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FABRICATION, CHARACTERIZATION, AND WEDM OPTIMIZATION OF Al-7175 HYBRID COMPOSITES WITH CERAMIC AND SUSTAINABLE WASTE REINFORCEMENTS

Aluminum metal matrix composites are valued for their lightweight nature, high performance, and favorable thermal expansion characteristics, preparing them to be suitable for aerospace, defense, automotive, athletic training equipment, and electronics applications. Al-7175 alloy, widely employed in aerospace for advancing structural components, is selected in this pilot study as a base material. reinforcements included varying weight percentages of Al_2O_3 (2, 4, 6, and 8%), SiC (three levels), and palm kernel shell ash (PKSA) as a sustainable waste-based additive. The composite are fabricated by stir casting method, and test specimens are prepared in accordance with international standards to evaluate stiffness, tensile strength, impact resistance, and wear behavior. The results revealed that incorporating Al_2O_3, SiC, and PKSA enhanced stiffnesses per the additives added in MMCsby1%, 1.5%, 1.6%, and 1.7% (as per the wt.%) and tensile strengthby8%, 10%, and 40, impact resistance by7%, 34%, 25%, and 42%, reduced wear by 2.4%, 22%, and 7.2%due to the synergistic effect of these reinforcements. An L9 orthogonal array and design of experiments (DOE) approach are employed to optimize Wire Electrical Discharge Machining (WEDM) parameters, for minimal surface roughness and optimal material removal rate (MRR). MRR reduction is linked to a higher T_{on}, voltage, wire feed rate, and T_{off} settings, with long-range producing higher MRR at minimum reinforcements level but increases in surface roughness. Optimal WEDM parameters are determined as T_{on} = 5, T_{off} = 5, voltage = 75, and wire feed = 6, enabling efficient and precise production ofAl-7175 hybrid metal matrix composites (HMMCs) reinforced with Al_2O_3, SiC, and PKSA across different weight fractions.

Keywords: AMMC; Al-7175 alloy; SiC; Al_2O_3; PKSA; Mechanical Properties; SEM; WEDM; and L9 Array (DOE); Stir casting

1. Introduction

1.1. Metal matrix composite

Beyond the combination and procurement of conventional materials such as ceramics and metals, there is significant potential for expanding into advanced, unconventional materials like metal matrix composites (MMCs). The precise optimization of constituent components in MMC manufacturing, particularly through the synergistic integration of ceramic reinforcements with metallic matrix alloys, forms the foundation for achieving superior performance. Material selection is driven by desirable attributes such as high efficiency, mechanical stability under thermal and mechanical stress, balanced rigidity and toughness, and, in certain ceramics, specialized sensitivity to operational conditions. Aluminum and silicon carbide, for example, exhibit markedly different mechanical characteristics: their respective Young's module is 70 GPa and 400 GPa, while their coefficients of thermal expansion are 24×10^{-6} °C^{-1} and 35×10^{-6} °C^{-1}. In prior studies, T6-conditioned A-6061/SiC/17p MMCs demonstrated excellent yield performance, achieving a Young's modulus of 510 MPa and retaining 96.6 GPa stiffness, highlighting the substantial mechanical benefits afforded by such reinforcement strategies [1]. Features may be further improved by a more profound understanding of the comparative quantity's structure and the distribution of each component inside

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a compound, as well as the conditions of dispensation. Several mechanistic practices. This method and intricate geometries make it the most suitable production procedure for challenging structures composed of composite materials. Despite the efforts of academics to categorizes various MMCs using the WEDM procedure, very little tedious work has been accomplished [2]. In wire electrical discharge machining (WEDM), tool electrodes are generally made from high-conductivity materials such as copper and brass, with wire diameters usually ranging from 0.10 mm to 0.25 mm. Although the cutting process does not include direct mechanical contact between the wire electrode and the workpiece, material removal is assisted by a series of regulated electrical discharges. These discharges, occurring inside a dielectric medium, release localized thermal energy that melts and vaporizes the workpiece material. The dielectric fluid aids in flushing away the eroded particles and in preserving steady spark production over the machining zone. Continuous and uniform spark discharge is maintained throughout operation; nevertheless, excessive spark output may lead to process instability, eventually prompting termination of the machining cycle [3,4]. Wire electrical discharge machining (WEDM) works without mechanical cutting forces, minimizing tensions at the tool-workpiece contact. This non-contact process is frequently used for creating precision components such as tools, gauges, dies, and intricate fittings. Its performance relies on associated elements, including electrode material, dielectric properties, discharge energy, and pulse characteristics. These parameters greatly impact material removal rate (MRR) and surface roughness (Ra). Optimizing them is tricky, since slight adjustments might generate big performance variances. Therefore, robust experimental designs and multi-objective optimization methodologies are crucial for building trustworthy process-performance correlations and boosting machining efficiency in WEDM applications [4]. Analyzed the specific properties of materials, including High Modulus Matrix Composites (HMMCs), and their appropriateness for component fabrication using electrical discharge machining. Moreover, the inquiry aims to finalizes its authority regarding numerous machining limits to get enhanced surface quality throughout an extensive region [5]. Examined the attributes of composite materials, including many phases, with special emphasis on the elongated configuration of certain phases. Furthermore, it underscores the impact of weight fraction or volume ratios on composite materials, whereby the incorporation of reinforced hard elements inside the matrix may either augment toughness or diminish the integrity of the composites. These effects are contingent upon the capacity and quality of metal matrix composites [6]. Accessibility and cost-effectiveness of particle reinforcements are significant benefits. The incorporation of a cast seems to be an essential component in improving the functioning of MMC and the current area. Cost reductions may be achieved by commercial strategies such as optimizing component components at a reduced cost, using efficient multipart manufacturing methods, and utilizing advanced automation capabilities. The decision to choose stir casting as the preferable process has been finalized. Particulate reinforcements demonstrate reduced cost and enhanced availability. Stir casting has been recognized as a very economical processing method [7].

