Study on micro-structure, hardness and optimization of wear characteristics of Al6061/TiB_2/CeO_2 hot-rolled MMCs using Taguchi method

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ABSTRACT. Aluminium composites are extensively used in several industries. The production of Metal Matrix Composite (MMCs) with varying wt. % of reinforcement/s leads to enhancement of wear and mechanical behavior properties. In the present work, varying wt. % of TiB_2 and constant wt. % of CeO_2 particulates were reinforced in Al6061 alloy to manufacture hybrid Al MMCs by Vortex (Stircasting) technique. Developed hybrid MMCs were hotrolled at 515°C of temperature. Hardness of hybrid MMCs was evaluated by using hardness test rig (Vickers). Results revealed that the hardness strength of developed hybrid MMCs increased with increase of the reinforcement content. The rate of wear of developed hybrid MMCs was evaluated by Pin-on-Disc wear test method. Test trials were conducted according to Taguchi technique. L27 array was implemented for evaluation of data. Effect of varying factors on the rate of wear and Coefficient of Friction (COF) was analyzed by applying ANOVA (Analysis of Variance) method. ANOVA outcomes showed that the reinforcement content had a more significant impact on wear behavior and COF of the MMCs. Finally, L27 array outcomes were verified through confirmation experiments. Wear fractography test shows the internal fractured structure of a wear specimen which was studied using a Scanning Electron Microscope (SEM).

KEYWORDS. Al6061, TiB_2-CeO_2, Stir casting, Hot rolling, Hardness, Wear behavior, Taguchi technique, Fracture behavior.

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INTRODUCTION

The current applications such as automotive, aerospace, and marine demand composite materials which are cost-effective and light in weight. The materials often exhibit limitations to meet their necessities of wear properties and mechanical behavior [1, 2]. Composites possess better properties compared with the base metal. Metal Matrix Composites (MMC) are innovative materials which contain the parent metal (base) alloy, reinforced with a material elements in the form of particles, short fibers and whiskers. These MMCs have improved properties as compared the parent metal [3]. So, MMCs have been successfully developed to be used as advanced materials usually, in combination of the matrix (metallic) and hard reinforcements in the form of particles, fibers and whisker's to fabricate MMCs with advanced combination of materials. MMCs with hard ceramic particles have a wide range of engineering applications. Al has some restraints for achieving better mechanical characteristics. Usually, MMCs have a significant presence in marine, automobile and aerospace applications. However, due to extensive usage of hybrid MMCs, the scope of end applications of composites has also widened and foremost goal being cost reduction. Being lightweight and ease to fabricate at low cost, Al alloys have attracted much attention for many industrial applications [4, 5]. Al composite becomes very brittle due to addition of ceramic particulates as a reinforcing agent. Hybrid composites have become the major assets in industrial applications [6]. The selection of reinforcements is a major factor in the material analysis. To further reduce weight, hard particles can be added as reinforcement to lightweight metal alloys such as copper (Cu), zinc (Zn), magnesium (Mg), stainless steel, and aluminium (Al) alloys [7]. When ceramic reinforcement is added to the basic matrix, the wear, mechanical, and corrosion properties of composites are improved in comparison to those of alloys [8-13]. The brittle and exceptional qualities of the particles of hard ceramic are present. Al MMCs enhanced with ceramic particles offer improved wear resistance. Al MMC fabrication entails number of problems, including the formation of porosity and incorrect reinforcement distribution. A key requirement is to achieve homogeneous reinforcement distribution inside base alloy. Al MMCs reinforced with hard ceramic particles have attracted the interest of numerous researchers. High oxidisation results from chemical reactions between the reinforcing particles and the base matrix. Relationships between the matrix and reinforcements can speed up oxidation. High diffusion inside the substantial interfacial regions in MMCs is primarily caused by oxidisation at the interface between both the matrix phase and hard particles. Hard reinforcing particulates in alloy generally protect the surfaces of base material against the abrasive action at the time of wear tests. Previous literature survey has revealed that, wear characteristics of MMCs with varying wt. %'s of hard ceramic reinforcing particulates were reported in very few research reports. So, Al MMCs with ceramic particulates are considered for wear and mechanical applications. It is imperative to study the wear behavior of Al composites under the impact of tough ceramic particles and changing variables like load, sliding velocity, and sliding distance. Taguchi method can be used to investigate and improvise the various variables that affect the produced AMMCs' qualities. The impacts of CeO_2 on the mechanical characteristics were assessed by Chao Liu [14]. The findings demonstrated that CeO_2 caused an enhancement in the mechanical characteristics of Al alloys. Increasing the weight percentage of CeO_2 improved the mechanical characteristics of Al in all composite samples, with porosities reaching their maximum level. The impact of CeO_2 particles on the microstructure and mechanical behaviour of Composite materials was researched by Xuedan Dong [15]. The results demonstrated that the MMCs' tensile strength was enhanced by the appropriate weight percentage of CeO_2. Researcher [16] studied the wear rate of Al + 10 % Si3N4 (40 μm particles) manufactured by stircasting method. It was concluded that, the wear loss increased with increasing load. Wear rates of Al MMCs reinforced with SiC fabricated by Stircasting method were evaluated. It was noted that, the rate of wear of composite reduced by increasing wt. % of ceramic particulates. Many researchers [17, 18] concluded that, sliding velocity at constant load led to increase in the wear loss. Hard particulates reinforced composites manufactured by the stircasting method revealed that, increase of hard particulates content led to enhancement of wear resistance of developed MMCs when compared with monolithic material. Researcher [19] stated that, Taguchi technique based on statistical analysis of tests can reduce time and also save cost as it suggests an optimum design. The approaches are initially based on concepts of the factorial designs and OA. The major advantage of this technique is that, multiple factors / parameters are considered at a time, including noise factors. Generally, this technique has been extensively used for optimization of the controllable parameters. The research investigators [20] used Taguchi technique to employ a unique design of the OA to study the effects of machining parameters by conducting number of experiments. Presently, this approach has been extensively used in several engineering fields and research works. [21]. Uvaraja and Natarajan [22] studied the effect of SiC-B4C reinforced Al-7075 hybrid composites fabricated by Stir casting technique. ANOVA and Regression analysis were used to evaluate / optimize the parameters of composite. The ANOVA outcomes conclude that, addition of hard ceramic particles reduces the wear rate of the developed Al composites. Shouvik Ghosh [23] evaluated the AMMCs wear loss by applying Taguchi method. It was seen that sliding speed and load considerably influenced the wear rate of developed composite. V Prasat [24] evaluated the effect of wear factors like wt. % of reinforcements, sliding speed and load on wear characteristics of developed MMCs. It was found that high wear resistance enhanced with increase in wt. % of reinforcement content in MMCs. For better comprehensive studies on wear characteristics, evaluation of various parameters is needed and the contribution effects of these process parameters were ignored in the previous research and hence it is necessary to evaluate the same. Taguchi method is selected due to robust design when compared to traditional design methods. Taguchi method basically employs important tools like S/N (Signal to Noise) ratio generally which shows better properties variance due to un-controllable process parameters. Based on the above literature, it is observed that most of the researchers worked on the mechanical properties and wear properties with different ceramic reinforcements like Al_2O_3, SiC, B_4C and so on. However, the researchers were not focused on the rolling effect of MMCs and its benefits on grain growth, enhancement of mechanical and wear properties. In the present research work, the effect of hot rolling on microstructure, hardness and wear behavior in Al6061 reinforced with TiB_2/CeO_2 MMCs using Taguchi Optimization is studied. The worn-out surfaces of the developed MMCs were analysed using SEM and EDS analysis.

