Design and Development of Coal Dust Filled Aluminium Alloy Composite

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Abstract

In this current study, lignite coal dust reinforced into Al 5083 alloy composites are fabricated by adopting stir casting approach by changing coal dust (CD) weight percentages from 0 wt.%, 6 wt.%, 8wt.% and 10 wt.%. The coal dust particulates of size less than 53 µm size were consistently blended in molten aluminum 5083 accompanied by stirring process. The physical as well as mechanical properties of coal dust filled AA 5083 alloy composites were evaluated experimentally. In result, void percentage of AA 5083 composites varied from 0.75% to 0.79% for 0 to 8 weight percent coal dust whereas value got reduced to 0.41 % for 10 weight percent coal dust composite and micro-hardness value raised from 71 HV to 76 HV with the increasing coal dust amount. Dry sliding wear tests were conducted for coal dust filled alloy composites by implementing Taguchi approach at four distinct loads (10N – 40N), sliding speed (100 rpm – 700 rpm), sliding distance (500-2000 m) and coal dust weight percentages (0 wt.% - 10 wt.%) respectively using pin-on-disc machine. Although, a series of steady state wear examination is also carried out by altering the speed of disc to 100 rpm (0.52 m/s), 300 rpm (1.57 m/s), 500 rpm (2.61 m/s) and 700 rpm (3.66 m/s) and normal loads 10N, 20N, 30 N and 40 N one by one while keeping other parameters constant before studying the Taguchi experimental outcome. Finally, for finding the wear characteristics of fabricated composites, the damaged faces were observed under scanning electron microscope (SEM).

Keywords: Specific wear rate; Steady state; ANOVA; Taguchi.

1. Introduction

The alloy composites find its tremendous applications in diverse areas because these materials possess many tailorable properties; also it is capable of delivering enhanced quality and endurable survival. With the passing days and ever escalating technologies and researches, engineers are developing novel materials that are capable of demonstrating outstanding and phenomenal properties. With the cutting-edge technology and investigation in the field of aluminium, it has brought forth development of its alloys with additional properties like reduced density, increased strength and lighter weight ratio, wear resistant and corrosion resistant. Past literatures revels the importance of electing reinforcement material in order to get desirable properties in the final alloy composites. Special focus is given to attain the enhanced mechanical properties in the final composites. There has been a growing interest into metal alloy composites possessing lower density and economical reinforcements.
Kukshal et al. [1] fabricated Al_2O_3-filled cast aluminium alloy A356 grade (by altering wt. % percentage of Al_2O_3 content from 0, 5, 10, 15, 20 and finally to 25) using stir casting technique. By performing theoretically and experimentally the performances were noted for mechanical, physical, fracture toughness and their results were compared by utilizing finite element analysis method. The outcomes exhibited improved hardness and enhanced impact, tensile, flexural strength with the incorporation of Al_2O_3 particles. In another study conducted by Kukshal et al. [2], fabricated SiC reinforced aluminium 365 alloy composites by stir casting technique. One such study was composed of evaluating properties like physical, mechanical and fracture toughness for the fabricated alloy composites, in which results showed that void content, tensile strength and hardness increased with the increment of SiC particles weight percentage into the alloy. Mamatha and her team mates [3] conducted a study in order to find out the thermal and thermo-mechanical, physical and mechanical properties of stir casted Alumina (Al_2O_3) filled Zinc-aluminium (ZA-27) in result observed that porosity content got escalated with the rise in

weight proportion of filler content. The contributing fact for this increase in porosity content was poor wettability amongst alloy matrix and reinforcement. Dhingra and Gulbransen [4] reported that the composite structures have proved to be the reduction of somewhat 25% over metal counterparts and reduced operational and maintenance cost.
Exceptional wear resistance can be classified as the utmost desirable trait in metal alloy composites. Past literature revealed that particle-reinforced metal composites under varying load ranges exhibits wear resistance that is 10 times greater than the un-reinforced materials [5].
Taguchi optimization technique is a method that exceptionally helps in reducing the total experiments that are mandatory to design the response function in comparison to the full factorial design of experiments. The Taguchi system basically formulated for obtaining procedure optimization and recognition of most advantageous fusion of the factors for a given response [6]. Considering the above mentioned facts, the Taguchi L_{16} method was taken on to examine the end result of each process parameters (i.e. coal dust wt. %, normal load, sliding speed and sliding distance) in predicting specific-wear rate for fabricated AA 5083/ coal dust reinforced composites. Fixing all other parameters constant at stable levels, the impact of normal load and sliding speed were studied individually. For this purpose, an attempt is made to examine and figure out the significance of more than one variable upon the wear rate values of metal alloy composites, because in actual process outcome wear rate is mixed effect of numerous factors and their intercommunication [7-11].

