CHAPTER – 5

RESULTS AND DISCUSSION

5. 1 Microstructure studies

5.1.1 Optical micrograph studies

The optical micrograph of the matrix alloy Al 2618 and Al 2618 –TiO₂ reinforced composites are shown in figure 5.1 and 5.2. These micrographs clearly reveal minimal micro porosities in both the base aluminum alloy and the developed composite. A fairly uniform distribution of TiO₂ particles in the matrix alloy is observed.

![Figure 5.1: Optical micrographs of Al 2618 alloy (a) 100X & (b) 200X](image)

![Figure 5.2: Al 2618-4wt. %TiO₂ heat treated composite (c) 100X (d) 200X.](image)
Figure 5.3 shows optical micrograph of Al 2618-6wt.%TiO₂ reinforced heat treated composite. Micrograph revealed the presence of CuAl₂ and TiO₂ particulates as the two most predominant phases distributed in the matrix material. The presence of fine CuAl₂ precipitates in the near vicinity of TiO₂ particulates was evident and confirmed by EDAX analysis which is shown in figure 5.4.

![Optical micrograph of Al2618-6wt.%TiO₂ reinforced heat treated composite, showing CuAl₂ precipitates. (500 X)](image)

**Figure 5.3: Optical micrograph of Al2618-6wt.%TiO₂ reinforced heat treated composite, showing CuAl₂ precipitates. (500 X)**

![EDAX analysis of Al2618-6wt.%TiO₂ reinforced composites](image)

**Figure 5.4: EDAX analysis of Al2618-6wt.%TiO₂ reinforced composites**

The larger amount of CuAl₂ phase precipitated in the metal matrix of the composites. During heat treatment process the precipitate was dissolved and homogeneously distributed in the metal matrix after solution heat treatment at 529°C for 2
hours and artificially aged at 199°C for 8 hours samples as shown in figure 5.3. Similar results were found for all unheat treated and T-6 heat treated samples.

5.2 Scanning Electron Micrographs (SEM) Studies

Figure 5.5 (a) and (b) shows the scanning electron micrographs of the TiO₂ particles which are used as a reinforcing material. The Titanium dioxide chosen for the present study are having irregular and different sizes which are seen from the SEM images.

![Figure 5.5: SEM of Titanium dioxide particles](image)

Figure 5.5: SEM of Titanium dioxide particles
Figure 5.6 shows the SEM images of Al 2618-2wt.%TiO$_2$ reinforced composites. The images of SEM indicated good interfacial bonding between the TiO$_2$ particulates and the matrix material such that voids or other discontinuities were not observed at the particulate-matrix interface. The presence of TiO$_2$ reinforcement in the composite material is confirmed by EDAX patterns, which is shown in figure 5.6 (b). SEM image of Al 2618-4wt.%TiO$_2$ heat treated composites is shown in figure 5.7. It is clearly evident that the distributions of the TiO$_2$ particulates are uniform in the matrix material.

(a) SEM image of the composite  
(b) EDAX of the composite material

**Figure 5.6: Al 2618-2wt.%TiO$_2$ composite and its EDAX patterns of TiO$_2$ particulate**

**Figure 5.7: SEM images of Al 2618-4wt.%TiO$_2$ reinforced composite (IIT)**
5.3 Density of the composites

The variation of the density of the developed composite materials is shown in figure 5.8. It is observed that the density of the composite material increases with increased content of TiO₂ reinforcement in the matrix material. The increase in the density of the composites is mainly due to the dispersion of higher density TiO₂ in the matrix material. The density of the TiO₂ is higher than the matrix alloy and hence the increase in weight percentage of TiO₂ in the matrix material will increase the density of the composites based on the rule of mixtures. The density of Al 2618-10wt.%TiO₂ composite material system is 2.7545 gm/cc which is 2.243 % higher than the matrix material.

![Density of the developed composite material](image)

Figure 5.8: Density of the developed composite material.

5.4 Hardness test results

5.4.1 Effect of reinforcement

Figure 5.9 shows the variation of Brinell hardness for different weight percent of TiO₂ reinforced composites. It is observed that the hardness of the composite increases as the reinforcement content of the TiO₂ is increased from 0 to 10 weight percentage. The
unheat treated composites shows a hardness improvement of 20.66 % for 10 weight percent of TiO$_2$ reinforced composite. The increase in hardness is expected since TiO$_2$ particles being a very hard dispersoid, contribute positively to the hardness of the composite. The increased hardness is also attributable to the hard TiO$_2$ particles acting as barriers to the movement of dislocations within the matrix material [146-147]. The dispersoid strengthening effect is expected to be retained even at elevated temperature and for an expected time period, because the particles are not reactive with the matrix phase [148-149]. The percent increase in the hardness is reduced with an increase of 8 to 10 weight fraction of TiO$_2$ particles.

![Graph showing hardness vs. weight percent of TiO$_2$ reinforcement](image)

**Figure 5.9: Hardness of the composites for different weight fraction**

### 5.4.2 Effect of quenching media

Figure 5.10 shows the effect of quenching media on the hardness of matrix material and Al2618-TiO$_2$ reinforced composite material. The maximum hardness of 99.3 BHN is obtained for the 10 weight percent of TiO$_2$ reinforced composites when the specimen is subjected to (Ice + water) quenched and artificially aged for 8 hours. For the same ageing duration, two other types of quenchants: water and air media shows little reduction in hardness. As observed in the studies of I.N.A. Oguocha et al. [57] hardening
at higher cooling rate is due to vacancy / Guinier-Preston-Bagryatskii (GPB) zones and dislocation. As the cooling rate increases, the amount of quenched vacancies that is necessary for GPB zones formation also increases. However, in the composites, the increased cooling rate also increases the dislocation density. At higher cooling rates, the amount of quenched-in vacancies available for precipitation and solute strengthening is increased in both the unreinforced alloy and the composites. This coupled with dislocation strengthening, accounts for the sharp increase in (ice + water) quenched heat treated composites.

Optical micrographs of the Al 2618-6wt%TiO₂ reinforced composites quenched in three different quenchants and artificially aged for 8 hours duration are shown in figure 5.11. The microstructure and grain sizes of (ice + water) quenched composites were found to be uniform and smaller grain size as compared to water and air quenched composites was observed. This is mainly attributed to the fact that during the heat treatment process quenching is a crucial step to suppress the precipitation to retain the super saturation of solid solution, control the distortion, and minimize the residual stress in aluminum alloy composites.