A substantial amount of demand is being experienced by the industry for the machining of hard materials and the creation of novel geometric product designs. The introduction of automation specifically for the purpose of modernizing processes that are already in place, as well as the growing needs of new sectors, are the primary drivers of this phenomenon. These sectors place a premium on high levels of productivity and the quality of their components, while also working to cut down on the amount of time and money spent on processing. As a result, it is of the highest significance to improve the manufacturing qualities of a particular component by using a prescribed MMC. Additionally, it is essential to achieve a high degree of surface smoothness and overall perfection [8].

While Al-based MMCs have been widely researched, hybrid Al-7175 composites reinforced with Al_2O_3, SiC, and waste-derived PKSA in different weight fractions remain substantially unexplored, especially for WEDM performance. Most known work focuses on single reinforcements, with little multi-objective optimization seeking both high MRR and low Ra. The impact of reinforcement ratios on spark stability, wear, and surface quality is sparsely documented, and few research combine mechanical property assessment with machining performance for process-property mapping. Addressing these gaps, this study aims to develop Al-7175-based HMMCs via stir casting, evaluate their mechanical and wear behavior, optimize WEDM parameters using L9 DOE, and establish correlations between reinforcement content, mechanical performance, and machining outcomes, while assessing the feasibility of incorporating PKSA for sustainable aerospace applications.

1.2. Matrix-metal-aluminum-stand-alone composite

When it comes to metal matrix composites, alloys that are related with aluminum have consistently established themselves as the chosen metal matrix material (MMM) with technological development. The development is basically defined by the broad range of high-end properties that it supplied at a price that is considered to be accessible and is in line with the norms of the market. AMMCs have a number of desirable properties, including increased specific stiffness and potency, enhanced raised thermal characteristics (in contrast to hard components), a defined heat capacity, and thermal expansion. These are only some of the attributes that make AMMCs appealing. AMMCs have been used in a variety of manufacturing processes, including electronic warm up sinks, sheet layers, automobile propel splash fins, components for explosion condensation element, and pressured fuel engines. These AMMCs have also been designed for usage in aviation systems and astronomical receiver reflectors. Due to the fact that these composites contain flexible qualities, they are ideal for a wide range of applications and have a wide variety of significance. Al-7075, Al-6061, A-357, A-359, Al-2618, and Al-2214 are only some of the aspects that have been

TABLE 1

Spectroscopic analysis of Al-7175 alloy composition

Constituent	Cr	Cu	Fe	Mg	Mn	Si	Zn	Ti	Al
wt.%	0.18-0.28	1.2-2	0.2	2.1-2.9	0.1	0.15	5.6	0.1	Bal.

extensively discussed in examine information within the area of exposure. The bulk of these studies have focused on lying on Al.

The spectrometric evaluations of the Al 7175 effort material that are carried out in the current investigation are shown in TABLE 1. Continuous investigation efforts contain prompted by the growing possibility of increased exposure and economic damage as a consequence of the utilization of aluminum metal matrix composites with Al-7175 allocation as a model. This manufacturing procedure needed the insertion of reinforcing components that are based on a matrix material. This matrix material contained a liquefy for a compound. Because of the very high temperature, it is required to approach it. The swirl cast method is a conventional production technique that has been extensively utilized. It demonstrates typical adaptability, which makes it especially well-suited with an AMMC manufacturing process. Fig. 1 depicts the layout of the stir-casting setup, which includes the incorporation of a stirring rod and the selection of stainless steel from the rotary material. These two factors are attributable to the enhanced thermal stability of AMMCs at high temperatures [9,10].

1.3. Stir casting technique

In the process of stir casting, which is a way to make mixed materials that happens in a liquid state, a removable stage (small fibers, porcelain materials) is mixed by turn to liquid-defined existing conditions metals with motorized beauty. When a liquid MMC mixture is sent, it is possible that it could also be taken out of action by a skill for making reliable metal. Swirl Casting stands out as a unique choice in the next features glance. When observed disconnected section live, there is a chance of a non-absolutely uniform homogenous mixture of broadcast (30% in conditions of amount different events taking away their specific meaning). There are now very thin gas threads in the mixture that are made. If contains close attention to a mould subdivision and place it separately, there could be a big difference between an adjustable subdivision and a fixed subdivision. This method is very easy to use and does not cost a lot of money.

2. Methods and procedures

A deep examination used a stir casting process in order to create a composite material that served as the primary focus of the inquiry. More specifically, the research made use of an Al 7175 matrix material, which is used as the basis for the investigation. Reinforcing components, such as silicon carbide with a granule size of 200 lattices, are added to this matrix material in order to strengthen it. Additionally, aluminum oxide is included in this additive amalgamation, which contributed to the formation of fine-grained solid debris known as PSPK. There are many acts involved in the procedure. Casting is the first step, which resulted in the production of a base material that had the necessary characteristics. Following that, the machining process obtain place on a Wire Electrical Discharge Machining (WEDM) platform, with a 0.25 mm dimension bronze thread serving as the primary cutting component. This machining procedure resulted in the fabrication of MMCs with dimensions of 100×100×10 mm, which is achieved by the use of the complex stir casting technique.