EXPERIMENTAL DETAILS

Production of MMCs

The Stir Casting (liquid metallurgy) method was chosen to produce hybrid MMCs [25]. Ingots of Al6061 and powders of TiB_2 and CeO_2 were used to obtain the necessary amount of raw ingredients for the fabrication of composites. An electrical furnace was used to melt the Al6061 alloy at a temperature of 775°C. The matrix material was melted in a crucible made of graphite. Generally speaking, graphite crucible provides good thermal resistance to shock and chemical erosion as well as high temperatures [26, 27]. The molten metal was mixed with the pre-heated reinforcements, such as TiB_2 (2.5%, 5%, 7.5%, and 10%) and constant 5% of CeO_2 particulates. Required amount of heated reinforcements was added, and stirring action was kept up constantly for three minutes at a speed of 300 rpm [28]. It is usually possible to achieve uniform dispersion of reinforced particles inside the base matrix through continuous stirring action. Finally, molten melt was continually poured into a heated metallic die. The cast components were removed from the metallic die after complete solidification. The thickness of created composites was then decreased from 10mm - 5mm in 12 passes by hot rolling cast components at a temperature of 515°C. Wire EDM was used to do pre-machining on the generated composite samples. ASTM-E384 standards for hardness test and ASTM-G99 standards for wear test samples were used for testing the samples.

Hardness

Using Vickers Microhardness test equipment, microhardness of produced composites was evaluated in accordance with E92-ASTM requirements. Hardness test was conducted using diamond cone with radius of curvature at the tip of 0.2mm and cone angle of 120°. Diamond point indenter with a load of 5 kg and dwell time of 15 seconds was used during the testing. At a temperature of 27°C, trials for hardness tests were conducted. To get the average hardness values, the hardness value of each specimen was determined at three distinct wear test specimen zones.

Wear test

Wear testing was done in accordance with the norms (ASTM). In the current study, tests against a steel disc were run with varied parameter levels (Grade: EN-32). Wire EDM was used to create test samples with a diameter of 8 mm and a thickness of 5 mm. By using the weight loss method, the wear loss of hot-rolled hybrid composites was investigated. During wear tests, the hot rolled hybrid Al composite samples were held rigidly towards rotating hard steel disc (EN-32 grade). After each and every test trial, the samples were measured for loss of weight. In the present research, the wear rate was determined based on the weight loss method (measuring weight at initial and final of the test specimens and difference was determined).

RESULT AND DISCUSSION

Micro-structural Analysis

At 515°C, hot-rolling of the alloy Al-6061 and hybrid MMCs (Al-6061 + TiB_2 + CeO_2) was effectively accomplished. The surfaces of the microstructure test samples were polished with diamond paste and emery sheets of a 400 grit size. To get a fine finish on the surface, the samples were then polished by using a velvet disc polishing apparatus. Through microscopic analysis, the uniform dispersion of TiB_2 and CeO_2 particles was investigated. The mechanical characteristics of MMCs were more significantly impacted by uniform dispersion of the reinforcing particles [27]. Optical microscopic image of base alloy, hybrid MMCs and hot rolled hybrid MMCs are as shown in the Fig. 1 (a-c). The illustration demonstrates the presence of reinforcing particles near the grain boundaries [28]. It was also discovered that the Al6061 alloy contains uniform amounts of hard ceramic TiB_2 particles. Results show that most of the reinforcing particles have aligned themselves with the direction of metal flow following hot rolling [29,]. Due to the existence of typically hard ceramic particles, which aids in improved grain refinements, the hybrid MMCs exhibit smaller sized grains when compared to the base alloy [32]. TiB_2, a grain refiner, is essential for the grain refining process in hybrid MMCs. The microstructure pictures of Al6061 alloy are shown in Fig. 2 (a), the microstructure images of hybrid MMCs before hot rolling are shown in Fig. 2 (b), and the microstructure of hybrid MMCs after hot rolling is shown in Fig.2 (c). From the results, it can be observed that hot rolling caused changes in the micro structure. Due to a change in grain morphology in the rolling direction, the grain structure has expanded. After hot rolling, there is visibly less porosity in both the matrix phase and the hybrid MMCs, and there occurs grain nucleation inside the grain boundaries. The strengthened link between the matrix and the TiB_2 particulates in the produced hybrid composites can be attributed to the particulates' increased wettability, the reinforcement's enhancement, and the homogeneous distribution of reinforcements inside the matrix alloy.