![Graph showing hardness vs TiO₂ weight percent for different quenching media](image)

**Figure 5.10: Effect of quenching media on the hardness of the composite**
Figure 5.11: Microstructure of Al2618-6wt.% TiO₂ composites quenched in different quenchant
5.4.3 Effect of ageing duration

Figure 5.12 shows the effect of ageing duration on the hardness of the composite materials which are quenched in three different types of content. It is observed that (ice + water) quenched specimens attain maximum hardness of 99.3 BHN for the ageing duration of 8 hours, where as water and air quenched specimens attains hardness of 95.6 and 86.5 BHN respectively. The improved hardness of the composite with increased ageing time can mainly be attributed to the fact that the increased ageing duration will accelerate the kinetics of precipitation hardening in composites. Further studies shows that increase in the ageing time decreases the hardness of the aluminum composites. This could be due to the coalescence of the precipitates into larger particles which will cause fewer obstacles to the movement of dislocation and also due to annealing out of the defects [150]. The formation of the coarser inter metallic precipitates is mainly due to the growth of the formed inter metallic precipitates. Coarser intermetallic precipitates leads to reduction in hardness in peak aged composites materials.

![Figure 5.12: (a) Air quenched samples](image-url)
Figure 5.12: (b) Water quenched samples

Figure 5.12: (c) (Ice + water) samples

Figure 5.12: Effect of ageing duration on hardness of AMC for different quenchant

5.4.4 Effect of heat treatment

The bar graph 5.13 shows the influence of heat treatment on the TiO$_2$ reinforced aluminum composites. The graphic mapping shows that heat treatment process improves the hardness of the composites and also the matrix material. Hardness of Al-10wt.%TiO$_2$
composites for unheat treated condition is 67.56 BHN and 99.3BHN for heat treated specimen. An improvement of 32.95 % is observed for 8 weight percent of TiO₂ composites. The reasons for increased hardness of the composites are discussed earlier in the section 5.4.1.

Figure 5.13: Effect of heat treatment on hardness of the composites

5.5 Tensile strength and Yield strength

Figure 5.14 & 5.15 are the graphs showing the effect of TiO₂ reinforcement on the ultimate tensile strength (UTS) and yield strength of the composites. It can be noted that the tensile strength and yield strength has increased with an increase in the weight fraction of TiO₂. An improvement in the tensile strength is observed when the reinforcement content increases from 2 to 8 weight percent of TiO₂, further increase in TiO₂ content leads to a reduction in strength value. A maximum of about 39.88% of increase in UTS and 32.92 % of yield strength is observed in Al2618-8wt%TiO₂ composites.
Figure 5.14: Tensile strength of TiO₂ reinforced aluminum composite

Figure 5.15: Effect of reinforcement on yield strength of TiO₂ reinforced composite

The increase in UTS of composite specimens is believed to be due to the presence of hard TiO₂ particles which strengthen the aluminum alloy matrix, imparting more resistance to the composites against the applied tensile strength. Improvement of strength is also due to the strong interface of TiO₂ particles in the matrix alloy. This increase in UTS and yield strength is consistent with the results obtained by the investigator who tested B₄C-reinforced aluminum alloy MMC [73]. Another factor promoting the improvement in strength of composites when compared to the matrix alloy is due to the
generation of high density of dislocation generated at TiO$_2$–Al alloy interphases due to the differences in coefficient of thermal expansion (CTE) between Al 2618 matrix metal around TiO$_2$ particles. (CTE of Al 2618 alloy = 22.3 $\mu$m/m$^0$c and TiO$_2$ is 9 $\mu$m/m$^0$c).

The decrease in the tensile strength of the developed composites with Al2618-10wt.%TiO$_2$ is due to the poor wettability of the reinforcement with the matrix material. The micro porosity formed at the higher weight fraction of TiO$_2$ reinforcement reduces the tensile strength. These factors will reduce the UTS at 10wt.%TiO$_2$ aluminum composites [34, 16]. This observation is similar to the behavior of Al-fly ash composites as reported by Anil Kumar et al. [151].

5.5.1 Effect of heat treatment

Ultimate tensile strength of heat treated specimens is in line with unheat treated samples as shown in graph 5.16. It is observed that the maximum ultimate tensile strength obtained is 174.68 M Pa. for 8wt.%TiO$_2$ reinforced composites for heat treated specimen. A marginal increase in the strength is observed on all the heat treated specimens as shown in figure 5.16.

![Figure 5.16: Effect of heat treatment on tensile strength in M Pa.](image-url)
The improvement in the strength of the composites and the matrix alloy on the
heat treatment can be mainly attributed to the formation of intermetallic precipitates in the
matrix alloy from a supersaturated solution. The rate of cooling adopted during the
quenching process has a profound influence on the formation of intermetallic precipitate
in the metal matrix composite. The superior tensile properties of the composites on heat
treated condition can be mainly attributed to the fine state of distribution of the
intermetallic phases. Smaller the inter metallic precipitate in precipitation hardening
materials, greater will be the resistance to the motion of the dislocation as these inter
metallic precipitates acts as the obstacles trying to pin down the dislocations. This
phenomenon will increase the resistance to the plastic deformation to the materials there
by leading to greater improvement in strength in the materials

Figure 5.17 shows the effect of heat treatment on yield strength of the
composites. Heat treated specimens show an improvement of 8.47 M Pa. when compared
to unheat treated specimens for Al 2618-8wt.%TiO₂ composite. Similar improvement is
also reported by the researcher Rupa das gupta et al. [53].

![Figure 5.17: Effect of heat treatment on yield strength in M Pa.](image-url)
5.5.2 Ductility

Figure 5.18 shows a graph of the ductility of the composite specimens and that of the matrix alloy, plotted against the TiO₂ content. The ductility test reveals that, addition of TiO₂ reinforcement in the matrix material drastically decreases the ductility of Al 2618-TiO₂ reinforced composites. A similar trend is also observed in the heat treated composite materials. This decrease in the ductility can be attributed to the embrittlement effect that is observed as a result of the presence of hard TiO₂ particles, which causes increased local stress concentration sites. The reinforcing particles resist the passage of the dislocations either by creating stress fields in the matrix or by inducing a large difference in the stress concentration between the matrix and the reinforcement [65]. The study of mechanical property of aluminum composites by Albiter. A. et al. revealed that, as the albite reinforcement content was increased, there were significant increases in the ultimate tensile strength, hardness and young’s modulus, accompanied by a reduction in its ductility [152].

![Graph](image_url)

Figure5.18: Effect of wt. % of TiO₂ reinforcement on percentage of elongation
5.5.3 Fractography

Figure 5.19 and 5.20 shows the SEM photographs of the tensile fractured surfaces of the cast Al 2618 and Al 2618-6wt.%TiO₂ reinforced composites. It is observed that the base matrix alloy has got larger dimples when compared with composite system studied for different content of TiO₂ reinforcement. Al 2618 matrix alloy, showing very large dimples indicate a ductile fracture as shown in figure 5.19, whereas in case of Al 2618-6wt.%TiO₂ composite, particles of TiO₂ and medium sized dimples are visible as evident from Figure 5.20.