The choice of dielectric medium that are used in order to promote the sparking phenomena that occurred between the tool and the work-pieces is the novel component of this method." Within the context of this situation, water is designated as the dielectric medium. The WEDM process is strengthened in terms of its accuracy and efficiency as a result of this selection, which brought a novel component into the equation of machining. Fig. 2 presents a schematic depiction of the WEDM configuration, which may be used to get a better understanding of the system. In order to shed light on the complexities of the process, this graphic provides an explanation of the location and interaction of the components. To summarize, the swirl casting technique, in conjunction with the careful selection of materials and techniques, made it possible to produce complicated MMCs that had dimensions and qualities that are exceptional. After that will utilize a design of experiments (DOE) that makes use of a L9 orthogonal array to modify the other four variables, including pulse-off time, after that have listed all of the distinct variables that may be altered during the procedure in TABLE 2. For the purpose of achieving the desired effect, nano-scale components are first cut, and then the surfaces of the sample pieces are honed using emery paper with varying grits. It is possible for us to achieve a mirror-like quality on both a specimen and an alumina postponement amid rubbing material by using disc polishing equipment. A combination of optical and scanning electron microscopes (SEMs) are used in the process of microstructure creation. By using Keller's reagent, it is possible to etch samples of composite fabrics. A Vickers hardness test is performed on the samples using a weight of 50 grammes in order to measure the amount of toughness. This test is performed after

TABLE 2

Defining the WEDM Procedure

Levels	Process parameters			
	Pulse on Time (TON)	Pulse OFF Time (TOFF)	Voltage Gap (V)	Wire Feed Rate (F)
1	5	9	55	6
2	7	7	75	8
3	9	5	95	10

the microstructure pictures have been taken. The smoothness of the exterior that had been machined using EDM is evaluated with the use of a surface area measuring smoothness device manufactured by Mitutoyo [11,12].

3. Outcome and discussions

3.1. Hardness test

Al_2O_3/SiC/PKSA are added to Aluminum Matrix Metal Composite (ALMMC) at weight percentages of 2-4%, 4-6%, and 6-8%. This is done using the stir casting process. The result is an increase in the hardness of the material. Fig. 1(a) provides a clear illustration of the variations in hardness that occur over a variety of reinforcement concentrations. This figure also highlights the collective hardness distribution of the composite that is produced with average of $n = 3$ trails with standard deviation of 2.8 and Coefficient of effectives ±0.95 with ASTM E10-18. Particularly noteworthy is the fact that the graph unequivocally demonstrates a significant increase in hardness that corresponds to increasing levels of Al_2O_3 and SiC solid waste of PKSA in the composite. By adjusting the added reinforcement, this experiment demonstrates that the swirl casting approach is successful in customizing the characteristics of the material. As a result, the mechanical performance of the ALMMC is effectively influenced.

3.2. Tensile test

Though the tensometer is being used, tensile tests are being carried out on a hybrid aluminum metal matrix composite that has been strengthened with 2, 4, 6, and 8 weight percent Al_2O_3/SiC/PKSA. The findings of these investigations are presented in the usual format together with the data that is displayed in TABLE 3, which ultimately results in the results of the tests of $n = 3$ trails and standard deviation of 4.2 with ASTM E8/E8M-16a. The addition of weight fraction Al_2O_3/SiC/PKSA to AMMCs for the purpose of reinforcing the material also seems to result in an enhancement in the material's tensile strength. This is the conclusion that can be drawn from the evidence presented. Fig. 1(b) illustrates the possibility of an improvement being made, which will lead to an increase in the percentage of Al_2O_3/SiC/PKSA weight that is contained inside a matrix.

3.3. Impact or crash examine

Fig. 1(c) illustrates that the use of strengthening agents such as Al_2O_3/SiC/PKSA results in an increase in weight percentage when the composite material that is being manufactured experiences an increase in its toughness. During the course of this study attempt, included 8 weight percent of Al_2O_3/SiC/PKSA, which demonstrates a high crash potency inside AMMCs.

