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Tribological Study on SiC+Graphene Reinforced Al319 Composite and Optimization of Stir Casting Parameters

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Abstract

The aluminium 319 (Al319) is a commonly used material for fabricating automobile components. Due to continuous friction and vibration, those components are subjected to significant wear. Therefore, it is necessary to improve the wear characteristics of this Al319. Hence, in this study Silicon Carbide (SiC) and Graphene nanoparticles (GNPs) are reinforce to Al319 via electro-magnetic stir casting method to optimize wear characteristics without its affecting mechanical properties. Various proposition of SiC and GNPs are investigated in this study among them 17%wt SiC along with 3%wt GNPs is identified as the most significant reinforcement method. Furthermore, the electro-magnetic stir casting process parameters are optimized with the help of a Response Surface Method (RSM) called Face Centered Central Composite Design (FCCD). As a result, 100Hz stirring intensity and 11min stirring time are obtained as optimal casting settings for the selected composite. Due to this optimization process, the wear rate of Al319 is reduced upto14.45% along with 30% increase in tensile and hardness properties including 1.52% increase in material density.

Keywords: Wear rate, Al319, silicon carbide, graphene, nanoparticle, face centered central composite design.

INTRODUCTION

The incorporation of advanced materials in composite structures has revolutionized various industrial sectors by offering enhanced performance and durability.Among various advanced materials, Silicon Carbide (SiC) and Graphene have immense potential due to their exceptional thermal, mechanical and electrical properties. Therefore, both SiCNano powders and Graphene Nano Particles (GNPs) are widely used as a reinforcement option for Metal Matrix Composite (MMC) fabrications [1]. Besides, the Aluminium Metal Matrix Composites (AMMCs) are lightweight materials which have robust activities in automotive, aerospace and aircraft engineering,if they possess the desired level of stiffness, strength, ductility and superior tribological characteristics. [2, 3].In the field of MMCs the incorporation of SiC and GNPs into Aluminium alloys shown a promising approach for developing high performance-less weight materials. Meanwhile, the Stir Casting is one of the cost effective and widely used fabrication technique for versatile production of AMMCs [4]. Rajan et al [5]. enhanced tensile and hardness properties of Al5083 alloy upto 47% and 12% respectively by reinforcing with 2% SiC.The author used Friction Stir Processing (FSP) method to reinforce 80nm (average) SiC particles into stir casted Al5083 alloy.For squeeze casted Al356 alloy, Kumar et al. [6]. used the same FSP technique to reinforce GNPs and obtained enhanced mechanical properties. After examining the prepared samples at various friction

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stir processed locations.The author concluded that, the GNPs reinforcement via FSP have enhanced the yield strength, tensile strength and ductility of Al356 upto 58%, 50% and 12% respectively.Similarly, Raheja et al [7]. and Sharma et al [8]. used FSP method to reinforce hybrid SiC-GNPs into Al5086 and SiC-GNPs, SiC-multi walled carbon nanotubes (MWCNTs) into Al6061 alloys respectively. According to those study findings, both the authors have achieved enhanced mechanical properties from reinforced aluminium alloys.

Even though, the FSP technique shown significant impact while reinforcing metal nanoparticles into AMMCs.It consume more time and effort to complete the reinforcement process due to various steps involved such as, casting, channel/groove/hole preparation for filling nanoparticles, and FSP [5-11].However, several studies achieved superior mechanical and micro-structural properties along with uniform dispersion of nanoparticles into the molten aluminium alloys at casting step itself [12-18].Arunkumar et al. [12] developed Al6061 alloy with 2% SiC reinforcement during two stage stir casting (also called rheocasting). The author also examined the impact of ultra-sonication and squeeze pressure on SiC reinforcement into the base alloy.The study revealed the rheostir casting technique along with squeeze pressure and ultrasonic vibration have significant potential to enhance mechanical properties of Al6061.In another study, Kumar et al. [13]. have achieved enhanced dry sliding wear characteristics while reinforcing Al6061 with two different metal nanoparticles. The author tried a hybrid ($CeO_2$with GNPs) nanoparticle reinforcement approach during stir casting. Then conducted several pin on disc wear tests to study the wear characteristics of reinforced Al6061at its dry condition.On the other hand, Ramanathan et al. [15] have identified stir casting as the most feasible and economic method for fabricating/reinforcing any MMCs. In addition, the author conducted criticalanalysis on existing study the reports related to stir casting, and foundoptimization of casting parameters, additives and furnace design can improve the mechanical characteristic of the fabricated/reinforced MMCs. Thus, Gurusami et al. [19] optimized stir casting parameters such as, stir speed, stir time and percentage of reinforcement materials for Al7010 alloy. The author implemented Response Surface Methodology (RSM) for optimizing those selected stir casting parameters. Thereby, identified reinforcement percentage as the most influencing parameter followed by stir time and stir speed.The optimal casting settings achieved in that study are 6% reinforcement, 750rpm stir speed and 7 min stir time along with lowest corrosion rate of 265.43 mm/yr.Similarly, Kumar et al. [20] identified weight % of GNPs reinforcement played a vital role (around 64% impact) for enhancing mechanical characteristics of Al6061 via stir casting. The author used Taguchi's L9 Orthogonal Array (OA) Design of Experiment (DoE) method and Grey Relation Analysis (GRA) for optimizing stir casting parameters. The second and third most influencing casting parameters identified through that study are stir speed (17%) and stir time (11%) respectively with 8% error.

However, a limited number of studies have enhanced the mechanical properties of Aluminium 319 alloy (Al319) which is a robust material for automobile component making. In early 2000, Konca et al. [21]. studied the wear characteristics of Al319 alloy against M2 steel disc coated with titanium nitride and titanium di-boride based compounds. The author conducted pin on disc wear test to examine the aluminium transfer rate between Al319 and M2 (coated and uncoated). As result, the author noticed lowestaluminium transfer rate between Al319 and M2 steel coated with either TiB_2 or TiCN. In other words, the TiB_2 and TiCN coating on M2 steel surface provided better lubrication propertieswhen sliding against Al319 alloy.Later Shalaby et al. [22]. studied the wear behavior of Al319 while reinforcing with two different nanoparticles namely, Al_2O_3 and Graphite. The author utilized stir casting process for such reinforcement and found uniform dispersion of nanoparticles into the alloy which in turn enhanced the wear properties of Al319.Another author Jayakumar et al. [23]. fabricated SiC reinforced functionally graded Al319 ring specimens via liquid stir casting followed by centrifugal casting method.Based on microstructural and pin on disc wear test observations, the author concluded 20% SiC particle reinforcement via stir casting could provide enhanced wear characteristics for Al319 alloy.Recently, Ali [24]. tried a hybrid reinforcement of Al_2O_3+TiO_2 nanoparticles into Al319 MMC using stir casting method. The author noticed increasing trend for both tensile and hardness properties while increasing the hybrid particle contents from 2-6% whereas, the impact energy was slightly diminished. However, the author observed that all those reinforced Al319 composites were significant for light weight automobile component fabrication.Andilab et al. [25] studied the impact of GNPs reinforcement on mechanical and electrical properties of Al319 material. The author utilized a hybrid approach of ultrasonic melting based semi-solid stirring process to reinforced GNPs into Al319 composite. At the end the study proved that, increasing amount of GNPs will improve the yield and tensile strengths of Al319 alloy along with good electrical conductivityand ductility. However, all those existing studies have examined only the impact of nanoparticle reinforcement on Al319 alloy's mechanical, tribological and electrical properties. The studies on optimizing stir casing parameters for Al319 were not yet identified even though such optimization were extremely done for various other AMMCs [26-31]. Among those optimization methods, Roy et al. [32] proved, the Face-centered Central Composite Design (FCCD) based DoE and RSM optimization strategy as the most significant as well as effective method for this kind of studies.