Figure 5.19: Fractured surface of Al 2618 alloy fractured surface (Heat treated)

Figure 5.20: Fractured surface of Al2618-6wt.% TiO₂ composite (heat treated)
Figure 5.21 shows the fracture surfaces of the Al 2618-2wt.%TiO$_2$ composites. The SEM images reveal a ductility mode of fracture accompanied by isolated microcracks in the matrix. Large areas of fracture surface were covered with a bimodal distribution of dimples, indicating the ductile rupture. A dimple is a half void and the voids were formed mainly at the particle matrix interface [28, 152].

![Fractured TiO$_2$ particle](image1)

**Figure 5.21: Fractured surface of Al 2618/2wt.%TiO$_2$ composite (heat treated)**

From the Fractography of composites, it can be concluded that the fracture occurs as the result of one or a combination of the following mechanisms.

1. Fracture of reinforcing particle
2. Partial debonding of particle-matrix interface and nucleation of voids
3. Growth of the voids and initiation of cracks in the matrix
5.6 Compressive strength

Figure 5.22 shows the effect of reinforcement on compressive strength for different weight percent of TiO$_2$ reinforced composites. It can be seen from the graph that, as the TiO$_2$ content is increased from 2 to 10 percent, the compressive strength increases by about 29.62 percent. This improvement is mainly due to the addition of hard TiO$_2$ reinforcement in the matrix material. Heat treated specimens show considerable improvement in the compressive strength as compared to unheat treated specimens. Figure 5.23 shows the effect of reinforcement on compressive strength of heat treated composites. Heat treated specimens show an improvement of 6.59 % compared to the unheat treated specimens for Al 2618-10wt.%TiO$_2$ composites.

![Figure 5.22: Effect of TiO$_2$ reinforcement on compressive strength of composite](image)
Figure 5.23: Effect of heat treatment on compressive strength in M.Pa

5.7 Impact strength

Results of the impact toughness of the Al 2618-TiO\textsubscript{2} reinforced composites and the matrix alloy Al 2618 are presented in figure 5.24 in terms of impact energy absorbed to fracture a material. Interpretation of test results revealed that there is a drastic decrease in the total energy and energy absorbed at the maximum load with the increase in content of TiO\textsubscript{2}, which indicated lowering of toughness of composites with an increase in TiO\textsubscript{2} content. This reduction in toughness can be attributed mainly to the presence of TiO\textsubscript{2} particles in matrix alloy, which acts as sites of embrittlement due to local stress concentration effects. The heat-treated specimens show considerable improvement in the impact strength.
Figure 5.24: Variation of Impact strength for different wt.% TiO$_2$

Figure 5.25 and 5.26 shows SEM of 4 and 2 weight fraction of Titanium dioxide reinforced composites for heat treated condition. The results are in line with the results obtained by S.C. Sharma [153]

Figure 5.25: SEM photograph of Al-4wt.% of TiO$_2$ reinforced composite (HT)
5.7.1 Effect of heat treatment

Heat treatment also influences the impact toughness of the TiO₂/Al composites. The effect of heat treatment on the impact toughness of the TiO₂ reinforced Al composites are shown in figure 5.27.

![Figure 5.27: Effect of heat treatment on Impact strength](image)

It is observed that, heat treated composites shows a marginal improvement of impact strength when compared to that of unheat treated composites. A reduction of 23.07% is observed for Al 2618-8wt%TiO₂ heat treated composites when compared to
unheat treated composite. The results are in agreement with results obtained by other researchers [154-155].

5.8 Dry Sliding wear studies

5.8.1 Effect of reinforcement

The variation of the wear rates for the different weight percent of TiO₂ reinforced composites are shown in figure 5.28. It is clearly observed that with increased content of TiO₂ reinforcement, there is a decrease in wear rates for all weight fraction of TiO₂ reinforced composites. A reduction of 31.5 % in the wear rate was observed for Al 2618-8wt.%TiO₂ reinforced composites when compared with matrix material.

![Graph showing wear rate vs weight fraction of TiO₂](image)

**Figure 5.28: Effect of TiO₂ reinforcement on wear rate of composite**

The improvement in wear resistance of Al-TiO₂ reinforced composites can be attributed to the following factors.

1. An improved hardness of composites on incorporation of hard TiO₂ reinforcement in the soft matrix alloy. Increase in hardness results in improvement of wear and
seizure resistance of materials. Increasing hardness of the composite material reduces the wear intensity.

2. The interfacial bond between the matrix and TiO₂ particulate reinforcement play a significant role in the wear process. Existence of excellent bond between the matrix and the reinforcing particles as evidenced by SEM figure 5.29 of the worn samples of titanium dioxide reinforced composites. Composites fabricated with lower particulate display higher wear resistance than their respective matrix alloy. Reinforcement morphology directly influences the wear rate of the particulate reinforced composites.

3. The subsurface deformed layer beneath the worn surfaces of MMC pins is composed of a number of distinct layers like mechanically mixed surface (MMS) layers. The MMS layers withstand high stresses without plastic deformation or fracture and are very effective in reducing the wear rate in case of composites. The experimental result of Naresh Prasad et al. reveal that incorporation of hard reinforcement (Red mud) leads to significant improvement in wear resistance of aluminum [156-157].

![SEM Images of Worn Samples](image)

Figure 5.29: SEM of the worn samples of Al 2618-4wt% TiO₂ Composite
The mechanism of material removal during the wear process of the unreinforced alloy is by plastic deformation and gouging. In the composites, the operating mechanism in addition to these, fracture of titanium dioxide particles leading to the formation of a thin layer at the interface, thereby providing protection to the matrix material [15].

5.8.2 Effect of load

The wear rate of TiO₂ reinforced Al composites with different applied loads are shown in figure 5.30. It is observed that the wear rate of the composites as well as the matrix alloy increases with an increase in the applied load. The wear rate of the composite materials is lower than matrix alloy for the entire load studied. The wear resistance of the material increase as the content of TiO₂ increases in the matrix material. A reduction of 32.62 % is observed for Al 2618-10wt. %TiO₂ at 80 N loads. As the load increases the penetration ability of the fractured particles will increase and remove the material on the pin surface [142]. The small particles of TiO₂ between the pin and the counter surface of a three-body abrasion remove the material on the surface of the pin. As the load increases the more fractured particles occur, which penetrate into the pin and flow through it. The composites with a higher weight fraction of TiO₂ shows lesser wear rates when compared with the matrix alloy [158-159].
Figure 5.30: Effect of normal load on wear rate of composite materials (UHT)

Figure 5.31 shows the effect of heat treatment on the wear rate for a different weight fraction of TiO\textsubscript{2} content. Heat treated composites show increased wear resistance as compared to unheat treated composites. Wear rate is reduced by 27.47\% for Al 2618-8wt.%TiO\textsubscript{2} composite at 60 N load.