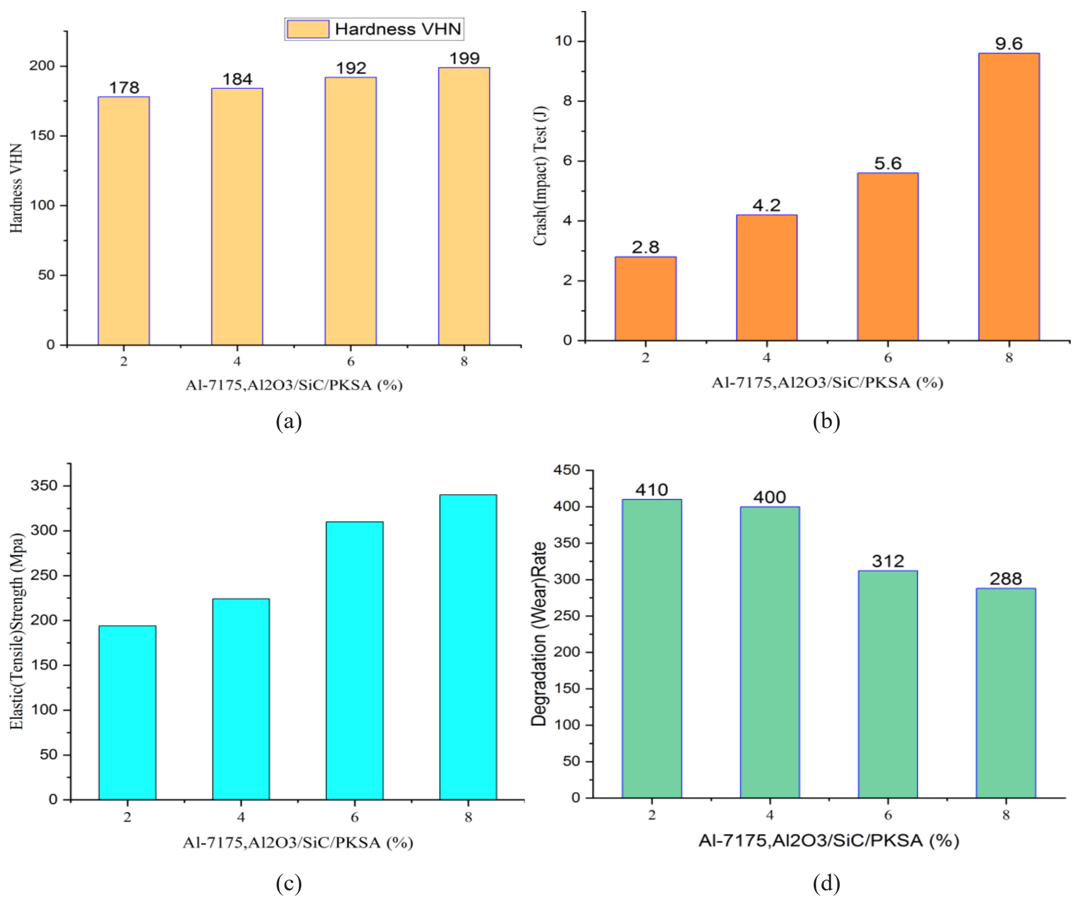

Fig. 1. (a) Average of 3 trails of Al_2O_3/SiC/PKSA wt. v/s Hardness, (b) Average of 3 trails of Al_2O_3/SiC/PKSA wt. v/s Impact Strength, (c) Average of 3 trails of Al_2O_3/SiC/PKSA wt. v/s Tensile Strength (d). Average of 3 trails of Al_2O_3/SiC/PKSA wt. v/s Wear

TABLE 3

Elastic strength, toughness, crash, and degradation data

Examples	Hardness- VHN	Tensile Strength (Mpa)	Crash(Impact) Test(J)	Degradation Rate
Al-7175,Al_2O_3/SiC/PKSA of 2%	178	194	2.8	410
Al-7175,Al_2O_3/SiC/PKSA of 4%	184	224	4.2	400
Al-7175,Al_2O_3/SiC/PKSA of 6%	192	310	5.6	312
Al-7175,Al_2O_3/SiC/PKSA of 8%	199	340	9.6	288

The stir casting process is used in order to include additional strengthening's into the AMMCs. This is done with the purpose of increasing the mechanical strength of the composite material. The fact that a broken test specimen is able to pass both the Izod and the tensile tests adds credibility to the idea that the break is ductile in character. The change in specimen toughness that occurs as a consequence of altering the weight percentage of Al_2O_3/SiC/PKSA inside the compound with one another.

3.4. Wear test

A pin-on-disc test system is used in order to carry out wear testing on the specimens that have been selected or represented as samples of 3 trails of each. There is a recording of the outcomes of an examination. Fig. 1(d) illustrates that average of 3 trails of each specimens a greater degree of reduction takes place when a smaller weight percentage of Al_2O_3/SiC/PKSA is integrated into Al-7175 during the strengthening process through ASTM G99-17 of compositions. The incorporation of a larger weight percent of Al_2O_3/SiC/PKSA into Al-7175 during the strengthening process, on the other hand, results in a reduced wear rate. One reason for this is that graphite has a self-lubricating property that is present in a certain percentage of its weight.

3.5. Manufacturing variables affect effectiveness

The MRR and Ra experimental results are shown in TABLES 4 and 5, which may be accessed here. Additionally, the source process parameters are displayed in this table.

Controlling four factors the Voltage Gap, the Pulse ON Time, the Pulse OFF Time, and the Wire feed Rate is the responsibility of the task that is now being done. The performance

TABLE 4

Process variables and the interactions with MRR investigated

Input Process variables				Output Response of MRR(mm^3/min)			
Pulse on Time	Pulse off Time	Voltage Gap	Wire Feed Rate	Al-7175, 2% Al_2O_3/SiC/PKSA	Al-7175, 4% Al_2O_3/SiC/PKSA	Al-7175, 6% Al_2O_3/SiC/PKSA	Al-7175, 8% Al_2O_3/SiC/PKSA
5	9	55	6	24.52	23.98	24.15	25.85
5	7	75	8	18.12	20.24	21.72	21.98
5	5	95	10	16.28	20.52	17.68	17.96
7	9	75	10	19.12	22.45	21.23	21.85
7	7	95	6	18.58	16.25	14.56	14.92
7	5	55	8	33.24	28.21	21.28	21.62
9	9	95	8	18.54	21.15	15.28	15.21
9	7	55	6	29.51	28.04	22.38	22.68
9	5	75	10	19.02	21.45	21.12	21.54

TABLE 5

Process variables and the interactions Ra investigated

Input Process variables				Surface roughness, Ra(µm)			
Pulse on Time	Pulse off Time	Voltage Gap	Wire Feed Rate	Al-7175, 2% Al_2O_3/SiC/PKSA	Al-7175, 4% Al_2O_3/SiC/PKSA	Al-7175, 6% Al_2O_3/SiC/PKSA	Al-7175, 8% Al_2O_3/SiC/PKSA
5	9	55	6	0.62	0.98	1.65	1.69
5	7	75	8	1.32	1.62	1.71	1.82
5	5	95	10	1.41	1.62	1.44	1.48
7	9	75	10	1.62	1.32	1.65	1.85
7	7	95	6	1.12	1.22	1.56	1.67
7	5	55	8	1.25	1.76	1.75	1.85
9	9	95	8	1.44	1.68	1.85	1.92
9	7	55	6	0.94	1.52	1.18	1.38
9	5	75	10	1.02	1.12	1.32	1.62

of the machine are influenced by a number of different process factors throughout the whole of the production process for making accurate products. Every parameter has the potential to be given a value, and those values may be placed into one of several preset categories [13,14].

3.6. Material Removal Rate (MRR)

According to the data shown in Figs. 2(a)-2(d), the standard Material Removal Rate (MRR) investigative significances caption towards existence are as follows: 20.97, 20.87, 18.70, and 18.15 mm^3/min, respectively. Using an Al-7175 metal matrix composite, the average Material Removal Rate (MRR) is essentially beginning inside and maintaining with 2, 4, 6, and 8% of weight percent Al_2O_3/SiC/PKSA.