Based on this literature review, though GNPs and SiC reinforcement enhanced the mechanical characteristics of various AMMCs, such mono or hybrid reinforcement technique for Al319 material was not yet studied significantly. Besides, optimization of casting parameters such as, stir time, stir speed and reinforcement percentage for Al319 material has a wider scope due to the advantage of FCCD based DoE approach. Hence, studies on hybrid metal nanoparticle reinforcement on Al319 alloy for optimizing its metallurgical properties are welcomed. Thus, this study investigated the impact of both GNPs and SiC mono as well as hybrid reinforcement on tribological characteristics of stir casted Al319 alloy. Further the stir casting process parameters and hybrid particle reinforcement percentage are optimized with the help of RSM technique prepared based on FCCD.The outcomes of this study hold significant implications for diverse industrial applications where lightweight, high-strength materials with excellent tribological properties are necessary. Also, by evaluating the tribological behavior and optimizing the fabrication process forSiC and GNPs reinforced Al319 composites, this research aims to contribute to the advancement of materials engineering, paving the way for the development of next-generation functional materials for full filling industrial demands.The detailed explanation on research methodology, material details, composite fabrication process, etc., are given in section 2 of this article. The section 3 will discuss about the study findings whereas,the section 4 will concludes this study outcomes along with its future directions.

MATERIALS AND METHODS

This study consist of two major experimental tasks, the first one is fabrication and understanding of wear characteristics of Al319 reinforced with two different nanoparticles. For completing this task, six different composite including one base composite (Al319 without any reinforcement) are fabricated via industrial stir casting approach (the detailed explanation is given in section 2.2). Then, the micro-structural and wear properties of those six composites are analyzed through microscopic study and conducting pin on disc wear tests. After completing such initial experimentations, the reinforced Al319 composite with good wear and micro-structural characteristics was identified for further proceedings. In the second most task, this study prepares a FCCD based DoE system for optimizing stir casting parameters for the identified SiC+GNPs reinforced Al319 sample. The tensile strength, micro-hardness and density of stir casted composites as per proposed DoE are to be examined in order to optimize casting parameters. Finally, the impact of optimal stir casting settings for SiC+GNPs reinforcement in Al319 is comparatively studied against as casted Al319 alloy material for concluding the achievements of this study. The RSM technique was implemented with the help of Design Expert software version 13 to perform optimization task.

Materials

The Aluminium 319 alloy (Al319) ingots having silicon and copper as a major alloying elements as given in table 1 are purchased from online market for the base alloy matrix material. Then 99% pure reinforcement materials such as, Silicon Carbide (SiC) nanopowders and Graphene Nanoparticles (GNPs) were obtained from Intelligent Materials Pvt. Ltd., Punjab, India. The average particle size of both SiC and GNPs ranges from 80nm to 100nm whereas, the density of this two nanoparticles are $3.2g/cm^3$ and $2.2g/cm^3$ respectively as per supplier details.

Table 1. Element composition of Al319 alloy.

Elements	**Si**	**Cu**	**Mn**	**Fe**	**Zn**	**Ti**	**Mg**	**Ni**	**Al**
Weight (%)	6.35	3.87	0.34	0.21	0.15	0.14	0.07	0.05	balance

Composite Fabrication

The fabrication of various composites as given in Table 2 was performed one by one using an electrical melting furnace equipped with electro-magnetic stirrer setup as shown in Figure 1.The range of SiC (15-20%) and GNPs (1-5%) reinforcement in this study are identified through the literature Aybarc et al. [4]. To begin the casting process, the furnace was slowly heated upto 800 degree centigarde then the Al319 ingots were loaded into the furnace for melting as proposed in existing studiesShalabyet al. [22] and Ali [24]. The molten Al319 alloy matrix was then carefully transferred to the electro-magnetic stirrer setup. The stirring was performed at a frequency of 50Hz for 5mins to achieve necessary vortex in order to apply 0.2% chlorine based degassing tablets and wetting agent (1% Magnesium) [22]. Then, the stirring is continued for another 5mins by gradual increase in stirring intensity from 50Hz to 75Hz before introducing any reinforcement materials. Afterwards, the required amount of SiC and GNPs are introduced into the meltand the stirring intensity is gradually increased from 75-100Hz for the duration of 10mins.Finally, the molten matrix was poured into the mold at 680degree centigrade, preheating of mold at 350 degree centigrade for 5-10mins is recommended to remove the moisture content.The reinforced Al319 samples fabricated via stir casting during this study are shown in Figure 2.

Table 2. SiC and GNPs reinforcement design matrix for Al319 alloy.

Sl. no.	**Sample/composite**	**Symbol**	**Design matrix**		
			Al319 (wt. %)	***SiC (wt. %)***	***GNPs (wt. %)***
1.	Base matrix	BM	100	-	-
2.	Mono reinforcement 1	MR1	80	20	-
3.	Mono reinforcement 2	MR2	95	-	5
4.	Hybrid reinforcement 1	HR1	80	15	5
5.	Hybrid reinforcement 2	HR2	80	17	3
6.	Hybrid reinforcement 3	HR3	80	19	1

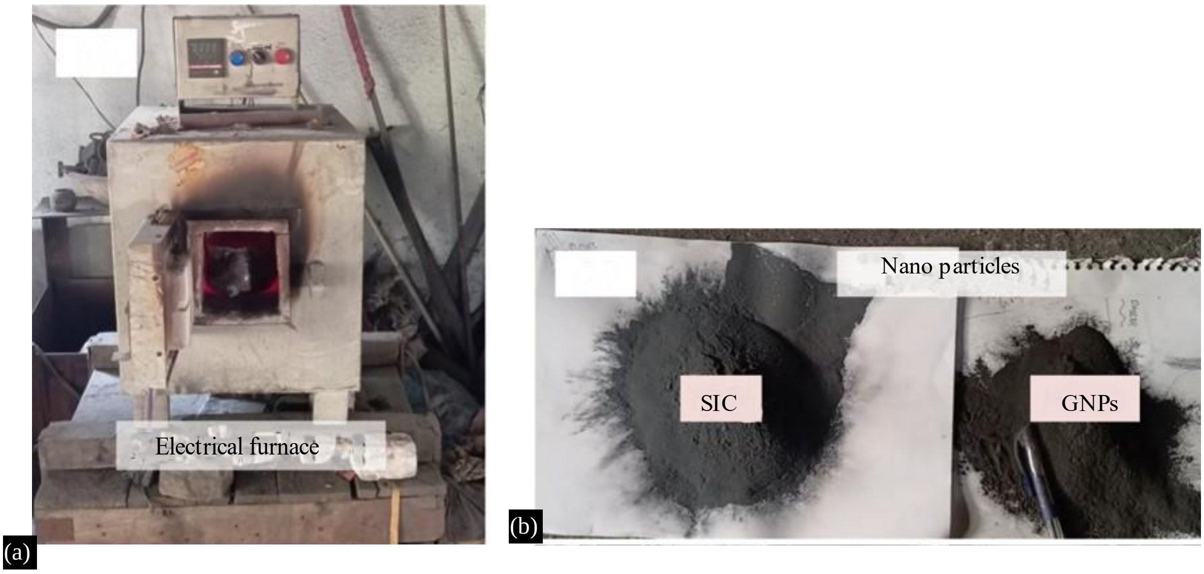

Figure1. Stir casting setup and study materials (a) melting of Al319 using furnace, (b) SiC and GNPs reinforcement particles, (c) electro-magnetic stirrer, and (d) mold for samples.