Figure 5.31: Effect of normal load on wear rate of composite materials (HT)
Examinations of the wear surfaces of the pins give information on the type of wear occurring. For lower loads relatively low wear rates are associated with smooth or slightly grooved surfaces shown in figure 5.32, whereas for higher loads surfaces are associated with high wear rates as in figure 5.33.

Figure 5.32: Wear tracks of Al2618-2wt% TiO₂ composite (heat treated)

Figure 5.33: Wear tracks of Al2618-8wt% TiO₂ composite (heat treated)
5.8.3 Effect of sliding velocity

Figure 5.34 shows the variation of wear rates of matrix alloy and its composite for different sliding velocity. With the increase in the sliding velocity there is a decrease in wear rate for all the different weight fractions of TiO₂ reinforced composites.

5.34: Effect of sliding velocity on wear rate of composite materials

However, at all the sliding velocities studied, the wear rates of the composites were much lower than the matrix alloy and reduced with increased content of TiO₂ reinforcement in the composites. Increased sliding velocity from 0.42 to 1.05 m/s reduces wear rate by 26.2 % for Al 2618-8wt. %TiO₂ composites as shown in figure 5.34. This can be attributed to the increased extent of oxidation of the aluminum alloy as a result of higher interfacial temperatures. Thicker oxide present helps to protect the sliding interfaces by lowering the wear rate. A factor which reduces the wear rate of the composites is due to enhancement in hardness of the composites. Increase in hardness results in improvement of wear and seizure resistance of materials. Wear mechanism during low speeds is mainly due to the removal of material by fracture of the
reinforcement and the matrix due to the high frictional force. At an intermediate speed, the predominant wear process was the formation of micro-grooves in the composite material. Researcher Vekataraman et al. [36] studied wear behavior of aluminum alloy composites and observed that the presence of a stable MML layer decreases the wear rate.

5.8.3.1 Effect of Heat treatment

Figure 5.35 shows the wear rate of the heat treated composites. Heat treated composites shows decreased wear rate and this improvement is mainly due to increased hardness of the heat treated composites. Heat treated composites shows a reduction of wear rate by 18.33% for 8 weight fraction of composite at sliding speed of 1.26 m/s.

![Graph showing effect of sliding velocity on wear rate of composite materials](image)

**Figure 5.35: Effect of sliding velocity on wear rate of composite materials**

5.8.4 Sliding distance

Figure 5.36 shows the variation of wear rate of the matrix alloy and the developed composites for different sliding distance. It is observed that there is an increase in wear rate with an increase in sliding distance for both the base alloy and its composite systems.
Figure 5.36: Effect of sliding distance on wear rate of composite materials

However, at all the sliding distances studied, the wear rates of the composites were much lower when compared to the matrix alloy and reduced with increased content of TiO₂ reinforcement. Wear rate is increased by 10% for the sliding distance of 2835 m for Al 2618-8wt.%TiO₂ composite whereas reduction in wear rate of 27.8% is obtained compared to matrix alloy. An increase in wear rate with an increase in sliding distance can be attributed to the fact that with an increase in sliding distance the temperature at the specimen disc interface increases and henceforth the material gets softened and tends to get into plastic state. The results are in line with the researcher [160].

5.8.5 Effect of heat treatment

Figure 5.37 shows the effect of heat treatment on wear rate of the composites. The figure shows that the wear rate of the composites increases with an increase in the applied load for Al2618-2wt.%TiO₂ reinforced composite. For the entire load studied the wear rate of the heat treated specimens shows the reduced wear rate when compared to unheat treated composites. An improvement of 27.60% is obtained for
Al 2618-2wt.%TiO₂ composites at 80N load. Heat treatment is favorable for improving the wear resistance of the composites [161].

![Graph showing wear rate vs load for unheat treated and heat treated composites.](image)

Figure 5.37 Effect of heat treatment on Al2618-2wt.% TiO₂ reinforced composite

5.9 Coefficient of friction

5.9.1 Effect of reinforcement

Figure 5.38 shows the effect of coefficient of friction on the Al 2618-TiO₂ reinforced composites. Increased content of TiO₂ results in the decrease in coefficient of friction. A maximum of 39.5 % reduction of the coefficient of friction is noticed in Al 2618-10wt.%TiO₂ composite. This reduction in the coefficient of friction of composites with increased content of titanium dioxide particles can be attributed to improvement in antifrictional behavior of reinforced particles which act as load bearing elements. The improvement in the anti frictional behavior of the cast composites can be mainly due to the lubricating effect of TiO₂. Titanium dioxide being an oxide, promotes lowering of coefficient of friction. It is reported that the presence of oxide layer between the mating
surfaces reduces the contact of the sliding members thereby reducing the co-efficient of friction [162].

![Diagram](image)

**Figure 5.38: Effect of weight fraction of TiO₂ on coefficient of friction.**

In addition to this, reduced coefficient of friction of composites can also be attributed to improved dispersion of TiO₂ particles, excellent bond and clean interface between matrix alloy and reinforcement and also smaller particle sizes of TiO₂. These factors favor the antifriction properties of the composites as reported by other researchers. For steady state wear conditions, the coefficient of friction decreases with increasing reinforcement content. Increased reinforcement content reduces the area fraction of the matrix in contact with the counter surface, thus minimizing the “smearing effect” of aluminum on the counter face surface and results in smaller temperature increase at the sliding interface.

**5.9.1.1 Effect of heat treatment**

Figure 5.39 shows the effect of heat treatment on coefficient of friction for 6 weight fraction of TiO₂ reinforced composites. Heat treated specimens exhibit reduced
coefficient of friction by 25.65 % for an applied load of 80N whereas for 40N of load a reduction of 26.58 % is noted.

![Graph showing effect of heat treatment on coefficient of friction](image)

**Figure 5.39:** Effect of heat treatment on coefficient of friction

### 5.9.2 Effect of load

Figure 5.40 shows the variations of coefficient of friction for different applied load on unheat treated composites. It is observed that for both the matrix alloy and TiO₂ reinforced composites, co-efficient of friction increases as the load increases. However, at all the loads studied, Al 2618-TiO₂ composites exhibits reduced co-efficient of friction with increased content of TiO₂ when compared with the Al 2618 matrix alloy. The co-efficient of friction is increased by 14.62 % for 4 weight percent of composites when compared to matrix material for 20 N of applied load.
Figure 5.40: Effect of normal load on coefficient of friction of composites

Figure 5.41 shows the variation of coefficient of friction for heat treated composites. Heat treated specimens show similar upward trend of coefficient of friction for both the matrix and their composite materials. A reduction of 15.69 % of coefficient of friction was observed for Al 2618-10wt.%TiO₂ reinforced composites when compared with un heat treated composites for applied load of 80N.