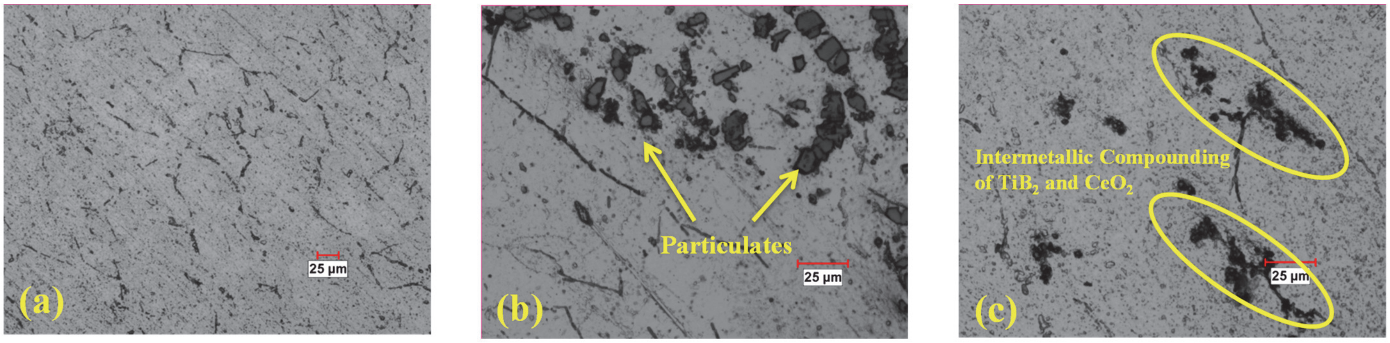

Figure 1: Microstructure of (a) Al alloy (b) Al6061+7.5% TiB_2+5% CeO_2 and (c) Hot rolled hybrid MMCs (Al6061+7.5% TiB_2+5% CeO_2)

Hardness

Hardness value of hot rolled hybrid MMCs was evaluated at three different zones on the sample surfaces and average hardness values at these zones were determined. The results of the hardness are depicted in the Fig. 2. The interaction between the hardness indenter and reinforcement particles in the MMCs is effected by several factors like size of the reinforcement particles, size and angle of the indenter and hardness of the base material. In the MMCs, depth of penetration is generally influenced by wt. % of reinforced particles. Hard ceramic particle offers better resistance to contact stress which restrains the abrasion and deformation between mating surfaces. So, hardness is improved by enhancement in wt. % of hard reinforced particles. Usually, the addition of hard particles generally prevents the motion of dislocations and this phenomena leads to increase in the composites hardness [29, 30]. When compared to the base matrix, it was discovered that the addition of TiB_2 and CeO_2 particles improved the hardness of the hybrid composite. TiB_2 components increase the dislocation density while the cast composites are solidifying [31, 32]. The mechanical characteristics of the composites were found to be improved as the CeO_2 level was raised, according to the researcher [33]. When the stircasting technique is used to create composites, the reinforcement and matrix can be bonded uniformly. This aids in enhancing the material qualities of created hybrid MMCs. Typically, the soft matrix's reinforcing ceramic particles support the load and provide greater resistance [34]. Ceramic particles (TiB_2) operate as load carrying elements in the current research effort and also take the maximum load applied for plastic deformation, which increases the hardness of created hybrid composites [31]. As a hard particle, TiB_2 enables the materials to flow without deforming. Additionally, when it exceeds the critical values, it will shatter without undergoing any more deformations. According to the Hall-Petch equation, a reduction in particle size increases hardness [35]. The improvement of the hardness of the hybrid composite reinforced by TiB_2 and CeO_2 can also be attributed to grain improvements. Finally, the strength of created hybrid MMCs is better influenced by the hard ceramic particles, like TiB_2 and CeO_2 concentration [36]. The aggregation of particles increased together with the weight percentage of reinforcing particulates. The agglomerated particles' internal structure was not sound and ineffective in withstanding forces. Additionally, the ability to transfer stress decreased. The irregular or unequal shape of the agglomerated particles caused cracks to emerge early in the process of plastic deformation.

Agglomeration was also shown to lower the hardness strength of hybrid composite at higher reinforcement weight percentages [33].

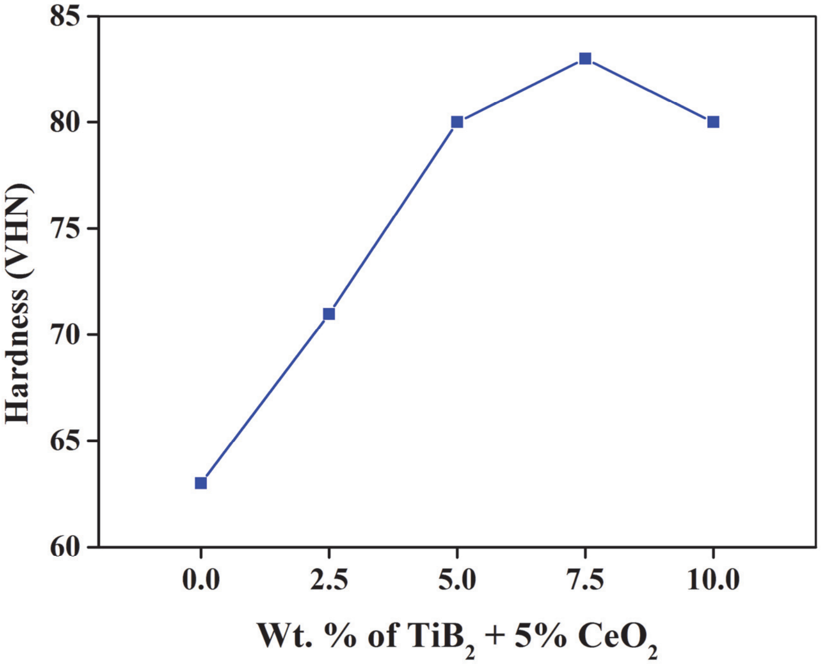

Figure 2: Hardness of composite with varying wt. % of TiB_2 and 5 % CeO_2

Wear behavior and COF

Objective of the present research is to study the importance of process parameters which were used in the current investigation to achieve the improved wear resistance and enhanced Coefficient of Friction (COF). The parameters and their varying levels used in this present research are depicted in Tab. 1. Samples were subjected to test trials according to the Taguchi technique with L27-OA. Design of test trials along with the outcomes of COF and wear rate is depicted in Tab. 2. Experiments were repeated 5 times (5 trials) for each MMCs test samples and average values were considered and tabulated in the Tab. 2. The standard deviation is observed ± 0.01 (g) for wear loss and ± 0.05 (μ) for COF.

Sl. No.	Parameters	Varying Levels		
		Level-1	Level 0	Level +1
1	TiB_2 (Wt. %)	2.5	5.0	7.5
2	Load (N)	15	30	45
3	Sliding Distance (m)	750	1000	1250

Table 1: Selected process parameters with their levels.