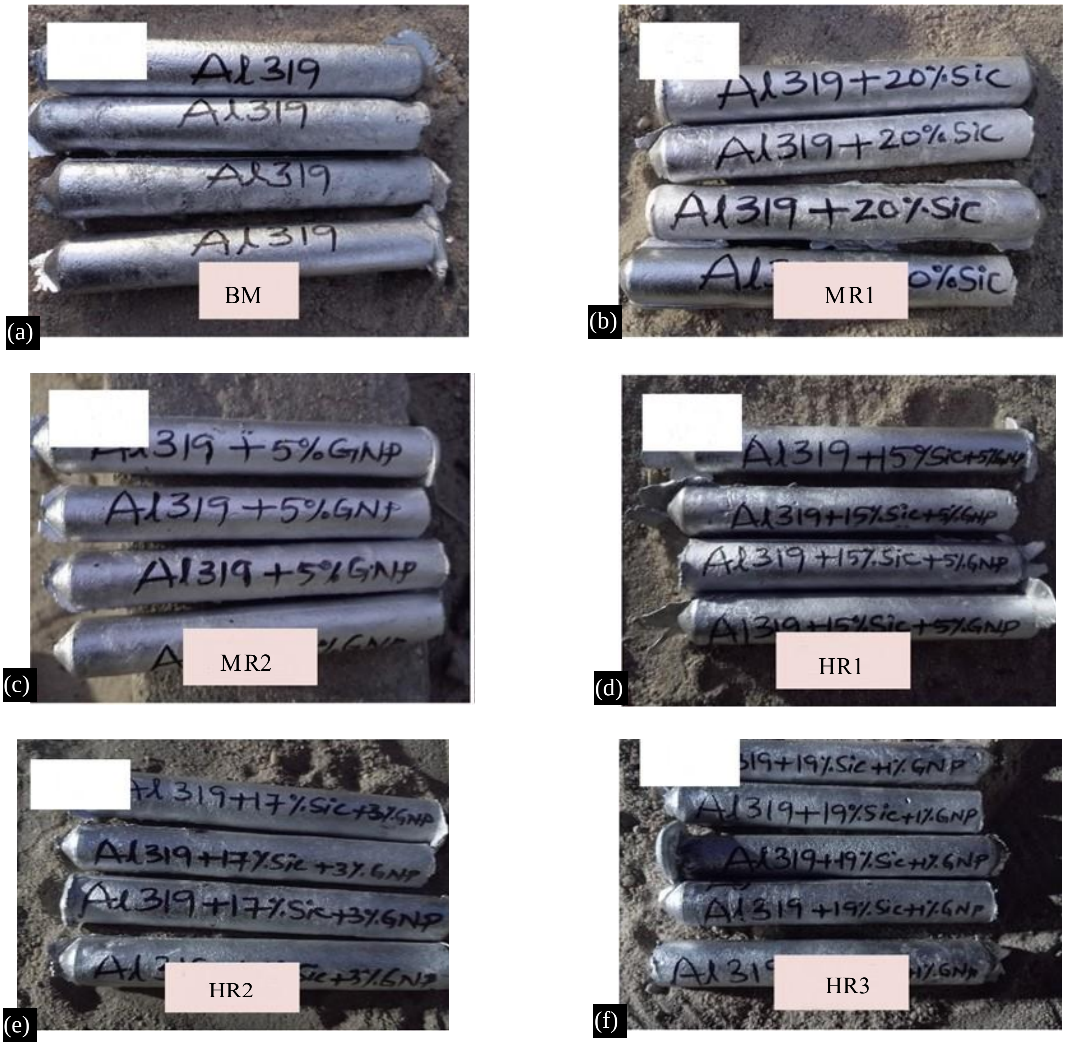

Figure 2. Fabricated study composite samples (a) BM, (b) MR1, (c) MR2, (d) HR1, (e) HR2, and (f) HR3.

Characterization of Composites

The surface morphology of prepared composite samples were examined through METZ-57 model METZER microscope. Initially, the abrasive disc grinding was done on the samples using aluminium oxide paste which is applied on the grinding disc surface. Then the polishing is performed on the microscopic samples using 1/0, 2/0, 3/0 and 4/0 grade emery sand papers. Subsequently, Keller's etchant contains 190ml of distilled water, 5ml of nitric acid, 3ml of hydrochloric acid and 2ml of hydrofluoric acid was applied on the polished surface of the samples for 1 minute. Finally, the etched samples were rinsed with running distilled water and dried with air blast for conducting microscopic study. Through this microscopic study, the reinforcement particle distribution and porosity of the reinforced samples were measured with the help of ImageJ software as shown in Figure 3 [33].

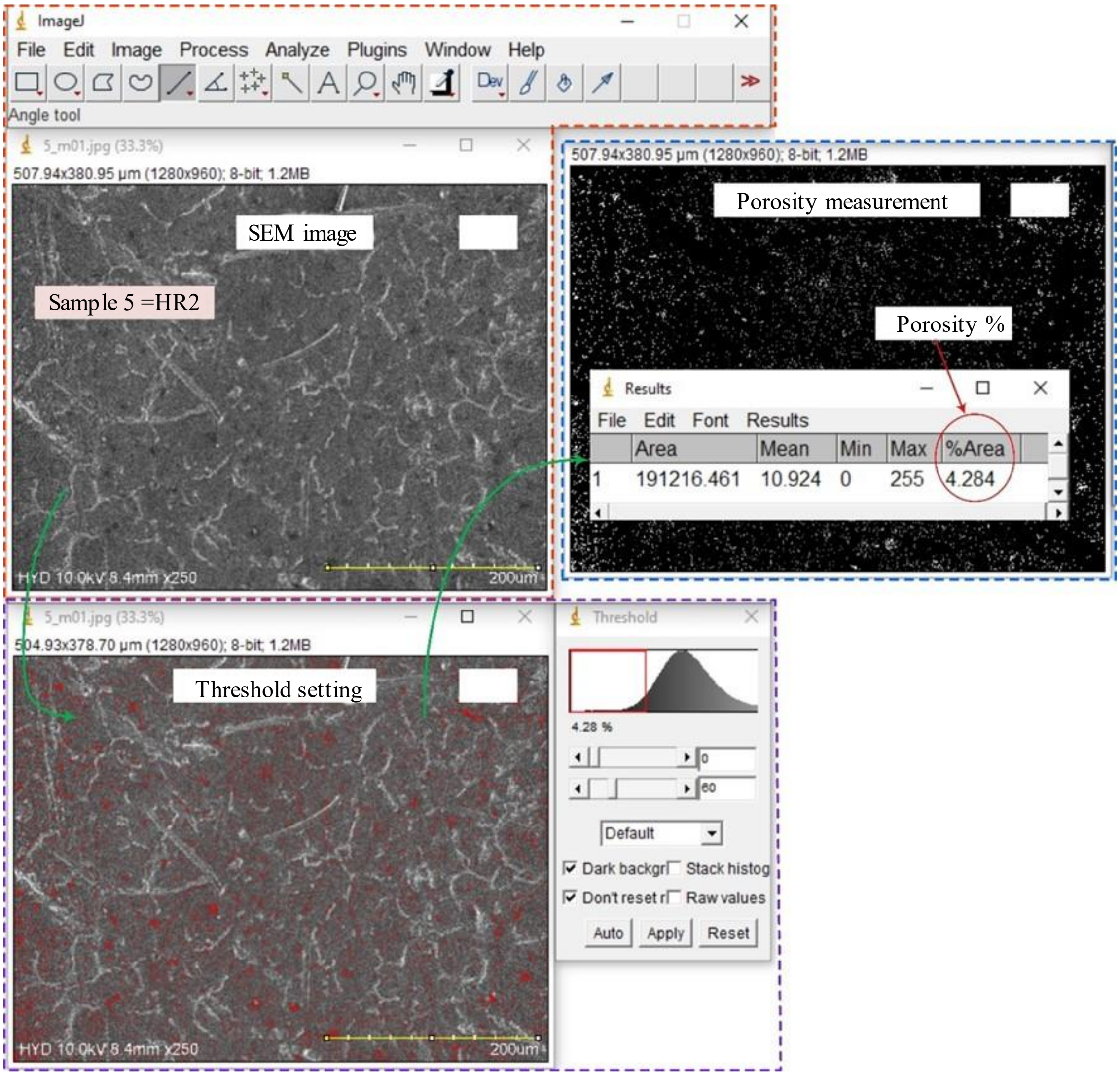

Figure3. Porosity measurement using ImageJ (a) SEM image of sample 5 (HR2), (b) threshold adjustment for identifying pores, and (c) porosity measurement.

