8 wt% (varying step of 2) TiB_2 by conventional stir casting route. The production of Al-6061/SiC/TiB_2 HMMC was carried out at 770°C furnace temperature followed by mechanical stirring at 600 RPM for 15 min. It was observed from experimental results that 5 wt% SiC + 10 wt% TiB_2 reported 8.18%, 20.19%, 9.46% increase in microhardness, tensile strength, flexural strength, respectively, in comparison with 5 wt% SiC + 2 wt% TiB_2. The presence of harder SiC and TiB_2 enhanced the load-carrying capacity of hybrid composite, which resulted in improved mechanical performance of as-cast Al-6061 composite. The comparison of tensile strength of TiB_2/SiC/Al-6061 (HMMC) with TiB_2/Al-6061 (MMC) is illustrated in figure 5. It is finally concluded from the plot that in comparison with TiB_2/SiC (hybrid reinforced composite) the TiB_2 (single-reinforced composite) shows superior tensile strength of Al-6061MMC. In another research the impact of SiC particulates on the mechanical performance of Al-6061 MMC was observed by Sivanathan *et al* [36]. Particulates of size 44 μm in 0, 2 and 4 wt% of SiC were dispersed in Al-6061 matrix through stir casting technique. It was observed from results that the accumulation of SiC particles marginally improved the mechanical properties of Al-6061/SiC MMC. The micro-hardness, compressive strength and tensile strength increase from 68 to 85 VHN, 22610 to 25324 N/m^2 and 125 to 157 MPa, respectively. The maximum increments by 25.6%, 25% and 12% in tensile strength, microhardness and compressive strength were reported for Al-6061/4% SiC composite when compared with Al-6061 base alloy. The ductility of reinforced composite decreased from 5.87% to 1.17% with an increase in reinforcement percentage and a total decrement of 80.06% was observed in comparison with pure alloy. In another investigation Maurya *et al* [37] added different wt% of SiC to assess the mechanical properties of AA-6061 MMC; 1, 2, 3 and 5 wt% of SiC with 1 wt% of Mg were cast through electromagnetic stir casting technique at a stir speed of 500 RPM for 12 min. The effects of SiC reinforcement on tensile strength and hardness were investigated and it was seen from experimental results that the addition of SiC particulates significantly enhanced the hardness and UTS of AA-6061/SiC MMC. The UTS and hardness of composite improved, respectively, by 4.3% and 12.5% for optimized process parameters.

Further, Selvam *et al* [38] manufactured AA-6061/FA/SiC HMMC through stir casting route. The mechanical properties of the developed composite were investigated and compared to those of AA-6061. SiC and FA reinforcements were added in the mutual proportion of 15 and 17.5 wt%. It was revealed from experimental outcomes that with increase in wt% of dual reinforcements, the macro-hardness and microhardness increased from 49.4 to 57.2 BHN and 69.5 to 78.8 HV, respectively. The UTS of AA-6061/FA/SiC HMMC increased by 23.12% as compared with AA-6061. In another study Umanath *et al* [39] inspected the effect of SiC particulates on the fracture toughness of Al-6061 MMC. The composite was developed with 15 vol% of SiC of 25 μm size through stir casting technique. The K_{1c} of heat-treated samples was obtained as per the ASTM E399 standard by a three-point bend test. The results of fracture toughness are illustrated in figure 6, which shows a comparison among base alloy, Al-6061/10 vol% and Al-6061/15 vol%. Observations show that the incorporation of SiC decreases the K_{1c} of reinforced composite marginally by 72.41% as compared with Al-6061alloy. The reduced K_{1c} of Al-6061/SiC MMC is

Table 4. Stir cast Al-6061 MMC process parameters.

Sr. no.	Reinforcing materials	Weight %/particles size	Preheat temperature (°C)	Cast temperature (°C)	Stir speed (RPM)	Stir time (min)	Properties evaluated	References
1.	Al-6061/SiC/TiB_2	5/2, 4, 6, 8, 10 and 30, 50 μm	800, 200	770	600	15	Mechanical and microstructure	[35]
2.	Al-6061/SiC	0, 2, 4 and 44 μm	350	750	650	–	Mechanical	[36]
3.	Al-6061/SiC	1, 2, 3, 5	250	650	500	12	Physical and mechanical	[37]
4.	Al-6061/FA/SiC	0, 7.5, 10/0, 7.5, 7.5	900	775	350	10	Mechanical and microstructure	[38]
5.	Al-6061/SiC	10, 15 and 25 μm	600	725	600	20	Fracture toughness	[39]
6.	Al-6061/SiC	2, 4, 6, 8 and 30 μm	200	660	450	10	Mechanical and microstructure	[40]
7.	Al-6061/SiC/Gr	6, 9, 12 and 125 μm	–	730	400	10	Mechanical and wear	[41]
8.	Al-6061/SiC/cenosphere	3/3, 6, 9	800	900–950	700	2–5	Mechanical	[42]
9.	Al-6061/SiC/ZrO_2	5 and 2, 3	600/650	1035	1060/1431	3	Mechanical and fatigue	[43]
10.	Al-6061/SiC/Gr	8 and 2, 4	500	700	300	17	Mechanical and tribological	[44]
11.	Al-6061/Al_2O_3	5, 10, 15, 20	–	–	–	–	Mechanical	[45]
12.	Al-6061/Al_2O_3	0, 2, 4 and 32 μm	400	780	600	–	Mechanical	[46]
13.	Al-6061/Al_2O_3	4, 6, 8	810	810	600	–	Mechanical and wear	[47]
14.	Al-6061/SiC/Al_2O_3/FA	5, 7.5, 10/5, 7.5, 10 and 5	600	720	–	–	Mechanical	[48]
15.	Al-6061/Al_2O_3/BA	5/8 and 37, 53, 75 μm	500	700	400/500	10	Mechanical and microstructure	[49]
16.	Al-6061/Al_2O_3/RM	2.5, 5, 7.5, 10%	–	750	450	5	Mechanical	[50]
17.	Al-6061/Al_2O_3/MOS_2	4, 8, 12 and 2, 4, 6	600	725	600	20	Mechanical and tribological	[51]
18.	Al-6061/SiC/B_4C	0.5, 1, 1.5, 2	450	800	–	–	Mechanical	[52]
19.	Al-6061/B_4C	5, 7 and 88 μm	200	750	250	5–8	Mechanical	[53]
20.	Al-6061/B_4C	9 and 88 μm	250	750	250	5/8	Mechanical and wear	[54]
21.	Al-6061/B_4C_p	7, 9 and 37 μm	–	750	250	5/8	Mechanical	[55]
22.	Al-6061/iron ore	2, 4, 6 and 150 μm	250	750	200	10	Mechanical	[56]
23.	Al-6061/Fe_2O_3	2, 4, 6, 8	–	750	300/350	5/10	Mechanical	[57]
24.	Al-6061/MWCNT	0.5, 1, 2, 3 and 10/30 nm	–	725	400/450	10	Microstructure, mechanical and wear	[58]
25.	Al-6061/frit	2, 4, 6, 8, 10	450	710	300/350	10	Mechanical	[59]
26.	Al-6061/Gr	6, 9 and 125 μm	250	800	250	5/8	Mechanical	[60]
27.	Al-6061/Gr/FA	3, 6 and 6, 3	1000 and 600	760/1000	200/400	10/20	Mechanical	[61]
28.	Al-6061/FA	0, 5, 10 and 25/45 μm	800/900	–	400	30	Fracture toughness	[62]
29.	Al-6061/FA/CNT	2, 3, 4 and 0.2	–	800	–	–	Mechanical	[63]
30.	Al-6061/CSA	1, 3, 5	300	750	600	10	Mechanical, microstructure and tribology	[64]
31.	Al-6061/WC/Gr	1, 2, 3, 4	400	720	500	8	Mechanical and microstructure	[65]
32.	Al-6061/Ti/E glass	1, 3 and 5	600/650	750	450	–	Mechanical	[66]
33.	Al-6061/TiC	3, 5, 7 and 3/4 μm	–	920	750	–	Fracture toughness	[67]
34.	AA-6061/AIN_p	5, 10, 15, 20 and 3/4 μm	750	1000	450	20	Metallurgical and mechanical	[68]
35.	Al-6061/ZrO_2/C	2/6	350	1000	450	10	Mechanical and tribology	[69]
36.	Al-6061/ZrO_2	3, 6, 9, 12 and 60 μm	400	750	500/700	5	Mechanical and microstructure	[70]
37.	Al-6061/SiC	10, 15 and 150/160 μm	–	650	–	15	Tribological	[71]
38.	Al-6061/SiC	5 and 50 μm	250	750	500	30	Sliding wear	[72]
39.	Al-6061/SiC	5/40 and 600 mesh	–	–	–	–	Wear	[73]

Table 4 continued

Sr. no.	Reinforcing materials	Weight %/particles size	Preheat temperature (°C)	Cast temperature (°C)	Stir speed (RPM)	Stir time (min)	Properties evaluated	References
40.	Al-6061/SiC	2/6 and 150 μm	–	710	400	10	Dry sliding wear	[74]
41.	Al-6061/SiC	2, 4, 6 and 20 μm	–	720	400	10	Mechanical, physical and tribological	[75]
42.	Al-6061/SiCp	5, 7.5, 10 and 5, 10, 15 μm	–	–	–	–	Dry sliding wear and friction	[76]
43.	Al-6061/SiC/Gr	2/0.5, 1, 1.5, 2 and 3	550	750	–	10	Tribological behavior	[77]
44.	Al-6061/SiC/Gr	0.4/1.6 and 0.5	500	750	–	24	Tribological and mechanical	[78]
45.	Al-6061/REP/SiC/Al_2O_3	0.5/2.5 and 2.5/7.5	–	–	–	–	Mechanical and tribology	[79]
46.	Al-6061/SiC/Al_2O_3	5/15	–	–	–	–	Dry sliding wear	[80]
47.	Al-6061/SiC/Al_2O_3	5/25 and 25 μm	600	725	600	20	Dry sliding wear	[81]
48.	Al-6061/SiC/Al_2O_3/Gr	1, 2.5, 4/3, 5, 7, 2.5, 4.6	500	630	300	5	Tribological	[82]
49.	Al-6061/SiC/Gr	0.4/1.6 and 0.5	500	750	–	24	Tribological and mechanical	[83]
50.	Al-6061/SiC/B_4C/talc	5, 10, 15/3/2	300	600/700	500	5/7	Mechanical and tribological	[84]
51.	Al-6061/SiC/E glass	9/1, 3, 5 and 60 μm	300	–	550	3/4	Wear behavior	[85]
52.	Al-6061/SiC/MWCNT	0.5, 1 and 15	620	750	450	5	Tribological	[86]
53.	Al-6061/Al_2O_3	6, 9, 12 and 125 μm	200	750	200	10	Mechanical and wear	[87]
54.	Al-6061/Al_2O_3/Gr /Si_3N_4	55/5/20, 30and 40 nm	150	850	500	2	Dry sliding wear	[88]
55.	Al-6061/Al_2O_3/Gr	5, 10, 15	500	800	400	30	Mechanical and tribological	[89]
56.	Al-6061/FA/Gr	10, 15, 20 and 4	450	–	–	5	Mechanical and wear	[90]
57.	Al-6061/Gr/WC	9 and 1, 2, 3	200	750	300	15	Tribological	[91]
58.	Al-6061/TiC	3, 5, 7	–	730	–	–	Wear characteristics	[92]
59.	Al-6061/TiO_2	2/10 and 10/20 μm	–	710	400	10	Wear coefficient	[93]
60.	Al-6061/TiB_2	4, 8, 12	700	710	450	10	Microstructure and wear	[94]
61.	Al-6061/Fe_2O_3/B_4C	5 and 2, 4, 6	200	685	250	10	Mechanical and wear	[95]
62.	Al-6061/B_4C	10	300	700	450	–	Tribological	[96]
63.	Al-6061/CSA	3, 6, 9, 12, 15 and 150 μm	–	750	450	10	Mechanical and tribological	[97]
64.	Al-6061/RD/CENO/E waste	5, 10, 15 and 40 μm	350	700	900	5	Mechanical and wear	[98]
65.	Al-6061/garnet	4, 8, 12 and 90/150 μm	–	–	–	–	Wear behavior	[99]
66.	Al-6061/bamboo char, B_4C	1, 2, 3 and 60 μm	550	800	–	–	Tribological	[100]
67.	Al-6061/TiB_2	3, 6, 9 and 2/10 μm	250	700	350	15	Mechanical and microstructure	[101]
68.	Al-6061/B_4C	4, 6, 8, 10, 12 and 10 μm	400	920	300	5	Microstructure and mechanical	[102]
69.	AA-6061/AIN_p	5, 10, 15, 20 and 3/4 μm	750	1000	450	20	Metallurgical and mechanical	[103]
70.	Al-6061/Al_2O_3	0.5, 1, 1.5	–	750	250	15	Microstructure, physical and mechanical	[104]
71.	AA-6061/TiC	15	600	630–1030	100–500	5/25	Microstructure and tensile	[105]
72.	Al-6061/B_4C	11 and 88 μm	250	750	250	5/8	Mechanical and microstructure	[68]
73.	Al-6061/ABO/SiC	5, 15 and 0.5/1, 8/14 μm	600	600	300	10	Microstructure and tensile	[106]
74.	Al-6061/Al_2O_3	1, 2, 3 and 30/70 nm	400	775	–	–	Microstructure and mechanical	[107]
75.	Al-6061/Si_3N_4	4, 6, 8, 10 and 2/10 μm	–	710	300	10	Microstructure and mechanical	[108]
76.	Al-6061/Al_2O_3/BA	5 and 4, 6, 8	400	750	500	5/7	Mechanical and microstructural	[109]

Table 5. Mechanical performance of stir cast Al-6061 MMC with different reinforcements.

Sr.no.	Compositions	Ultimate tensile strength/load	Hardness	Percentage elongation	Compressive strength	Impact strength	References
1	Al-6061/5 wt% SiC/2 wt% TiB_2	112.8 MPa	68.4 VHN	13.12	–	–	[35]
	Al-6061/5 wt% SiC/4 wt% TiB_2	118.4 MPa	71.2 VHN	13.6	–	–	
	Al-6061/5 wt% SiC/6 wt% TiB_2	126.8 MPa	72.0 VHN	14.10	–	–	
	Al-6061/5 wt% SiC/8 wt% TiB_2	134.2 MPa	73.23 VHN	14.8	–	–	
	Al-6061/5 wt% SiC/10 wt% TiB_2	142.2 MPa	74.52 VHN	15.4	–	–	
2	Al-6061/0 wt% SiC	125 MPa	68 VHN	5.87	22610 N/m^2	–	[36]
	Al-6061/2 wt% SiC	134 MPa	77 VHN	3.93	23056 N/m^2	–	
	Al-6061/4 wt% SiC	157 MPa	85 VHN	1.17	25324 N/m^2	–	
3	AA-6061	276 MPa	40 HRB	–	–	–	[37]
	AA-6061/1 wt% SiC	278 MPa	41.5 HRB	–	–	–	
	AA-6061/2 wt% SiC	281.2 MPa	42 HRB	–	–	–	
	AA-6061/3 wt% SiC	283.3 MPa	42.3 HRB	–	–	–	
	AA-6061/4 wt% SiC	288 MPa	45 HRB	–	–	–	
4	Al-6061	145 MPa	38 BHN	14	–	–	[38]
	Al-6061/7.5 wt% SiC/7.5 wt% FA	173 MPa	49.4 BHN	10	–	–	
	Al-6061/10 wt% SiC/7.5 wt% FA	213 MPa	57.21 BHN	4	–	–	
5	AA-6061	276 MPa	40 HRB	–	–	–	[40]
	AA-6061/2 wt% SiC	281 MPa	42 HRB	–	–	–	
	AA-6061/4 wt% SiC	287 MPa	43 HRB	–	–	–	
	AA-6061/6 wt% SiC	291 MPa	46 HRB	–	–	–	
	AA-6061/8 wt% SiC	298 MPa	51 HRB	–	–	–	
6	AA-6061	98 MPa	121 VHN	–	–	–	[41]
	AA-6061/6 wt% SiC	118 MPa	182 VHN	–	–	–	
	AA-6061/9 wt% SiC	142 MPa	191 VHN	–	–	–	
	AA-6061/12 wt% SiC	151 MPa	194 VHN	–	–	–	
7	AA-6061	–	63 HV	21.7	–	–	[42]
	AA-6061/3 wt% SiC/3 wt% CENO	–	64 HV	19.4	–	–	
	AA-6061/3 wt% SiC/6 wt% CENO	–	68 HV	11.9	–	–	
	AA-6061/3 wt% SiC/9 wt% CENO	–	70 HV	8.5	–	–	
8	AA-6061/5 wt% SiC	67.2 MPa	45.8 RHN	–	–	–	[43]
	AA-6061/2 wt% SiC/3 wt% ZrO_2	96.1 MPa	53.6 RHN	–	–	–	
9	AA-6061	200 MPa	60 BHN	25	–	–	[44]
	AA-6061/8 wt% SiC	205.9 MPa	76.3 BHN	6.67	–	–	
	AA-6061/8 wt% SiC/2 wt% Gr	209.2 MPa	69.3 BHN	5.00	–	–	
	AA-6061/8 wt% SiC/4 wt% Gr	218.7 MPa	66.2 BHN	6.67	–	–	
10	AA-6061/5 wt% Al_2O_3	150 MPa	61.15 VHN	–	–	–	[45]
	AA-6061/10 wt% Al_2O_3	190 MPa	64.21 VHN	–	–	–	
	AA-6061/15 wt% Al_2O_3	240 MPa	79.04 VHN	–	–	–	
	AA-6061/20 wt% Al_2O_3	310 MPa	89.91 VHN	–	–	–	