Tab. 2 shows the experimental findings of wear loss and COF for composite samples under various process settings. To determine the level of significance for each process parameter, an ANOVA was used. It was feasible to determine which component controls the other elements by using the ANOVA technique. Additionally, the relevance level of each processing parameters used in this study may be assessed. Investigational studies were carried out at a level of significance of 0.05. Parameters with a P-value of < 0.05 were considered to evaluate the significance of the performances [37, 38]. An ANOVA result for wear loss of the developed composite is depicted in Tab. 3. It reveals that, the wt. % of reinforcement is a highly significant factor with maximum % (53.14) of contribution between the other parameters followed by load and the sliding-distance was the least significant parameter.

Sl. No.	TiB_2 (Wt. %)	Load (N)	Sliding Distance (m)	Wear Loss (Gms)	COF (μ)
1	2.5	15	750	0.060	0.35
2	2.5	15	1000	0.065	0.50
3	2.5	15	1250	0.080	0.30
4	2.5	30	750	0.075	0.20
5	2.5	30	1000	0.060	0.30
6	2.5	30	1250	0.074	0.20
7	2.5	45	750	0.065	0.15
8	2.5	45	1000	0.063	0.16
9	2.5	45	1250	0.082	0.15
10	5.0	15	750	0.040	0.50
11	5.0	15	1000	0.045	0.35
12	5.0	15	1250	0.055	0.38
13	5.0	30	750	0.051	0.45
14	5.0	30	1000	0.050	0.40
15	5.0	30	1250	0.060	0.30
16	5.0	45	750	0.050	0.35
17	5.0	45	1000	0.080	0.30
18	5.0	45	1250	0.078	0.31
19	7.5	15	750	0.020	0.70
20	7.5	15	1000	0.040	0.50
21	7.5	15	1250	0.041	0.65
22	7.5	30	750	0.050	0.70
23	7.5	30	1000	0.039	0.45
24	7.5	30	1250	0.040	0.50
25	7.5	45	750	0.045	0.55
26	7.5	45	1000	0.040	0.60
27	7.5	45	1250	0.060	0.40

Table 2: L27-OA Taguchi trial and results.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Cont. (%)	Remarks
TiB_2 (Wt. %)	1	0.0034445	0.0034445	0.0034445	50.9670	0.0000003	53.14	Significant
Load (N)	1	0.0007605	0.0007605	0.0007605	11.2528	0.0027445	11.73	Significant
Sliding Distance (m)	1	0.0007220	0.0007220	0.0007220	10.6832	0.0033764	11.13	Significant
Error	23	0.0015544	0.0015544	0.0000676			23.98	
Total	26	0.0064814					100	

Table 3: ANOVA outcomes for Wear loss.

The ANOVA results for COF of the developed MMCs are depicted in Tab. 4. It reveals that, the wt. % of reinforcement is extremely significant factor with a maximum % (62.41) of impact between the other parameters, followed by the sliding distances and load.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Cont. (%)	Remarks
TiB_2 (Wt. %)	1	0.417089	0.417089	0.417089	73.3123	0.0000000	62.41	Significant
Load (N)	1	0.088200	0.088200	0.088200	15.5030	0.0006571	13.19	Significant
Sliding Distance (m)	1	0.032089	0.032089	0.032089	5.6403	0.0262734	4.80	Significant
Error	23	0.130852	0.130852	0.005689			19.58	
Total	26	0.668230					100	

Table 4: The ANOVA outcomes for COF.

Main Effect Plots of varying factors of wear loss and COF of developed Al composite are shown in Fig. 3 and 4 respectively. From Fig. 3, it can be observed that, addition of hard reinforcements improved the wear resistance of the developed composite. The hard particulates have better load capability which avoids the Al matrix from negative action by decreasing in depth of penetrations [39]. The MMCs revealed better wear rate with increasing reinforcing particulate contents. It also revealed that the wear rate of developed MMCs was reduced by increasing the TiB_2 and CeO_2 content in the base alloy. Similar outcome was witnessed by many research investigators [40, 41]. From Fig. 3, it is clearly seen that, level-3 of reinforcement provides wt. % and level-1of sliding distance (m), applied load (N) at the optimal levels for achieving minimum wear loss of MMCs. It also reveals that, increasing applied load from 15 N - 45 N, the wear loss of developed composite increased. When a load is applied on hybrid MMCs samples intensely against the hard disc, increased stress acts on hard and sharper particulates. Generally, this produces a high rubbing action which leads to plastic deformation. Also, it reduces the strength between hard reinforcement and the matrix. As a consequence of this, the hard particulates get broken and move towards the matrix alloy and large amount of material is removed from developed composite samples [42, 43]. Also, increased wear rate was observed for the process parameters such as sliding distance between 750 m - 1250 m. The particles protruding on Al composites surface generally cause sharp asperity and this led to non-uniform interactions in the test samples and counter interface which cause high wear loss of composites [44].