On the other hand, the wear characteristics of prepared Al319 reinforced composites were examined through pin on disc experiments as per ASTM G99 standards using 8mm diameter pin specimen.The wear rate of prepared specimens are determined under low (10N), medium (15N) and high (20N) loading conditions at minimum (600m) and maximum (2400m) sliding distances in order to ensure the significant application of reinforced specimens in distinct working environment. The table3 will explain about the various wear test conditionsfollowed during this study. The wear rate during this study was measured based on weight loss method using equation (1), whereas, the density of reinforced samples was measured using equation (2) based on Archimedes principle [34]. The experiments are repeated 3 times to ensure the results.

$$\text{Wear rate} = \frac{\Delta w}{\rho \times d_s} \text{ (mm}^3\text{/m)} \tag{1}$$

Where, Δw is weight difference in sample before and after wear test, d_s is sliding distance and ρ is the density of sample.If, ρ_{water} is water density (1000 kg/m^3), w is the weight of the sample, also IV_W and IV_W are initial and volume of water. Then the density of composite is measured as,

$$\text{Density of sample} = \frac{w}{FV_W - IV_W} \times \rho_{water} \tag{2}$$

Table 3. Wear test planning.

Parameters	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Load (N)	10	15	20	10	15	20
Sliding distance (m)	600	600	600	2400	2400	2400
Sliding velocity (m/sec.)	2	2	2	2	2	2

Optimization Strategy

After analyzing wear and morphological characteristics of all prepared composites, the best reinforcement composition is identified for further extension of this study. In this second stage, the stir casting process parameters namely, stirring intensity (frequency) and stir duration are optimized according to the output responses such as, tensile strength, micro-hardness, wear rate and density of composite. The experiments are designed with the help of FCCD design of experiment (DoE) method. Because, this study needs a DoE for two independent stir casting process parameters at 3 significant levels as given in table 4 which is not possible in other available DoE methods like, Box Behnken, full factorial, etc. Hence, RSM-FCCD method is opted in this study to prepare a DoE is shown in table 5.Roy et al. [32]also suggested the FCCD based RSM as an effective method to bring optimal solutions for experimental studies with less number of experiments. For each experimental runs, the tensile and micro-hardness of the samples are measured as per ASTM E8 and ASTM E384. The levels of input parameters are selected according to initial experimental observations. Wherein, the wear test condition 6 (Test 6) as mentioned in table 3 is followed to calculate wear rate of each experimental runs.

Analysis of Variance (ANOVA) analysis was also performed to evaluate the significance of statistical data (response values of each experimental runs) and their interaction with all input factors using Design Expert software [35]. Finally, statistical model equations for all responses were obtained as given in equation (3)-(6) according to the proposed FCCD method. Through those statistical equations, the relationships between the optimizing input parameters and output responses are established as similar to previous author Bhushan [36].

Table 4. Input process parameters and their levels.

Parameters	**Level 1**	**Level 2**	**Level 3**
Stirring intensity (Hz)	70	85	100
Stirring time (min)	8	10	12

Table 5. Design of experiment prepared based on RSM-FCCD.

Exp. no	Stirring intensity	Stir time	Tensile strength	Micro-hardness	Wear rate	Density
	Hz	min	MPa	HV	mm^3/m	kg/m^3
1	70	10	309.85	130.25	3.4591	2761
2	85	12	317.05	131.83	3.4554	2751
3	70	12	310.71	130.04	3.4582	2759
4	100	10	323.84	135.81	3.4549	2747
5	85	10	316.41	132.17	3.4565	2754
6	85	10	316.42	132.16	3.4561	2754
7	70	8	307.29	129.73	3.4611	2763
8	85	10	316.41	132.18	3.4565	2755
9	85	8	314.01	131.67	3.4573	2756
10	100	8	321.56	135.28	3.4545	2754
11	85	10	316.39	132.16	3.4567	2755
12	85	10	316.43	132.13	3.4566	2754
13	100	12	324.42	135.35	3.4553	2744

$$\text{Tensile strength} = 316.41 + 6.99\,A + 1.55\,B - 0.14\,AB + 0.4484\,A^2 - 0.8666\,B^2 \quad (3)$$

$$\text{Micro-hardness} = 132.16 + 2.74\,A + 0.09\,B - 0.06\,AB + 0.8603\,A^2 - 0.4197\,B^2 \quad (4)$$

$$\text{Wear rate} = 0.0564 - 0.0023\,A - 0.0007\,B + 0.0009\,AB + 0.0007\,A^2 + 0.0001\,B^2 \quad (5)$$

$$\text{Density} = 2754.14 - 6.33\,A - 3.17\,B - 1.5\,AB + 0.5172\,A^2 + 0.0172\,B^2 \quad (6)$$

RESULT AND DISCUSSION

Wear Characteristics of Reinforced Al319

The obtained wear rate from prepared composite materials at various pin on disc experimental conditions are graphically presented in figure 4. From figure 4(a) it is inferred that the wear rate of Al319 is reduced while introducing both SiC and GNPs contents. However, the wear rate tends to increase linearly with increase in load from 10-20N.Since, the pin on disc experiment is conducted at two different sliding distance (600m and 2400m) the wear rate of reinforced composites at 2400m sliding distance is shown in figure 4(b). The test results shown that, the addition of SiC and GNPs significantly improved the wear resistance property of Al319 alloy. Ultimately, the reinforced composite designated as HR2 (i.e) 17%wt SiC + 3%wt GNPs reinforced Al319 achieved the best wear resistance characteristics either in sliding distance 600m or in sliding distance 2400m. This increase in wear resistance from HR2 composite is reasonable due to the hardness and lubrication properties of both SiC and GNPs. Similar results were also reported by Srinivas et al. [37] while reviewing reinforced Al319 alloys. The lowest wear rate of 1.8157 mm^3/m is achieved at maximum load during this study from Al319+17%wt SiC+3%wt GNPs composite which is 62.31% lesser than the wear rate of Al319 at similar condition. In contrast, at lower load (10N) the wear rate of 17%wt SiC+3%wt GNPs reinforced Al319 composite is marginally above the Al319 alloy. But, the wear rate of reinforced Al319 is found stable for the tested range of loads (10-20N) which is not observed in Al319.Therefore, the reinforced Al319 ensures the wide range of application than the Al319 base alloy. Overall, the reinforcement of both SiC and GNPs via stir casting had significant positive impact on wear resistance of Al319 according to this study.