Figure 5.41: Effect of normal load on coefficient of friction of composites
5.9.3 Sliding Velocity

Figure 5.42 shows the variation of the coefficient of friction of matrix material and Al 2618-TiO$_2$ composites with increased sliding velocities.

![Graph showing coefficient of friction vs. sliding velocity](image)

**Figure 5.42: Effect of sliding velocity on coefficient of friction of composites**

It is observed that the coefficient of friction decreases as the sliding speed increases. However, at all the sliding velocities studied, TiO$_2$ reinforced composites possess lower co-efficient of friction when compared to the matrix alloy. The co-efficient of friction is reduced by 24.02 % for Al 2618-6wt.%TiO$_2$ composites when compared to the matrix material at a sliding velocity of 0.84m/s.

Figure 5.43 shows the influence of heat treatment on the coefficient of friction. Heat treated composites shows a similar downward trend of coefficient of friction for both the matrix and their composite materials.
5.9.4 Sliding distance

Figure 5.44 shows the effect of sliding distance on the co-efficient of friction for both the matrix alloy and their composites. It can be interpreted from the graph that, coefficient of friction of the composite material is lower than the matrix alloy for all the sliding distance studied. A very marginal increase in co-efficient of friction for both matrix alloy and composites is observed with increased sliding distance. Coefficient of friction is increased by 25.92 percent for the increased sliding distance of 2205 m for the 8 weight percentage of TiO₂ reinforced composites as shown in figure 5.44. For all the sliding distance studied, a composite material shows the increased coefficient of friction when compared with the matrix material. This marginal increase can be attributed to increased surface temperature of the sliding surfaces at larger sliding distances. Further, at larger sliding distances, there is a possibility of damage to the oxide film formed between the sliding surfaces and also the probability of formation of asperity junctions to increase. These two factors will contribute to increase in the co-efficient of friction of the composites.
5.10 Sand abrasive

5.10.1 Effect of reinforcement

Figure 5.45 shows the variation of the abrasive wear rate of heat treated TiO$_2$ reinforced aluminum composites. It is observed that the wear rate of TiO$_2$ reinforced composite decreases with the increase in reinforcement content in the matrix alloy. The wear rate of matrix material Al 2618 alloy is 9.49 $\times$ 10$^{-5}$ mm$^3$/m and Al 2618-8wt.%TiO$_2$ shows reduction in wear rate of 6.405 $\times$ 10$^{-5}$ mm$^3$/m. The reduction in the wear rate is because of higher hardness of the composite material. The presence of hard TiO$_2$ particles protects the soft ductile matrix by reducing the extent of penetration of the abrasive particles on the surface [46]. The graph indicates a 32.5 % reduction in wear rate is noticed in heat treated composites for the applied load of 6N.
Figure 5.45: variation of abrasive wear rate Al-TiO$_2$ reinforced composites

5.10.2 Effect of heat treatment

Figure 5.46 shows the influence of heat treatment on the abrasive wear rate of Al-TiO$_2$ reinforced composites. In all the samples studied, heat treated samples do exhibit better performance than unheat treated specimens. The wear rate of unheat treated 6 weight fraction of titanium dioxide reinforced composites is $8.724 \times 10^{-5}\text{mm}^3/\text{m}$ whereas heat treated composites shows a reduction in wear rate of $7.678 \times 10^{-5}\text{mm}^3/\text{m}$. It is observed that, an improvement of reduction in wear rate is 8.16 % for Al 2618-8wt.%TiO$_2$ reinforced composite.
5.10.3 Effect of load

Figure 5.47 and 5.48 shows the effect of load on abrasive wear rate of aluminum alloy and TiO$_2$ reinforced composites. The wear rate of both the unheat treated and heat treated specimen shows a similar trend, but the wear resistance in case of heat treated specimens are better compared to unheat treated specimens. There is a steady increase in wear up to a load of 8N and a steep increase in wear is observed at 10N for the composite material studied. The increase in the wear loss with increased load can be attributed to the larger extent of plastic deformation at higher loads and an increased effective contact area between rubber wheel and specimen. At higher loads wear loss of composites has increased with the applied load since the extent of fracture of the reinforcement also increases as the load. Heat treated specimens show little reduction in wear rate but the overall pattern of variation is almost similar. The decrease in abrasive wear loss of the heat treated composites can be attributed to improved hardness. During heat treatment process precipitation hardening and improved grain structures lead to higher hardness.
5.10.4 Worn surface analysis

Figure 5.49 shows the SEM images of 2 and 8 weight fractions of titanium dioxide reinforced composites. The SEM image of (a) and (b) shows that the plastic grooving and ploughing is more for lower weight fraction of reinforcement. The minimum grooving is observed for higher reinforcement and this improvement can be mainly attributed to the increased hardness of the composites for a higher weight fraction.
of reinforcement. Due to lower hardness of the matrix material the abrasive particles are capable to dig in and plough out the material which increases the wear rate in matrix material. In harder composite material, the abrasive particles do scratch the surfaces with minimum ploughing out leading to lower material removal [163]. The SEM images in figure 5.49 shows the scratches on the worn surface of the composites.

(a) Al 2618-2wt.% TiO₂ composite
(b) Al 2618-8wt.% TiO₂ composite
(c) Al-8wt.% TiO₂ composite (2000X)
(d) Al-8wt.% TiO₂ composite (4000X)

Figure 5.49: Abrasive wear of TiO₂ reinforced composite Load: 6N, Heat treated
5.11 Corrosion studies

5.11.1 Corrosion rate

The variation of corrosion rate in 3.5%NaCl of the matrix alloy and Al-TiO₂ reinforced composite materials are studied with increased content of reinforcement as shown in Figure 5.50. Increased content of reinforcements in the matrix alloy improves the corrosion resistance of the developed composites. Al 2618 matrix alloy has exhibited a corrosion rate of 2.375472 mpy, where as Al 2618-8wt.%TiO₂ has exhibited corrosion rate of 2.26424 mpy. A similar trend is observed by Zuhair M. Gasem [164]

The corrosion test data for the heat treatment specimens is shown in the figure 5.51, which indicates that, heat treatment process shows improvement in the corrosion resistance for both the base alloy and for the TiO₂ reinforced composite material. The results are in agreement with the results obtained by K.H.W. Seah et al [165]. Figure 5.52 shows the micrographs of corroded surface of aluminum alloy and Al2618-8wt.%TiO₂ reinforced composites. Figure 5.53 is the Potentiostat graphical output obtained on corrosion behavior of Al 2618-4wt.%TiO₂ reinforced composite.