Table 5 continued

Sr.no.	Compositions	Ultimate tensile strength/load	Hardness	Percentage elongation	Compressive strength	Impact strength	References
11	Al-6061	125 MPa	68 HV	5.8	–	–	[46]
	Al-6061/2 wt% Al_2O_3	143 MPa	75 HV	4.27	–	–	
	Al-6061/4 wt% Al_2O_3	164 MPa	81 HV	3.03	–	–	
12	Al-6061/4 wt% alumina	111.98 MPa	56 HV	14.22	–	–	[47]
	Al-6061/6 wt% alumina	118.94 MPa	66 HV	11.31	–	–	
	Al-6061/8 wt% alumina	127.11 MPa	70 HV	7.58	–	–	
13	Al-6061	115 MPa	30 BHN	–	–	–	[48]
	Al-6061/5 wt% SiC/5 wt% Al_2O_3/5 wt% FA	117 MPa	53 BHN	–	–	–	
	Al-6061/7.5 wt% SiC/7.5 wt% Al_2O_3/5 wt% FA	126 MPa	64 BHN	–	–	–	
	Al-6061/10 wt% SiC/10 wt% Al_2O_3/5 wt% FA	129 MPa	45 BHN	–	–	–	
14	Al-6061	160 MPa	28 VHN	–	–	4.2 J	[49]
	Al-6061/5 wt% Al_2O_3	178 MPa	28.3 VHN	–	–	5.2 J	
	Al-6061/5 wt% Al_2O_3/8 wt% BA	180 MPa	30.5 VHN	–	–	6.4 J	
15	Al-6061/2.5 wt% Al_2O_3/2.5 wt% red mud	170 MPa	17.2 HRB	–	–	–	[50]
	Al-6061/5 wt% Al_2O_3/5 wt% red mud	173 MPa	18.6 HRB	–	–	–	
	Al-6061/7.5 wt% Al_2O_3/7.5 wt% red mud	185 MPa	18.9 HRB	–	–	–	
	Al-6061/10 wt% Al_2O_3/10 wt% red mud	192 MPa	21.5 HRB	–	–	–	
16	Al-6061/4 wt% Al_2O_3/2 wt% MoS_2	219.7 MPa	96.78 BHN	–	–	–	[51]
	Al-6061/8 wt% Al_2O_3/4 wt% MoS_2	237.2 MPa	104.76 BHN	–	–	–	
	Al-6061/12 wt% Al_2O_3/6 wt% MoS_2	259.5 MPa	107.5 BHN	–	–	–	
17	Al-6061/0.5 wt% SiC/0.5 wt% B_4C	107.64 MPa	30.43 BHN	9.20	–	8.24 J	[52]
	Al-6061/1 wt% SiC/1 wt% B_4C	117.16 MPa	31.23 BHN	8.80	–	6.41 J	
	Al-6061/1.5 wt% SiC/1.5 wt% B_4C	117.70 MPa	32.9 BHN	7.89	–	6.1 J	
	Al-6061/2 wt% SiC/2 wt% B_4C	128.24 MPa	45.9 BHN	7.53	–	4.32 J	
18	Al-6061	134 MPa	70.34 VHN	–	270 MPa	–	[53]
	Al-6061/5 wt% B_4C	162 MPa	102.1 VHN	–	322 MPa	–	
	Al-6061/7 wt% B_4C	185 MPa	120.5 VHN	–	357 MPa	–	
19	Al-6061	133.5 MPa	70.3 HV	11.2	–	–	[54]
	Al-6061/9 wt% B_4C	185.4 MPa	151.4 HV	3.9	–	–	
20	Al-6061	133 MPa	67 HV	–	287 MPa	–	[55]
	Al-6061/7 wt% B_4C	155 MPa	119 HV	–	330 MPa	–	
	Al-6061/9 wt% B_4C	175 MPa	139 HV	–	355 MPa	–	
21	Al-6061	173.3 MPa	72.6 BHN	5.32	–	–	[56]
	Al-6061/2 wt% iron ore	180.7 MPa	93.52 BHN	5.19	–	–	
	Al-6061/4 wt% iron ore	196.6 MPa	94.94 BHN	4.87	–	–	
	Al-6061/6 wt% iron ore	240.5 MPa	103.59 BHN	4.24	–	–	
22	Al-6061	112.4 MPa	28.5 BHN	7.28	–	–	[57]
	Al-6061/2 wt% Fe_2O_3	118.6 MPa	31.94 BHN	6.84	–	–	
	Al-6061/4 wt% Fe_2O_3	128.2 MPa	31.95 BHN	5.72	–	–	
	Al-6061/6 wt% Fe_2O_3	135.6 MPa	30.57 BHN	4.28	–	–	
	Al-6061/8 wt% Fe_2O_3	141.2 MPa	37.47 BHN	5.64	–	–	

Table 5 continued

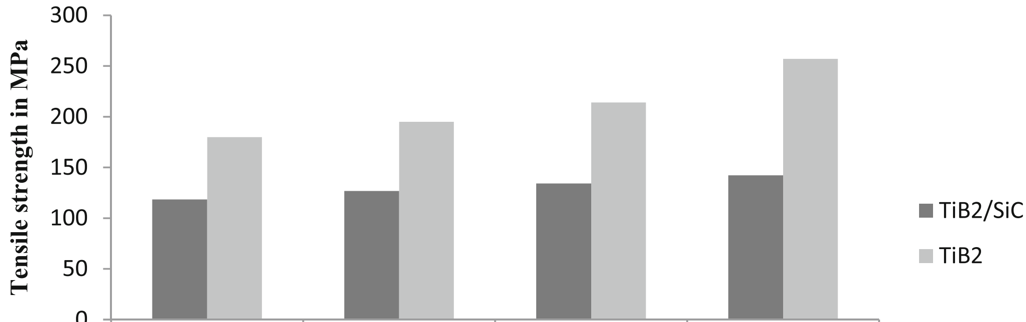
Sr.no.	Compositions	Ultimate tensile strength/load	Hardness	Percentage elongation	Compressive strength	Impact strength	References
23	Al-6061/2 wt% frit	114 MPa	58 VHN	–	560 MPa	–	[59]
	Al-6061/4 wt% frit	137 MPa	67 VHN	–	587 MPa	–	
	Al-6061/6 wt% frit	164 MPa	84 VHN	–	592 MPa	–	
	Al-6061/8 wt% frit	122 MPa	96 VHN	–	610 MPa	–	
	Al-6061/10 wt% frit	104 MPa	98 VHN		595 MPa		
24	Al-6061	140 MPa	98 VHN	14.8	–	–	[60]
	Al-6061/2 wt% graphite	186 MPa	88 VHN	17	–	–	
	Al-6061/4 wt% graphite	192 MPa	83 VHN	24.9	–	–	
25	Al-6061	2010.4 N	25.16 BHN	14	–	–	[61]
	Al–6061/3 wt% Gr/6 wt% FA	2069.3 N	26.71 BHN	10	–	–	
	Al-6061/6 wt% Gr/3 wt% FA	1941.8 N	30.26 BHN	4	–	–	
26	AA-6061	184 MPa	48 VPN	10	–	–	[62]
	AA-6061/5 wt% FA	222 MPa	52 VPN	3.45	–	–	
	AA-6061/10 wt% FA	249 MPa	61 VPN	3.20	–	–	
27	Al-6061/2 wt% FA	132.1MPa	53 HBW	–	–	–	[63]
	Al-6061/2 wt% FA/0.2 wt% CNT	78.7 MPa	59.2 HBW	–	–	–	
	Al-6061/3 wt% FA/0.2 wt% CNT	147.7 MPa	55.3 HBW	–	–	–	
	Al-6061/4 wt% FA/0.2 wt% CNT	60.8 MPa	49.8 HBW	–	–	–	
28	Al-6061	68 MPa	67 VHN	–	–	–	[64]
	Al-6061/1 wt% CSA	102 MPa	71.2 VHN	–	–	–	
	Al-6061/3 wt% CSA	130 MPa	74.8 VHN	–	–	–	
	Al-6061/5 wt% CSA	143.6 MPa	81.6 VHN	–	–	–	
29	Al-6061	99.74 MPa	60.5 BHN	3.5	570.09 MPa	–	[65]
	Al-6061/1 wt% WC	123.7 MPa	65.5 BHN	4.91	696.78 MPa	–	
	Al-6061/2 wt% WC	133.03 MPa	67.1 BHN	6.07	823.01 MPa	–	
	Al-6061/3 wt% WC	155.3 MPa	69 BHN	6.2	846.13 MPa	–	
	Al-6061/4 wt% WC	97 MPa	56.6 BHN	7	894.13 MPa	–	
30	Al-6061/1 wt% Ti/1 wt% E glass	150 MPa	78 VHN	–	–	–	[66]
	Al–6061/1 wt% Ti/3 wt% E glass	155 MPa	87 VHN	–	–	–	
	Al–6061/3 wt% Ti/3 wt% E glass	125 MPa	70 VHN	–	–	–	
	Al-6061/3 wt% Ti/5 wt% E glass	145 MPa	50 VHN	–	–	–	
31	Al-6061	165 MPa	44 VHN	8.9	–	–	[68]
	Al-6061/5 wt% AIN_p	182 MPa	55 VHN	8.1	–	–	
	Al-6061/10 wt% AIN_p	205 MPa	67 VHN	7.6	–	–	
	Al-6061/15 wt% AIN_p	228 MPa	74 VHN	5.8			
	Al-6061/20 wt% AIN_p	241 MPa	91 VHN	4.1			
32	Al-6061	128 MPa	30 HRC	–	–	–	[69]
	Al-6061/2 wt% ZrO_2/2 wt% Gr	166 MPa	41 HRC	–	–	–	
	Al-6061/6 wt% ZrO_2/2 wt% Gr	175 MPa	43 HRC	–	–	–	
	Al-6061/2 wt% ZrO_2/6 wt% Gr	143 MPa	38.5 HRC	–	–	–	
	Al-6061/6 wt% ZrO_2/6 wt% Gr	151 MPa	40 HRC	–	–	–	

Table 5 continued

Sr.no.	Compositions	Ultimate tensile strength/load	Hardness	Percentage elongation	Compressive strength	Impact strength	References
33	Al-6061/3 wt% ZrO_2	110 MPa	80 BHN	–	–	–	[70]
	Al-6061/6 wt% ZrO_2	120 MPa	90 BHN	–	–	–	
	Al-6061/9 wt% ZrO_2	145 MPa	98 BHN	–	–	–	
	Al-6061/12 wt% ZrO_2	115 MPa	82 BHN	–	–	–	
34	AA-6061	90 MPa	56 BHN	8.3	–	–	[74]
	AA-6061/2 wt% SiC	118 MPa	73 BHN	7.1	–	–	[79]
	AA-6061/4 wt% SiC	140 MPa	85 BHN	5.4	–	–	
	AA-6061/6 wt% SiC	168 MPa	97 BHN	4.4	–	–	
	Al-6061/5 wt% Al_2O_3/5 wt% SiC	54 MPa	85.5 HV	2.1	–	30 J	
	Al-6061/7.5 wt% Al_2O_3/7.5 wt% SiC	73 MPa	90.17 HV	6.8	–	34 J	
	Al-6061/0.5 wt% REP/2.5 wt% Al_2O_3/2.5 wt% SiC	89 MPa	85.67 HV	7.2	–	50 J	
	Al-6061/1.5 wt% REP/5 wt% Al_2O_3/5 wt% SiC	102 MPa	88.17 HV	10.0	–	56 J	
	Al-6061/2.5 wt% REP/7.5 wt% Al_2O_3/7.5 wt% SiC	123 MPa	92.8 HV	11.5	–	46 J	
36	Al-6061	126 MPa	61 BHN	5.4	380 MPa	–	[84]
	Al-6061/5 wt% SiC/3 wt% B_4C/2 wt% talc	135 MPa	65 BHN	7.9	404 MPa	–	
	Al-6061/10 wt% SiC/3 wt% B_4C/2 wt% talc	168 MPa	67 BHN	7.2	414 MPa	–	
	Al-6061/15 wt% SiC/3 wt% B_4C/2 wt% talc	140 MPa	74 BHN	6.3	424 MPa	–	
37	AA-6061	149.76 MPa	93 VHN	15.1	–	–	[87]
	AA-6061/6 wt% Al_2O_3	167.93 MPa	104 VHN	12.8	–	–	
	AA-6061/9 wt% Al_2O_3	173.61MPa	152 VHN	11.6	–	–	
	AA-6061/12 wt% Al_2O_3	193.47 MPa	183 VHN	103	–	–	
38	Al-6061/3 wt% TiC	174 MPa	–	8.4	–	–	[92]
	Al-6061/5 wt% TiC	206 MPa	–	7.5	–	–	
	Al-6061/7 wt% TiC	230 MPa	–	7	–	–	
39	AA-6061	89.54 MPa	65.53 VHN	–	–	–	[94]
	AA-6061/4 wt% TiB_2	98.31 MPa	70.26 VHN	–	–	–	
	AA-6061/8 wt% TiB_2	113.03 MPa	71.13 VHN	–	–	–	
	AA-6061/12 wt% TiB_2	137.86 MPa	72.46 VHN	–	–	–	
40	Al-6061	270 MPa	107 VHN	16	–	23 J	[95]
	Al-6061/5 wt% Fe_2O_3	283 MPa	112 VHN	15.1	–	21 J	
	Al-6061/5 wt% Fe_2O_3/2 wt% B_4C	301 MPa	121 VHN	14	–	17 J	
	Al-6061/5 wt% Fe_2O_3/4 wt% B_4C	324 MPa	130 VHN	12.5	–	15 J	
	Al-6061/5 wt% Fe_2O_3/6 wt% B_4C	382 MPa	139 VHN	11.2	–	11 J	
41	Al-6061	70 MPa	40.86 BHN	–	–	–	[97]
	Al-6061/3 wt% CSA	140.5 MPa	49.9 BHN	–	–	–	
	Al-6061/6 wt% CSA	160.2 MPa	55.2 BHN	–	–	–	
	Al-6061/9 wt% CSA	157.08 MPa	54.9 BHN	–	–	–	
	Al-6061/12 wt% CSA	123.02 MPa	51.6 BHN	–	–	–	
	Al-6061/15 wt% CSA	104.02 MPa	45.3 BHN				

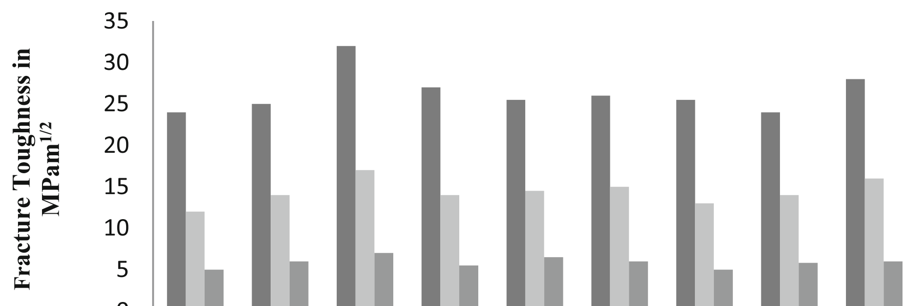
Table 5 continued

Sr.no.	Compositions	Ultimate tensile strength/load	Hardness	Percentage elongation	Compressive strength	Impact strength	References
42	AA-6061	180 MPa	73 HV	6.2	–	–	[101]
	AA–6061/3 wt% TiB_2	195 MPa	132 HV	6	–	–	
	AA-6061/6 wt% TiB_2	214 MPa	138 HV	5.9	–	–	
	AA-6061/9 wt% TiB_2	257 MPa	142 HV	5.7	–	–	
43	AA-6061/4 wt% B_4C	185 MPa	51.3 VHN	–	–	–	[102]
	AA-6061/6 wt% B_4C	191 MPa	58 VHN	–	–	–	
	AA-6061/8 wt% B_4C	200 MPa	71 VHN	–	–	–	
	AA-6061/10 wt% B_4C	207 MPa	75 VHN	–	–	–	
	AA-6061/12 wt% B_4C	215 MPa	80.8 VHN	–	–	–	
44	AA-6061	110 MPa	50 BHN	–	–	–	[104]
	AA-6061/0.5 wt% alumina	205 MPa	60 BHN	–	–	–	
	AA-6061/1 wt% alumina	248 MPa	78 BHN	–	–	–	
	AA-6061/1.5 wt% alumina	220 MPa	71 BHN	–	–	–	
45	Al-6061	135 MPa	70.4 VHN	–	–	–	[68]
	Al-6061/11 wt% B_4C	185 MPa	157.3 VHN	–	–	–	
46	AA-6061	102 MPa	62 VHN	–	–	–	[108]
	AA-6061/4 wt% Si_3N_4	110 MPa	76.5 VHN	–	–	–	
	AA-6061/6 wt% Si_3N_4	174 MPa	83.2 VHN	–	–	–	
	AA-6061/8 wt% Si_3N_4	178 MPa	83.6 VHN	–	–	–	
	AA-6061/10 wt% Si_3N_4	204 MPa	86.8 VHN	–	–	–	
47	Al-6061/5 wt% Al_2O_3	138.5 MPa	30.2 HV	8.2	310 MPa	6.9 J	[109]
	Al-6061/5 wt% Al_2O_3/4 wt% BA	146.8 MPa	32.8 HV	8.6	347 MPa	6.4 J	
	Al-6061/5 wt% Al_2O_3/6 wt% BA	151.1 MPa	35.2 HV	7.4	380 MPa	5.8 J	
	Al-6061/5 wt% Al_2O_3/8 wt% BA	141.9 MPa	28.4 HV	5.9	411 MPa	5.2 J	



	5:4 SiC+TiB2 / Base Alloy	5:6 SiC+TiB2 / 3 TiB2	5:8 SiC+TiB2 / 6 TiB2	5:10 SiC+TiB2 / 9 TiB2
TiB2/SiC	118.4	126.8	134.2	142.2
TiB2	180	195	214	257

Figure 4. Samples used for mechanical characterization as per ASTM standards. (a) Tensile test sub-specimens. (b) Impact test specimens. (c) Compressive strength specimens. (d) Microhardness specimens [49, 109].



	1	2	3	4	5	6	7	8	9
Al-6061 alloy	24	25	32	27	25.5	26	25.5	24	28
Al-6061+10 Vol.% SiC	12	14	17	14	14.5	15	13	14	16
Al-6061+15 Vol.% SiC	5	6	7	5.5	6.5	6	5	5.8	6

Figure 5. Comparison between ultimate tensile strength of Al-6061/SiC/TiB_2 HMMC and Al-6061/TiB_2 MMC [35, 101].

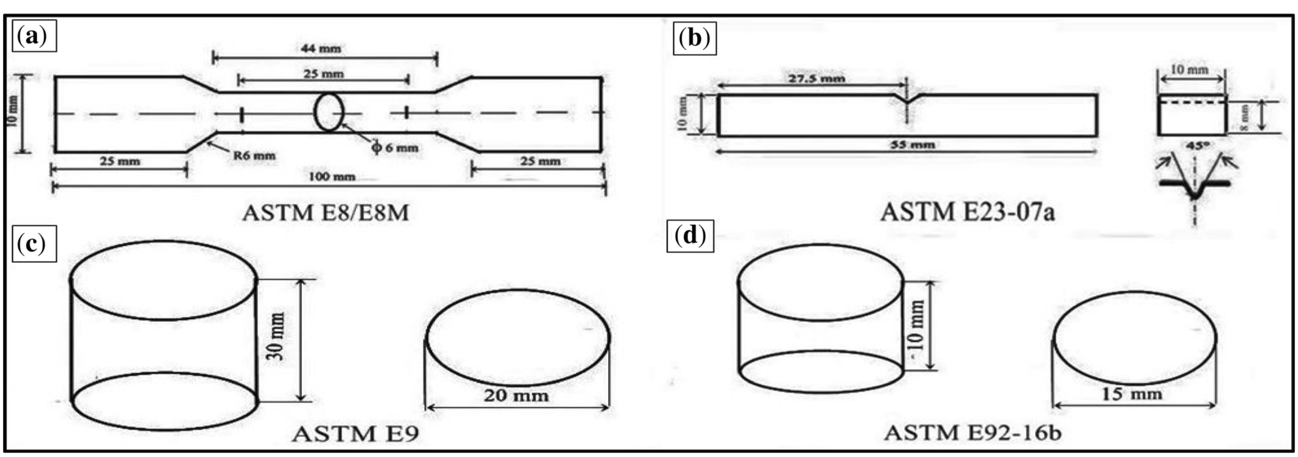


Figure 6. Fracture toughness comparison between Al-6061 alloy and Al-6061 reinforced with 10/15 wt% of SiC particles [39].

attributed to the presence of residual stresses on cast samples because of rapid heat treatment. In a similar study conducted by Maurya *et al* [40] they developed AA-6061-SiC MMC to assess the influence of SiC particulates on the mechanical properties of manufactured composite. The composite was reinforced with 2, 4, 6 and 8 wt% of SiC of 30 μm particle size via electromagnetic stirring. Mechanical results show that with increasing weight % of SiC (2/8 wt%) the hardness and tensile strength of composite increase gradually from 40 to 51 HRB and 276 to 298 MPa, respectively. Prashant *et al* [41] performed a comparative study on Gr-reinforced AA-6061 MMC and SiC-reinforced AA-6061 MMC. The fabrication of composite was accomplished through stir casting route using 125 μm size and equal 6, 9 and 12 wt% of Gr and SiC. It is noticed from experimental results that the addition of SiC particulates increases the microhardness from 98 to 151 VHN, whereas addition of Gr particulates decreases the microhardness from 98 to 76 VHN. The impact of 3 wt% of SiC and 3, 6, 9 wt% of cenosphere particulates on the mechanical properties of reinforced composite was studied by Ashoka *et al* [42]. The mechanical mixing was carried out at 700 RPM for 2/5 min. It is seen from test results that incorporation of cenosphere with SiC reinforcements increases the young modulus and hardness of HMMC from 61 to 68 GPa and 63 to 70 VHN, respectively.