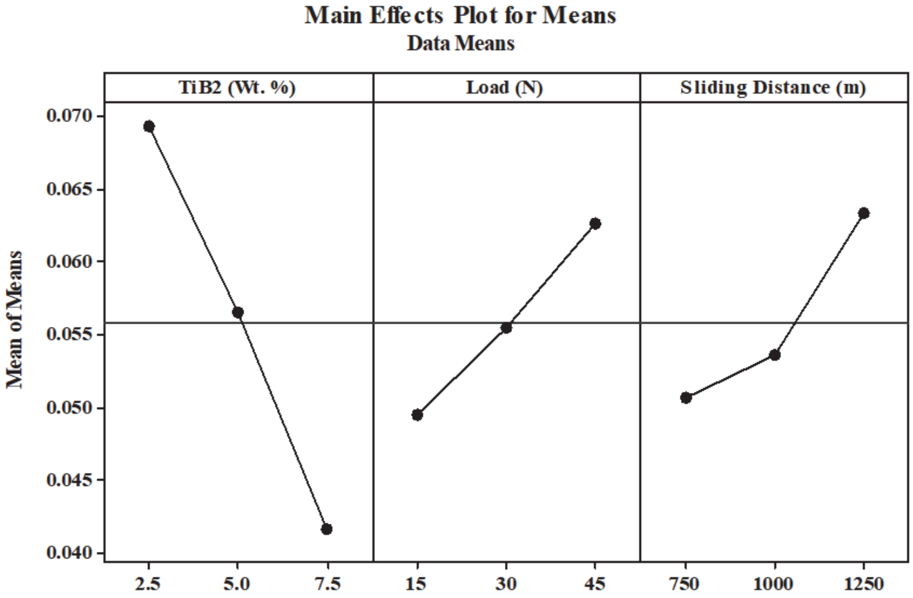

Figure 3: Effect of varying factors on wear loss

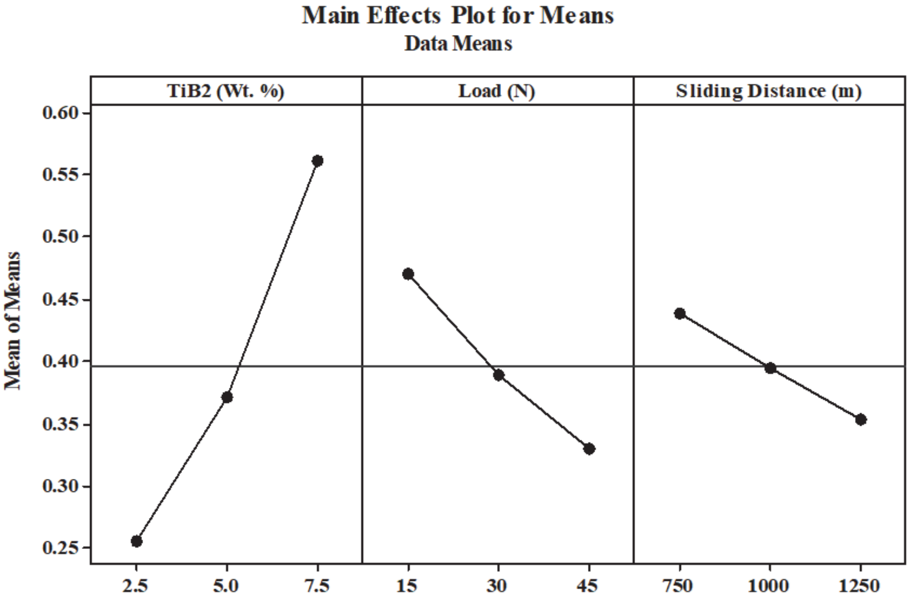

Figure 4: Effect of varying factors on COF.

Wear rate increased due to increase in the sliding distance. Generally, this led to increase in temperature of the surfaces at high sliding speed, causing high softening effect on developed composite. And also, it was observed that development of high surface damages results in high wear rate [43]. Fig. 3, shows that reinforcement (7.5 %), load at 15 N, and sliding distance of 750 m are the optimal levels. The Fig. 4 shows that, when the load is increased, there is a reduction in COF in developed MMCs. The main reason for this may be a development of MML, which generally leads to reduce COF of MMCs. Fig. 4 shows that, COF increased with increasing in wt. % of reinforced particulates. A similar outcome was found [45] and in the case of composites with high wt. % TiB_2 reinforcements, COF was seen to be high when compared with MMCs with lower wt. % of TiB_2. Fig. 4 depicts that COF is reduced with increasing sliding distance. Related outcomes were found [46] and it was seen that, COF of MMCs was low due to presence of TiB_2 content. Similar results were witnessed by other researcher [47]. The ceramic particulates of the AMMCs caused creation of MML which resulted in reduction of COF. The main effect graph (Fig. 4) shows the optimal conditions which led to achieve the better wear rate and COF. The ranking of each parameter at varying levels are shown in Tabs. 5 and 6. Process parameters are highly significant and also it is observed that wt. % of reinforcements is a major influencing factor followed by the other process factors which are considered in this investigation.

Levels	TiB_2 (wt. %)	Load (N)	Sliding Distance (m)
1	0.06933	0.04956	0.05067
2	0.05656	0.05544	0.05356
3	0.04167	0.06256	0.06333
Delta	0.02767	0.01300	0.01267
Rank	1	2	3

Table 5: Response table of means for wear loss.

Levels	TiB_2 (wt. %)	Load (N)	Sliding Distance (m)
1	0.2567	0.4700	0.4389
2	0.3711	0.3889	0.3956
3	0.5611	0.3300	0.3544
Delta	0.3044	0.1400	0.0844
Rank	1	2	3

Table 6: Response table of means for COF.

Interaction graph (Fig. 5 and 6) indicates the influence of parameters used to evaluate the wear loss. Other investigators [48, 49] concluded that, the process factors having higher slopes in plots exhibit higher significance. Also, it is expressed that, the plotted lines in interaction plots are non-parallel, so it can be seen that there is an enhanced interaction between the process parameters.