In the case of metal matrix composites (MMCs), it is discovered that a reduction in the material removal rate (MRR) may be achieved by increasing the weight proportion using Al_2O_3/SiC/PKSA. Among the Al_2O_3/SiC/PKSA particles that are included inside the MMCs, the MRR has the capability to soften them. Because of their high heat conductivity and stiffness, respectively, reinforcements and Al_2O_3 both contribute to a decrease in MRR. This contributes to the overall reduction in MRR. The results of this research indicate that MRR values may often be identified by the enhancement with Pulse on Time. This is due to the fact that an increase in pulse-on time indicates that a spark has happened during the process of wire electric discharge machining variables. The superior pulse on time addresses ejections, pulse during rises in deliberation, and the development of deep deprived position that takes place when specimen material is compared to superior substance [15,16].

3.7. Surface roughness-Ra

A surface roughness investigation are carried out on Al-7175/Al_2O_3/SiC/PKSA, and Figs. 5(a)-5(d) illustrates the exit variables that are observed throughout the study. The weights of 2, 4, 6, and 8%, together with a constituent portion that serves to reinforce the structure, are the components that make up these reactions. Figs. 5(a) through 5(d) illustrate a degree of surface roughness that is consistent throughout the whole surface. Upon examination of Figs. 5(a)-5(d), it becomes evident that the surface roughness has an average value of 1.31 µm. This are accomplished by using an adequate quantity of Al-7175 in connection with 2, 4, 6, and 8% weight of Al_2O_3/SiC/PKSA. The results showed that the surface roughness is significantly improved. The PKSA values that are obtained for these values are 1.02, 1.12, 1.18, and 1.38 µm respectively.

An increasing weight % with strengthening exits may be seen throughout the process of metal matrix composites

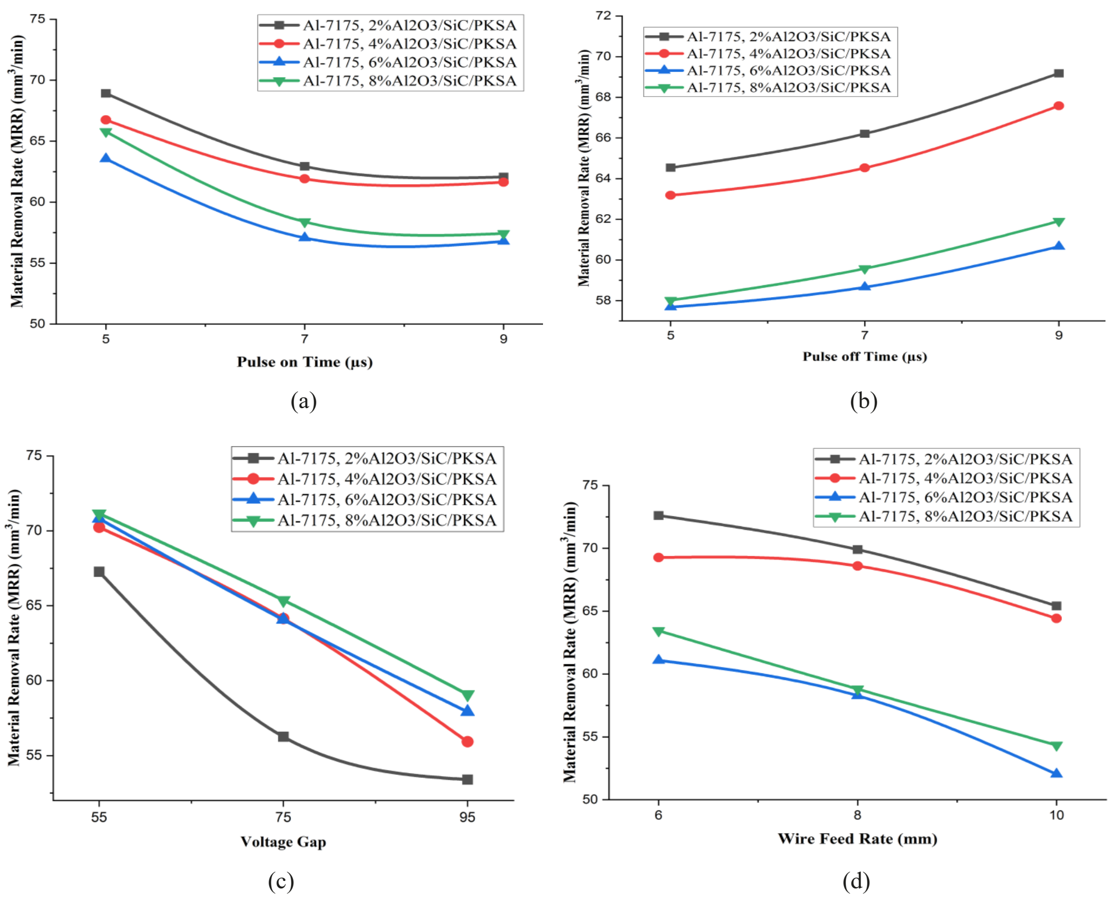

Fig. 2. (a) Average of Al_2O_3/SiC/PKSA wt. with T_{on} v/s MRR, (b) Average of Al_2O_3/SiC/PKSA wt. with T_{off} v/s MRR, (c) Average of Al_2O_3/SiC/PKSA wt. with Voltage v/s MRR (d). Average of Al_2O_3/SiC/PKSA wt. with Wire Feed Rate v/s MRR