2. Experimental details

2.1. Specimen preparation

AA 5083 as matrix material and coal dust (Lignite coal; purchased from Matasukh coal mines, Rajasthan state mines and minerals limited, Rajasthan, India) particles as a reinforcement filler were used for fabricating the desired composites. Table 1 represents the composition of procured Al 5083 plates (Al 5083 alloy; purchased from Nextgen steel and alloys, Mumbai, India) in accordance with the test reports of Brukers' optical emission spectroscopy at Materials and research center lab, MNIT, Jaipur.

Table 1. Composition of aluminium 5083 alloy

Al %	Mg %	Zn %	Fe %	Mn %	Cr%	Ti%	Cu %	Ni%	Others
93.2	5.04	0.148	0.56	0.065	0.065	0.023	0.024	0.016	0.484

2.2. Composite Fabrication

In this research, coal dust (CD) particles filled AA 5083 alloy composites are manufactured at 4 distinct weight quantity (0 wt. %, 6 wt. %, 8 wt. %, 10 wt. %) by adopting stir-casting technique. The aluminium 5083 alloy was melted using muffle furnace and this metal melt is controlled at 760°C for about 10 minutes; subsequently, the temperature of the furnace is reduced to 600°C to keep the melt between solidus and liquidus temperature. AA 5083 alloy when reached its liquidus temperature, the micron size (less than 53μm) low grade lignite CD particulates (density 1.3 g/cm^3) were added within this melt and is mixed using a mechanical stainless steel (SS) stirrer rotating at a speed of 300 rotation/min so as to blend the coal particulates uniformly in the matrix of alloy for 3-4 minutes. Hereafter, the liquefied mixture is drained into cast iron permanent mold of desired dimensions, held together and allowed to cool to a low temperature i.e. to room temperature, moderately. By this method various compositions of samples were fabricated.

Afterwards, once solidification process completed, composites were later removed from the mould and markings were completed according to test standards.

2.3. Physical and Mechanical characterization

2.3.1. Density

Void percentage and theoretical density of a composite was evaluated by Agarwal and Broutman in regards of weight fraction as per given equations (1) and (2). Composite density is evaluated by employing rule of mixture as mentioned below;

$$\rho_{\text{composite}} = \frac{1}{\frac{W_A}{\rho_A} + \frac{W_P}{\rho_P}} \qquad (1)$$

Where, W_A and W_P represents the weight fraction of alloy 5083 and particulate filler, whereas, $\boldsymbol{\rho}_A$ and $\boldsymbol{\rho}_P$ represents density of alloy and particulate filler. The void content (V_c) in the composites is evaluated using following equation:

$$V_c = \left(\frac{\rho_{th.} - \rho_{exp.}}{\rho_{exp.}}\right) \text{ x } 100 \qquad (2)$$

Where, $\boldsymbol{\rho}_{th}$ is theoretical density and $\boldsymbol{\rho}_{exp.}$ is experimental density.

2.3.2. Micro-hardness

Most of the researchers observed that with the increment in reinforcement percentage, hardness also improved [12]. Sahin et al. [13] discovered that, by increasing the volume rate of SiC particulates into Al 2024 alloy matrix, the composite hardness increased linearly which may be contributed due to larger ceramic phase in the matrix of alloy. Micro-hardness test was executed using UHL Vickers hardness tester machine. Because of hardness variations in composites due to distribution of reinforcement particles a single micro hardness test value may not be illustrative for the overall hardness. Hence, four series of reading were noted.

2.3.4. Tensile test

The tensile test as per ASTM standard was performed on aluminium alloy composite using universal testing machine to discover their mechanical properties. It is elaborated in [14] that the strength of composite can be increased by making changes in strength due to the dislocations, sub grains and residual stress respectively.