![Figure 5.50: Effect of TiO₂ reinforcement on corrosion behavior of composite](image_url)
Figure 5.51: Effect of heat treatment on corrosion of composite materials

(a) Matrix material  (b) 8 wt.% of TiO₂ composite

Figure 5.52: Micrographs of TiO₂ reinforcement on corrosion

Figure 5.53: Potentiostat graphical output on corrosion behavior of Al 2618- 4wt.% TiO₂ composite
5.12 Statistical model

5.12.1 Hardness model

5.12.1.1 Prediction of hardness model

The response function representing the hardness of the composite material is expressed as,

\[ Y = f(X_1, X_2, X_3) + \varepsilon \]  \hspace{1cm} (5.1)

Where \( Y \) is the response for the heat treatment factors (Brinell hardness), \( \varepsilon \) is the error, \( X_1 \) is the type of quenchant(Q), \( X_2 \) is ageing duration (A) in hours and \( X_3 \) is weight percentage of TiO2 reinforcement (R).

The second order response model for the three selected factors is given by Equation 5.2.

\[ Y = b_0 + b_1Q + b_2A + b_3R + b_{11}Q^2 + b_{22}A^2 + b_{33}R^2 + b_{12}QA + b_{13}QR + b_{23}AR \]  \hspace{1cm} (5.2)

Where \( b_0 \) is the constant coefficient of the regression equation, the coefficients \( b_1, b_2 \) and \( b_3 \) are linear constants, \( b_{11}, b_{22} \) and \( B_{33} \) is the quadratic constants and \( b_{12}, b_{13} \) and \( b_{23} \) are the interaction constant terms of regression equation. The values of coefficients of the polynomial of the equation 5.2 are calculated by the regression method. The Minitab software package was used to calculate the coefficients of the polynomial equation. The regression summary of this model is shown in the table 5.1. The statistical regression model as determined by regression analysis is shown in equation 5.3.
Table 5.1 Regression summary of the hardness model

<table>
<thead>
<tr>
<th>Factors</th>
<th>Coef</th>
<th>SE coef</th>
<th>T</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>5.94</td>
<td>7.516</td>
<td>0.79</td>
<td>0.439</td>
</tr>
<tr>
<td>Q</td>
<td>27.044</td>
<td>4.631</td>
<td>5.84</td>
<td>0.000</td>
</tr>
<tr>
<td>A</td>
<td>25.933</td>
<td>4.398</td>
<td>5.90</td>
<td>0.000</td>
</tr>
<tr>
<td>R</td>
<td>21.361</td>
<td>4.398</td>
<td>4.86</td>
<td>0.000</td>
</tr>
<tr>
<td>Q X Q</td>
<td>-3.061</td>
<td>1.027</td>
<td>-2.98</td>
<td>0.008</td>
</tr>
<tr>
<td>A X A</td>
<td>-4.478</td>
<td>1.027</td>
<td>-4.36</td>
<td>0.000</td>
</tr>
<tr>
<td>R X R</td>
<td>-3.044</td>
<td>1.027</td>
<td>-2.96</td>
<td>0.008</td>
</tr>
<tr>
<td>Q X A</td>
<td>-2.0400</td>
<td>0.7262</td>
<td>-3.30</td>
<td>0.004</td>
</tr>
<tr>
<td>Q X R</td>
<td>-1.9417</td>
<td>0.7262</td>
<td>-2.67</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Hardness (BHN) = $5.94 + 27.044Q + 25.933A + 21.361R - 3.061Q^2 - 4.478A^2 - 3.044R^2 - 2.0400QA - 1.9417QR$ ---- (5.3)

5.12.1.2 Discussion on statistical model

The regression summary table 5.1 shows that, the coefficient of the main factors, have positive value, which shows that, they have a significant effect on increasing the hardness of the material. The coefficient of interaction constant (A *R) is more than error coefficient, this value is not considered for developing the stat model. The interactions (Q*A) and (Q*R) have negative effects. The P-value in the regression summary table 5.1 shows the significance of the individual factors which, is estimated by the regression modeling procedure. Using the developed statistical model (5.3) theoretical hardness was computed and the values are values are plotted in the graph 5.54. The predicted hardness shows a maximum error of -4.83 for the 16th experimental test.
5.12.1.3 Verifying the adequacy of the model

Table 5.2 shows the adequacy test results of the developed model. $R^2$ value is 0.9376, which shows that 93.7% of experimental data fits the developed model. The number of factors selected for this model fits into the regression equation, which, is illustrated from adjusted $R^2$ value. Since the value of $R^2$ is close to the adjusted $R^2$ value, the model appears to be fit for the data and has the adequate predictive capability. The predicted model yields an error of 2.5175 BHN, which is indicated as standard error of estimate.

Table 5.2: Testing the adequacy of the model

<table>
<thead>
<tr>
<th>Dependent</th>
<th>hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>27</td>
</tr>
<tr>
<td>Squared multiple $R^2$</td>
<td>0.9376</td>
</tr>
<tr>
<td>Adjusted squared multiple $R$</td>
<td>0.9099</td>
</tr>
<tr>
<td>Standard error of estimate</td>
<td>2.5175</td>
</tr>
</tbody>
</table>
5.12.1.4 Validation of the model

The confirmation experiment was performed, by conducting three tests using a specific combination of the factors and levels, which are shown in Table 5.3. Confirmation experiment shows a minimum error of 1.01% for the 1st test and maximum error of 3.162% for the 3rd confirmation test. Figure 5.55 show the difference between experimental and theoretical model for the confirmation test. Since the experimental values are very close to the predicted values, the model is capable of predicting the wear rate in the selected range values.

Table 5.3: Confirmation test parameters (hardness model)

<table>
<thead>
<tr>
<th>TEST</th>
<th>Quenching media</th>
<th>Ageing duration</th>
<th>Wt.% of TiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air</td>
<td>4h</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Water</td>
<td>8h</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Ice+ Water</td>
<td>12h</td>
<td>6</td>
</tr>
</tbody>
</table>

![Confirmation test results](image)

**Figure 5.55: Confirmation test results**
5.12.2 Sliding wear model

5.12.2.1 Prediction of Wear model

The response function representing the dry sliding wear behavior of the composite material is expressed as,

\[ Y = f(x_1, x_2, x_3) + \varepsilon \quad \text{(5.4)} \]

Where \( Y \) is the response to the dry sliding wear and \( \varepsilon \) is the error, \( X_1 \) is sliding velocity (S) in m/s, \( X_2 \) is the load (L) in N and \( X_3 \) is the weight fraction of TiO\(_2\) reinforcement (R). The second order polynomial regression equation used to represent the wear rate for three factors is given by equation 5.5.

\[ Y = b_0 + b_1S + b_2L + b_3R + b_{11}S^2 + b_{22}L^2 + b_{33}R^2 + b_{12}SL + b_{13}SR + b_{23}LR \quad \text{(5.5)} \]