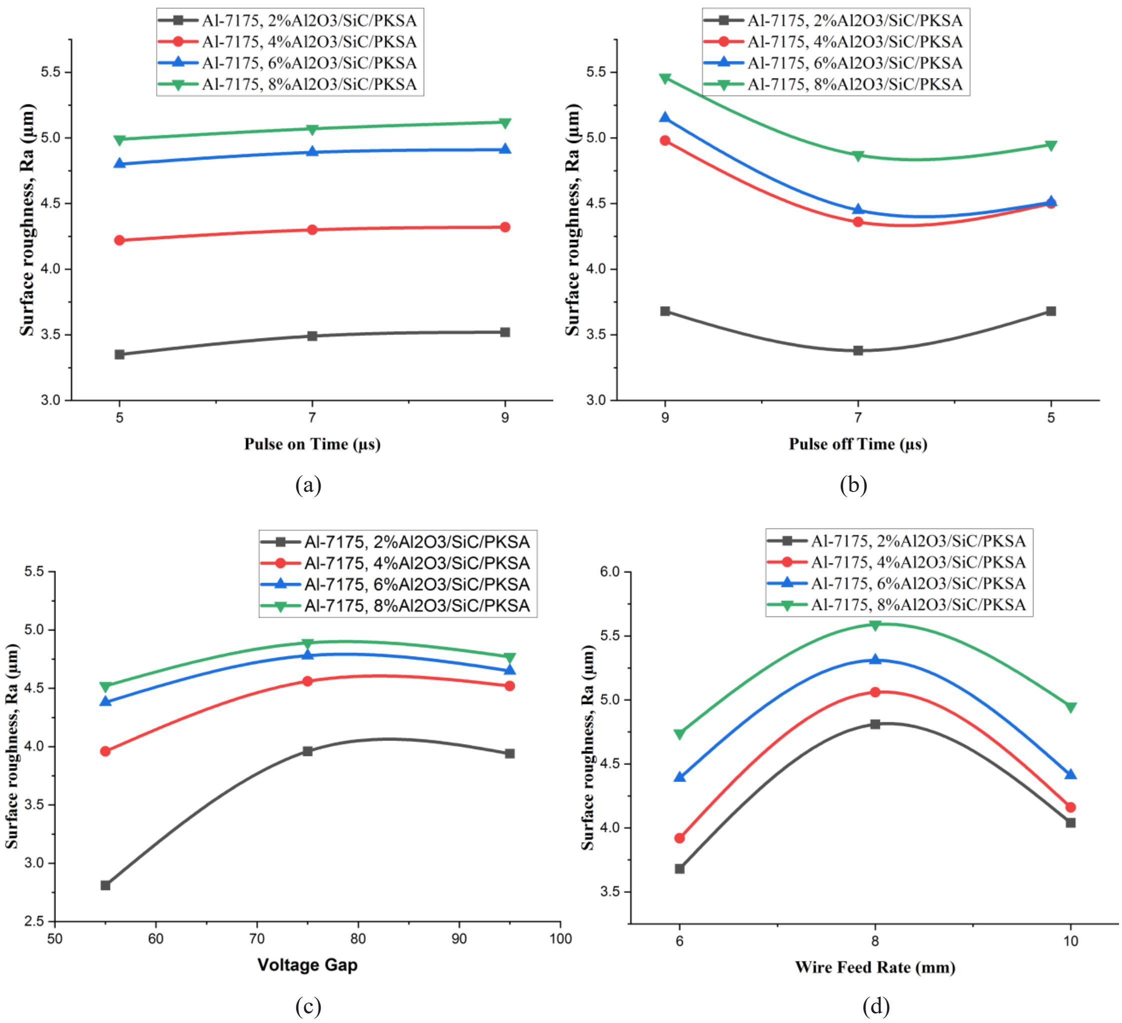

Fig. 3. (a) Average of Al_2O_3/SiC/PKSA wt. with T_{on} v/s Ra, (b) Average of Al_2O_3/SiC/PKSA wt. with T_{off} v/s Ra, (c) Average of Al_2O_3/SiC/PKSA wt. with Voltage v/s Ra (d). Average of Al_2O_3/SiC/PKSA wt. with Wire Feed Rate v/s Ra

(MMCs) when it is possible to conduct experiments as shown in Figs. 3(a) through 3(d). The inclusion of hard particles in MMCs as a reinforcement are shown to be directly responsible for the surface roughness increasing over time. This is discovered as a direct result of the presence of hard particles. Because of the spark that are formed when the tool and the work components came into touch with one another during a wire electric discharge machining variation, this becomes in addition showed its surface roughness lowered as the pulse-on time is raised. The surface roughness will grow in a manner that is proportionate to the increase in the pulse-off time. There is the potential to manage ejections by increasing the pulse-on time. The pulse through gives the deepest point on the work components concentration, which in turn causes a rise in material that is both higher and more concentrated [17].

3.8. Microstructure and SEM examination

Figs. 4 and 5(a)-5(d) illustrates the link between Al_2O_3/SiC/PKSA and the distribution of sections, as well as the characteristics of the material that are related with the direction that the scanning electron microscope (SEM) assists. As a result of the fact that the Al_2O_3/SiC/PKSA section allocation is similar across all of the research samples, Figure4-aimage labeled “Initial cracks” shows linear microcracks distributed within the aluminum matrix, frequently originating near heterogeneities. These crack origins are co-located with particle-rich zones and near small voids, indicating that stress concentration at particle--matrix interfaces and local defects drive crack nucleation. Likely causes include thermal mismatch stresses (Al vs ceramic reinforcements), incomplete wetting at the interface, and residual tensile stresses from solidification shrinkage. Such cracks act as preferential paths for rapid crack propagation under loading and will markedly reduce toughness and fatigue life; their presence explains reductions in impact resistance and ductility observed in samples with poorer particle dispersion or higher reinforcement fractions. Fig. 4(b) shows irregular, often rounded cavities identified as micropores. These features are typical of gas entrapment during melt processing, inadequate degassing, or shrinkage porosity exacerbated by particle clustering (which hinders feeding during solidification). High reinforcement loading and increased melt viscosity can trap gases and create interdendritic porosity. Microporosity serves as a stress raiser,