2.3.5. Tribo-performance evaluation

In accordance to ASTM G 99 test standard, for dry sliding wear test pin-on-disc (figure 1) test rig (MAGNUM, India) equipment was operated for the tribological assessment of friction materials under room temperature. Specimen was hooked and settled in the tool holder and load was enforced against the specimen in such a way that face of the desired specimen comes in touch with the rotating disc built of hardened steel (EN-32, surface roughness of 0.6 µRa and hardness about 72 HRC). The resulting height loss in the specimen experienced during wear testing was measured in microns. Calculation for specific wear loss (mm^3/N-m) was done using formula:

$$\text{Specific wear rate} = \frac{\Delta m}{\rho \text{ x } v \text{ x } F \text{ x } t} \qquad (3)$$

Δm = mass loss, in kg, $\boldsymbol{\rho}$ = Experimental density, kg/mm^3, v = Sliding speed, m/sec, F = Normal load, N, t = Time, seconds.

Figure 1: The arrangement of pin-on-disc wear test apparatus at tribology lab, MNIT

3. Experimental design

As discovered from past studies, the wear rate gets affected by a considerable number of process variables like sliding speed, sliding distance, reinforcement type, size of reinforcement, normal load, weight percentage of reinforcement, time. Thus, important concerning factors are shortlisted at the start and experiments are run to discover the inconsequential factors as earliest as possible. Performing conditions under taken to accomplish wear tests are shown in table 2.

Table 2 Levels of factors used for wear test experiment

Control factors	Level				
	I	II	III	IV	Units
A, Coal dust wt.	0	6	8	10	%
B, Normal load	10.00	20.00	30.00	40.00	N
C, Sliding speed	0.52	1.57	2.61	3.66	m/s
D, Sliding distance	500	1000	1500	2000	m

Taguchi's experimental approach reduces the number of experiments to 16 runs only offering an ease of doing the experiments and thereby saving time [15]. In current work, S/N ratio was chosen in accordance to the principles of "the smaller-the better" characteristics.

4. Results and discussions

4.1. Physical and Mechanical Characterization

4.1.1. Density and void percent of coal dust alloy composite

Experimental density of CD reinforced AA 5083 alloy composites is calculated by making use of Archimedes principle based densitometer and this calculated experimental density is compared with theoretical density whose results are presented in table 4. The results illustrates that with the increasing CD quantity into the alloy, the void percentage in the fabricated composites is also increasing. It can be concluded from the data that the experimental density of alloy 5083 composites containing 0, 6, 8 and 10 wt.% CD is less when compared to the theoretical density. The reason being that theoretical outcomes are generally established on the basis of idealistic assumptions that differs from the values attained experimentally and also could be due to the presence of porosity. However, in comparison to unreinforced AA 5083 alloy, the CD particle reinforced composites showed lower density and further it tend to decrease with the increase in coal content.

Table 3 Density of CD filled AA 5083 alloy composites

Composite	Experimental density (g/cm^3)	Theoretical density (g/cm^3)	Void content (%)
AA5083 + 0wt.% coal dust	2.63	2.65	0.75

AA5083 + 6wt.% coal dust	2.51	2.53	0.79
AA5083 + 8wt.% coal dust	2.50	2.52	0.79
AA5083 + 10wt.% coal dust	2.45	2.46	0.41

In stir casting procedure for casting particulate filled composites, it is very tough to ignore voids in any fabricated composite as it is an unpreventable parameter. The density of fabricated composites tends to decrease with the rise in weight percentage of CD particulates. Whereas, void content increases from 0.75 % to 0.79 % from 0 weight percent to 8 weight percent of CD filled alloy composite, but the value decreases to 0.41 % for 10 weight percent CD filled alloy composite.

4.2.2. Micro-hardness of coal dust alloy composite

The change in the value of micro-hardness with respect to the CD filled AA 5083 composite is demonstrated in figure 2. Micro hardness of CD particulate filled AA 5083 alloy composites considerably got increased with the increase in CD particulates in contrast to the unfilled AA 5083 alloy. The hardness value of fabricated composites was found to be 76 HV which was the maximum hardness value amongst all the fabricated composites at 10 wt. % CD particulates. Particle strengthening and grain refinement effects could be considered as the leading factors that attributed for the increment in the hardness value with the increasing wt. % of the coal particles.