In a separate study, Ramesh *et al* [43] assessed the mechanical characteristics of AA-6061/SiC/ZrO_2 HMMC. The composite was fabricated using 5 wt% of SiC and 2:3 wt% of SiC:ZrO_2 composition through conventional stir casting route. The significant improvements of 43.02% in UTS and 17.03% in hardness were observed at 2 wt% SiC/3 wt% ZrO_2/AA-6061 when compared with 5 wt% SiC/AA-6061. The fatigue strength of AA-6061/SiC/ZrO_2 HMMC was reported to be more than that of the single-reinforced composite. In another research Pavithram *et al* [44] developed AA-6061 HMMC reinforced with 8 wt% of SiC (50 μm) with 2 and 4 wt% of Gr (60 μm) particulates via liquid metallurgical route. It is reported from the experimental outcome that with the addition of dual reinforcements the UTS and YS of Al-6061/SiC/Gr HMMC increase from 200 to 218 and 110 to 132.74 MPa, respectively. The hardness of hybrid composite initially increases with the accumulation of SiC reinforcements and later decreases with dual reinforcements (SiC and Gr). The improvement in microhardness for SiC/AA-6061 composite is attributed to enhanced wettability and homogenous bonding between matrix and reinforcements in comparison with Gr/AA-6061 composite. Moreover, with an increase in SiC and Gr reinforcements the tensile strength of composite increases gradually; however, this behavior is mainly due to the increased load sharing capacity of the Al-6061 matrix due to the incorporation of SiC and Gr content.

In a separate work, Kandpal and Singh [45] inspected the mechanical characterization of AA-6061 MMC reinforced with 5, 10, 15 and 20 vol% Al_2O_3 via stir casting method. It was reported from experimental results that with the accumulation of Al_2O_3 content from 5 to 20 vol% the hardness and tensile strength of reinforced composite had enhanced from 61.15 to 89.91 VHN and 150 to 310 MPa, respectively. The tensile strength increased by 106.6% and the hardness increased by 47.03% for Al-6061/20 vol% Al_2O_3 in comparison with Al-6061/5 vol% Al_2O_3. In a study Sivananthan *et al* [46] have also assessed the mechanical properties of Al-6061 MMC incorporated with aluminum oxide (Al_2O_3). The composite was developed via stir casting method using 0/4 wt% Al_2O_3 of 32 μm particle size. The maximum values of tensile strength, hardness and compressive strength were reported for Al-6061/4 wt% Al_2O_3. The hardness and UCS of reinforced composite increased, respectively, by 19.1% and 9% when compared with Al-6061. The UTS of Al-6061/Al_2O_3 increased from 125 to 164 MPa with the addition of 0/4 wt% reinforcements. However, percentage elongation of the reinforced composites decreased from 5.8% to 3.03%. Ekambaram and Murugan [47] characterized the mechanical properties of Al-6061 alloy reinforced using Al_2O_3 particulates. The Al-6061 MMCs were produced through stir casting technique with 4, 6 and 8 wt% of Al_2O_3. The mechanical mixing was carried out using a mild steel stirrer at 600 RPM. Three sets of specimens were prepared to evaluate microhardness, UTS and ductility of Al-6061 MMC. It was found from mechanical tests that on increasing wt% of Al_2O_3 the microhardness and UTS of particulate-reinforced composite increased gradually. However, the hardness and UTS for Al-6061/8 wt% Al_2O_3 increased, respectively, by 25% and 13.51% when compared with Al-6061/4 wt% Al_2O_3. The ductility of cast composite decreased from 14.22% to 7.5% with the addition of Al_2O_3.

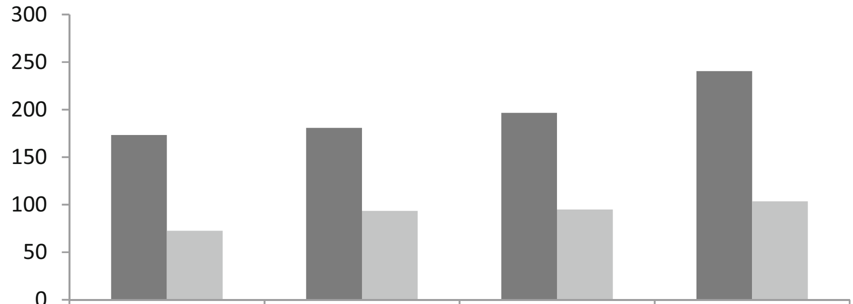
Hima Gireesh *et al* [48] have prepared Al-6061/Al_2O_3-hybrid-reinforced MMC strengthened with SiC and FA reinforcements via stir route of casting. Equal 5, 7.5 and 10 wt% of Al_2O_3/SiC mixed with 5 wt% of FA were used to investigate the mechanical characterization of HMMC. The experimental outcomes demonstrated that the addition of triple reinforcements up to 10:5 wt% (Al_2O_3/SiC:FA) had increased the tensile strength from 117 to 129 MPa whereas the YS and hardness of hybrid composite increased up to 7.5 wt% SiC/Al_2O_3. It was concluded from results that the tensile strength increased by 12%, hardness increased by 113% and YS increased by 122% when compared with AA-6061. Yaspal *et al* [49] analyzed the effect of BA and alumina particulates on the mechanical characteristics of Al-6061 HMMC. The composite was fabricated with 5 wt% of Al_2O_3 and 8 wt% of BA through stir casting technique. The particulate size of BA was 37, 53 and 75 μm. The stir action was completed at 400/500 RPM for 10 min. It was revealed from test results that UTS, impact strength and microhardness of reinforced composite decreased with increasing particulate size from 37 to 53 μm. The maximum value of hardness, UTS and impact strength, obtained at 37 μm particulate size, was

5 VHN, 180 MPa and 6.4 J, respectively. Further, Quarder *et al* [50] have reported the mechanical characteristics of Al-6061 MMC reinforced with Al_2O_3 and RM. The fabrication of composite was done at a cast temperature of 750°C followed by mechanical mixing at 450 RPM for 5 min by vortex method. Fabricated composites contain an equal proportion of 2.5, 5, 7.5 and 10 wt% of Al_2O_3 and RM. It was found from experimental results of Al-6061/Al_2O_3/RM HMMC that amongst different compositions, the 10 wt% of reinforcement reported maximum tensile strength (192 MPa) and hardness (21.5 HRB). The overall improvements in UTS and hardness were observed to be 12.94% and 26.47, respectively, at 10 wt% of composition when compared with 2.5 wt% of composition.

According to a separate study conducted by Pitehayyapillai *et al* [51] on Al-6061/Al_2O_3/MoS_2 HMMC through stir casting process the accumulation of alumina particulates increased the hardness and UTS of HMMC whereas amalgamation of MoS_2 with Al_2O_3 reduced the tensile strength and hardness. The hybrid composite was developed using 4, 8, 12 wt% of alumina (Al_2O_3) and 2, 4, 6 wt% of molybdenum disulfide (MoS_2). The mechanical mixing for molten slurry was performed at 600 RPM for 20 min. The hardness and UTS of the composite were determined according to ASTM E10-07 and E08-8 standards using Taguchi's design of experiment. It was revealed from test results that the Taguchi design of analysis validated the best optimum parameters that showed maximum UTS (259.3 MPa) and hardness (107.56 BHN), which were 12 wt% Al_2O_3 and 4 wt% MoS_2. It is concluded from ANOVA results that Al_2O_3 wt% is the most significant factor that enhances the mechanical performance of hybrid-reinforced MMC.

Reddy *et al* [52] studied the mechanical behavior of Al-6061 MMC reinforced using silicon carbide (SiC) and boron carbide (B_4C). The 0.5, 1, 1.5 and 2 wt% of SiC and B_4C particulates were reinforced with Al-6061 alloy by liquid metallurgical technique. It was noticed from test results that 2 wt% SiC/2 wt% B_4C/96 wt% Al-6061 showed superior flexural strength, hardness and UTS in comparison with other compositions. However, the impact energy for 0.5 wt% SiC/0.5 wt% B_4C/99 wt% Al-6061 was reported to be the maximum. Total improvement of 19.13%, 50.4% and 92.76%, respectively, in tensile strength, hardness and flexural strength of Al-6061/SiC/B_4C HMMC was reported in comparison with AA-6061. In another work Auradi and Kori [53] prepared Al-6061/B_4C MMC to assess various mechanical properties like tensile strength, compressive strength and hardness. The single-reinforced composite was fabricated by a two-stage stir casting process at a casting temperature of 750°C using 5 and 7 wt% of B_4C and K_2TiF_6 salt. It was observed from mechanical results that the UTS and UCS of Al-6061/B_4C MMC increased by 22.1%, 38.8% and 12.7%, 32.06% for 5 and 7 wt% of B_4C particulates when compared with AA-6061. Moreover, the hardness of composites increases from 70.34 VHN (AA-6061) to 120.5 VHN (7 wt% B_4C/AA-6061). According to Rajesh *et al* [54] the Al-6061 MMC reinforced with B_4C showed significant improvement in mechanical properties when compared with Al-6061 base alloy. The composite was fabricated by stir casting method using $K_2T_iF_6$ flux and pre-heated reinforcement at 9 wt%. The reinforced composite was dispersed using a zirconia coated stirrer at 250 RPM for 5/8 min. The UTS, hardness and specific strength of reinforced composite increased by 38.8%, 115.3% and 42.8%, respectively, at 9 wt% of B_4C. The percentage elongation of B_4C/Al-6061 composite decreased by 65.17% with the addition of reinforcements. In a separate work the mechanical performance of Al-6061/B_4C_p MMC was assessed by Rajesh *et al* [55]. The B_4C_p was reinforced inside the Al-6061 matrix via the liquid metallurgical route (two-step addition) using 7 and 9 wt% of reinforcement. Marginal improvements by 17%, 38.4% and 14.98%, 23.6%, respectively, in UTS and UCS were reported at 7 and 9 wt% of particulates. Furthermore, with the addition of reinforcements the hardness of AA-6061/B_4C_p MMC increases from 67 to 139 HV; however, ductility decreased from 13.4% to 5.0%. It is concluded from the experimental outcome [68, 81, 85, 90] that the presence of hard B_4C particulates is attributed to resistance offered by B_4C particulates to plastic deformation, which increases the strain energy of reinforced composite; however, pre-heating of B_4C in Al matrix with $K_2T_iF_6$ as a wetting agent also enhanced the bond strength between Al-6061 and B_4C, which resulted in better mechanical properties of Al-6061/B_4C MMC. Moreover, amongst different wt%, 9 wt% of B_4C-reinforced Al-6061 MMC showed the maximum UTS and hardness of 185.4 MPa and 151.4 HV, respectively.

Marachakkanavar *et al* [56] have performed the experimental study on Al-6061 alloy reinforced with iron ore to investigate the mechanical properties. Al-6061 MMC was strengthened with 2, 4, 6 wt% of iron ore of 150 μm particle size by stir route of casting method. After fabrication, cast samples were heat treated (T6) at 525°C for 6 h followed by age hardening at 175°C for 8 h. The UTS and BHN of composite increase from 173.3 to 240.5 MPa and 72.6 to 103.59 BHN, respectively, in comparison with pure Al-6061 and results are demonstrated in figure 7. The ductility of as-cast composite reduced by 20.3% when compared with base alloy. In a separate research, Phanibhusshana *et al* [57] examined the mechanical strength of hematite (Fe_2O_3)-reinforced Al-6061 MMC. The Fe_2O_3 particulates were incorporated within Al-6061 matrix in varying steps of 2, 4, 6 and 8 wt% by liquid metallurgical technique. The incorporation of Fe_2O_3 inside the AA-6061 was performed at 300/350 RPM for 5/10 min. It is evident from test results that with the accumulation of 2/8 wt% Fe_2O_3, the macrohardness increases from 28.5 to 37.4 BHN. The hardness and UTS were enhanced by 31.47% and 25%, respectively, in comparison with Al-6061 matrix. Moreover the mechanical strength of Al-6061/iron ore and Al-6061/Fe_2O_3 MMC was found to be better than



	Al-6061	Al-6061/2 % IO	Al-6061/4 % IO	Al-6061/6 % IO
Tensile strength in MPa	173.3	180.7	196.6	240.5
Macrohardness in BHN	72.6	93.52	94.94	103.59

Figure 7. Effects of iron ore particles on UTS and Brinell hardness of Al-6061 metal/matrix composite [56].

that of the AA-6061 because of the presence of harder and brittle Fe_2O_3 micro-particles, which distributed the applied load from AA-6061 matrix to Fe_2O_3 reinforcements.

In another work, the impact of surface treatment and artificial hardening on the mechanical strength of Al-6061 MMC reinforced through multi-wall carbon nanotube (MWCNT) was studied by Manjunatha and Dinesh [58]. The solution heat treatment of stir cast Al-6061/MWCNT MMC was performed at 555°C for 8 h followed by the aging process. It is evident from a result that that with an increase in aging time, the microhardness of as-cast composite increases marginally and this is due to the hardening of Al-6061 by MWCNT particulates at optimized aging temperature and time. Moreover, amongst different aging times, 175°C for 10 h yielded superior mechanical properties of heat-treated samples. Further, Ramesh *et al* [59] have studied the effect of frit particulates on tensile strength, hardness and UCS of Al-6061 cast composite analyzed and compared to Al-6061 alloy. The Al-6061 MMC was synthesized with 2, 4, 6, 8 and 10 wt% of frit particulates through liquid metallurgy stir casting technique. Significant enhancement in mechanical strength was reported with the accumulation of frit particles. The hardness of cast composite increases continuously with increasing frit wt%, whereas the UTS and UCS of Al-6061/frit MMC increase up to 6 wt% of reinforcement; thereafter, they get reduced. The total improvements in UTS, hardness and UCS were, respectively, reported as 46.51%, 29.17% and 55.1% at 10 wt% of frit particles in comparison with 2 wt% of frit particles. The improved mechanical strength is attributed to the close packing of pre-heated frit particles with matrix alloy and the presence of hard ceramic particles inside the soft Al-6061 matrix.

Nagaral *et al* [60] fabricated AA-6061/Gr MMC via two-step casting process to determine the mechanical properties. The Al-6061 alloy was mixed with 3, 6 and 9 wt% of Gr reinforcements at 250 RPM for 5/8 min. It was noticed from test results that the accumulation of Gr reinforcements marginally increases the tensile strength and ductility of reinforced AA-6061/Gr MMC. The UTS of Al-6061/Gr MMC increased by 29.94% at 6 wt% and 36.18% at 9 wt%; however, the hardness of composite decreased due to the addition of Gr content. It is concluded that the presence of graphite particulates acts as solid lubricants on the surface of as-cast composite, which deforms easily when subjected to normal load, resulting in lesser hardness than that of the base alloy.

In another investigation, Hyderali *et al* [61] fabricated Al-6061-reinforced MMC using 3, 6 wt% of graphite (Gr) and 6, 3 wt% of FA. The tensile strength of Gr/FA/Al-6061 HMMC was determined using a UTM and the hardness using a Brinell hardness tester. Three samples, Al-6061, Al-6061/6% Gr/13% FA and Al -6061/3% Gr/6% FA, were developed through stir casting technique at stirrer speed of 200/400 RPM for 10/20 min. The mechanical result indicated that the utmost value of hardness (30.26 BHN) was obtained at 6 wt% Gr and 13 wt% FA. The stress/strain graph showed that the maximum tensile load at specimen fracture was 2069.3 N at 10% elongation. It is concluded that the presence of graphite and FA marginally improves the mechanical strength of Al-6061 composite and it exhibits superior properties than those of the base alloy. According to Bhandakkar *et al* [62] the fracture toughness (K_{1c}) of AA-6061/FA composite decreases from 18.21 to 14.27 MPa $m^{1/2}$ when FA particles increase from 0 to 10 wt%. The total decrement of 21.63% in fracture toughness was noticed when compared with base alloy. This behavior of K_{1c} is due to the presence of small cracks that cause weak interfacial bonding between FA and AA-6061 matrix resulting in lower fracture toughness. Further, it was observed from mechanical results that with the accumulation of FA weight fraction, the UTS, YS and hardness of reinforced composite had increased marginally. In a separate work the mechanical behavior of Al-6061

MMC reinforced with FA and CNT was evaluated by Parswajinan *et al* [63]. The fabrication of hybrid composite was done using 2, 3, 4 wt% of FA and 0.2 wt% of CNT through stir route of casting. The mechanical properties like UTS, impact energy and hardness of composites were calculated and compared to those of un-reinforced alloy. It was obtained from mechanical results that the addition of 3 wt% of FA and 0.2 wt% of CNT significantly increased the UTS by 147.76 MPa; however, the hardness of composite increases to 59.2 BHN at 2 wt% of FA. The maximum improvements of 11.81% and 11.69%, respectively, in UTS and hardness of Al-6061/FA/CNT HMMC were reported in comparison with Al-6061 alloy; yet, no improvement in impact strength was noticed. Further, Varalakshmi and Kumar [64] characterized the mechanical behavior of AA-6061MMC strengthened with coconut shell ash (CSA) using optimized parameters. The composite was produced using 1, 3, 5 wt% of CSA through stir casting process. The mixing of the molten slurry was carried out at a melt temperature of 750°C and stir speed of 600 RPM for 10 min using a stainless steel mechanical stirrer. The impacts of CSA on microhardness and UTS of Al-6061/CSA MMC were determined and compared to those of AA-6061. It was found from test observation that UTS and microhardness of reinforced MMC increased remarkably with the incorporation of CSA wt%. The maximum values of hardness and UTS were observed at Al-6061/5 wt% CSA, which were 143.66 MPa and 82 VHN, respectively.