Where \( b_0 \) is the constant coefficient of the regression equation, the coefficients \( b_1, b_2 \) and \( b_3 \) are linear constants, \( b_{11}, b_{22} \) and \( B_{33} \) are the quadratic constants and \( b_{12}, b_{13}, \ldots \), \( b_{23} \) are the interaction constant terms of regression equation. The values of coefficients of the polynomial of the equation 5.5 are calculated by the regression method. The Minitab software package was used to calculate the coefficients of the polynomial equation. The regression summary of this model is shown in the 5.4. The coefficient of \( L \) and \( R \) quadratic constant and interaction constant \( L \ast R \) are more than error coefficient these values are not considered for developing the statistical model. The statistical regression model as determined by regression analysis is shown in equation 5.6.
Table 5.4: Regression summary for the wear rate model

<table>
<thead>
<tr>
<th>Effect</th>
<th>Coefficient</th>
<th>SE Coefficient</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.017151</td>
<td>0.003017</td>
<td>5.68</td>
<td>0.000</td>
</tr>
<tr>
<td>S</td>
<td>-0.022071</td>
<td>0.005298</td>
<td>-4.17</td>
<td>0.000</td>
</tr>
<tr>
<td>L</td>
<td>0.000130</td>
<td>0.000018</td>
<td>7.15</td>
<td>0.000</td>
</tr>
<tr>
<td>R</td>
<td>-0.000997</td>
<td>0.000182</td>
<td>-5.47</td>
<td>0.000</td>
</tr>
<tr>
<td>S*S</td>
<td>0.008045</td>
<td>0.002448</td>
<td>3.29</td>
<td>0.004</td>
</tr>
<tr>
<td>S*L</td>
<td>-0.000096</td>
<td>0.000017</td>
<td>-5.57</td>
<td>0.000</td>
</tr>
<tr>
<td>S*R</td>
<td>0.000903</td>
<td>0.000173</td>
<td>5.24</td>
<td>0.000</td>
</tr>
</tbody>
</table>

WEAR = 0.017151−0.022071S+.000130L−0.000997R + 0.008045S^2 − 0.000096SL + 0.000903SR ---(5.6)

5.12.2.2 Discussion on Mathematical model

The regression summary table 5.4 shows that, the coefficient of the main factors: sliding speed and reinforcement have negative value, which shows that, they have a significant effect on reducing the wear rate of the material, whereas, normal load applied on the composite material have a positive effect on the wear rate. The interactions (S*L) negative effects, while (S*R) has a positive effect on the wear rate. The theoretical wear rate was calculated using the equation 5.6 and the values are plotted in the table 5.5. The experimental wear rate is slightly higher than the theoretical models value. The theoretical values are in close agreement with the experimental values. The p-value in the regression summary table 5.4 shows the significance of the individual factors which, is estimated by the regression modeling procedure.
Table 5.5: Experimental and theoretical wear rate

<table>
<thead>
<tr>
<th>Test</th>
<th>Experimental Wear rate (mm$^3$/N-m)</th>
<th>Theoretical wear (mm$^3$/N-m)</th>
<th>Test</th>
<th>Experimental Wear rate (mm$^3$/N-m)</th>
<th>Theoretical wear (mm$^3$/N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>0.005308</td>
<td>15</td>
<td>0.00443</td>
<td>0.004207</td>
</tr>
<tr>
<td>2</td>
<td>0.0048</td>
<td>0.004831</td>
<td>16</td>
<td>0.00459</td>
<td>0.004987</td>
</tr>
<tr>
<td>3</td>
<td>0.00433</td>
<td>0.004354</td>
<td>17</td>
<td>0.00489</td>
<td>0.004889</td>
</tr>
<tr>
<td>4</td>
<td>0.00656</td>
<td>0.006296</td>
<td>18</td>
<td>0.00482</td>
<td>0.004791</td>
</tr>
<tr>
<td>5</td>
<td>0.00618</td>
<td>0.005819</td>
<td>19</td>
<td>0.00316</td>
<td>0.003082</td>
</tr>
<tr>
<td>6</td>
<td>0.00518</td>
<td>0.005342</td>
<td>20</td>
<td>0.00311</td>
<td>0.003328</td>
</tr>
<tr>
<td>7</td>
<td>0.00758</td>
<td>0.007283</td>
<td>21</td>
<td>0.00331</td>
<td>0.003573</td>
</tr>
<tr>
<td>8</td>
<td>0.00662</td>
<td>0.006806</td>
<td>22</td>
<td>0.00349</td>
<td>0.003301</td>
</tr>
<tr>
<td>9</td>
<td>0.00624</td>
<td>0.006329</td>
<td>23</td>
<td>0.00373</td>
<td>0.003547</td>
</tr>
<tr>
<td>10</td>
<td>0.00359</td>
<td>0.003819</td>
<td>24</td>
<td>0.00393</td>
<td>0.003792</td>
</tr>
<tr>
<td>11</td>
<td>0.00411</td>
<td>0.003721</td>
<td>25</td>
<td>0.00361</td>
<td>0.003521</td>
</tr>
<tr>
<td>12</td>
<td>0.00384</td>
<td>0.003623</td>
<td>26</td>
<td>0.0038</td>
<td>0.003766</td>
</tr>
<tr>
<td>13</td>
<td>0.00437</td>
<td>0.004403</td>
<td>27</td>
<td>0.00391</td>
<td>0.004012</td>
</tr>
<tr>
<td>14</td>
<td>0.00423</td>
<td>0.004305</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

5.12.2.3 Verifying the adequacy of the model

Table 5.6 shows the adequacy test results of the developed model. R$^2$ value is 0.9676, which shows that 96.76% of experimental data fits the developed model. The number of factors selected for this model fits into the regression equation, which, is illustrated from adjusted R$^2$ value. Since the value of R$^2$ is close to the adjusted R$^2$ value, the model appears to be fit and has the adequate predictive capability. The Predicted model yields an error of 0.000239147mm$^3$/N-m, which is indicated as standard error of estimate.
Table 5.6: The adequacy test results of the model.

<table>
<thead>
<tr>
<th>Dependent</th>
<th>Wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>27</td>
</tr>
<tr>
<td>Squared multiple r</td>
<td>0.9676</td>
</tr>
<tr>
<td>Adjusted squared multiple R</td>
<td>0.9578</td>
</tr>
<tr>
<td>Standard error of estimate</td>
<td>0.000239147</td>
</tr>
</tbody>
</table>

5.12.2.4 Validation of the model

The confirmation experiment was performed, by conducting three tests using a specific combination of the factors and levels, which are shown in table 5.7. The theoretical wear rate was estimated using the developed model equation 5.6. Confirmation test were performed by selecting a set of factors as shown in table 5.7. Confirmation experiments show a maximum error of 5.8% for 1st test and minimum error of -0.02122 for the third confirmation test. Since the experimental values are very close to theoretical values, the model is capable of predicting the wear rate in the selected range values.