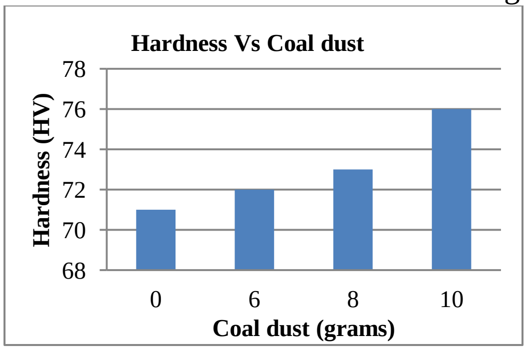


Figure 2: Variation of micro-hardness with amount of coal dust

4.2.3. Tensile strength of coal dust alloy composite

For determining the mechanical properties of fabricated 5083 alloy composites, the tensile tests was conducted using computer-aided universal testing machine as per the standards of ASTM. It is very clear from figure 3 that tensile strength is increasing with the increment in the amount of CD particles, i.e. tensile strength value observed was 142 MPa for 0 wt. % CD, which increases to 147 MPa for 6 wt. % CD, 182 MPa for 8 wt. % CD and it increases to 199 MPa for 10 wt. % CD particles in 5083 alloy composite. The thermal inconsistency between the metallic matrix and the reinforcing particles leads to the increase in tensile strength value, which in return contributes in a significant mechanism of increasing the dislocation density of the matrix and consequently leading to increase in the overall strength of the alloy composite [16].

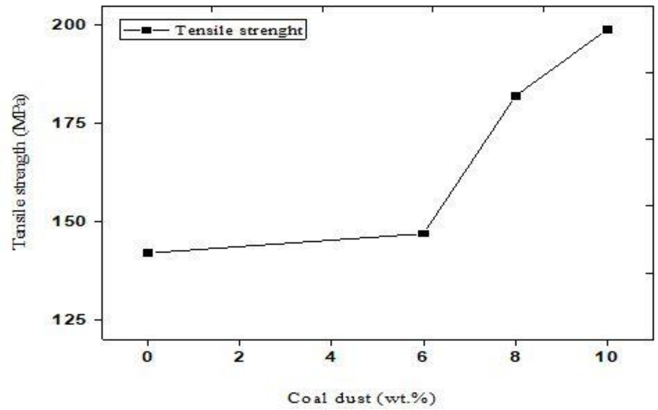


Figure 3: Graph for tensile strength with amount of CD particle

4.2.4. Taguchi experiment analysis

The results of experimental design for L_{16} orthogonal array are displayed in table 5. The overall mean was found to be -8.77 dB for the S/N ratio of W_s (specific wear). Taguchi experimental technique is implemented to determine dominant factors responsible for overall decrease in specific wear rate of CD filled AA 5083 alloy composites. This interpretation for wear rate was made by making use of software generally utilized for the designing of experimental applications called MINITAB 16 software.

Any product which is under investigation, its variation in quality characteristics is denoted by "signal" in response to a factor introduced in an experimental design. However, there are other external factors as well that are not included in the actual experiment but somehow affects the outcomes of an experiment. It can be clearly perceived by looking at table 7 that coal dust weight percentage has more remarkable effect on the specific wear rate thereafter by sliding speed, load, and sliding distance.

Table 5: L_{16} orthogonal experimental array design

Sr. No.	Coal filler (%)	Normal Load "N"	Sliding Speed "m/s"	Sliding distance "m"	Specific wear rate (mm3/N-m) × 10^{-13}	S/N ratio (db)
1	0	10	0.52	500	5.193	-14.54
2	0	20	1.57	1000	2.594	-8.49
3	0	30	2.61	1500	5.190	-14.52
4	0	40	3.66	2000	1.529	-3.92
5	6	10	1.57	1500	5.386	-14.63
6	6	20	0.52	2000	4.616	-13.29
7	6	30	3.66	500	3.858	-11.74
8	6	40	2.61	1000	6.448	-16.12
9	8	10	2.61	2000	2.952	-9.82
10	8	20	3.66	1500	1.968	-6.29
11	8	30	0.52	1000	1.845	-5.73
12	8	40	1.57	500	1.848	-5.74
13	10	10	3.66	1000	1.466	-4.14
14	10	20	2.61	500	1.833	-6.08
15	10	30	1.57	2000	1.038	-1.14
16	10	40	0.52	1500	1.465	-4.14

The effect of leading control factors on the specific wear rate for the overall mean value of S/N are plotted onto graphs as shown in figure 4.