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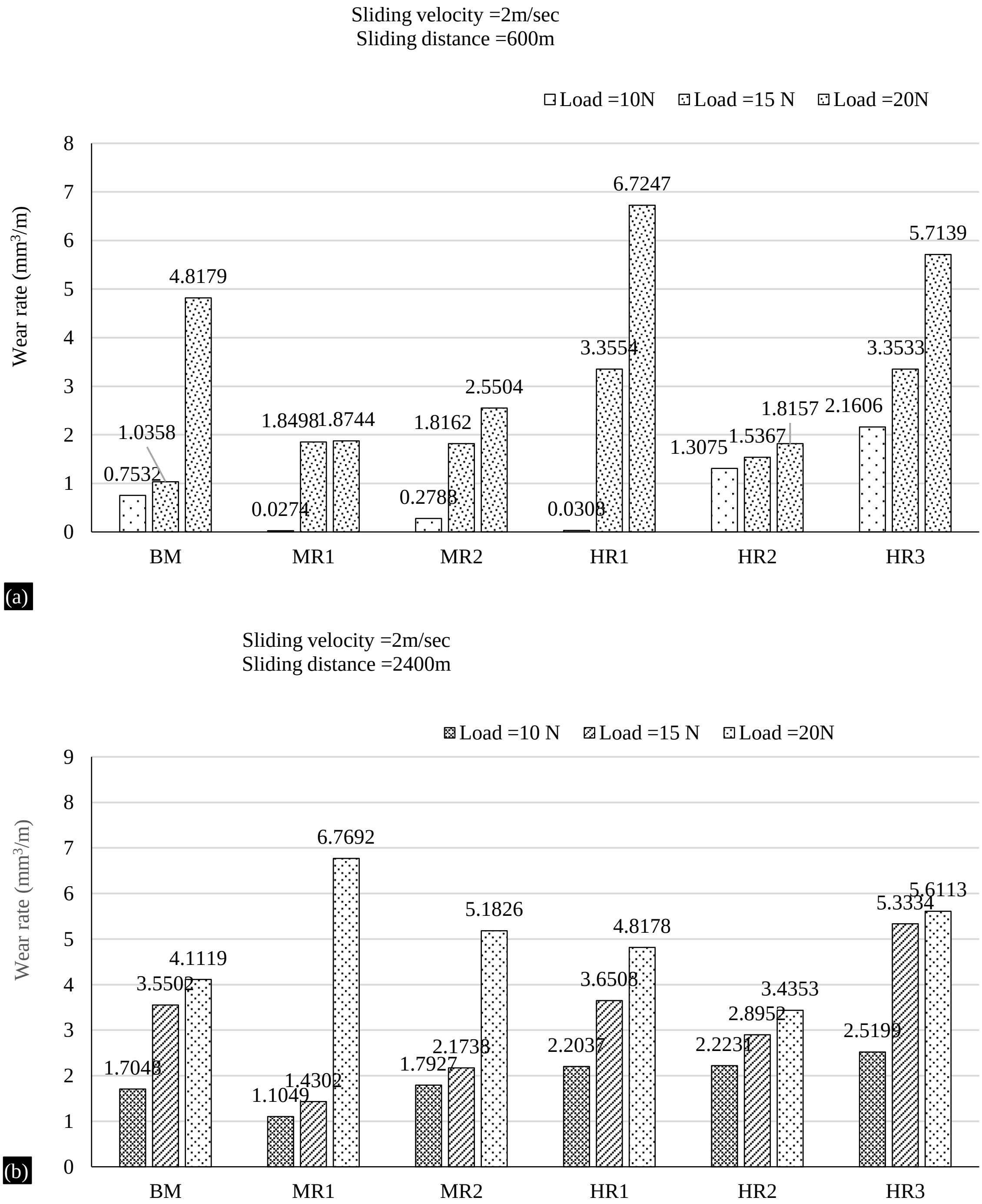

Figure 4. Wear rate of prepared composites (a) at sliding distance 600m, and (b) at sliding distance 2400m.

Microstructural Characteristics

The microstructure of all six prepared composites are studied with the help of microscope. The samples are collected, polished and etched as mentioned in the procedure. The microscopical outcome of all prepared composites are shown in Figure 5. From this figures micro-pores are observed from all samples due to electro-magnetic stir casting procedure. Specifically, from Figure 5(a) α-phase of Al319 is noticed in the form of lighter regions. This formation of α-Al319 helps to hold the reinforcement particles such as SiC and GNPs to enhance wear and hardness properties of Al319 composite [38]. Figure 5(b)-5(f) confirmed the uniform dispersion of reinforcement particles (SiC and GNPs) inside the molten Al319 alloy.Particularly, the distribution of SiC particles are easily identified as larger and dark features (in some regions it look like straight line). In contrast, the GNPs are appeared as finer irregular dark features due its smaller particle size (100nm) than the SiC particle. The irregularity in particle shape and size confirmed the stir casting process is significant to break the structure of both SiC and GNPs in order to achieve uniform distribution rather than settling them at one region.

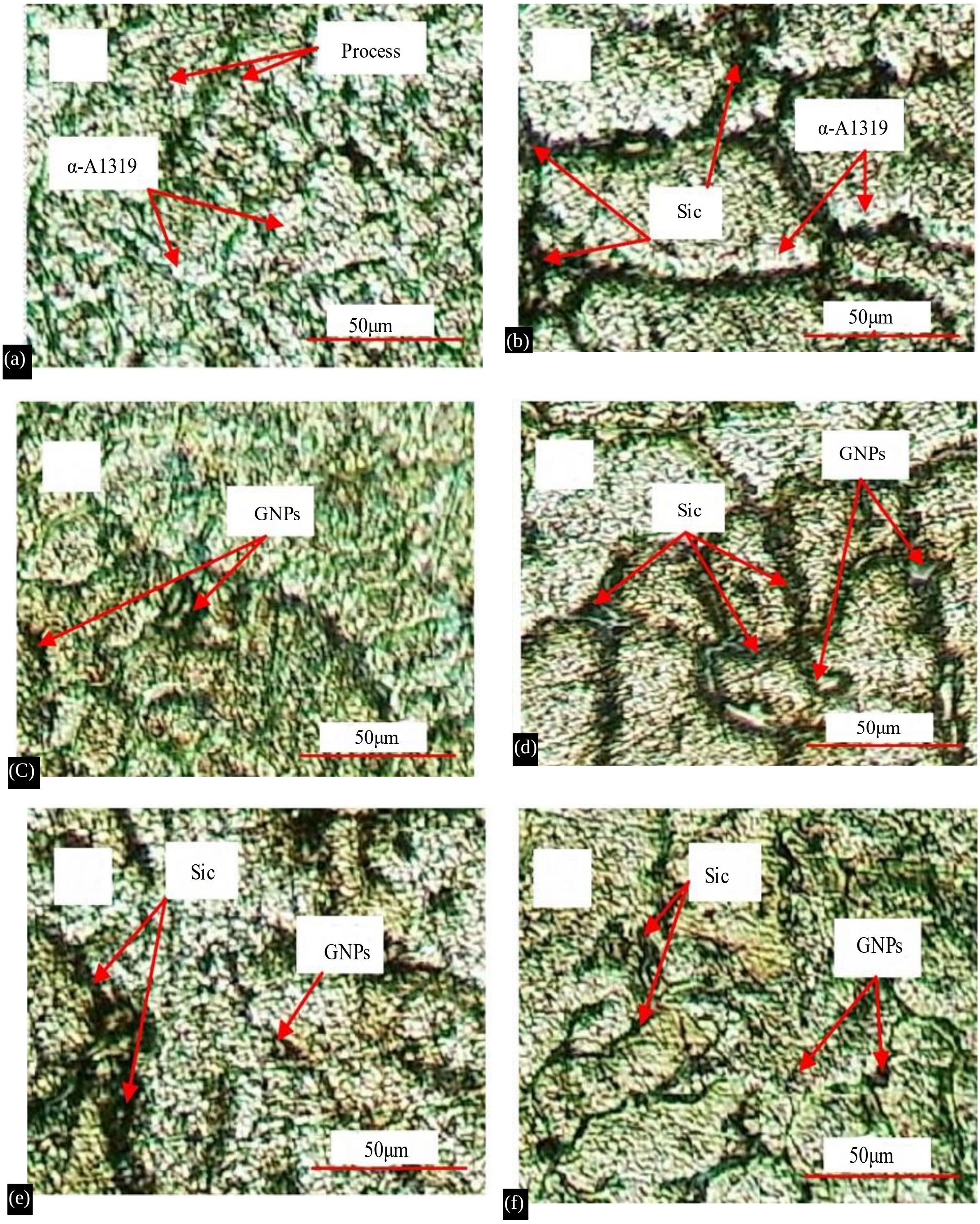

Figure 5. Microstructure of prepared composites (a) BM, (b) MR1, (c) MR2, (d) HR1, (e) HR2, and (f) HR3.