In a separate research, the comparative study of tungsten carbide (WC) and graphite (Gr) reinforcement on the mechanical performance of Al-6061 MMC was performed by Swamy *et al* [65]. The composite was developed using equal proportions of 1, 2, 3 and 4 wt% of WC and Gr reinforcements through vortex method. It was seen from experimental results that in comparison with Gr-reinforced composite the WC-reinforced composite showed higher hardness, compressive strength and tensile strength. The maximum value of mechanical properties was obtained at 3 wt% of WC; afterwards the properties get reduced. However, the UTS and UCS of Al-6061 MMC increased with addition of Gr content. The ductility of Al-6061/WC MMC decreased with the accumulation of WC particles, whereas Al-6061/Gr MMC exhibited superior ductility than Al-6061/WC MMC. Further, Kumar *et al* [66] fabricated Al-6061 HMMC reinforced with titanium (Ti) and E-glass fiber particulates. The experiment was performed using 1, 3 and 5 equal wt% of Ti/E glass via stir casting method. The pre-heated reinforcements were added into a furnace at 750°C temperature followed by impeller mixing at 450 RPM. The results obtained through mechanical tests showed a maximum increment in tensile strength and hardness at 1:3 wt% of Ti and E-glass reinforcements. The microhardness of composite increased by 25% when compared with base alloy; however, no such improvement was reported in UTS. It was also observed that in comparison with Ti particulates the E-glass fiber significantly improved the mechanical properties of the Al-6061/Ti/E-glass HMMC. In a study, Raviraj *et al* [67] observed the influence of titanium carbide (TiC) reinforcements on fracture toughness (K_{1c}) of Al-6061 MMC. The TiC particles varied in steps of 3, 5 and 7 wt% inside the Al-6061 matrix through liquid casting method. The particulate size of TiC reinforcement was 3/4 μm. The specimens for K_{1c} were prepared according to ASTM E399 standards. It is reported from the experimental study that incorporation of TiC particulates decreases the K_{1c} of Al-6061/TiC MMC from 19.2 to 16.4 MPa $m^{1/2}$, though composites with sample composition of 3 and 7 wt% of TiC show higher K_{1c} than 5 wt% of TiC particulates.

The metallurgical properties of stir cast Al-6061 (T6) MMC reinforced with 5, 10, 15 and 20 wt% of aluminum nitride particles (AINp) were evaluated by Kumar and Murugan [68]. In this study, a stir casting setup equipped with bottom pouring arrangement was used to fabricate the composites. The results of mechanical properties indicated that the maximum values of macrohardness and microhardness were obtained at 20 wt% of AINp, which were 79 BHN (107.89% from base alloy) and 91 VHN (106.81% from base alloy), respectively. The variation of the stress/strain curve shows that 20 wt% of AINp composite possesses the maximum strength with less ductility. It was also reported that YS and UTS of AA-6061/AINp MMC increased, respectively, by 95.12% and 46.95% compared with the AA-6061 base matrix. In another investigation, Pandiyarajan *et al* [69] inspected the mechanical behavior of Al-6061 HMMC reinforced with zirconium dioxide (ZrO_2) and graphite (Gr). The AA-6061/ZrO_2/Gr HMMCs were fabricated using 2:2, 6:2, 2:6 and 6:6 weight ratios of ZrO_2 and Gr through stir route of casting process. It was observed from experimental outcomes that for addition of reinforcements (ZrO_2:Gr) up to 6:2, the microhardness and UTS increased from 30 to 43 HRC and 128 to 175 MPa, respectively. The maximum improvements in hardness and UTS reported were, respectively, 30.23% and 26.85% at 6:6 wt% of ZrO_2/Gr when compared with AA-6061. In a separate work a similar finding was obtained by Udayshankar and Ramamurthy [70] on mechanical performance of Al-6061 MMC reinforced with 3, 6, 9 and 12 wt% of ZrO_2 (60 μm) through stir casting method. It is found from observations that above 9 wt% of reinforcement the wettability between the Al-6061 matrix and ZrO_2 decreases, which causes poor bonding between matrix and reinforcement, resulting in reduced strength and hardness. The samples were casted at melting temperature of 750°C followed by reinforcement mixing by 500/700 RPM for 5 min. Further, it was concluded that up to 9 wt% of ZrO_2 the UTS and microhardness of composite increase marginally from 110 to 145 MPa and 80 to 98 BHN, respectively, and thereafter get reduced to 115 MPa and 82 BHN at 12 wt% of ZrO_2. The maximum improvement in hardness and UTS by 31.81% and 22.5% was reported at 9 wt% of ZrO_2 when compared with 3 wt% of ZrO_2.

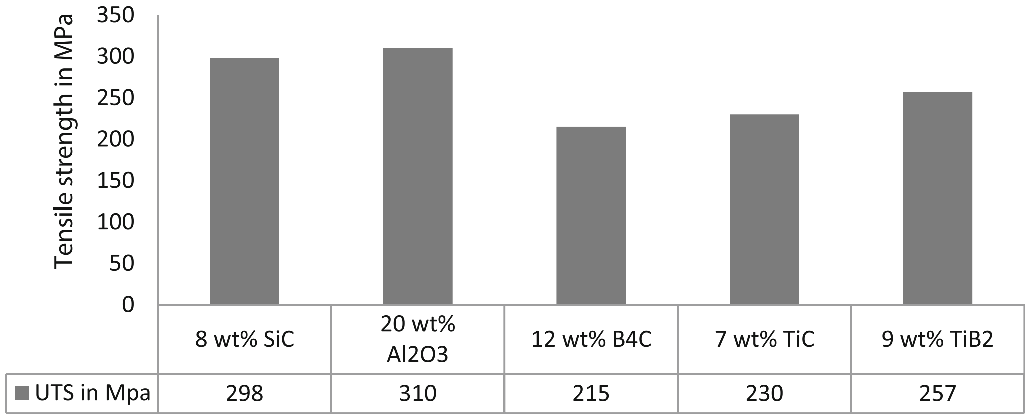


Figure 8. Maximum tensile strength of single-reinforced Al-6061 MMC at different wt% of reinforcements [40, 45, 92, 101, 102].

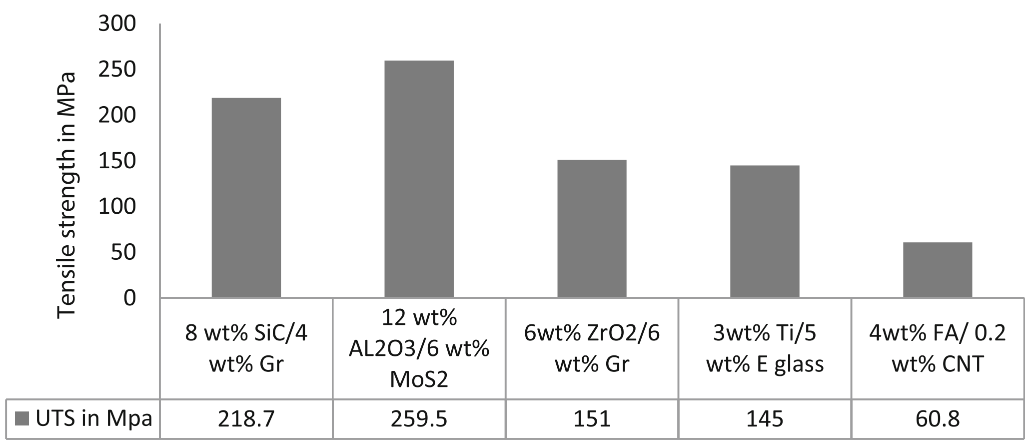


Figure 9. Maximum tensile strength of hybrid-reinforced Al-6061 MMC at different wt% of reinforcement [44, 51, 63, 66, 69].

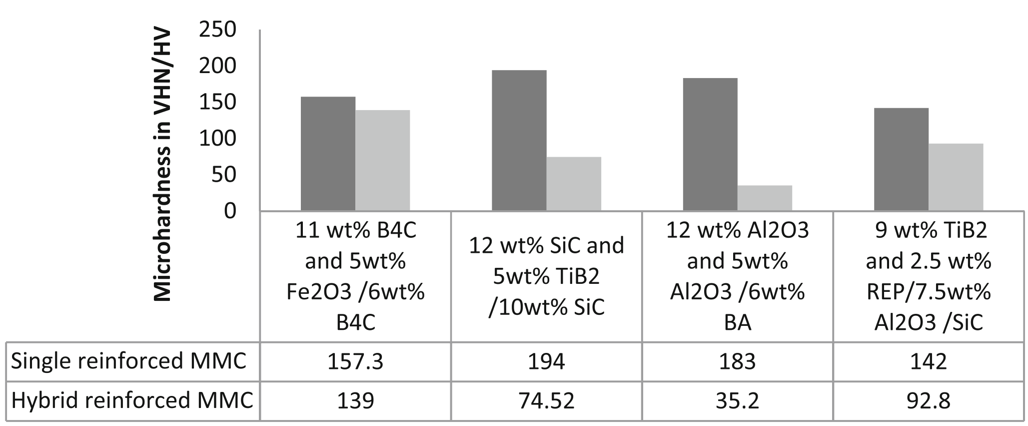


Figure 10. Comparison between maximum microhardness of single- and hybrid-reinforced Al-6061 MMC [35, 41, 68, 79, 87, 95, 101, 109].

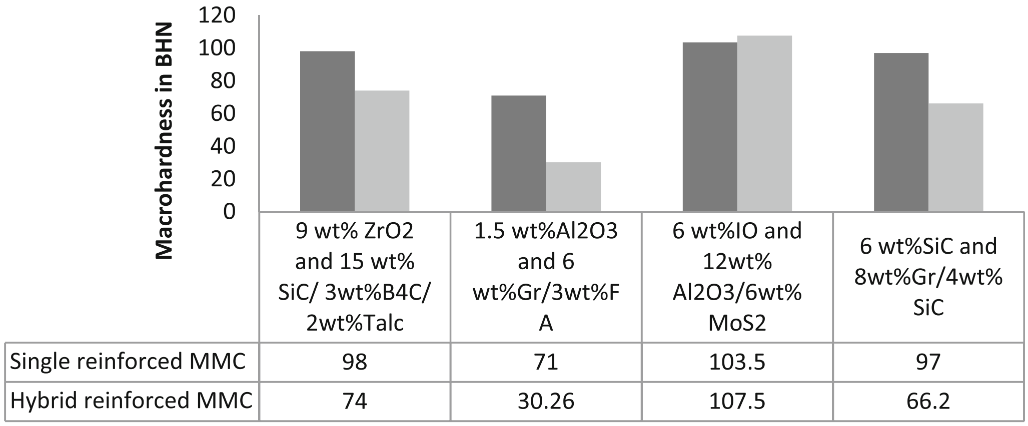


Figure 11. Comparison between maximum macrohardness of single- and hybrid-reinforced Al-6061 MMC [44, 51, 52, 56, 70, 74, 84, 104].

The comparative analyses of tensile strength (figures 8 and 9), microhardness (figure 10) and macrohardness (figure 11) with single- and hybrid-reinforced MMC are illustrated in figures 8–11. The plots revealed that the single-reinforced composite showed superior mechanical properties than hybrid-reinforced composite. Moreover the UTS, UCS and hardness of reinforced Al-6061 composites increased with increasing wt% and reducing particulate size of reinforcements. Amongst all the significant research works on Al-6061 MMC [44, 45, 51, 56, 65, 79, 87, 95], the maximum UTS (310 and 259.5 MPa) is reported with Al_2O_3 as single-reinforced composite and with Al_2O_3/MoS_2 as hybrid-reinforced composite, respectively [45, 51]. The maximum macrohardness (107.5 and 103.59 BHN) is obtained for Al_2O_3/MoS_2/Al-6061 MMC (hybrid-reinforced composite) and iron ore/Al-6061 MMC (single-reinforced composite), respectively [51, 56], whereas the maximum microhardness (194 and 139 VHN) is obtained for SiC/Al-6061 MMC (single-reinforced composite) and Fe_2O_3/B_4C/Al-6061 MMC (as hybrid-reinforced composite) [41, 95]. Moreover, the highest UCS (894.13 MPa), % elongation (25%) and impact strength (56 J) are reported with WC-, REP/Al_2O_3/SiC- and Gr/SiC-reinforced Al-6061 MMC, respectively [44, 65, 79].

Finally, it was concluded from mechanical results that as compared with Al-6061 alloy the Al-6061 MMC composite exhibited superior mechanical properties. The addition of primary reinforcements (SiC, Al_2O_3, TiB_2 and B_4C) marginally improves the UTS, UCS and hardness of Al-6061 MMC. This may be due the fact that these reinforcements are harder and stiffer than base alloy, which act as obstacles in the motion of dislocations [37, 38]. Another theory reported by several researchers is that during solidification thermal stresses are developed in composites due to the variation in the coefficient of thermal expansion between matrix and reinforcements that cause formation of dislocation density at the interface of reinforcement and base matrix. This results in improvement of mechanical strength of cast composite due to dislocation density [45, 46, 50]. Further, pre-heating of reinforcements, optimization of stir parameters and heat treatment of specimens also add strength to the reinforced composite [56, 57]. However, the reason for lesser mechanical strength was porosity and clustering of reinforcements also quoted by several researchers [49, 51, 59, 62].

3.2 *Tribological characterization of stir cast Al-6061 MMC*

In this section, the tribological aspect of Al-6061 MMC has been discussed and compared to that of the base alloy. The outcomes of tribological properties are demonstrated in table 6 with sample composition and wear parameters. The specimens of wear analysis were prepared as per ASTM G99 standards [77, 78, 84, 88, 95, 99]. The wear properties of as-cast specimens were determined using a pin on disk wear tester. The systematic arrangements of the pin on disk setup, sample configuration and counterpart disk are illustrated in figure 12(a)/(c) [59, 61, 63]. The input process parameters used for wears study were nominal applied load, rotational speed, sliding velocity and sliding distance to determine wear characteristics such as weight loss (WL), specific wear rate (SWR), wear resistance (WR), coefficient of friction (COF) and volumetric wear loss (VWL) [72, 79, 92].

A study was conducted by Mishra *et al* [71] on stir cast Al-6061/SiC MMC to investigate the tribological properties; 10 and 15 wt% of SiC and 150/160- μm size of as-cast composite were amalgamated with Al-6061 alloy to determine wear and COF of fabricated composite using a pin on disk experimental setup. Taguchi L9 orthogonal array was used to determine the effect of wear parameters on tribological characteristics. The results obtained at

Table 6. Tribological analysis of stir cast Al-6061 metal/matrix composites

Sl. no.	Reinforcements	Weight/volume (%)	Wear samples size (dia. and length in mm)	Counterpart hardness	Applied load (N)
1	SiC	10, 15	Ø10 and 25	EN 31 steel 65 HRC	10, 20, 30
2	SiC	5	–	Chromium steel 658 HB	20, 46, 110, 173, 200
3	SiC	5, 10, 15, 20, 25, 30, 35, 40	Ø8 and 32	EN 31 steel 65 HRC	10, 20, 30
4	SiC	2, 4, 6	Ø10 and 25	–	10, 20, 30, 40, 50, 60
5	SiC	2, 4, 6	–	EN 31 steel 60 HRC	10, 20, 30, 50
6	SiC	5, 7.5, 10	Ø6 and 30	EN 32 steel 62/65 HRC	10, 20, 30
7	SiC and Gr	2 and 0.5, 1, 1.5, 2, 3	Ø8 and 25	EN 31 steel	5, 10, 15, 20
8	SiC and Gr	0.4, 0.8, 1.2, 1.6 and 0.5	Ø10 and 20	Steel disk 62 HRC	10, 20, 30, 40
9	SiC, Al_2O_3,CeO_2	2.5/7.5, 0.5/2.5	Ø10 and 12	Stainless steel	10, 20, 30
10	SiC and Al_2O_3	5 and 15	–	–	39.24, 58.86
11	SiC, Al_2O_3	5/25	Ø8 and 40	Hardened steel 256 HV	29.43, 39.24, 49.05
12	SiC, Al_2O_3 and Gr	3, 5, 7 and 1, 2.5, 4 and 4, 2.5, 6	–	–	–
13	SiC and B_4C	5, 10, 15 and 3	Ø10 and 30	Hardened steel 62 HRC	10, 20, 40
14	SiC, B_4C and talc	5, 10, 15	–	–	20
15	SiC and E glass	9 and 0, 1, 3, 5	–	Carbon chromium 58 HRC	20
16	SiC and MWCNT	0.5, 1 and 15	–	Cast iron 63 HRC	0.5, 1, 1.5
17	Al_2O_3	6, 9, 12	–	–	19.62
18	Al_2O_3 and Gr	10, 20, 45, 95 and 5	Ø6 and 45	EN 31 steel	10, 20, 30
19	Al_2O_3 and Gr	5, 10, 15 and 5	Ø2.5 and 10	EN 45 steel 65 HRC	10, 20, 30
20	Mg, FA and Gr	4 and 10, 15, 20 and 4	Ø10 and 35	EN 31 steel	30
21	Gr and WC	9 and 1, 2, 3	–	–	10.20.30
22	TiC	3, 5, 7	Ø6 and 50	EN 32 steel 65 HRC	9.81, 29.4, 49.1
23	TiO_2	2, 4, 6, 8, 10	Ø10 and 25	High C/Cr steel 60 HRC	10, 20, 30, 40
24	TiB_2	4, 8, 12	–	EN 31 steel	5, 10, 15
25	Fe_2O_3 and B_4C	5 and 2, 4, 6	–	Mild steel	20, 40
26	B_4C	10	–	EN 31 steel 65 HRC	10, 20, 30, 40, 50
27	Coconut shell ash	3, 6, 9, 12, 15	–	–	10
28	Cenosphere, rock dust, CRT	5, 10, 15	Ø10 and 30	EN 31 steel 65 HRC	30
29	Garnet	4, 8, 12	–	EN 24 steel 229 BHN	10, 20, 30, 40, 50
30	Bamboo char, B_4C	1, 2, 3	–	–	9.8, 19.6, 29.4

Sl. no.	Reinforcements	Sliding/rotational speed (m/s/RPM)	Sliding distance (m)	Outcomes	References
1	SiC	2, 3, 4	1000, 1750, 2500	Addition of SiC improves wear resistance	[71]
2	SiC	200, 346, 700, 1053, 1200	–	In comparison with AA-6061, the wear rate of Al-6061/SiC increases with increasing RPM	[72]
3	SiC	2	2000	Wear rate enhanced with increasing distance and load; however, COF decreased with increasing load	[73]
4	SiC	2.62	1000, 2000, 3000, 4000, 5000, 6000	Wear loss of Al-6061/SiC increased with applied load and sliding distance	[74]
5	SiC	100, 300, 500	200, 400, 600, 800, 1000	Al-6061/SiC demonstrated significantly higher wear resistance than Al7075/Al_2O_3	[75]
6	SiC	1, 2, 3	1000	Acute wear rate was noted when load and sliding speed exceeded 20 N and 2 m/s	[76]