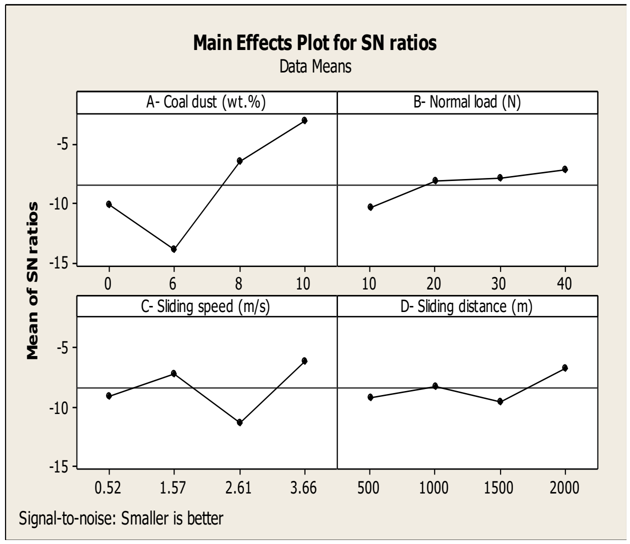


Figure 4: Effect of coal dust, normal load, sliding speed and sliding distance on wear rate

4.2.5. ANOVA

The function of Analysis of variance (ANOVA) was applied to determine which control factor undertaken i.e. coal dust wt. %, normal load, sliding speed and sliding distance significantly affects the quality characteristics. It is observed that P value of coal dust factor is 0.014 is lowest amongst normal load (0.244), sliding speed (0.083) and sliding distance (0.296).

Table 6: ANOVA table for specific wear rate- Coal dust filled- AA 5083 alloy composites

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coal dust (wt. %)	3	228.180	221.180	76.060	22.12	0.014
Normal load (N)	3	23.797	23.797	7.932	2.41	0.244
Sliding speed (m/s)	3	61.641	61.641	20.547	6.25	0.083
Sliding distance (m)	3	19.393	19.393	6.464	1.97	0.296
Error	3	9.867	9.867	3.289		
Total	15	342.879				

4.3. Steady state specific wear

4.3.1.Impact of load and sliding speed on wear rate

The steady state wear rates is measured as a function of normal load on coal dust filled AA 5083 alloy composites as illustrated in figure 5. Results of this study illustrated that unfilled aluminium alloy showed more wear rate in comparison to the coal particulate - AA 5083 alloy under steady state sliding velocity: 0.52 m/sec, test duration: 15 minutes, and sliding distance: 468m respectively. It is discovered in this study that there is difference in specific wear rate values when compared between the unfilled and CD filled composites (Figure 5). Based on the wear test data it is revealed that with the increase in CD weight percentage the wear rate tend to decrease. Specific wear rate keeps on increasing as the load applied is increased for all speeds. The reason being that higher load tend to increase the frictional thrust which in result leads to increased debonding and ultimately fracture [17].

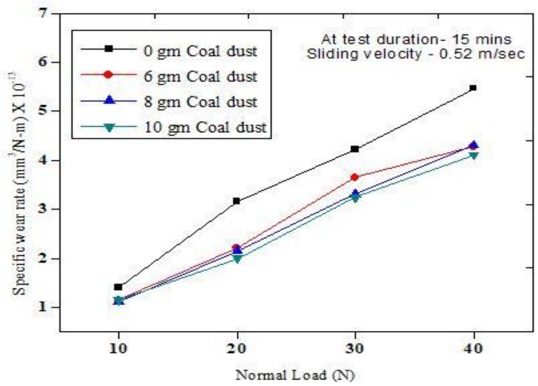


Figure 5: Variation in specific wear rate with normal load for CD filled AA 5083 alloy composites (at constant sliding velocity: 0.52 m/s (100 r/min), test duration: 15 minutes, and sliding distance: 468 m)

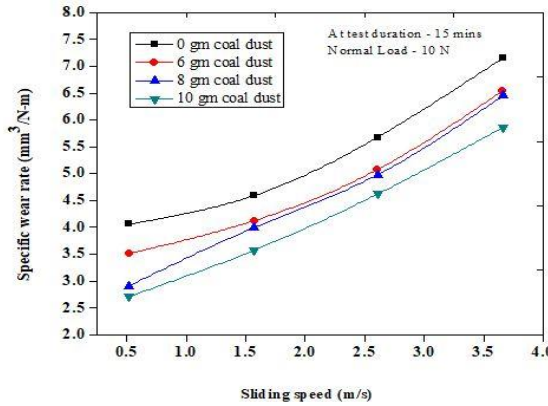
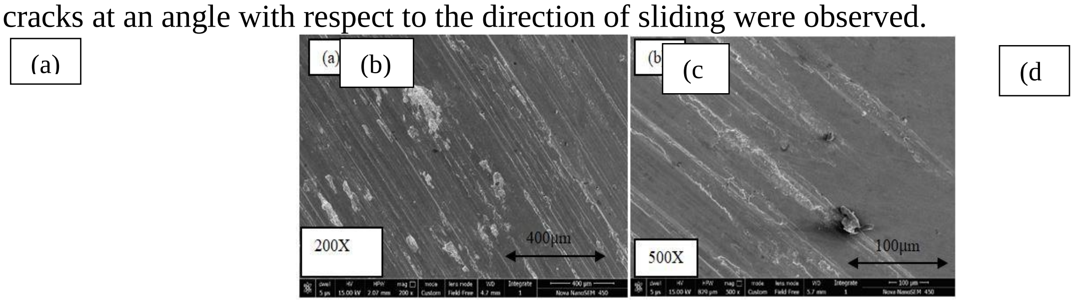