Figure 6 depicts the porosity of various composites prepared during this study. From this figure, the porosity of SiC and GNPs reinforced Al319 composites are not consistence with the reinforcement matrix. For example, MR1 (i.e) 20%wt SiC reinforced Al319 the porosity marginally reduced, but it increased upto 5.989% while reinforcing Al319 with 5%wt GNPs. Similarly, for dual reinforcement techniques, HR1 and HR2 methods shown reduced porosity than the base metal (Al319), but it is increasing for HR3 matrix. This contradictive porosity results shown there may be inconsistence in the formation of air bubbles during stir casting. This is reasonable due to environmental condition. The HR1 matrix which contains 80%wt of Al319 + 15%wt of SiC + 5%wt of GNPs have shown minimum porosity level.However, this minimum porosity will help to achieve maximum hardness and other mechanical characteristics. It will also, increasedthe overall weightof the reinforced Al319 composite. Since Al319 is widely used in automobile industries, increasing overall weight of this material during reinforcement is generally not recommended [24]. Therefore, optimization of this stir casting process parameters could help to maintain optimal porosity level for the composite. Also, based on microstructural, wear and porosity results, the composite fabricated as per HR2 matrix method have shown superior performance wear characteristics as well as obtained with reduced porosity than BM. Hence, the electro-magnetic stir casting parameters such as, stir intensity and stir time are optimized using RSM-FCCD method for HR2 (Al319+17%wt SiC+3%wt GNPs) composite as follows.

ANOVA Results

To optimize casting parameters for 17%wt SiC and 3%wt GNPs reinforced Al319 composite, initially the significance of quadratic models created using RSM-FCCD method verified through ANOVA approach as given in table 6. According to Mohamadigangaraj et al. [39], the p-value should be less than 0.05 for a significant model. For this study, the ANOVA results shown <0.0001 p-value for all output responses tensile strength, micro-hardness, wear rate and density. This indicates the proposed RSM-FCCD quadratic model is significant to predict optimal solutions. However, the efficiency of each response models are also examined in terms of regression coefficient (R^2). As a result, the tensile strength model achieved the ultimate efficacy of 1 whereas, the micro-hardness, wear rate and density model achieved second (0.9998), third (0.9834) and fourth (0.9800) position in terms of regression coefficient.Additionally, the not significant lack-of-fit values indicates rare chance for larger F-values due to noise. This findings are necessary for a significant quadratic model to perform an optimization task [40].

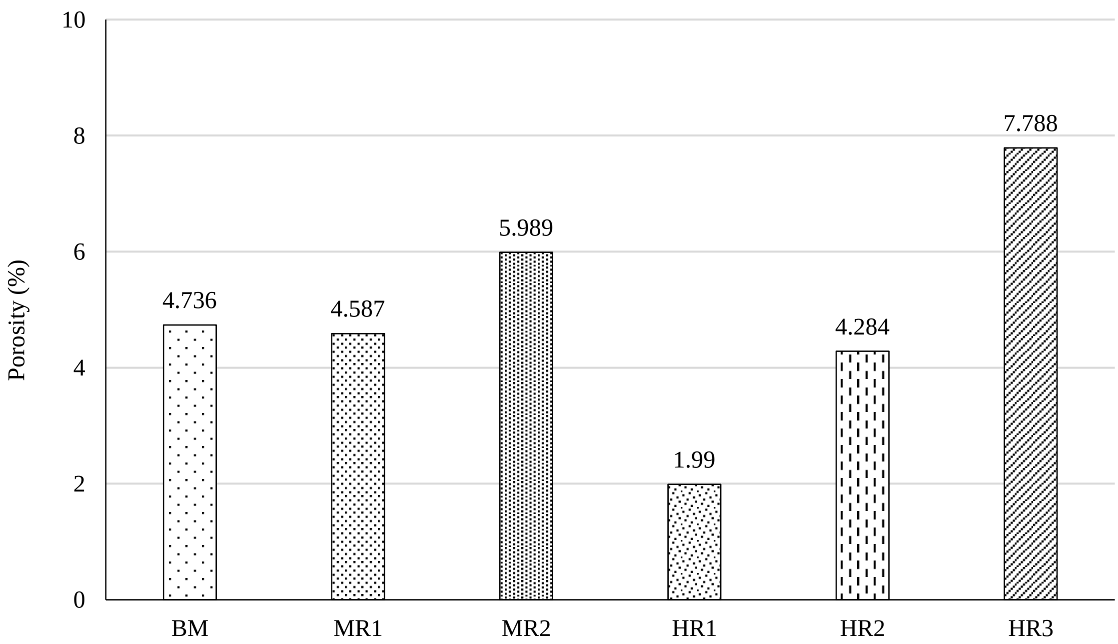

Figure 6. Porosity of prepared composites.

Table 6. ANOVA table for responses from FCCD.

Source	Sum of Squares	Degrees of freedom	Mean Square	F-value	p-value	Remark
Tensile strength						
Model	310.25	5	62.05	88292.14	< 0.0001	significant
A-Stirring intensity	293.58	1	293.58	4.18E+05	< 0.0001	
B-Stir time	14.48	1	14.48	20599.38	< 0.0001	
AB	0.0784	1	0.0784	111.56	< 0.0001	
A^2	0.5554	1	0.5554	790.33	< 0.0001	
B^2	2.07	1	2.07	2951.01	< 0.0001	
Residual	0.0049	7	0.0007	-	-	-
Lack of Fit	0.004	3	0.0013	6.12	0.0563	not significant
Pure Error	0.0009	4	0.0002	-	-	-
Cor Total	310.26	12	-	-	-	-
R^2	1.0000	Adjusted R^2	1.0000	Predicted R^2	0.9999	-
Micro-hardness						
Model	47.07	5	9.41	8660.44	< 0.0001	significant
A-Stirring intensity	44.94	1	44.94	41338.47	< 0.0001	
B-Stir time	0.0486	1	0.0486	44.71	0.0003	
AB	0.0144	1	0.0144	13.25	0.0083	
A^2	2.04	1	2.04	1880.67	< 0.0001	
B^2	0.4864	1	0.4864	447.46	< 0.0001	
Residual	0.0076	7	0.0011	-	-	-
Lack of Fit	0.0062	3	0.0021	5.91	0.0594	not significant
Pure Error	0.0014	4	0.0003	-	-	-
Cor Total	47.08	12	-	-	-	-
R^2	0.9998	Adjusted R^2	0.9997	Predicted R^2	0.9986	-
Wear rate						
Model	3.92E-05	5	7.83E-06	82.7	< 0.0001	significant
A-Stirring intensity	3.04E-05	1	3.04E-05	330.38	< 0.0001	
B-Stir time	2.67E-06	1	2.67E-06	28.16	0.0011	
AB	3.42E-06	1	3.42E-06	36.15	0.0005	
A^2	1.41E-06	1	1.41E-06	14.93	0.0062	
B^2	1.19E-08	1	1.19E-08	0.1252	0.7339	
Residual	6.63E-07	7	9.47E-08	-	-	-
Lack of Fit	4.55E-07	3	1.52E-07	2.92	0.164	not significant
Pure Error	2.08E-07	4	5.20E-08	-	-	-
Cor Total	0	12	-	-	-	-
R^2	0.9834	Adjusted R^2	0.9715	Predicted R^2	0.8856	-
Density						
Model	310.72	5	62.14	68.44	< 0.0001	significant
A-Stirring intensity	240.67	1	240.67	265.04	< 0.0001	
B-Stir time	60.17	1	60.17	66.26	< 0.0001	
AB	9	1	9	9.91	0.0162	
A^2	0.7389	1	0.7389	0.8137	0.397	
B^2	0.0008	1	0.0008	0.0009	0.9769	
Residual	6.36	7	0.908	-	-	-
Lack of Fit	5.16	3	1.72	5.73	0.0625	not significant
Pure Error	1.2	4	0.3	-	-	-
Cor Total	317.08	12	-	-	-	-
R^2	0.9800	Adjusted R^2	0.9656	Predicted R^2	0.8553	-

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Figure 7represents the regression plots of RSM-FCCD predicted vs actual experimental values for tensile strength, micro-hardness, wear rate and density. The x-axis values represents the actual values of each respective responses obtained through experimentations, while the y-axis shows the RSM-FCCD predicted responses. From figure 7(a) the points are perfectly lies on the fit line (45° inclined linear line shown in that figure) which indicates, the predicted tensile strength values are in-line with the actual experimental values. Hence, the regression coefficient R^2=1 for tensile strength is reasonable. Similarly, from figure 7(b) the RSM-FCCD predicted micro-hardness values are almost equal with the experimental values, therefore the micro-hardness quadratic model achieved 0.9998 regression coefficient. On the other hand, figure 7(c) and 7(d) are showing some deviated points from the fit line which indicates the wear rate and density prediction model may produce error while optimizing process parameters. However, the regression coefficient above 0.9 is more than enough for this kind of prediction model to achieve optimal solutions with better factor to response correlation [41]. Therefore, the proposed RSM-FCCD models are found significant for optimizing electro-magnetic stir casting process parameters during this study.