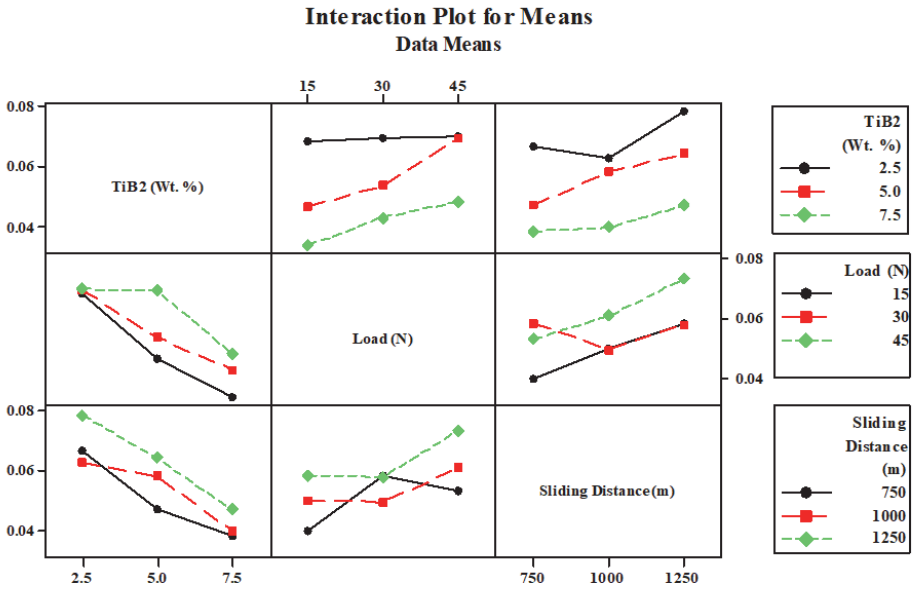

Figure 5: Interaction graphs for wear loss

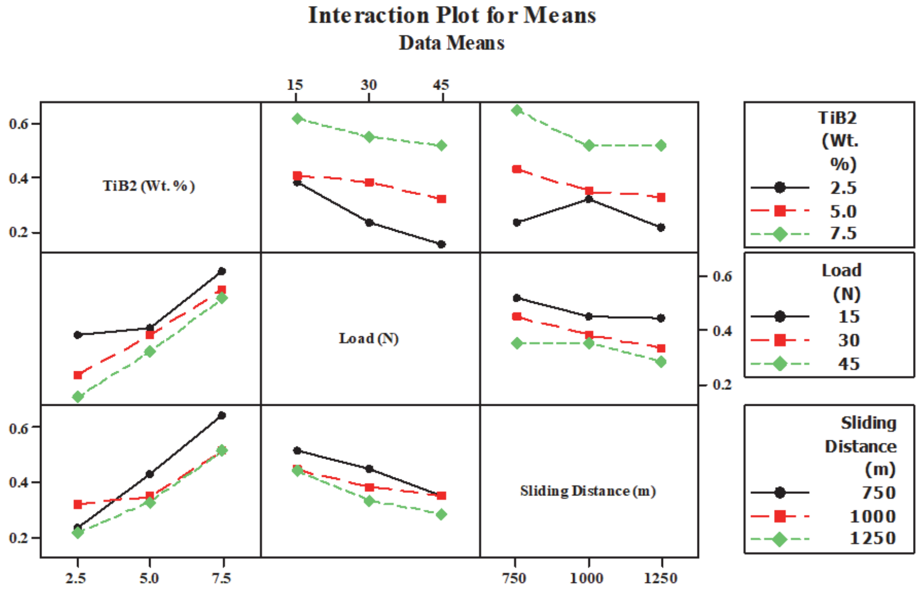

Figure 6: Interaction graphs for COF.

Interaction plots for wear rate and COF exist in developed hybrid MMCs as depicted in Fig. 5 and 6. It can be concluded that the plotted lines are intersect (crossing) each other. Therefore, it shows a better interaction between the parameters which was observed in the present research work. The model adequacy was also evaluated by analysis of residuals. Generally, it helps to study the model fits. Normal probability plots were utilized to identify the residuals and non-normality structure, which is less when the model fits very well. The residual v/s. order graphs were used to observe the time dependence in residuals. Residual v/s. fits plots were drawn based on the outcomes of residuals vs abscissa on ordinate. A histogram plot of the residual generally enables to define whether the obtained data is skewed, Fig. 7 and 8 depict residual graphs of wear loss and COF of developed composites.

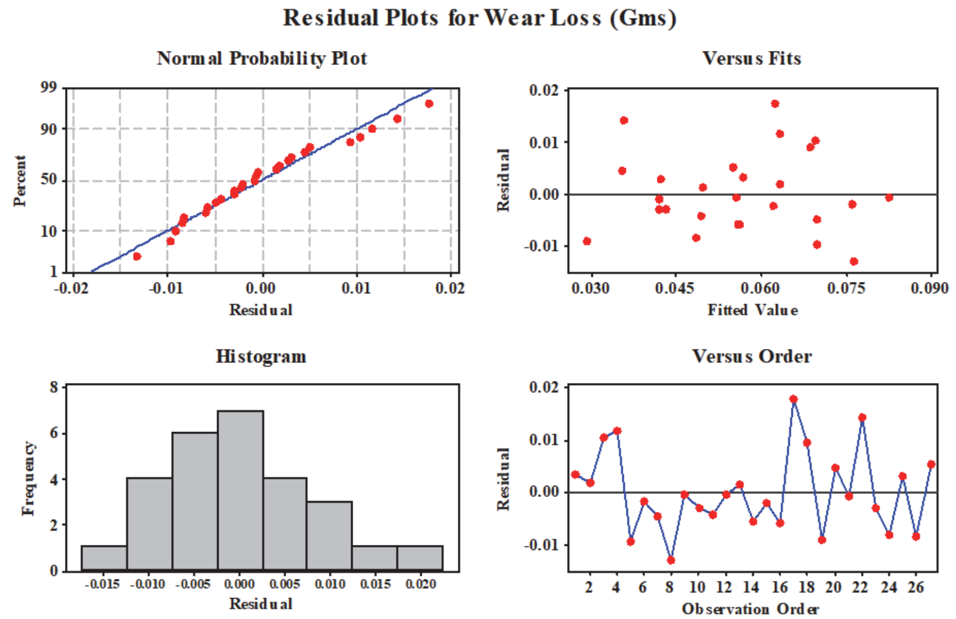

Figure 7: The residual graphs for wear loss

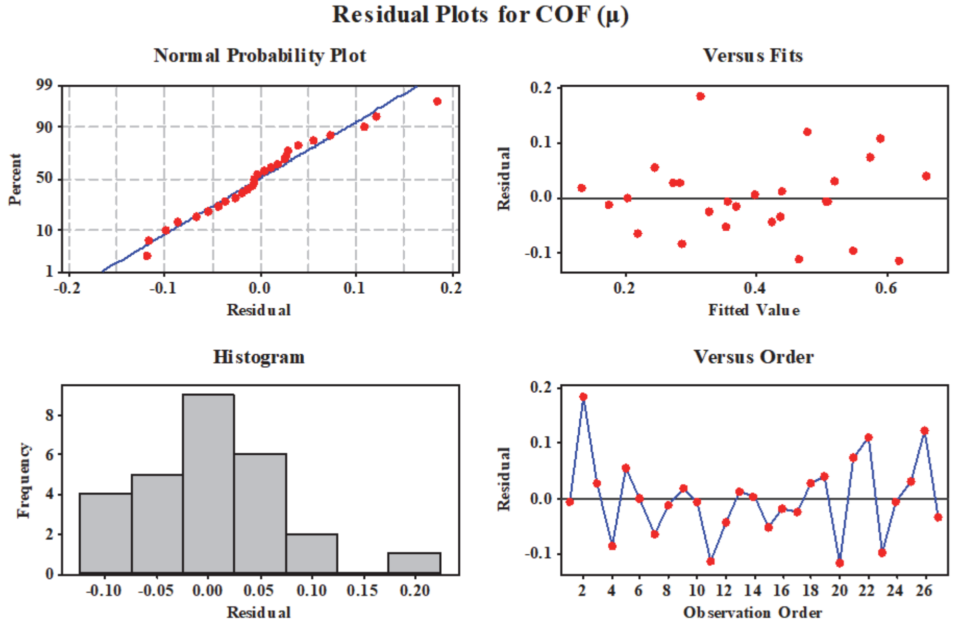

Figure 8: The residual graphs for COF.