Figure 6: Variation in specific wear rate with sliding velocity for CD filled AA 5083 alloy composites (at constant normal load: 10N, test duration: 15 minutes, and sliding distance: 468 m)

Four different sliding velocities (i.e. 0.52 to 3.66 m/s) were undertaken for studying wear rate. It is observed that as sliding velocity is increasing, the wear rate is also escalating (figure 8). Specific wear rate without CD particulate is more for all range of sliding velocity in comparison to when CD is added in certain amount i.e. with the reinforcement of CD particles specific wear decreases slightly. The wear rate curve (figure 6) illustrates highest wear in case of unfilled AA 5083 composite and lowest for 10 wt. % CD-filled AA 5083 alloy composites. The contributed reason for this type of behaviour in 10 wt. % CD composites is reinforcement of higher amount of reinforcing particulates into the alloy AA 5083.

4.3.2. Wear surface morphology

The use of SEM images makes it convenient to qualitatively identify the dominant mechanism that operates, and thus, gain insight into the influence of the coal particulates on the wear process of metal alloy composites. From figure 9, long and continuous grooves in the direction of sliding could be observed. Also with the increasing speed under constant load condition cavities reduces and formation of deep grooves takes place. Whereas with the increase in both load and speed, grooves grow wider and deeper with some matrix area smeared along the sliding direction. Deep cracks at an angle with respect to the direction of sliding were observed.



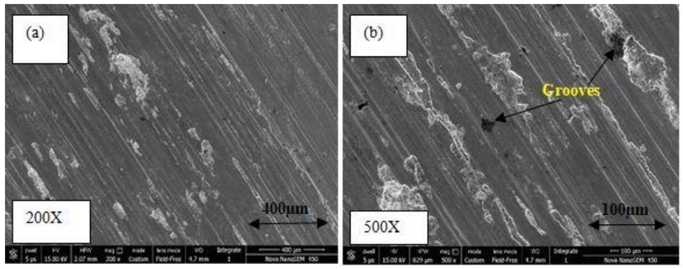


Figure 7: (a),(b) SEM micrographs of 0 wt. % CD 5083 alloy at speed 700rpm and 10N load, and (c),(d) SEM micrographs of 10 wt. % CD 5083 alloy at speed 700rpm and 10N load

5. Conclusion

The following conclusions were acquired from the observed outcomes:

1. Compared to the unreinforced AA 5083 alloy, the CD particle reinforced composites showed lower density and further it tend to decrease with the increase in coal content. Slight increase in micro-hardness (from ~71 to 76 HV) was observed when weight fraction of the composite increased from 0 wt.% to 10 wt.% of coal dust, which prevents the deformation of material resulting in increased hardness value.
2. Tensile strength amount noted to be 142 MPa for 0 wt. % CD, which increased to 147 MPa for 6 wt.% CD, 182 MPa for 8 wt.% CD and it got increased to 199 MPa for 10 wt.% CD particles in 5083 alloy composite.
3. CD weight percentage displayed a direct correlation with the wear rate. Fusion of 6, 8 and 10 wt. % of CD particles with AA 5083 alloy resulted in a reduction of wear rate at lower load values (10, 20, 30 and 40 N).
4. Sliding speed shows a direct relationship with the specific wear rate of fabricated composite, i.e. as the sliding speed increased, the specific wear rate increases because of rise in temperature that lead to the softening of the matrix and composite, whereas bonding efficiency decreased with the increase in wear rate.
5. Taguchi's design method is implemented so as to procure optimal parameter for specific wear rate. As the CD weight percentage is raised from 0 to 10 wt. %, the specific wear rate value got increased for all sliding speeds (100, 300, 500 and 700 rpm) and loads (10, 20, 30 and 40N).

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