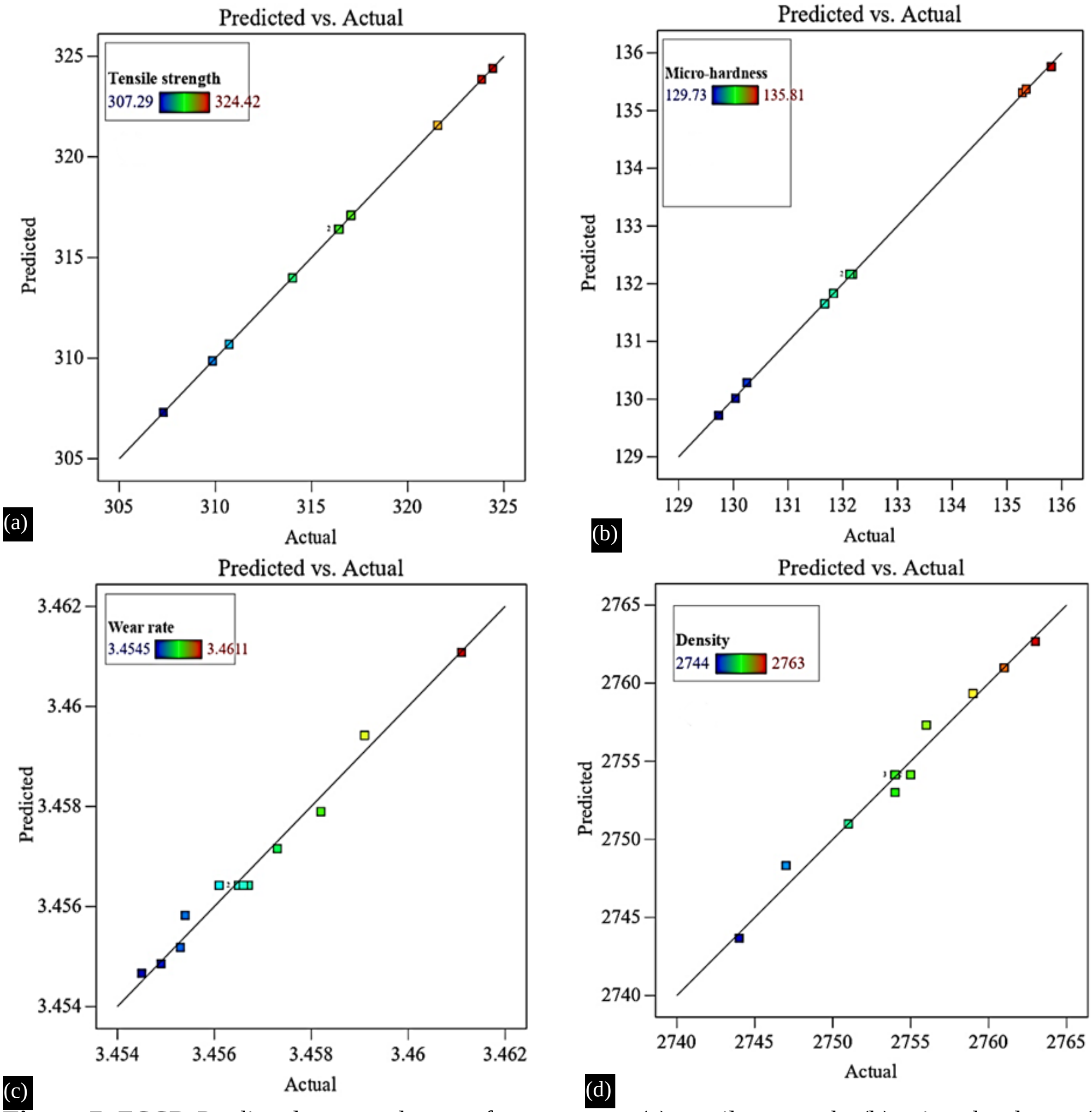

Figure 7. FCCD Predicted vs actual curve for responses (a) tensile strength, (b) micro-hardness, (c) wear rate, and (d) density.

Mechanical Characteristics

Furthermore, the sensitiveness of mechanical characteristics of reinforced aluminium composite on selected input process parameter levels are analyzed with the help of 3D contour plots as given in figure 8. From figure 8(a) the tensile strength is increasing while increasing the stirring intensity and stirring time, which indicates uniform distribution of reinforcement particle (17%wt SiC and 3%wt GNPs) inside the Al319 alloy. Particularly, the stirring intensity had more impact on improving tensile strength of the composite than the stir time. The maximum tensile strength predicted from the RSM-FCCD model during this study is 324.4MPa at extreme level of both intensity and stir time. From figure 8(b) the micro-hardness value increases linearly with increase in stirring intensity from 70-100Hz, while it marginally increases with increase in stir time from 8-10min and then marginally reduced after 10min. This observation in micro-hardness result may be reasonable due to increased porosity at higher stir time. Similarly, the trends of wear rate and density changes according to increase in input parameters are studied from Figure 8(c) and 8(d). Based on results, both wear rate and density of fabricated composite arereducing while increasing the stirring intensity. The uniform distribution of SiC and GNPs particles at higher stirring intensity is the ultimate reason behind this reduction in wear rate and density properties of Al319 composite fabricated at higher intensity. Similar results were also identified by previous author Badizi et al. [42] optimizing stirring intensity for different Al alloy with SiC reinforcement.