Table 6. continued

Sl. no.	Reinforcements	Sliding/rotational speed (m/s/RPM)	Sliding distance (m)	Outcomes	References
7	SiC and Gr	0.5, 1, 1.5, 2	1000, 2000, 3000	Addition of SiC/Gr reduces the wear rate and COF	[77]
8	SiC and Gr	0.5	1000	Al-6061/1.2% SiC/0.55 Gr showed maximum wear resistance	[78]
9	SiC, Al_2O_3,CeO_2	0.5, 1, 2	500, 1000, 1500, 2000	Wear rate increased by 87.28% in comparison with AA-6061	[79]
10	SiC and Al_2O_3	200, 400	–	Maximum wear resistance was obtained at 15% reinforcements.	[80]
11	SiC, Al_2O_3	1.57	1413	Dry sliding wear behavior decreased with increasing vol% of SiC and Al_2O_3	[81]
12	SiC, Al_2O_3 and Gr	1.0446, 1.832	–	Presence of Gr marginally improves the tribological characteristics of as-cast Al-6061 HMMC	[82]
13	SiC and B_4C	150, 300, 400	2000, 3000, 4000	SiC 10% and B_4C 3% exhibited enhanced tribological characteristics	[83]
14	SiC, B_4C and talc	600	1500	44% improvement in wear resistance was noticed at 15% SiC content	[84]
15	SiC and E glass	1.832	500/1500	Wear rate decreases with increasing wt% of SiC and E glass	[85]
16	SiC and MWCNT	–	636	Improved tribological characteristics were obtained with SiC and MWCNT particles with load being the most significant factor	[86]
17	Al_2O_3	1.256	500, 1000, 1500, 2000, 3000	Maximum wear rate was reported at 19.62 N load and 300 RPM	[87]
18	Al_2O_3 and Gr	1, 2, 4	–	Addition of Al_2O_3 and Gr showed improved tribological characteristics than single reinforcement	[88]
19	Al_2O_3 and Gr	0.8, 1.6, 2.4	1000	Applied load was largely influencing factor amongst others parameters	[89]
20	Mg, FA and Gr	1000, 1500, 2000	–	Up to 15% FA and 4% Gr, specific wear rate decreases	[90]
21	Gr and WC	1, 2, 3	50, 1500, 2500	Enhanced wear rate and COF were observed at 9% Gr - 3% WC particulates	[91]
22	TiC	1.5, 3, 4.5	–	With addition of TiC content wear rate increases significantly	[92]
23	TiO_2	–	90, 180, 270, 360, 450, 540	Wear coefficient of Al-6061/TiO_2 lowered at maximum load and distance	[93]
24	TiB_2	2.61, 500	2000	Wear resistance and COF improve significantly with addition of TiB_2 content	[94]
25	Fe_2O_3 and B_4C	–	720	Al-6060/5% Fe_2O_3/6% B_4C demonstrated superior wear	[95]
26	B_4C	0.5, 1, 1.5, 2	200, 400, 600, 800	With increasing applied load WR and COF increased but due to MML WR and COF increased marginally	[96]
27	Coconut shell ash	1.5	1000	Wear rate decreased up to 6 wt% but COF increased gradually with CSA addition	[97]
28	Cenosphere, rock dust, CRT	4	1000	Incorporation of CENO/RD/CRT up to 15% enhances the wear resistance of Al-6061	[98]
29	Garnet	1.25, 1.85, 2.45, 3.05	500, 1000, 1500, 2000, 3000	Wear resistance superior than that of AA-6061 and enhanced with addition of garnet	[99]
30	Bamboo char, B_4C	400, 500, 600	500	Enhancement of tribological properties due to cooperating effect of bamboo char and B_4C contents	[100]

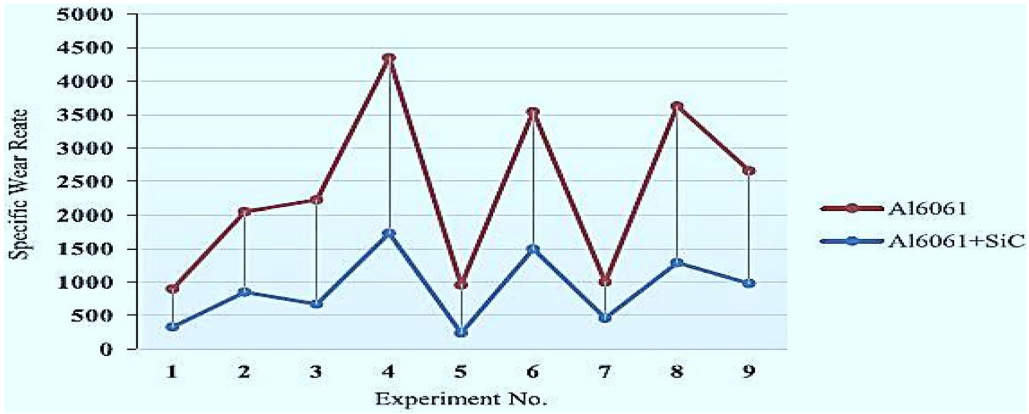


Figure 12. (a) Wear testing machine (pin on disk) setup [61]. (b) Wear specimen configuration [59]. (c) Pin and counterpart arrangement [63].

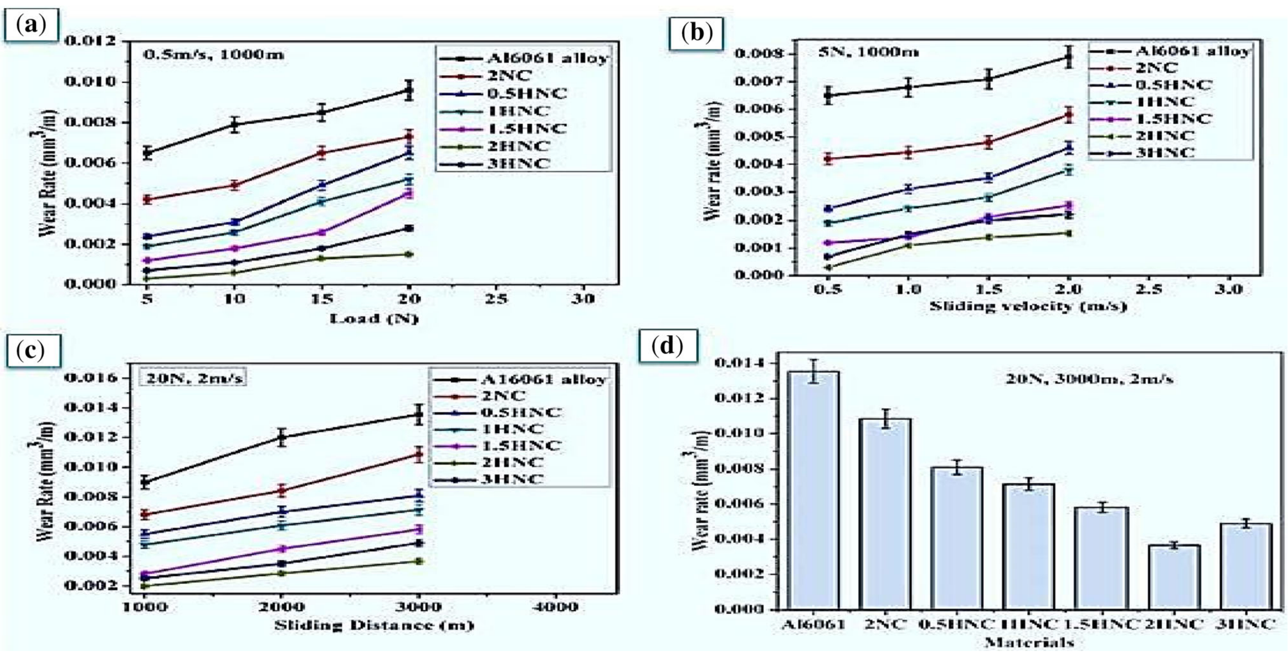


Figure 13. Comparison between specific wear rate of Al-6061 alloy and Al-6061 + SiC MMC [72].

10 wt% of SiC show that the sliding distance has a great effect on wear rate in comparison with sliding velocity and applied load. However, at 15 wt% of SiC, applied load has major influence on wear rate over sliding speed and sliding distance. The influence of applied load on COF was significantly higher than those of sliding distance and sliding velocity. In another research, Bhat and Kakandikar [72] revealed the dry sliding wear performance of Al-6061 MMC incorporated with 5 wt% SiC through surface response methodology (RMS). The wear test of Al-6061 MMC was carried out using a pin on disk tribometer. Nine experiments were performed under variable rotational speed and normal load to estimate the SWR of AA-6061 and Al-6061 composite. It is revealed from wear results as shown in figure 13 that Al-6061 composite has better WR as compared with Al-6061 alloy. The tribological results show that by increasing rotational speed (200/1200 RPM) and keeping load constant, the wear rate increases significantly; however, a similar finding was reported with increasing load (20/200 N) and keeping speed constant.

Further, Mishra and Srivastava [73] also examined the dry sliding WR of stir cast Al-6061 MMC reinforced with 5/40 wt% SiC in the varying step of 5. The particulate sizes of 150 and 600 μm were used to investigate tribological properties. The wear analysis of Al-6061-SiC MMC was performed using a tribometer, normal load of 10, 20, 30 N, rubbing distance of 2 km and sliding velocity of 2 m/s. The wear results showed an increase in SWR with increasing sliding distance and normal load. However as mesh size increased from 150 to 600 µm, reduction in WR was also reported. The COF vs. load results showed reduction in COF with the addition of load; however, 600-µm size specimens have better COF than 150-µm size. Finally, it was concluded that 600-µm particles size at 35 wt% of SiC was the optimized parameter that showed higher WR and COF. In a similar research conducted by Kumar *et al* [74] on dry sliding wear behavior, SiC-reinforced Al-6061 MMC under all testing conditions exhibits better WR than base alloy. The composite was reinforced with 2, 4 and 6 wt% of SiC and 150 µm size particles by liquid metallurgy technique. The variation of VWL with different weight fractions under various wear parameters demonstrates that on increasing sliding distance and load, the VWL increases marginally; however, with accumulation of particulates (2/6 wt%), the VWR decreases. The wear result of SiC-reinforced Al-6061 MMC shows that SiC enhances the hardness of composite marginally, which further increases the WR of Al-6061 MMC.

In another investigation, Kumar *et al* [75] did comparative study on wear factor of SiC/AA-6061 MMC and Al_2O_3/AA-6061 MMC. The composites were prepared through liquid metallurgical route using equal 2, 4 and 6 wt% of SiC and Al_2O_3. In one trial the wear factors were tested under applied load of 10 N at rotating speed of 100, 300 and 500 RPM and in another trial under applied load of 20, 30 and 50 N at constant speed of 100 RPM. It was concluded from the wear study that in comparison with Al-7075 reinforced composite, the Al-6061 reinforced composite exhibited higher WR. Moreover the Al-6061/SiC composite at 6 wt% of reinforcement showed the lowest SWR in comparison with other weight percentages. In a separate study, Murthy *et al* [76] discovered the tribological characteristics of Al-6061/SiC particulates MMC under a dry sliding condition. The fabrication of composite was done via stir casting process using 5, 7.5 and 10 wt% of SiC. It is observed from wear results that the SWR of Al-6061/SiC MMC increases with an increase in applied load and sliding speed. Further, it is concluded from tribological results that amongst other parameters the sliding speed has a maximum influence over wear mechanism of Al-6061-SiC MMC; moreover, the composite fabricated with 10 wt% SiC showed the maximum COF.

In a separate research, Reddy *et al* [77] studied the tribological performance of as-cast AA 6061/SiC/Gr HMMC. The effects of SiC (2 wt%) and Gr (0.5, 1, 1.5, 2 and 3 wt%) on WR and COF were assessed using a pin on disc apparatus. It is seen from wear results as illustrated in figure 14 that wear rate of Al-6061 alloy and Al-6061/SiC/Gr hybrid composite increases gradually with increasing load, velocity and sliding distance. The wear rate of the hybrid composite showed total reduction of 20%, 40.2%, 47.3%, 57%, 73% and 64% in comparison with pure AA 6061. Moreover, with addition in applied load the COF of composite enhances and with sliding distance and velocity it reduces. In another relative study, the tribological performance of SiC and Gr particulates dispersed in Al-6061 MMC was evaluated by Manivanan *et al* [78] at 10/40 N applied load, 0.5 m/s sliding velocity and 1000 m sliding distance to analyze wear performance of Al-6061/SiC/Gr HMMC. The experimental outcome relates the wear rate of HMMC with the hardness of composite using archer equation ($V = KWS/3H$); that is more the hardness, higher the WR. Therefore enhancement in WRis attributed to the hardness of SiC particulates on the surface of hybrid

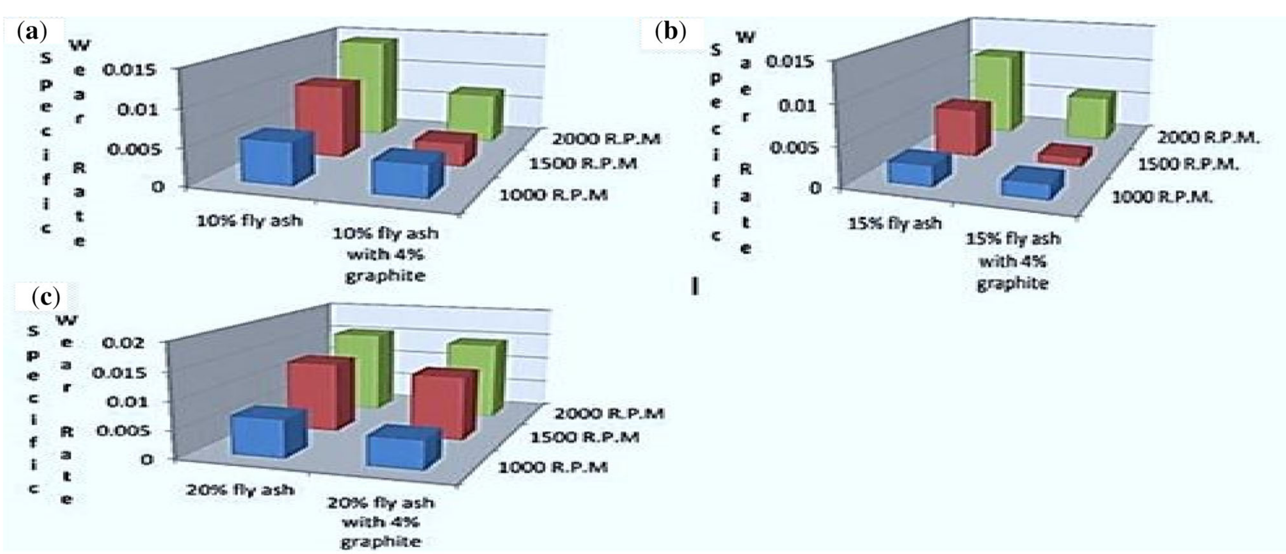


Figure 14. Wear rate of Al-6061/SiC/Gr HMMC. (a) Wear rate vs. load. (b) Wear rate vs. sliding velocity. (c) Wear rate vs. sliding distance. (d) Wear rate vs. reinforcing materials [77].

composite and presence of Gr content, which acts as a thick lubricating layer on the surface of hybrid composite [48, 50]. The COF of the hybrid composite is observed to be less as compared with base alloy and this is due to the hard SiC, which reduces the plastic deformation, and adhesion at the contact surface of composite results in lower COF.

In another comparative research, Sharma *et al* [79] investigated the tribological characteristics of stir cast Al-6061 HMMC reinforced with silicon carbide, alumina and cerium oxide (CeO_2). The wear rate of Al-6061 hybrid-reinforced composite was determined using a pin on disk setup, 10, 20 and 30 N load, 0.5, 1.0 and 2.0 m/s sliding velocity and 0.5, 1, 1.5 and 2 km sliding distance. From test results, it was analyzed that the WR of Al-6061 with triple reinforcements ($SiC/Al_2O_3/CeO_2$) improved marginally by 87.28% when compared with dual reinforcements (SiC/Al_2O_3). The marginal improvements in WR of HMMC are primarily due to the presence of CeO_2 (rare earth metal), which works as a barrier in resistance of plastic deformation. Further, Umanath *et al* [80] have also examined the wear performance of stir cast Al-6061 (T6) MMC reinforced through SiC and Al_2O_3 under dry sliding condition. It was reported from the study that 15% $SiC/Al_2O_3/Al$ HMMC showed higher WR than 5% $SiC/Al_2O_3/Al$ HMMC. Amongst all the input factors, the volume fraction was the most significant parameter for improved wear performance. From surface response graph it was also noticed that the wear rate of the hybrid composite increased with increasing applied load and rotational speed from 39.24 to 58.86 N and 200 to 400 RPM, respectively. In another investigation, Umanath *et al* [81] also studied the wear behavior of Al-6061/SiC/Al_2O_3 HMMC under dry sliding conditions. In this study, HMMCs were manufactured by stir casting technique using 25 μm size and 5/25 vol% of SiC and Al_2O_3 in equal proportions. It was observed from wear results that height loss of specimen was directly related to the rubbing distance and maximum height loss was obtained at 1413 m. It is also revealed from the results that as load progresses the wear loss of the composite increases, whereas the height loss of Al-6061 (T6) base alloy increases more rapidly than than that of the Al-6061 (T6) cast alloy. Finally it is concluded from the research that dual reinforcements decrease the wear loss of the hybrid composite gradually. Bhandare and Sonawane [82] fabricated Al-6061 particulates MMC through stir route of casting technology using SiC, Al_2O_3 and Gr reinforcements; 1, 2.5, 4 wt% of SiC, 3, 5, 7 wt% of Al_2O_3 and 2.5, 4.6 wt% of Gr reinforcements were used to evaluate tribological behavior of Al-6061 HMMC. The tribological properties such as SWR and COF were investigated at a sliding velocity of 1.0446 and 1.832 m/s. It was noticed from wear analysis that with the addition of reinforcements ($SiC/Al_2O_3/Gr$) the WR of hybrid composite decreased marginally. However the value of COF increases at the smaller weight fraction of reinforcements but after this, it reduces as reinforcements content increase.

In another work, Uvaraja and Natarajan [83] reveal from tribological results that SWR of AA-6061-SiC-B_4C HMMC decreases with an increase in sliding distance and increases with increase in applied load. They concluded that the developed HMMC showed superior tribological properties than pure AA-6061 and in comparison with SiC, the B_4C content significantly enhanced the WR of the developed composite. The improved SWR and COF of Al-6061/SiC/B_4C HMMC are attributed to the addition of boron particles, which has excellent abrasion resistance. In a similar study (AA-6061/SiC/B_4C) with additional reinforcement (talc) Kumar *et al* [84] evaluated the tribological characteristic of Al-6061/B_4C/talc HMMC; 5, 10, 15 wt% of silicon carbide particulates (SiCp), 3 wt% of B_4C and 2 wt% of talc were dispersed into Al-6061 through stir casting process at 450 RPM stir speed for 10 min. Total improvements by 12.5%, 45% and 62.5% in WR and 4.4%, 19% and 41% in the friction coefficient were noticed for 5, 10, 15 wt% of SiCp/Al-6061 MMC when compared with AA-6061. It was reported from the research that talc showed solid lubrication property although boron carbide possessed good hardness, which resulted in better tribological performance than that of AA-6061. It is also revealed from the tribological outcome that material loss occurs due to the thermo-mechanical effect, which causes heat generation by rubbing action at the interface of the tool and specimen. In another work, Benal and Shivanand [85] used 9 wt% SiC and 1, 3, 5 wt% E-glass fiber to compare the effect of heat-treated samples and non-heat-treated samples on wear properties of Al-6061 HMMC. The cast samples were heat-treated at 530°C for 12 h followed by water quenching and artificial aging at 175°C for 3, 5 and 7 h. The results demonstrate that non-heat-treated samples possess less WR than heat-treated samples. Moreover, the specimen with 5 h duration at 175°C and 1000 m sliding distance showed superior wear properties than other samples. This specimen however possessed the maximum hardness, which also contributed to enhancement in wear properties of Al-6061/SiC/E-glass HMMC. Further, Padmavathi and Ramakrishnan [86] studied the tribological properties of Al-6061/SiC/MWCNT HMMC. The Al-6061 composite was reinforced with 0.5 and 1 wt% of MWCNT and 15 wt% of SiC through stir route of casting method. The wear tests were conducted on a pin on disk wear test rig under 0.5, 1 and 1.5 N load and 636 RPM rotational speed. It is noticed from tribological results that the SWR of hybrid composite decreases with an increase in wt% of reinforcements under all loading conditions. However, with the addition of SiC and MWCNT reinforcements, a marginal decrement in friction coefficient was also observed. It is finally concluded from outcome results that the presence of MWCNT significantly advances the tribological performance of Al-6061/SiC/MWCNT hybrid composite.