The residuals in Figs. 7 and 8 of normal probability plots are within a straight line, indicating evenly distributed errors. This demonstrates that the residuals have a better fit and are distributed equally. In the meanwhile, the points are ostensibly close to a straight line, and the collected data shows no signs of departure. The residual vs. fitted value graphs exhibit a random pattern that, in most cases, denotes a non-linear connection. Furthermore, it is shown that the residual points are evenly distributed on either side of the zero line, which normally denotes that the residual density is about the same. The residuals plots demonstrate that there is no discernible pattern on either side of the zero line in the residual v/s. order plot, which highlights significant influence in the order of data collection. The histogram plot using the standardized residual in this investigation reveals less skewness and the absence of outliers. The results also demonstrate the presence of residuals from minimum to maximum range, demonstrating the high accuracy of the results [50, 51]. A Regression Analysis was validated using the input data in accordance with the results. Regression equation is used to show the link between wear factors. Relation found by the regression study of the wear rate and COF is presented in the Eqn. 1 and Eqn. 2 as shown below:

$$\text{Wear Loss (gms)} = 0.0451852 - 0.00553333\ \text{Wt. \%} + 0.000433333\ \text{Load} + 2.53333\text{e-}005\ \text{Sliding Distance} \quad (1)$$

$$\text{COF } (\mu) = 0.400741 + 0.0608889\ \text{Wt. \%} - 0.00466667\ \text{Load} - 0.000168889\ \text{Sliding Distance} \quad (2)$$

Within the constraints of the process parameters employed in the current inquiry, the regression analysis and equations are applied to forecast the results. Comparisons between predicted and experimentation results are displayed in graphical representations to assess the accuracy of predicted values. Figs. 9 and 10 show the results of the experimental and predicted values of wear loss and COF of the created hybrid MMCs. Plots show that there is a stronger correlation between experimental and predicted values [52].

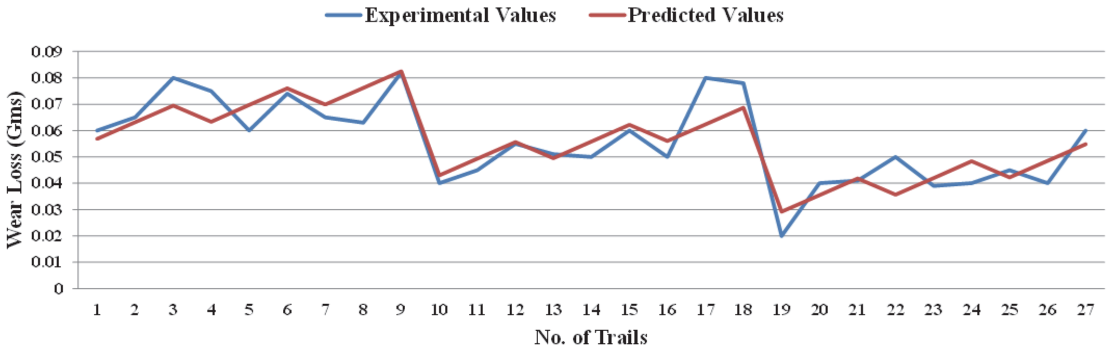

Figure 9: Comparison between experimental v/s. predicted values for wear loss.

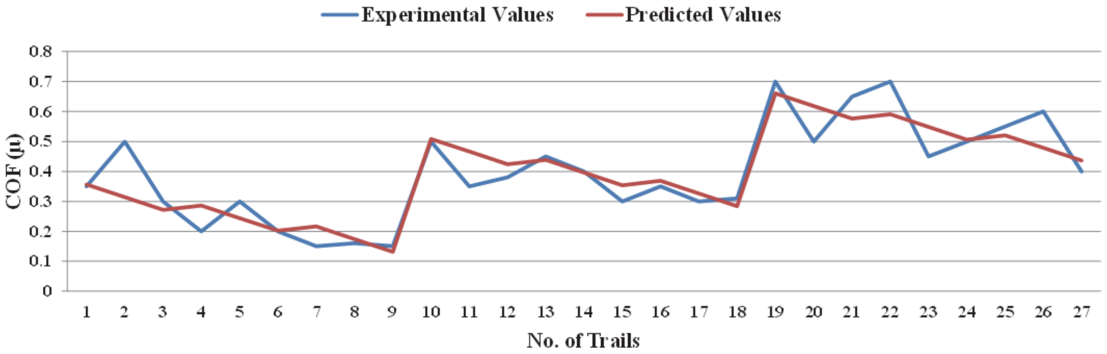

Figure 10: Comparison between experimental v/s. predicted values for COF.

Confirmation test trials were carried out for evaluation of wear rate and COF of developed hybrid composite. Optimum levels of the factors were selected from MEP for Means. Tab. 7 depicts values of optimal level for carrying out of confirmatory test trials and Tab. 8 depicts the results of confirmatory tests trials.

Parameters / Factors	TiB_2 (wt. %)	Load (N)	Sliding Distance (m)
Optimized Values (wear loss)	7.5	15	750
Optimized Values (COF)	2.5	45	1250

Table 7: Optimal parameters for confirmatory test trials of wear loss and COF.

Characteristics	TiB_2 (wt. %)	Load (N)	Sliding Distance (m)	OA Exp. outcomes	Confirmatory Exp. outcomes	Error (%)
Wear loss	7.5	15	750	0.020 (grams)	0.019 (grams)	5
COF	2.5	45	1250	0.15 (μ)	0.16 (μ)	6.25

Table 8: Confirmatory outcomes of wear loss and COF.

From the confirmation test results, 6.25 % of deviation in results was found in COF of hybrid MMCs. The wear test shows 5 % of deviation. It can be concluded that this is within the acceptable limit. SEM analysis was studied for the wornout surfaces samples. Usually, the rate of wear depends on the characteristics of the wornout surface of the developed composite. Fig 11 (a) depicts the SEM images of worn-out surface for monolithic alloy. Fig. 11 (b) shows the SEM images of worn-out surface for 7.5% TiB_2 + 5% CeO_2 reinforced hybrid composites. The worn debris particulates probably behave similarly to particles that abrade the third body. The test specimens and counter face are clogged with TiB_2 and CeO_2 particles, which led to micro-plow marks on the surface of the created hybrid composites. Significant material transfer between the sliding surfaces was a feature of the MMCs' wear surfaces. With improved bonding, reinforced particles might be distributed throughout the base material, increasing wear resistance. Large amounts of debris are visible in the produced hybrid MMCs pathways (Fig. 11) (a). The consistent sliding wear tracks with reasonable lower debris are shown in Fig. 11 (b). Hot-rolled hybrid MMCs low wear loss may be attributable to the material's higher density, which leads to greater interfacial bonding between the particles and the matrix alloy than in base samples. Additionally, it was noted that there was less fracture initiation at the interface of the matrix and hard particles in the hot-rolled hybrid MMCs reinforced up to 7.5% of TiB_2 and 5% of CeO_2 with a load of 15 N and sliding speed of 750 m [53].