Table 5.7 Confirmation test parameters

<table>
<thead>
<tr>
<th>TEST</th>
<th>Sliding speed (m/s)</th>
<th>Normal load (N)</th>
<th>Wt % of TiO₂</th>
<th>Experimental Wear rate (mm³/N-m)</th>
<th>Theoretical wear (mm³/N-m)</th>
<th>% of error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84</td>
<td>40</td>
<td>4</td>
<td>0.005</td>
<td>0.005308</td>
<td>5.809518</td>
</tr>
<tr>
<td>2</td>
<td>1.05</td>
<td>80</td>
<td>6</td>
<td>0.00489</td>
<td>0.004889</td>
<td>-0.02122</td>
</tr>
<tr>
<td>3</td>
<td>1.24</td>
<td>60</td>
<td>6</td>
<td>0.00373</td>
<td>0.003547</td>
<td>-5.16308</td>
</tr>
</tbody>
</table>
5.12.3 Abrasive wear model

5.12.3.1 Prediction of abrasive wear model

The response function representing the abrasive wear of the composite material is expressed as,

\[ Y = f(X_1, X_2) + \varepsilon \quad \text{(5.7)} \]

Where \( Y \) is the response for the abrasive wear rate in grams, \( X_1 \) is the weight fraction of TiO₂ reinforcement (R), \( X_2 \) is load (L) in Newton and \( \varepsilon \) is the error. The second order polynomial regression equation used to represent the abrasive wear for two factors is given equation 5.8.

\[ Y = b_0 + b_1 R + b_2 L + b_{11} R^2 + b_{22} L^2 + b_{12} RL \quad \text{(5.8)} \]

Where \( b_0 \) is the constant coefficient of the regression equation, the coefficients \( b_1 \) and \( b_2 \) are linear constants, \( b_{11} \) and \( b_{22} \) are the quadratic constants and \( b_{12} \) is the interaction constant terms of regression equation. The values of coefficients of the polynomial of the equation 5.8 are calculated by the regression method. Minitab-software package was used to calculate the values of the coefficients for developed model. The regression summary for the developed model is shown in the table 5.8. The statistical model as determined by regression analysis is shown in equation 5.9.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Coefficient</th>
<th>Standard error</th>
<th>Standard coefficient</th>
<th>T</th>
<th>P – Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>1.048</td>
<td>0.046</td>
<td>0</td>
<td>22.988</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>-0.046</td>
<td>0.022</td>
<td>-0.387</td>
<td>-2.079</td>
<td>0.051</td>
</tr>
<tr>
<td>L</td>
<td>0.001</td>
<td>0.022</td>
<td>0.01</td>
<td>0.053</td>
<td>0.958</td>
</tr>
<tr>
<td>R * R</td>
<td>-0.002</td>
<td>0.003</td>
<td>-0.1</td>
<td>-0.58</td>
<td>0.569</td>
</tr>
<tr>
<td>L * L</td>
<td>0.017</td>
<td>0.003</td>
<td>0.888</td>
<td>5.154</td>
<td>0</td>
</tr>
<tr>
<td>R * L</td>
<td>-0.005</td>
<td>0.003</td>
<td>-0.179</td>
<td>-1.701</td>
<td>0.105</td>
</tr>
</tbody>
</table>

111
Abrasive Wear unheat treated = 1.048 – 0.046R + 0.001L – 0.002R² +0.017L² -0.005RL  ----(5.9)

5.12.3.2 Discussion on statistical model

The regression summary table 5.8 shows that, the coefficient of the main factors: Reinforcement has negative value, which shows that, they have a significant effect on reducing the wear rate of the material. Whereas, normal load applied on the composite material have a positive effect on the wear rate. The interactions (R*R) and (R*L) negative effects, while (L*L) has a positive effect on the wear rate. The p-value in the regression summary table 5.8 shows the significance of the individual factors which, is estimated by the regression modeling procedure.

![Figure 5.56: Percentage of error obtained from theoretical model](image)

The theoretical wear rate was calculated using statistical model 5.9. Figure 5.56 shows the percentage of wear rate error obtained from theoretical model. Maximum error of 6.5 % is obtained 23rd test run. The theoretical values are in close agreement with the experimental values.

The figure 5.57 explains the effects of two factors at five levels on the abrasive wear rate. The wear rate of the composite material decreases as the reinforcement content
of the TiO₂ is increased from 0 to 8 wt. % as shown in the graph. This reduction in wear rate is expected since TiO₂ particles being a very hard dispersoid, contribute positively to the hardness of the composite. The lower wear rate of composites is observed for the maximum content of titanium dioxide. Also, wear rate increases linearly as the applied load increase. From the figure 5.57 it is clear that factors combination of R5 and L1 yields minimum wear rate for unheat treated composites.

![Main effects plot for mean value of abrasive wear in gram](image)

**Figure 5.57 Main effect plot of mean value of abrasive wear in gram**

5.12.3.3 Verifying the adequacy of the abrasive wear model

Table 5.9 shows the summary for verifying the adequacy of the model. The value of squared multiple of R is 0.989 for unheat treated composites, which shows that 98.5 % of experimental data fits the developed model. The number of factors selected for the developed model is 0.973 which is illustrated from adjusted R² value. Since the value of squared multiple of R is close to the adjusted R² value, the model appears to be fit and has the adequate predictive capability. The Predicted model yields an error of 0.028 grams which is indicated as standard error of estimate in table 5.9.
Table 5.9: Summary for verifying the adequacy of the model

<table>
<thead>
<tr>
<th>Dependent</th>
<th>Abrasive wear (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>25</td>
</tr>
<tr>
<td>Squared multiple R</td>
<td>0.989</td>
</tr>
<tr>
<td>Adjusted squared multiple R</td>
<td>0.973</td>
</tr>
<tr>
<td>Standard error of estimate</td>
<td>0.028</td>
</tr>
</tbody>
</table>

5.12.3.4 Validation of the model

The confirmation experiment was performed by conducting three tests using a specific combination of the factors and levels which are shown in table 5.10. The theoretical wear was estimated using the developed model equation 5.9. Table 5.10 shows the deviation of theoretical wear rate from the experimental results. Since the experimental values are very close to the predicted values, the model is capable of predicting the wear rate in the selected range values.

Table 5.10: Confirmation test parameters (abrasive model)

<table>
<thead>
<tr>
<th>TEST</th>
<th>Wt.% of reinforcement</th>
<th>Load</th>
<th>Experimental Wear</th>
<th>Theoretical Wear</th>
<th>Percentage of error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>4N</td>
<td>0.97</td>
<td>0.932</td>
<td>4.077253</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>10N</td>
<td>1.15</td>
<td>1.162</td>
<td>-1.0327</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>8N</td>
<td>1.203</td>
<td>1.184</td>
<td>1.605</td>
</tr>
</tbody>
</table>