In another investigation Bharath *et al* [87] developed AA-6061 MMC with 6, 9, 12 wt% of alumina through liquid casting route to assess the wear characteristics at rotational speed of 300 RPM and applied load of 19.62 N. It was analyzed from the experimental outcome that WL of developed composite decreased with the addition of alumina particulates. This behavior was attributed to the presence of hard Al_2O_3 particles inside the matrix alloy, which resisted the plowing action and resulted in improved WR of the developed composite. According to Hariharasakthisudhan *et al* [88] the triple-reinforced composite (Al_2O_3/Gr/Si_3N_4) showed lesser SWR and COF than dual-reinforced composite (Al_2O_3/Gr). The wear properties of Al-6061/Al_2O_3/Gr/Si_3N_4 HMMC were evaluated under dry sliding condition. The SWR of composite with Si_3N_4 particles increased with an increase in normal load (10/30 N) and sliding speed (1/4 m/s). Finally, it was concluded that Si_3N_4 developed a stable bond between AA-6061 and Gr reinforcement that marginally improved the WR of reinforced composite. The material removal mechanism was the thermal softening of the composite due to abrasive wear and plastic deformation of materials. In another study Premnath *et al* [89] analyzed the tribological characteristics of Al-6061/Al_2O_3/Gr HMMC. It was seen from 3D surface plots that SWR of composite improved with addition in load; however, SWR reduced with an increase in sliding velocity. It was also reported from the research that the presence of self-lubricated graphite content and hard Al_2O_3 particulates improved the WR of HMMC significantly. It was concluded from the experimental design that load was the most significant factor followed by sliding velocity and wt% of particle reinforcements on SWR of HMMC. Moreover the friction coefficient of dual-reinforced composite decreased with an increase in normal load. In a separate work Kumar *et al* [90] correlated the wear characteristics of FA/Mg/Al-6061HMMC and graphite/Mg/Al-6061HMMC. Seven experiments were performed with the sample composition of Al-6061/4 wt% Mg/10, 15, 20 wt% FA and Al-6061/4% Mg/10, 15, 20 wt% FA/4 wt% Gr. The wear plots indicate that on increasing speed from 500 to 2500 RPM, the SWR of composite increases for Gr reinforcement. However, the value of SWR decreased with the addition of FA content up to 15 wt%; thereafter, SWR increased. It is finally concluded from the comparison between Gr and FA reinforcements (shown in figure 15) that the presence of Gr slightly improves the WR of reinforced composite due to its lubrication effect. Further, Ponugati *et al* [91] have optimized the tribological performance of stir cast Al-6061 HMMC. The composite was fabricated using 9 wt% of Gr and 1, 2, 3 wt% of WC at 300 RPM stir speed for 15 min to reinforce particles inside the matrix. A total of 30 experiments were performed as per the statistical technique (design of experiment) to investigate the wear loss and COF. The wear loss and COF were also optimized using Fuzzy Gray Relation Analysis (FGRA). It was concluded that amongst different weights % and wear parameters the 9:3 wt% of Gr and WC at 30 N applied load, 3 m/s velocity and 0.5 km sliding distance reported minimum SWR and COF of Al-6061/Gr/WC HMMC.

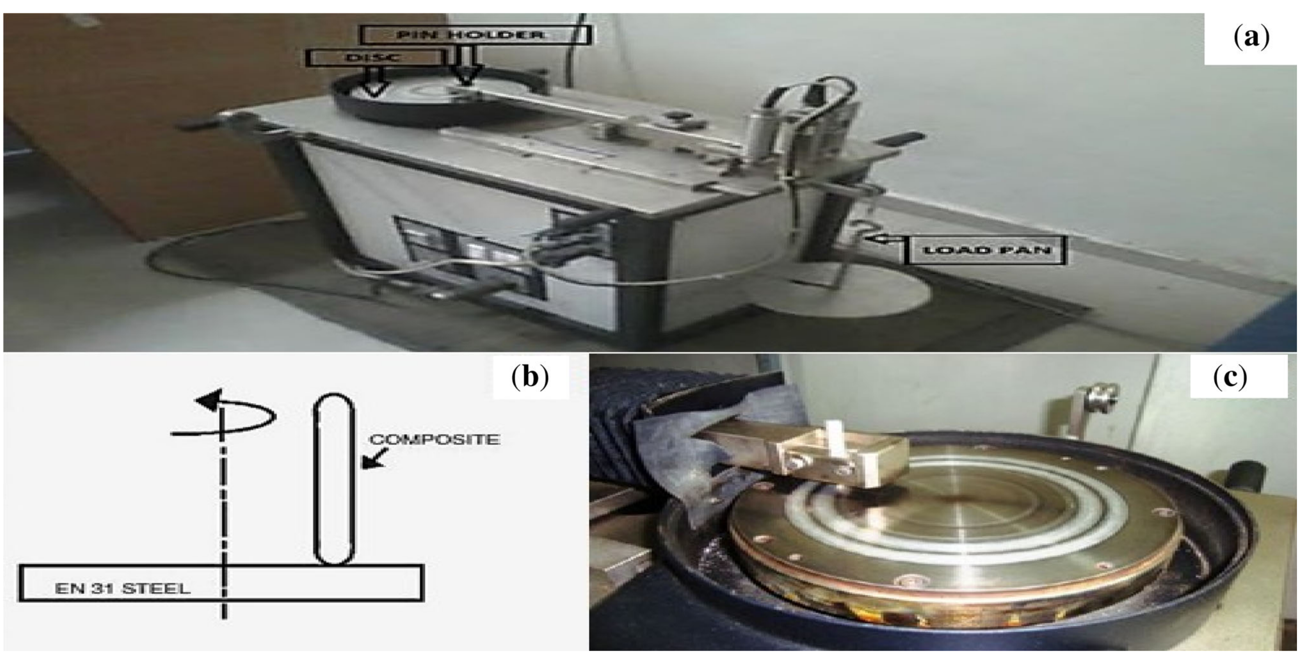


Figure 15. Comparison between specific wear rates of (a) 10, (b) 15 and (c) 20 wt% fly ash and, respectively, 10, 15, 20 wt% fly ash + 4 wt% graphite [90].

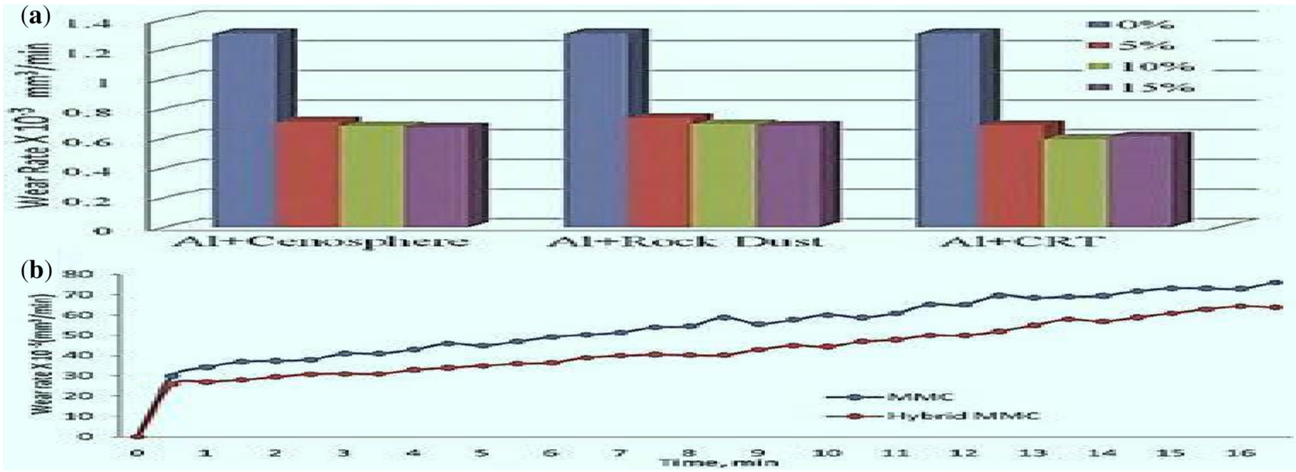


Figure 16. (a) Wear rate of Al-6061+RD/CENO/CRT HMMC. (b) Wear plot of Al-6061 MMC and Al-6061 HMMC [98].

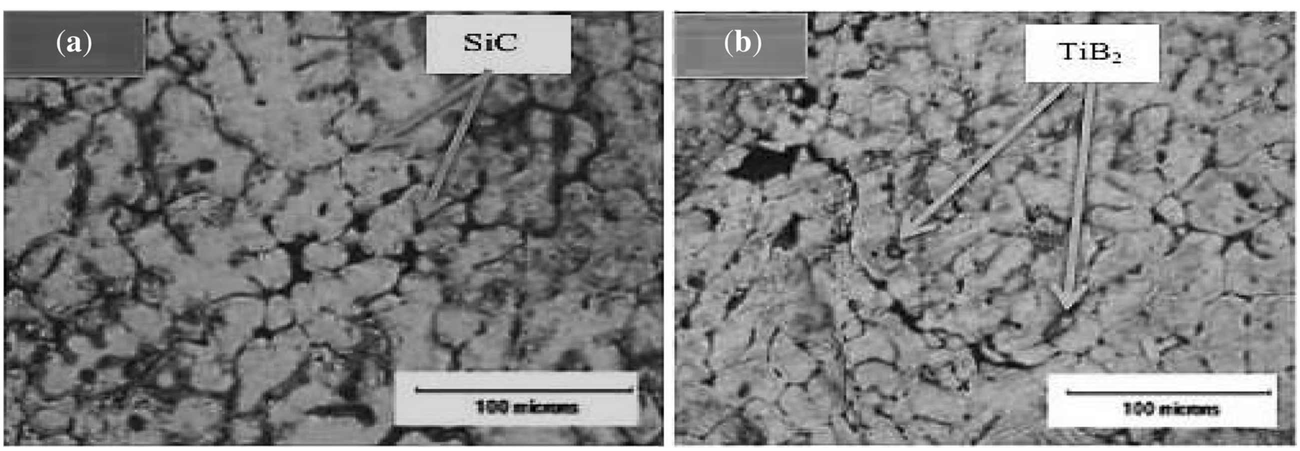


Figure 17. Optical microscopic images of Al-6061/SiC/TiB_2. (a) Al-6061/5 wt% SiC/2 wt%TiB_2. (b) Al-6061/5 wt% SiC/4 wt% TiB_2, adapted from [35].

The AA-6061/TiC MMC was fabricated by Gopalkrishan and Murgun [92] through stir route of casting technique to assess the wear behavior of single-reinforced composite. The effects of TiC particulates (3, 5, 7 wt% of TiC) on tribological properties of reinforced composite were studied at different loads and sliding velocities. It was seen from wear plots that WR of composite increased gradually with increasing normal load and sliding velocity. However, the SWR of TiC/AA-6061 MMC increased steeply with the accumulation of TiC particulates for different wear parameters. This behavior is mainly due to the thermal softening of material, which causes sharp plastic deformation on the surface of AA-6061/TiC resulting in high wear rate. In a separate research Ramesh *et al* [93] developed Al-6061/TiO_2 MMC by stir casting route to evaluate the wear coefficient (WC) of the reinforced composite; 2/10 wt% of TiO_2 and 1 wt% of Mg with 20 μm particle size were cast to analyze the VWL and WC. The WC was validated using predicted value (Archer and Yang model) and experimental value under various sliding distance and loading conditions. The results indicated that the wear loss of reinforced composite was much lower than that of the un-reinforced alloy. The VWL of composite is attributed to heavy deformation and materials loss due to the thermal softening of composite at higher load. From the Archard model of WC, it was observed that the WC of reinforced Al-6061 MMC decreased with incorporation of 2/10 wt% of TiO_2 at 30 N load and 0.36 km rubbing distance. This behavior is mainly because of the harder TiO_2 content, which increases the hardness of the composite. The values obtained from experimental and predicted models for WC are approximately similar, which confirms that the results attained by the Archard model for WC are accurately predicted. Further, tribological properties of AA-6061/titanium debride

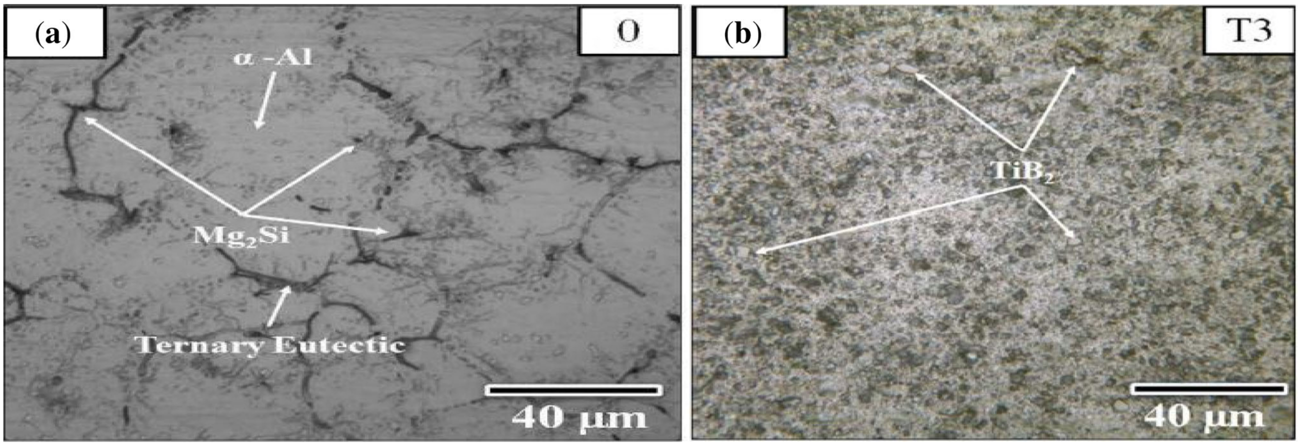


Figure 18. Optical photomicrographs of aluminum 6061 reinforced with TiB_2. (a) Al-6061 (O) pure alloy. (b) Al-6061 (T3) + 3 wt% TiB_2, adapted from [101].

(TiB_2)-reinforced MMC were investigated by Suresh and Moorthi [94]. Varied weight fractions of TiB_2 v were 0, 4, 8 and 12%. The wear tests of AA-6061/TiB_2 MMC were studied under different applied loads and rotational speeds. From wear results it was observed that on increasing wt% from 0 to 12, the WR of reinforced composite increased marginally. However, the value of COF was maximum at a low wt%; thereafter it declined gradually with increasing wt% of TiB_2.

Mummourthni *et al* [95] studied the Al–Mg–Si (Al-6061) MMC using 5 wt% of Fe_2O_3 and 2, 4, 6 wt% of B_4C. In this research the wear characteristics like WL, SWR and COF were evaluated. The wear specimen was dispersed at stir speed of 250 RPM for 10 min. The result obtained from wear study indicated that the SWR of hybrid composite decreased by 77% at 20 N load and 85% at 40 N load when compared with AA-6061. The marginal improvement in WR was due to work hardening effect of harder Fe_2O_3 and B_4C particles on the surface of matrix alloy (Al-6061). The COF of Al-6061/Fe_2O_3/B_4C increased up to 5:2 wt% of Fe_2O_3:B_4C. In other relative research by Monikadan *et al* [96], the tribological performance (WL and COF) of AA-6061 MMC with single-reinforced B_4C particles (10 wt%) was investigated. The wear test on fabricated AA-6061/B_4C composite was performed according to G99-05 ASTM standards using a pin on disk wear tribometer. The wear parameters like load, sliding velocity and rubbing distance were used to evaluate tribological characteristics. It is noticed from results that with the addition of normal load and sliding distance, the WL and COF of reinforced composite increase gradually; however the WL and COF reduced at higher sliding speed. This performance is attributed to the formation of a mechanical mixed layer (MML) on the contact surface of specimen, which reduces the WR and COF of AA-6061/B_4C MMC.

Further, Lakshmikanthan and Prabu [97] observed the effect of input parameters on tribological properties of stir cast Al-6061 MMC reinforced with 3, 6, 9, 12 and 15 wt% of CSA; 10 N applied load, 15 m/s sliding velocity and 1 km sliding distance were selected in this research to investigate the wear behavior of fabricated composite. It is noticed from wear graphs that up to 6 wt% of CSA, the wear rate decreases at a slower rate; thereafter it advances steeply with the addition of CSA. However, on increasing sliding distance, the wear rate gets reduced under all loading conditions. In a separate work, Prakash *et al* [98] evaluated the effect of rock dust (RD), cenosphere (CENO) and E-waste glass reinforcements on dry sliding wear properties of Al-6061 HMMC. Nine experiments were performed using an equivalent proportion of 5, 10 and 15 wt% with 40 µm particle size. The results obtained for Al-6061/RD/E-waste HMMC shown in Fig 16(a) show that the accumulation of particulate reinforcements significantly reduces the wear rate of composite. However, from figure 16(b) it is analyzed that the wear rate exhibited by MMC is higher than that by HMMC. Finally, it was concluded from research that cenosphere and E glass reinforcements showed better wear results than RD. According to Sharma [99] input parameters have significantly affected the SWR and COF of Al-6061/garnet MMC. The SWR increases with an increase in applied load and sliding velocity from 10 to 50 N and 1.25 to 3.05 m/s, respectively. The average COF of developed composite reduced with increasing reinforcement particulates, sliding velocity and sliding distance. It is finally concluded from the results that formation of the hard layer at the surface of composite acts as a solid lubricant, which reduces wear rate and frictional coefficient. Further, Chethan *et al* [100] studied the tribological performance of stir cast Al-6061 hybrid-reinforced MMC using 1, 2 and 3 equal wt% of bamboo char (BC) and B_4C. It was analyzed through results that the WR of the HMMC increased with the incorporation of BC and B_4C reinforcements whereas the SWR of composite decreased with increasing applied load and sliding speed.