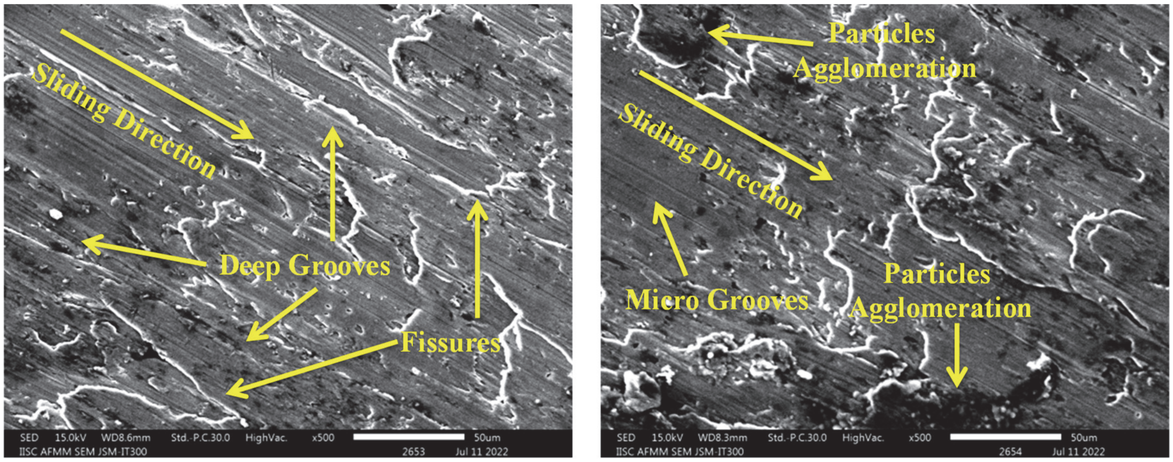

Figure 11: SEM fractography of (a) monolithic (b) hot rolled hybrid composites.

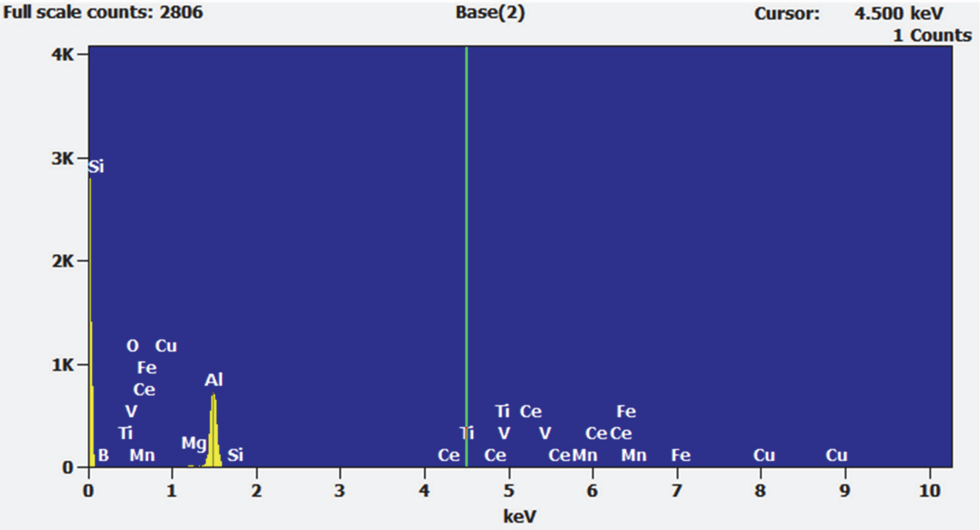

Figure 12: EDS study for the Al7075+7.5% TiB_2+5% CeO_2.

From EDS study of wornout surface of hybrid hot rolled MMCs, it is seen that the "O" (oxygen) content on wornout surface is high. This indicates the presence of oxidation on the wornout surfaces of developed hybrid MMCs. To evaluate the chemical compositions of the Al6061-TiB_2-CeO_2 composite, EDS study was carried out on the hot-rolled hybrid MMCs samples. The outcomes are as depicted in Fig 12. The study clearly shows the existence of Al, Ti and Ce particulates over various peaks. The outcome shows the "Ti" peak from EDS study. It evidences the addition of TiB_2 particulates in developed MMCs. "Ce" peak is also observed from the EDS study. It evidences addition of CeO_2 particulates in the developed composites [54, 55].

CONCLUSIONS

The research project entails a study of the microstructure, mechanical, and wear properties of monolithic, ascast, and hot-rolled hybrid MMCs. The following are the results of the current work:

- Under both as-cast and hot-rolled circumstances, the microstructure study indicates the homogeneous dispersion of TiB_2+CeO_2 particles with improved bonding among reinforcement and matrix material.
- In the present study, Al6061 – TiB_2 (2.5%, 5% and 7.5%) – CeO_2 (5%) hot rolled hybrid composites were successfully fabricated by Stir Casting method.
- Hardness of the developed hybrid composite improved by addition of reinforcement content. Taguchi optimization method was implemented to examine the wear rate of developed hybrid composite. Reduced wear loss of developed MMCs was obtained at optimal process parameter values of 7.5 % SiC, 15 N of load and 750 m of sliding distance.
- Optimum process parameter to achieve the minimum COF of developed MMCs was obtained at 2.5 % of TiB_2, 45 N of load and 1250 m of sliding-distance.
- The outcomes of confirmation test results show that a maximum of 6.25 % error in COF and 5 % of error in wear loss. It can be concluded that, it is within acceptable limits.
- From SEM analysis, it was concluded that less fracture initiation was seen in hot rolled hybrid MMCs. Improved bonding among the interface at matrix and reinforcements were also observed.
- The EDS study shows "Ti" and "Ce" peaks. It evidences the successful incorporation of TiB_2 and CeO_2 particulates in developed hybrid composites.

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