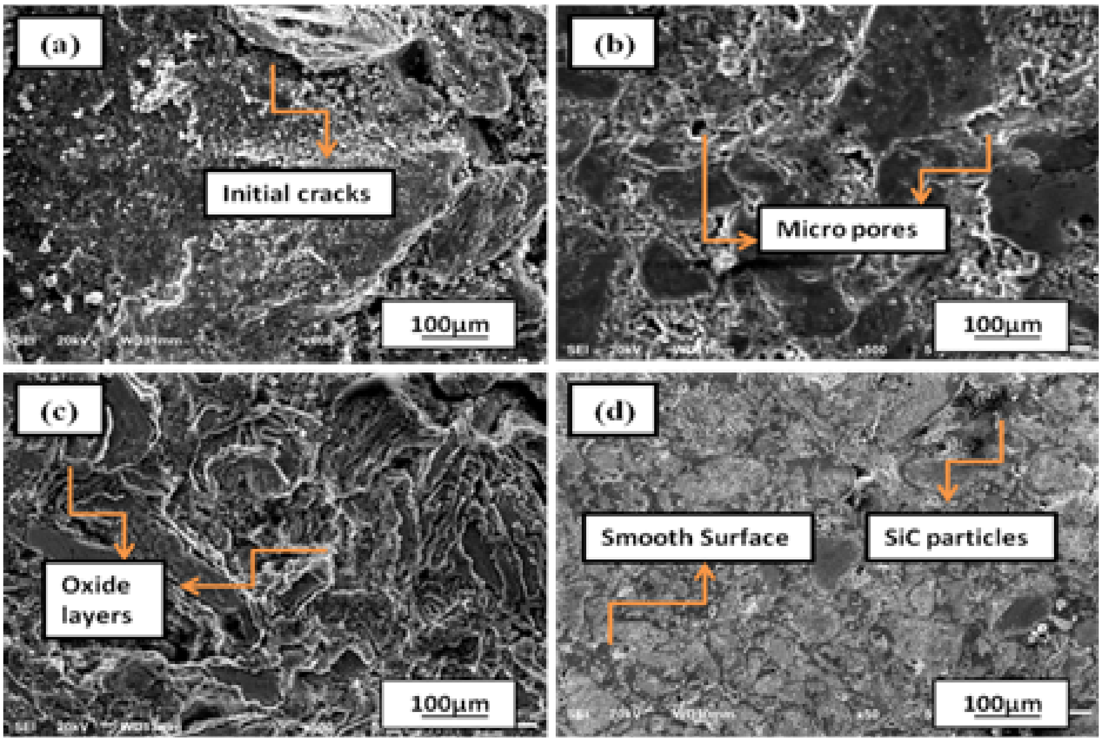

Fig. 4. SEM of (a) Al-7175, 2%Al_2O_3/SiC/PKSA, (b) Al-7175, 4%Al_2O_3/SiC/PKSA, (c) Al-7175, 6%Al_2O_3/SiC/PKSA, (d) Al-7175, 8%Al_2O_3/SiC/PKSA

lowers the effective load-bearing cross-section, and degrades tensile strength and wear performance. From a machining perspective, surface-connected pores increase surface roughness and promote non-uniform material removal in processes like WEDM.

Fig. 4(c) displays flaky/lamellar oxide films and oxide-enriched regions on the matrix surface. These are most likely α-Al_2O_3 or other aluminum oxide films formed during high-temperature exposure of the melt and then entrapped during stirring/solidification. Oxide layers at the particle-matrix interface inhibit metallurgical bonding and impede load transfer; they also promote interfacial debonding during mechanical loading, leading to particle pull-out and premature failure. The presence of oxides also correlates with increased local brittleness and can explain localized variations in hardness and wear behavior. Fig. 4(d) shows relatively smooth matrix regions with well-embedded SiC particles and limited interfacial gaps. These areas indicate good wetting and dispersion of reinforcement, producing stronger interfacial bonding and effective stress transfer from the matrix to the hard particles. Well-bonded SiC particles contribute to increased hardness and enhanced wear resistance (by bearing surface loads and resisting ploughing). If particle fractures (rather than pull-out) are observed, this implies the interface strength exceeds particle tensile strength a desirable outcome for load-bearing applications.

The SEM observations reveal a competition between beneficial, well-bonded reinforcement domains that improve hardness/wear resistance and defect-rich domains (pores, oxides, cracks) that degrade toughness and machining/surface quality. Addressing casting-related porosity and oxidation is therefore critical to fully realize the mechanical and tribological advantages of Al-7175/SiC/Al_2O_3/PKSA hybrid composites.

The fracture location of each tensile specimen was examined using high-intensity electron beam imaging with a raster scan pattern. Fig. 5(a) shows a few well-dispersed dark particles in a continuous Al matrix with visible grain boundaries and minimal clustering. At 2 wt.% reinforcement, particles were largely isolated and uniformly distributed, indicating good wetting and mixing during stir casting. Modest hardness/wear gains are expected with minimal ductility loss. Particle area fraction and BSE/EDS mapping confirm chemistry. In Fig. 5(b), particle density increases; SiC/PKSA appears as larger, irregular dark regions with occasional small clusters. Higher loading improves hardness but may introduce local stress concentrators. EDS spot analyses and cluster size quantification are recommended. Fig. 5(c) reveals clustered zones, irregular interfaces, and possible micro-voids at 6 wt.% loading. Hardness and wear improve, but ductility may drop; WEDM MRR decreases and Ra rises. SEM fracture imaging and porosity checks are suggested. Fig. 5(d) shows the highest particle density, grain-boundary pinning, and interconnected reinforcement networks. Grain refinement is evident, but agglomeration and interface defects increase embrittlement risk. TEM/SEM interface studies, spacing measurements, and fatigue correlations are advised.