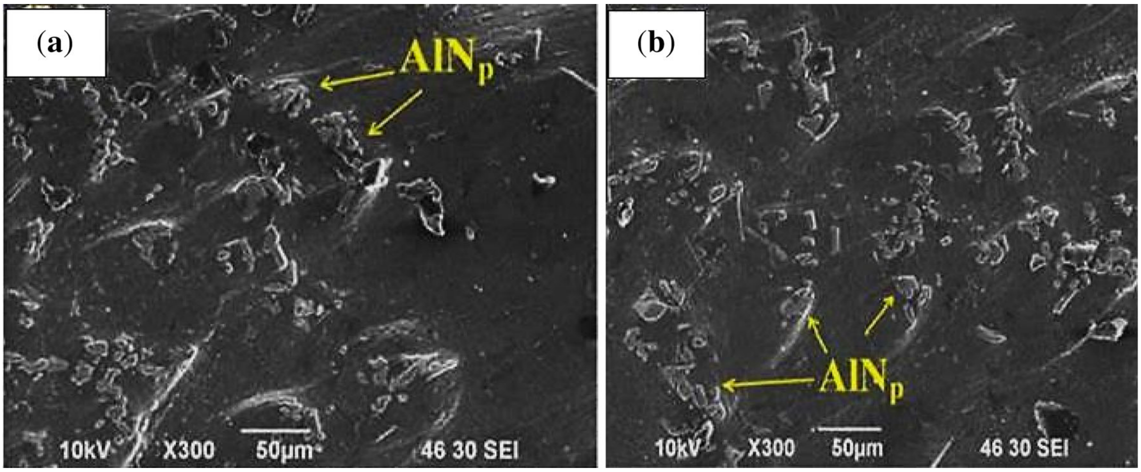


Figure 19. SEM photomicrographs of AA-6061/AIN$_p$ composite. (a) AA-6061/10 wt% AIN$_p$. (b) AA-6061/15 wt% AIN$_p$, adapted from [68].

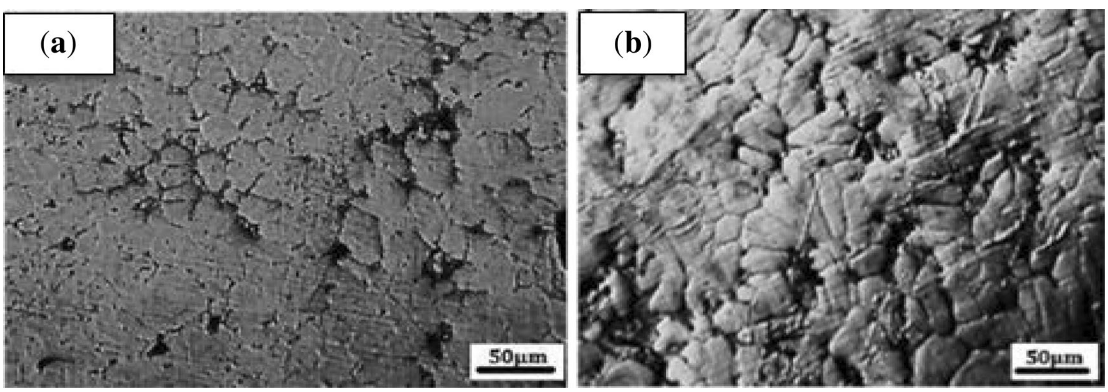


Figure 20. Optical microstructural images of Al-6061/nano-Al_2O_3. (a) Al-6061 matrix alloy. (b) Al-6061/0.5 wt% nano-Al_2O_3, adapted from [106]

Furthermore, it is revealed from the study that the average COF of hybrid composite gets stabilized at lower rotational speed and longer sliding distance. The enhanced wear behavior of HMMC is attributed to the dispersion of B_4C and BC contents in which BC particulates act as solid lubricants and B_4C particulates prevent surface deformation, resulting in improved WR of Al-6061/BC/B_4C HMMC.

Amongst several considerable studies on tribological performance of Al-6061 MMC, the presence of Gr significantly improves the WR and COF of composite [77, 78, 82]. This is due to the fact that graphite itself acts as a solid lubricant, which forms a protective layer between wear sample and counterpart that possibly reduces friction between rubbing areas [88, 89]. In several research works on Al-6061 MMC the hardness of SiC, Al_2O_3, TiC and B_4C particulates resisted the plowing action due to establishment of MML on the contact surfaces, resulting in improved WR [71, 72, 77, 85, 88, 89, 96]. Further, agro-industrial waste (CSA, FA, BC and RM) also contributed to reduce the WR and COF of AA-6061 MMC [90, 97, 100].

From the tribological outcome with numerous reinforcements it was concluded that Al-6061 MMC exhibited superior tribological characteristics than Al-6061 base alloy. The wear rate of composite increases with increasing sliding speed, applied load and sliding distance; however, with the accumulation of reinforcement wt%, the wear rate of cast composite decreases drastically. It is also revealed from studies that amongst various wear parameters the applied load is the most significant factor that highly influences the tribological properties of Al-6061 MMC. The thermo-mechanical effect is quoted as the reason for the material loss due to the thermal softening of materials.

3.3 *Microstructural characterization of stir cast Al-6061 MMC.*

The surface morphology and fractography analysis of stir cast Al-6061 MMC with different reinforcements has been reviewed and discussed here with OM and SEM photomicrographs.

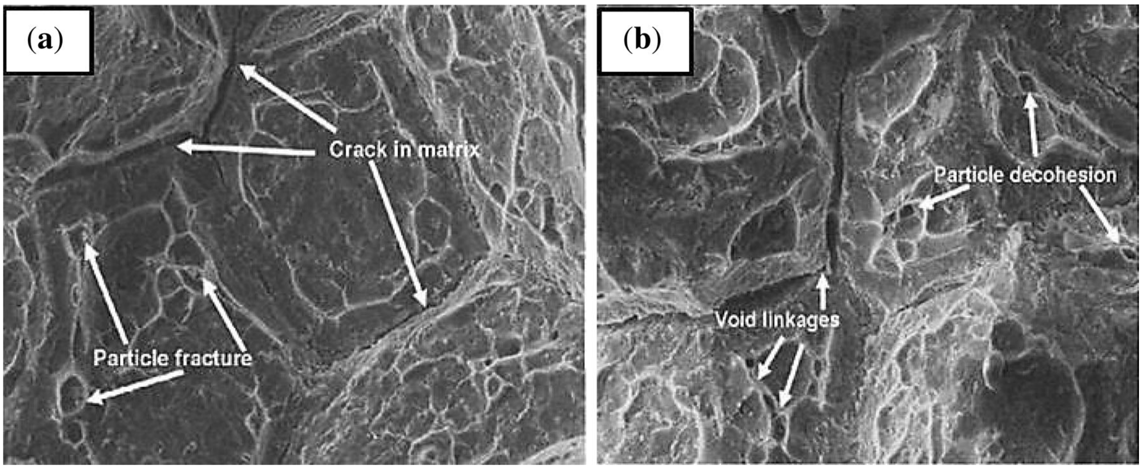


Figure 21. SEM fractographs of Si_3N_4-reinfoced Al-6061 composite. (a) Tensile fracture of reinforcing phase and matrix. (b) Decohesion and void between Al-6061 and Si_3N_4 reinforcement, adapted from [108].

Hillary *et al* [35] assessed the microstructural behavior of Al-6061/SiC/TiB_2 HMMC with hexafluorotitanate (K_2TiF_6) salt. The pre-heating of reinforcements was done at 800°C (SiC) and 250°C (TiB_2) to remove moisture content and other impurities. The mechanical stirring was performed at 600 RPM for 15 min. It is observed from the experimental study that as the wt% of TiB_2 increases the nucleation sites increase and the grain size decreases. The microstructural images illustrated in figure 17 show the presence of SiC and TiB_2 particulates inside Al-6061 alloy. The addition of K_2TiF_6 salt improves the wettability between melt and particles, which results in homogeneous distribution of reinforcements particles inside the matrix. It was concluded from microstructural analysis that the optimized stir parameters were responsible for achieving good bonding between matrix and reinforcements. In another study, Pazhouhanfar and Eghbali [101] investigated the morphology behavior of TiB_2-reinforced Al-6061 MMC. In this study the uniform distribution of TiB_2 particles was seen through OM and SEM micrographs around the intergranular and transgranualar regions of the Al-6061 matrix without any agglomerations. The microstructure of reinforced composite illustrated in figure 18 shows the presence of Mg_2Si (thin black layer), and ternary eutectic phase is also seen in some regions of AA-6061. The preheating of TiB_2 content at 250°C for 2 h and addition of k_2TiF_6 salt were reported as the reason for strong bonding between AA-6061 and TiB_2 particles.

In a separate work, Moses *et al* [102] have studied the effect of various process parameters (stir speed, stir time, stir blade angle and casting temperature) on morphology analysis of stir cast AA-6061/15% TiC MMC. The microstructural results revealed that low stirring speed (100 RPM) and minimum stirring time (5 min) are responsible for poor distribution of particles inside the melt. However, as the stirring speed and stirring time increased, respectively, from 100 to 500 RPM and 5 to 25 min, the

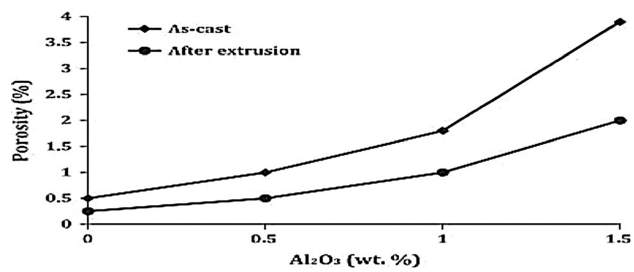


Figure 22. Effect of nano-Al_2O_3 wt% on porosity % of Al-6061 MMC [106].

dispersion of TiC inside AA-6061 improved significantly and fair distribution of particulates was also seen. Further, it was reported that 30° blade angle gave uniform distribution of TiC inside AA-6061 with no particle clustering whereas at 0° and 60° blade angles, heterogeneous distributions with more agglomeration were also observed. Further, it was revealed from microstructure that at low casting temperature (650°C) the particles distributed heterogeneously inside the melt due to low viscosity and high frictional resistance; however, high casting temperature (1030°C) resulted in large amount of porosity content. The optimum value of casting temperature obtained is 850°C, which reduces the viscosity and porosity of as-cast composite and results in homogenous distribution of particles inside Al-6061 MMC. In another research, Guan *et al* [103] have also investigated the impact of stirring parameters on microstructural characteristics of Al-6061 MMC. The reinforced composite amalgamated with 5 wt% of aluminum borate whisker (ABO_w) and 5 and 15 wt% of SiCp. The sizes of ABO_w and SiCp reinforcements were 1 and 8/14 μm, respectively. The dispersion of stir cast Al-6061/SiCp/ABO_w MMC was done using a mechanical stirrer at 300 RPM for 10 min at different cast temperatures of 680, 650, 640 and 630°C. The photomicrograph reveals that the

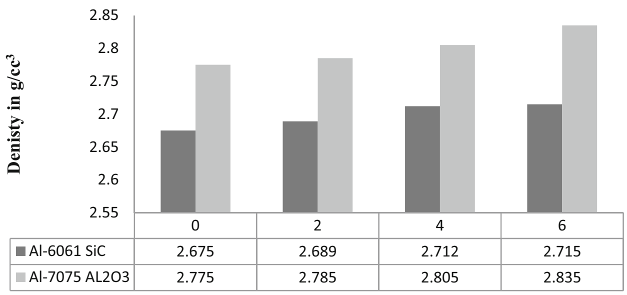


Figure 23. Comparison of experimental density between SiC/Al-6061 and Al_2O_3/Al-7075 MMC [75].

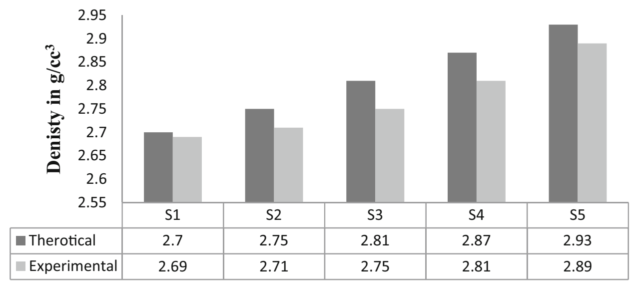


Figure 24. Theoretical and experimental density of Al-6061/Fe_2O_3/B_4C HMMC vs. wt% of reinforcements [95].

homogeneity of as-cast composite increases with decreasing stir temperature and increasing stir time. Experimental results demonstrated that amongst different casting temperatures, 640°C showed homogeneous microstructure without any particle clustering and agglomeration.

Further, Auradi *et al* [104] evaluated the microstructural behavior of Al-6061 MMC reinforced with B_4C. The composites were fabricated through a two-step mixing technique using 5/20 wt% B_4C of 88 μm particulates size with $K_2T_iF_6$ salt. The SEM micrograph of Al-6061/B_4C MMC with single-step mixing showed non-homogeneous dispersion of reinforcements inside the Al matrix with large particulates clustering. However, two-step mixing process resulted in fair distribution of B_4C particles within the Al-6061 matrix without any voids and clustering of particles. The presence of halide salt ($K_2T_iF_6$) also improved the wettability between Al-6061 and B_4C. In another investigation, Kalaiselvan *et al* [105] studied the microstructural analysis of stir cast AA-6061/B_4C MMC at 4, 6, 8 and 10 wt%. OM images showed uniform distribution of reinforcement inside the matrix and it was uniformly distributed in all regions of the matrix; however, small traces of Ti layer were also noticed. It was found from EDAX analysis that 1.35% of Ti compound was present due to the incorporation of k_2TiF_6 flux that was added for removing oxides from base matrix and to ensure uniform wettability between AA-6061 and B_4C content. The uniform distribution of reinforcement inside the matrix could be due to similar density of B_4C (2.52 g/cm^3) and Al-6061 (2.7 g/cm^3).

In a research, the microstructure of AA-6061/aluminum nitride (AIN) MMC was investigated by Kumar and Murugan [68]. The composites were prepared through stir casting route at an agitator speed of 450 RPM for 20 min. The SEM photomicrograph illustrated in figure 19 shows clear interfacial bonding between AIN_p and AA-6061 and the AIN_p particles are distributed uniformly within the matrix without any cracks and porosity. However some traces of Mg_2Si are also present in several regions of the matrix, which according to the study was the element present in matrix alloy and additional Mg as a wetting agent. Further, Ezatpour *et al* [106] investigated the microstructure characteristics of stir cast Al-6061 MMC using nano-alumina (Al_2O_3) particulates. The photomicrographs shown in figure 20 indicate the fair distribution of Al_2O_3 particles inside the Al-6061 matrix with small voids and agglomerations. It is concluded from the experimental outcome that these voids increase with increasing wt% of alumina particles and this is primarily due to the entrapment of gases during melting. SEM results of fabricated composite demonstrated the iron-rich phase (Fe_3SiAl_{12}) with Al_2O_3 agglomerated particles and also occurrences of some nucleation pores around inter-grain regions. The presence of Fe_3SiAl_{12} was mainly due to the milling of alumina particles with steel balls. In another research Srivastava and Chaudhari [107] studied the fracture analysis of tensile specimens having 1, 2 and 3 wt% of alumina nanoparticles (70 nm) through microstructural characterization. The SEM fractography of Al-6061/Al_2O_3 specimens revealed small dimples and cleavages that showed mixed-mode fracture for 1NC and 2NC specimens as there was no uniform bonding between matrix and reinforcement; however, for 3NC specimen the brittle fractured mode was reported due to uneven cracks and grain size. In the same way Ramesh *et al* [108] have also investigated the tensile fractured behavior of AA-6061 alloy and AA-6061/Si_3N_4 MMC through SEM analysis; 4, 6, 8 and 10 wt% of Si_3N_4 particles of 2/10 μm particle size were reinforced inside the Al-6061 matrix via stir casting method. It was revealed from microstructure images that the base alloy (AA-6061) showed large and uniform voids, which indicated ductile fracture, whereas AA-6061/Si_3N_4 composite showed brittle fracture due to the presence of non-uniform smaller grains. The SEM results in figure 21 show that the possible fracture mechanism of tensile specimens is due to non-uniformity of voids and nucleation of microcracks that cause de-bonding between Si_3N_4 and Al-6061. Further, Mahadevan *et al* [110] performed fatigue fracture examination on heat-treated Al-6061/SiCp composite using SEM fractography. The samples of fatigue fracture were solutionized at 530°C for 1 and 3 h followed by aging at 170°C for 4 h. The SEM photomicrograph revealed that fractured samples failed partially due to ductile fracture as confirmed through dull marks in a perpendicular direction of crack initiation.

Table 7. Density and porosity results of stir cast Al-6061 MMC.

Sr. no.	Nomenclature	Theoretical Density (g/cm^3)	Experimental Density (g/cm^3)	Porosity (%)	References
1	Al-6061	–	2.68	–	
	Al-6061/1wt% SiC	–	2.69	–	
	Al-6061/2wt% SiC	–	2.70	–	[5]
	Al-6061/3wt% SiC	–	2.71	–	
	Al-6061/5wt% SiC	–	2.72	–	
2	Al-6061	2.70	2.68	0.74	
	Al-6061/2wt% SiC	2.71	2.69	0.73	
	Al-6061/4wt% SiC	2.72	2.71	0.367	[40]
	Al-6061/6wt% SiC	2.73	2.72	0.366	
	Al-6061/8wt% SiC	2.74	2.73	0.364	
3	Al-6061	–	2.67	–	
	Al-6061/5 wt% SiC/5 wt% Al_2O_3/5 wt% FA	–	2.48	–	
	Al-6061/7.5 wt% SiC/7.5 wt% Al_2O_3/5 wt% FA	–	2.56	–	[48]
	Al-6061/10 wt% SiC/10 wt% Al_2O_3/5 wt% FA	–	2.44	–	
4	Al-6061/2.5 wt% Al_2O_3/2.5 wt% RM	2.72	2.64	2.94	
	Al-6061/5 wt% Al_2O_3/5 wt% RM	2.74	2.65	3.28	[50]
	Al-6061/7.5 wt% Al_2O_3/7.5 wt% RM	2.76	2.66	3.62	
	Al-6061/10 wt% Al_2O_3/10 wt% RM	2.78	2.67	3.95	
5	Al-6061	2.7	2.67	0.9	[54]
	Al-6061/9 wt% B_4C	2.68	2.59	3.1	
6	Al-6061	–	2.69	–	
	Al-6061/2 wt% Fe_2O_3	–	2.48	–	[57]
	Al-6061/4 wt% Fe_2O_3	–	2.73	–	
	Al-6061/6 wt% Fe_2O_3	–	2.79	–	
	Al-6061/8 wt% Fe_2O_3	–	2.81	–	
7	Al-6061	2.7	2.69	0.37	
	Al-6061/1 wt% CSA	2.68	2.66	0.75	[64]
	Al-6061/2 wt% CSA	2.62	2.60	0.76	
	Al-6061/3 wt% CSA	2.58	2.59	0.38	
8	AA-6061	2.70	2.68	0.74	
	AA-6061/2 wt% SiC	2.71	2.69	0.73	[76]
	AA-6061/4 wt% SiC	2.72	2.70	0.735	
	AA-6061/6 wt% SiC	2.73	2.73	–	
9	Al-6061	2.7	2.685	0.56	
	Al-6061/2 wt% SiC/0.5 wt% Gr	2.71	2.669	1.51	
	Al-6061/2 wt% SiC/1 wt% Gr	2.704	2.648	2.1	
	Al-6061/2 wt% SiC/1.5 wt% Gr	2.701	2.603	2.5	[77]
	Al-6061/2 wt% SiC/2 wt% Gr	2.698	2.594	2.9	
	Al-6061/2 wt% SiC/3 wt% Gr	2.695	2.569	3.2	
	Al-6061/2 wt% SiC/3 wt% Gr	2.695	2.569	3.2	
10	Al-6061	2.70	2.67	11.1	
	Al-6061/2.5 wt% Al_2O_3/2.5 wt% SiC/	2.73	2.71	7.3	
	Al-6061/5 wt% SiC/5 wt% Al_2O_3	2.77	2.76	3.5	
	Al-6061/7.5 wt% SiC/7.5 wt% Al_2O_3	2.81	2.80	13.6	[79]
	Al-6061/0.5 wt% REP 2.5 wt% Al_2O_3/2.5 wt% SiC/	2.76	2.75	3.62	
	Al-6061/1.5 wt% REP 5 wt% SiC/5 wt% Al_2O_3	2.80	2.79	3.57	
	Al-6061/2.5 wt% REP 7.5 wt% SiC/7.5 wt% Al_2O_3	2.84	2.83	3.52	
11	Al-6061	2.7	2.69	0.37	
	Al-6061/5 wt% Fe_2O_3	2.75	2.71	1.45	
	Al-6061/5 wt% Fe_2O_3/2 wt% B_4C	2.81	2.75	2.13	[95]
	Al-6061/5 wt% Fe_2O_3/2 wt% B_4C	2.87	2.81	2.09	
	Al-6061/5 wt% Fe_2O_3/6 wt% B_4C	2.93	2.89	1.36	
12	Al-6061	–	–	0.5	
	Al-6061/0.5 wt% Al_2O_3	–	–	1.1	[106]
	Al-6061/1 wt% Al_2O_3	–	–	1.8	
	Al-6061/1.5 wt% Al_2O_3	–	–	4	

Table 7 continued

Sr. no.	Nomenclature	Theoretical Density (g/cm^3)	Experimental Density (g/cm^3)	Porosity (%)	References
13	Al-6061/5 wt% Al_2O_3	2.76	2.734	0.95	[109]
	Al-6061/5 wt% Al_2O_3/4 wt% BA	2.728	2.695	1.2	
	Al-6061-5wt% Al_2O_3-6wt% BA	2.712	2.669	1.58	
	Al-6061/5 wt% Al_2O_3/8 wt% BA	2.696	2.635	2.26	

Table 8. Key findings of Al-6061 MMC on overall characterization.