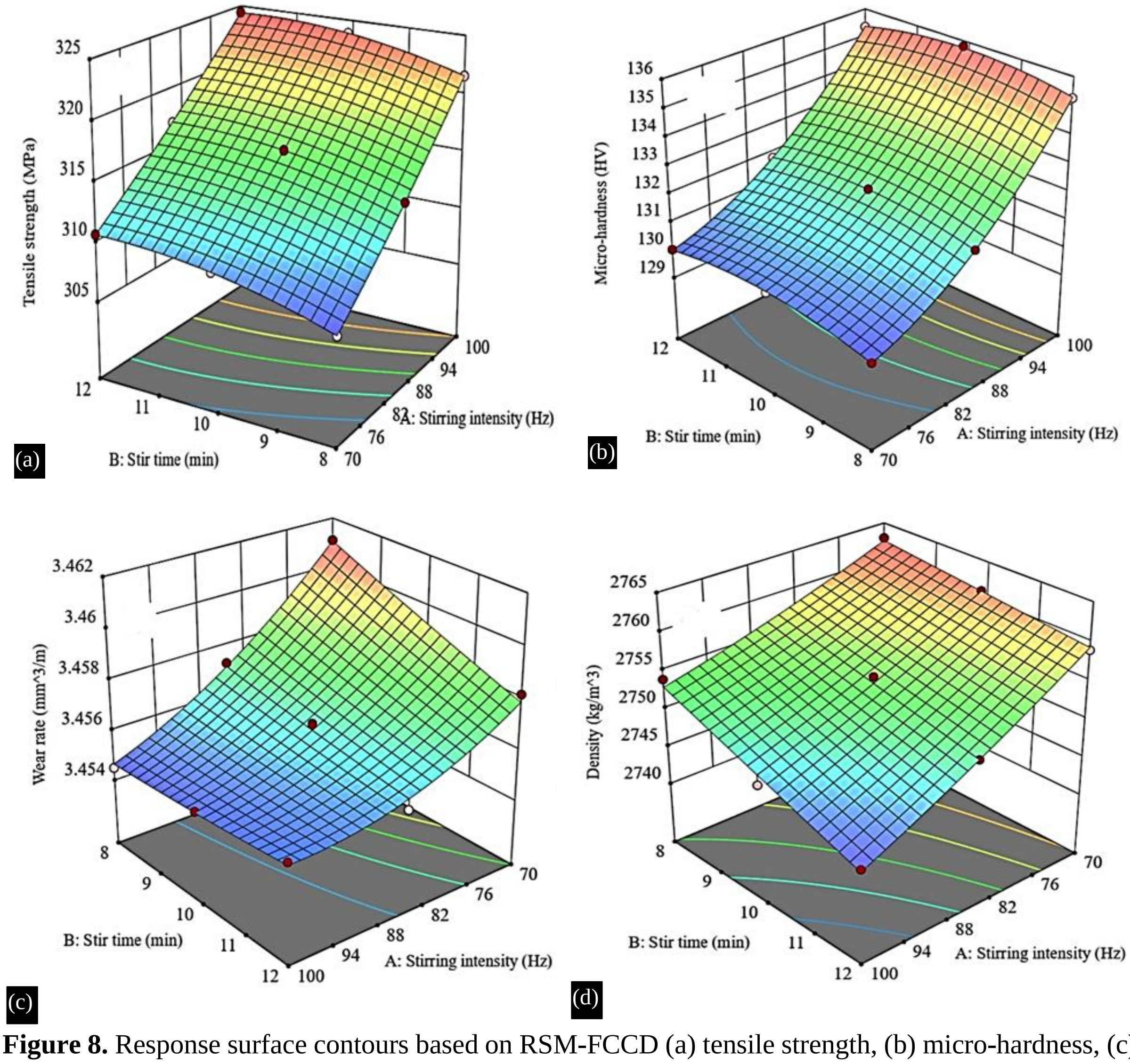

Figure 8. Response surface contours based on RSM-FCCD (a) tensile strength, (b) micro-hardness, (c) wear rate, and (d) density.

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Optimal Solutions

Finally, the multi-parameter optimization was done with the help of RSM-FCCD numerical optimization method. For obtaining optimal solutions, maximum objective (or) goal is selected for tensile and micro-hardness properties, because these two properties are to be enhanced by SiC and GNPs reinforcement during this study. On the other hand, the objective of this study is to minimize the wear rate of Al319 alloy by SiC and GNPs reinforcement. Therefore, minimum goal is selected for wear rate parameter with top priority (importance 3). At the meantime, the density of fabricated material should be minimum as possible due to the application of Al319 in automobile industry. But, the lower density in reinforced composite may be promote increased porosity leading to poor wear characteristics. Hence, the less importance (1) is given to minimize the density of proposed composite (Al319 + 17%wtSiC + 3%wtGNPs). The detailed description of optimization criteria followed during the study are given in table 7. After initializing the optimization criteria, the RSM-FCCD calculated the optimal solutions for this study as shown in Table 8.

From table 8, the first optimal solution is selected in which the RSM-FCCD shown 100Hz stirring intensity and 11.03min stirring time as the optimal input settings for fabricating Al319 + 17%wtSiC + 3%wtGNPs composite via electro-magnetic stir casting technique. While performing the desirability test, the top five optimal solutions suggested by the RSM-FCCD method are achieved 0.958 desirability which very close to 1 (ultimate best). Therefore, the confirmatory experiments are conducted on samples fabricated at 100Hz stirring intensity and 11min stir time. The results obtained from this confirmatory experiments are shown in table 9. According to the confirmatory test results, the proposed RSM-FCCD model optimized the results with approximately 0.04-2% error. Hence this optimization method is significant for this kind of studies to get an optimal solutions. Besides, the obtained optimal finding are compared with tensile strength, micro-hardness, wear rate and density of non-reinforced Al319 base metal. As a result,around 30% improvement in tensile strength and micro-hardness were achieved from the optimized solution whereas, the wear rate is minimized upto 17.38% due to optimization.

Table 7. Criteria for optimization.

Name	Objective / Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Stirring intensity	is in range	70	100	1	1	3
B:Stir time	is in range	8	12	1	1	3
Tensile strength	maximize	307.29	324.42	1	1	3
Micro-hardness	maximize	129.73	135.81	1	1	3
Wear rate	minimize	3.4545	3.4611	1	1	3
Density	minimize	2744	2763	1	1	1

Table 8. Top five optimal solutions obtained from RSM-FCCD.

Sl.no.	Stirring intensity (Hz)	Stir time (min)	Tensile strength (MPa)	Micro-hardness (HV)	Wear rate (mm^3/m)	Density (kg/m^3)	Desirability	Remark
1	100	11.03	324.349	135.664	3.455	2745.923	0.958	Selected
2	100	11.058	324.356	135.658	3.455	2745.858	0.958	
3	100	10.994	324.339	135.671	3.455	2746.007	0.958	
4	100	11.085	324.363	135.652	3.455	2745.795	0.958	
5	100	11.112	324.369	135.647	3.455	2745.733	0.958	

Table 9. Confirmatory test result

Parameter	Optimized result	Experimental result	Error %	Impact of optimization
Stirring intensity (Hz)	100	100	-	-
Stir time (min)	11.03 ~ 11	11	-	-
Tensile strength (MPa)	324.349	328.170	1.16	29.71% ↑
Micro-hardness (HV)	135.664	135.720	0.04	30.74% ↑
Wear rate (mm^3/m)	3.4550	3.5179	1.79	14.45% ↓
Density (kg/m^3)	2745.923	2741.000	0.18	1.52% ↑
Note: ↑ - increase from BM (Al319); ↓ - decrease from BM (Al319)				

CONCLUSIONS

The major conclusions from this study are highlighted as follow,

1. The reinforcement of 20%wt SiC particles improved the wear characteristics of Al319 initially upto 50% at higher loads whereas, the wear rate is further reduced upto 62.31% while reinforcing with 17%wt SiC and 3%wt GNPs. This indicates the advantage of both SiC and GNPs particles had significant positive impact on wear characteristics of Al319 composite than their mono reinforcement technique.
2. From the microscopic study, it was inferred that, the stir intensity around 75-100Hz and stir time around 10min are significant to achieve uniform distribution of both SiC and GNPs particles in Al319 matrix.
3. However, the porosity results shown there was inconsistence in air bubble and metal oxide formation due to fabrication conditions. Hence, the study was further continued to optimize electro-magnetic stir casting parameters.
4. The ANOVA results shown positive signs on proposed RSM-FCCD quadratic model for optimizing electro-magnetic stir casting parameters by indicating very less p-value (<0.0001) for all response parameters.
5. Additionally, the regression coefficient of all response modelwere achieved above 0.9 which enough for performing optimization task using the proposed RSM-FCCD model.
6. While analyzing the mechanical properties of Al319 + 17%wtSiC + 3%wtGNPs composite, higher tensile strength was achieved at maximum level of stirring intensity and time whereas, micro-hardness was maximum for high and intermediate level of stir intensity and stir time.
7. In contrast, the wear resistance of Al319 + 17%wtSiC + 3%wtGNPs composite improved while maintaining intensity and time at lower range.
8. Hence, optimal levels of stirring intensity (100Hz) and stir time (11min) were obtained from the proposed RSM-FCCD model at 0.958 desirability along with 0.4-2% error.
9. Therefore, the proposed RSM-FCCD method is suggested for similar kind of experiments to optimize process parameters. Additionally, Al319 + 17%wtSiC + 3%wtGNPs composite is recommended for the replacement of existing Al319 alloy because of 30% improvement in tensile strength and micro-hardness along with 14.45% reduction in wear rate.

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