4. Conclusions

Al-7175/Al_2O_3/SiC/PKSA is created utilizing the liquid-state process with 2%, 4%, 6%, and 8% weight. Wire cut electric discharge machining are used in order to examine the sample. During this experiment, also taken into account are the rate of material removal and the roughness of the surface. An overview

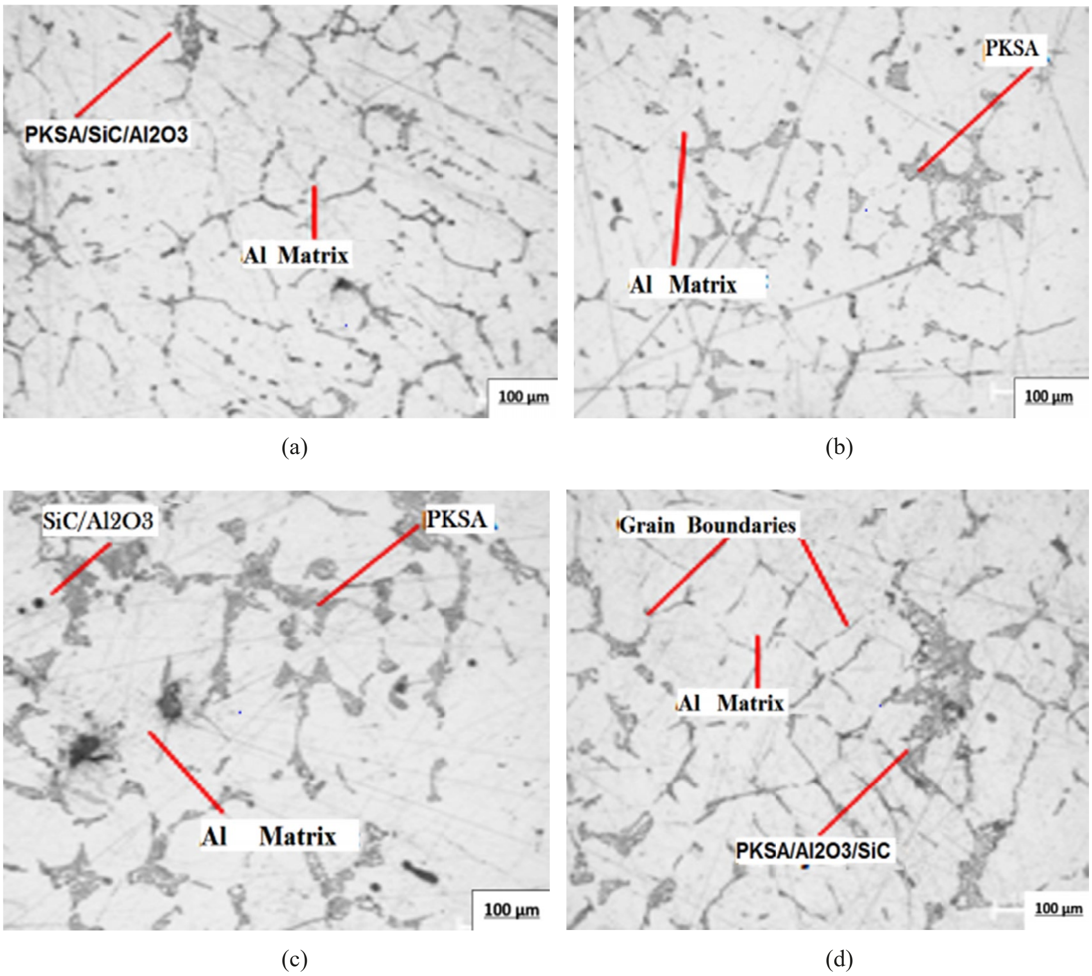

Fig. 5. Microstructures of (a) Al-7175, 2%Al_2O_3/SiC/PKSA, (b) Al-7175, 4%Al_2O_3/SiC/PKSA, (c) Al-7175, 6%Al_2O_3/SiC/PKSA, (d) Al-7175, 8%Al_2O_3/SiC/PKSA, Dark contrast regions correspond to reinforcement phases (SiC, Al_2O_3 and PKSA); increasing particle density and grain-boundary pinning are evident with higher wt.%

of the observations has been compiled, and it may be found outlined below.

- Al-7175/Al_2O_3/SiC/PKSA hybrid metal matrix composites (MMCs) are successfully fabricated using the cost-effective stir casting method.
- Incorporation of Al_2O_3, SiC, and PKSA significantly improved hardness, Tensile strength, and impact resistance compared to unreinforced Al7175.
- Reinforced composites exhibited reduced wear rate, demonstrating the synergistic tribological benefits of ceramics and waste-based additives of PKSA.
- Scanning electron microscopy (SEM) and optical microstructural analysis confirmed a homogeneous dispersion of reinforcements particles within Al-7175.
- The pulse-off time, in conjunction with the voltage gap that exists between the tool and the workpieces, is the fundamental factors that must be considered while machining the MRR trail by wire feed. The bare minimum value that is need for this procedure is this one.
- Furthermore, in addition to the Al_2O_3/SiC/PKSA reinforcements that are included into Al-7175, the rate at which material is being withdrawn is gradually decreasing.
- Due to the fact that wire electrical discharge machining (WEDM) has the capability to machine composite materials that are difficult to cut, the percentage of reinforcements in Al-7175 increases as the surface roughness of the value increases. On the other hand, the percentage of reinforcements in MMCs stays constant regardless of the process rate of material removal.

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