Sl. no.	Properties	Key findings
1.	Mechanical	Max. UTS of 310 MPa is obtained with Al-6061 MMC reinforced with 20 wt% Al_2O_3
		Max. UCS of 894.13 MPa is obtained with Al-6061 MMC reinforced with 4 wt% WC
		Max. macro-hardness of 107.5 BHN is obtained with Al-6061 MMC reinforced with 12 wt% Al_2O_3/6 wt% MoS_2
		Max. impact strength of 46 J is obtained with -reinforced Al-6061 MMC reinforced with 2.5 wt% REP/7.5 wt% Al_2O_3/7.5 wt% SiC
2.	Tribological	Max reduction of 73% is obtained in wear rate
		Wear resistance improved by 87.20% with SiC/Al_2O_3/REP when compared with base alloy
		FGRA reported 30 N, 3 m/s and 500 m as optimized parameters with superior wear properties
		Presence of rare earth metal, talc and graphite reinforcements worked as solid lubricant
3.	Microstructural	The pre-heating of reinforcements and addition of K_2TiF_6 and Mg improves the wettability between matrix and reinforcements
		For tensile specimens, brittle mode of fracture was observed
		Above 15 wt%, large clustering and voids were seen
		Low stir speed and minimum stir time results in non-homogeneous distribution
		Two-step mixing showed better microstructure than single-step mixing
		The optimized stir parameters reported for homogenous distribution are as follows: stir speed: 300/500 RPM, stir time: 5/15 min, casting temperature: 650/850°C
8.	Physical	Al-6061/SiC MMC possesses lesser experimental density than Al-7075/Al_2O_3 MMC
		Compared with ceramic reinforcements (SiC, Al_2O_3, B_4C) agro-industrial reinforcement showed lesser density
		In most studies, porosity % increases with addition of wt% except REP/SiC/Al_2O_3-reinforced Al-6061 MMC

Moreover there was no sign of dimples over the crack surface but strong evidence of striation marks within the crack propagation region, indicating ductile mode of fracture. Finally, it was concluded that the presence of ductile dimples inside the fracture surface confirmed the uniformity of SiCp inside the Al-6061matrix.

From microstructure analysis, it is observed that the particulate reinforcements disperse randomly inside the matrix alloy without any specific orientation. The presence of particles inside the matrix phase is clearly visible with fair distribution; however, some cracks and particle clustering were also observed at some regions. The SEM fractography of tensile specimens revealed de-bonding and particles fracture, which are mainly responsible for the brittle mode of fracture. Finally, it is concluded from these photomicrographs that above certain level of reinforcements the particle clustering and agglomeration start developing, which results in non-homogeneous dispersion of particulates inside MMC.

3.4 *Density and porosity analysis of stir cast Al-6061 MMC.*

The aluminum alloys are conventionally reinforced with particulates reinforcements like B_4C (2.52 g/cm^3), SiC

Table 9. Applications of Al-6061 MMC with various particulates reinforcements.

Sl. no.	Material	Applications	Components	References
1.	SiC-reinforced Al-6061MMC	Marine and automobile	Propeller shaft, brake rotors, calipers, brake rotors, liners, connecting rod, driveshaft, brake disc and engine cradle	[19, 22, 52]
2.	Al_2O_3-reinforced Al-6061 MMC	Internal combustion engine and high-temperature applications	Engine piston, engine cylinder head, brake, cardan shaft	[21]
3.	B_4C-reinforced Al-6061 MMC	Defense and wear resistance application	Armor tanks, bullet proof vest, cam shaft, valves	[19, 52]
4.	Gr-reinforced Al-6061 MMC	Space application and heavy duty applications	Hubble Space Telescope, engine bearing, piston ring, engine value, cylinder liner, cam shaft	[20]

(3.2 g/cm^3) and Al_2O_3 (3.9 g/cm^3), which enhance the density of as-cast composite [111, 112]. However, in several studies, addition of light-weight agro-industrial waste such as FA (2.1 g/cm^3), BA (1.95 g/cm^3) and RHA (2 g/cm^3) reduces the density of MMC [113, 114]. The experimental density of cast composite is calculated using the Archimedes theory, whereas theoretical density is discovered by rule of mixture [115–117]. Moreover, the porosity percentage is evaluated by comparing experimental density and theoretical density [109]. In this section, the effects of various particulate reinforcements on density and porosity of Al-6061 MMC are discussed.

Ezatpour *et al* [106] examine the effect of nano-alumina particles on the porosity of cast Al-6061 MMC and it is observed from figure 22 that with the addition of nanoparticles from 0 to 1.5 wt%, the porosity percentage of as-cast composites increases from 0.5% to 4%. Similar findings of increased porosity % with increasing reinforcement % were also reported by several researchers [36, 54]. In another work, Reddy *et al* [77] studied the theoretical density, experimental density and porosity % of Al-6061 HMMC reinforced with SiC and Gr and it was analyzed from experimental results that porosity % of Al-6061/SiC/Gr HMMC increased from 0.56% to 3.2%. Moreover, as compared with single-reinforced composite (Al-6061/SiC), the hybrid-reinforced composite (Al-6061/SiC/Gr) possesses lower density and this can be due to the presence of light-weight graphite (2.26 g/cm^3) particulates. A separate study was conducted by Sharma *et al* [79] on porosity %, theoretical density and experimental density of Al-6061 HMMC with triple reinforcements (Al_2O_3/SiC/CeO_2) and it was discovered from experimental results that Al-6061/Al_2O_3/SiC/CeO_2 composite exhibited higher density than base alloy and it increased linearly with the accumulation of Al_2O_3/SiC/CeO_2 reinforcements. In this study another finding reveals that the porosity of Al-6061 alloy is reported to be 11.1%, which significantly reduces to 3.52% with the addition of 2.5 wt% REP (CeO_2) and 7.5 wt% of SiC and Al_2O_3. Further, Kumar *et al* [75] perform comparative analysis on experimental density of Al-6061/SiC MMC and Al-7075/Al_2O_3 MMC; it is observed from the experimental outcome that Al-6061 reinforced composite exhibits lower density than Al-7075 reinforced composite and the comparisons of results are illustrated in figure 23. In research work [47, 52, 75], on SiC/Al-6061 MMC, it has been investigated that the incorporation of SiC inside the base matrix increases the density of Al-6061 alloy linearly. Similar results of increased density with addition of different reinforcements (Al_2O_3 and Fe_2O_3) were observed by various authors [91, 95]. The variation of theoretical and experimental density of Al-6061/Fe_2O_3/B_4C MMC is demonstrated in figure 24 [63, 95]. However, in a separate study on AA-6061-SiC/Al_2O_3/FA HMMC, Hima Gireesh *et al* [48] reported lesser density of reinforced HMMC than un-reinforced Al-6061 alloy. In this study the reverse trend of

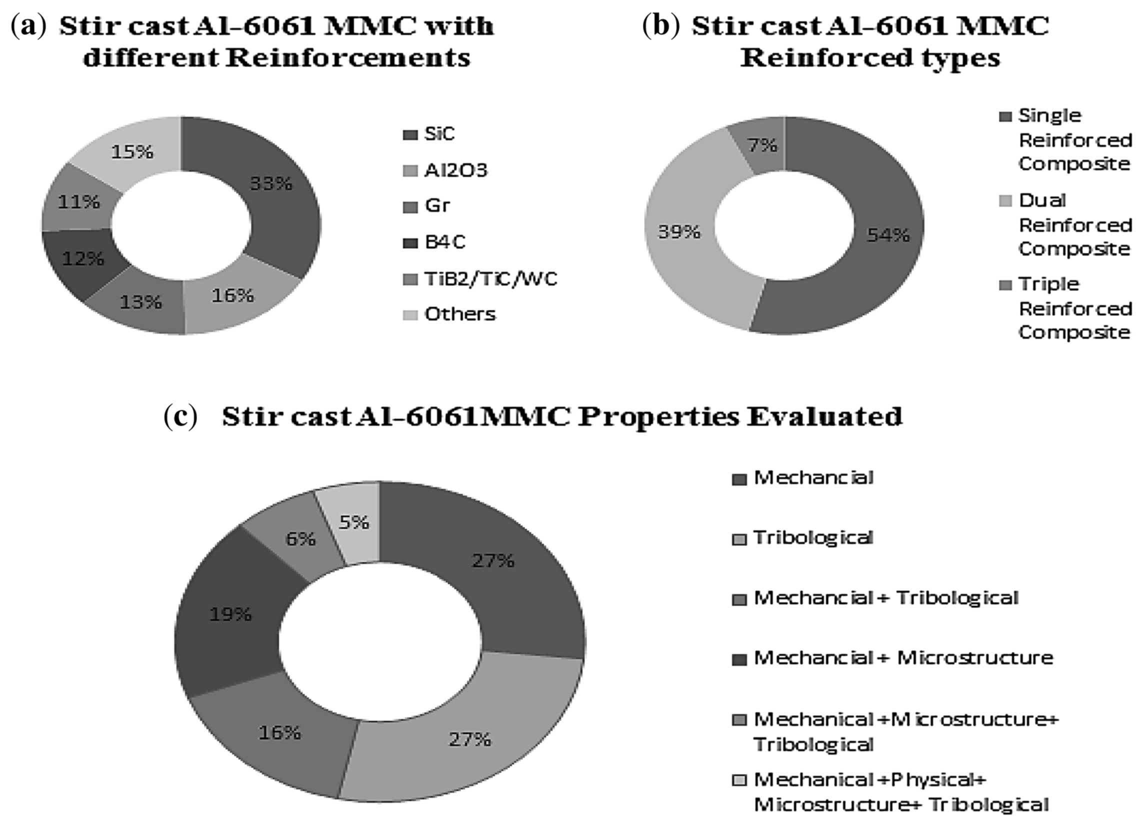


Figure 25. Analysis of stir cast Al-6061 MMC. (a) Al-6061 MMC with different reinforcing materials. (b) Al-6061 MMC with single, dual and triple reinforcements. (c) Al-6061 MMC with different properties.

decreasing density (2.67/2.44 g/cm^3) with incorporation of particulate reinforcements (SiC, Al_2O_3, FA) was also observed. However in separate works, a similar finding is obtained by other researchers [65, 109] in which the incorporation of agricultural waste such as CSA and BA reduces the density of as-cast Al-6061 MMC. In another research on Al-6061/B_4C MMC, Rajesh *et al* [55] obtained a similar behavior. In this study the fabricated composite possesses lower density than Al-6061 alloy, and according to the authors this is due to the presence of light-weight boron carbide (2.52 g/cm^3) particulates inside the Al matrix. Finally, it is observed that as compared with conventional reinforcements the agro-industrial reinforcements exhibit lesser experimental density. The reported works on theoretical and experimental density of stir cast Al-6061 MMCs with porosity % are illustrated in table 7.

4. Summary

In this research, the mechanical, tribological, microstructural and physical properties of Al-6061 MMC are discussed briefly and on that basis the major key findings are listed in table 8. The results obtained through considered research consolidate that the addition of particulate reinforcement in various combinations significantly improves the mechanical and tribological performance of Al-6061 MMC. However, amongst numerous reinforcements, Al_2O_3, SiC and TiB_2 marginally contribute to mechanical strength whereas Gr and B_4C enhance the tribological characteristics. The incorporation of industrial and agro-waste (FA, RM, BA, CSA, BCA) as secondary reinforcements also shows high potential with enhanced mechanical and tribological properties of

Al-6061 MMC. Based on the literature survey, it is discovered that the dispersion of SiC, Al_2O_3, B_4C and Gr with Al-6061 alloy finds several engineering applications in automobile, aerospace and defense sectors. The key applications of Al-6061 MMC with specific components are illustrated in table 9. The concluding remarks of literature work on stir cast Al-6061 MMC through single, dual and triple reinforcements with various process parameters are summarized in figure 25(a)/(c). It is observed from figure 25 that in comparison with other reinforcements, SiC is reinforced maximum time (35%) with Al-6061 MMC. However, Al-6061 alloy mostly disperses with single reinforcements when compared with dual and triple reinforcements. Amongst overall properties the tribological and mechanical were investigated maximum time by researchers on Al-6061 MMC.

5. Conclusions

The review paper attempted to present a comprehensive research review on the characterization of stir cast Al-6061 MMCs with multiple particulates reinforcements. Based on the literature, following broad conclusions were drawn and discussed as follows.

1. The carbide, oxides, nitrides and agro-industrial reinforcements such as SiC, B_4C, TiC, WC, TiB_2, Al_2O_3, TiO_2, ZrO_2, MoS_2, Fe_2O_3, Gr, FA, RM, CNT and MWCNT in single, dual and multiple reinforcements were successfully incorporated in Al-6061 MMC through stir route of casting process. The accumulation of these reinforcements in particulates form considerably improved the mechanical, tribological and physical performance of Al-6061 composites.
2. The mechanical properties of Al-6061 MMC increased marginally with the addition of particulate reinforcements. Amongst various reinforcements Al_2O_3 SiC, WC and Fe_2O_3 significantly improved the UTS, UCS and hardness of cast Al-6061 MMC. Other reinforcements like FA, RM and glass fiber also strengthened the composites. However, the ductility and impact strength of reinforced composites decreased with an increase in reinforcement wt%.
3. Tribological properties such as SWR, VWR, WR, WL and COF of Al-6061 MMC significantly improved with the addition of solid reinforcements. The Gr, SiC, B_4C and Al_2O_3 particulates significantly improved the SWR and COF of Al-6061 MMC. However, incorporation of Gr was considered to be the best reinforcement for tribological properties due to its self-lubrication effect; it formed a scratch-resistant layer on the surface of as-cast composites, which enhanced the WR and COF of Al-6061 MMC.
4. Microstructural behavior of Al-6061 MMC through photomicrographs revealed that up to some level of reinforcement, uniform interfacial bonding with homogeneous distribution inside the matrix was observed; however, at higher weight fraction some voids, particles clustering, agglomerations and cracks were also reported by many authors.
5. However, addition of Mg and K_2TiF_6 enhanced the bonding and wettability between solid matrix and particulate reinforcements.
6. It was found from physical characterization that theoretical and experimental density of Al-6061 alloy increased with an increase in SiC, Al_2O_3 and Fe_2O_3 and decreased with BA, B_4C and CSA. In the most studied feature, porosity % showed a direct relationship with wt% of reinforcements. However, the presence of light-weight B_4C, Gr, FA, BA and CSA reinforcements was considered to be the most beneficial reinforcement to reduce the density of Al-6061 composites with less porosity %.

6. Future scope

In the current scenario, the need of high-performance, lightweight, low-cost material is increasing day by day amongst academic researchers. From many alternatives, the choice of agro-industrial wastes like groundnut shell ash (GSA), RHA, BLA, maize stalk ash (MSA) and bauxite residue (BR) is gaining more attention for metallurgists in the development of Al-based MMC. The right processing and synthesis of these materials may convert waste into green reinforcements. In the last many years, these waste materials were used in the form of ashes as complementary reinforcement with conventional ceramics reinforcements; however, very less work has been reported with these wastes (agro-industrial) as primary reinforcement. Moreover, the high cost and less availability of ceramic reinforcement pose many challenges for academic researchers. On the other side, the remarkable properties of agro-industrial ashes like availability, light weight, low processing cost, good adhesion, easy to handle and cost effectiveness could maximize the potential of composite materials. The additions of these reinforcements not only reduce the cost of fabricating composites but will improve the various physical, mechanical and tribological properties of developed MMC. Economic utilization of these ashes in powder form might provide alternative engineering materials for the metallurgists in the marine, automotive, defense and aerospace sectors. Furthermore, the limitation of conventional stir casting process could be overcome with the advanced ultrasonic-assisted stir casting processes in combination with bottom pouring vacuum-assisted technique for the production of Al-6061 MMC.

Notations

Al-6061	Aluminum 6061
Al-PMMC	Aluminum particulates metal/matrix composite
ASTM	American Society for Testing and Materials
BHN	Brinell hardness number
COF	Co-efficient of friction
GPa	Pressure in giga pascal
HMMC	Hybrid metal/matrix composite
HV	Vicker hardness
J	Impact energy in joule
MMC	Metal/matrix composite
MPa	Pressure in mega pascal
N	Applied load in newton
OM	Optical microscopy
SEM	Scanning electron microscopy
UCS	Ultimate compressive strength
UTS	Ultimate tensile strength
VHN	Vicker hardness number
YS	Yield strength
WL	Weight loss

SWR	Specific wear rate
m/s	Meter per second
wt%	Weight percentage
g/cm^3	Gram per centimeter cube
°C	Temperature in degree celsius
Ø	Diameter in mm
µm	Micrometer

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