Chapter - 5

Results and Discussions
CHAPTER-5

RESULTS AND DISCUSSIONS

5.1 Metallic coating of TiO$_2$ particles

Fig. 5.1 shows the SEM photographs of uncoated and nickel coated TiO$_2$ particles. The procured TiO$_2$ powder has an irregular morphology whereas coated TiO$_2$ have a spherical morphology. Further, presence of Ni-P coating on titanium dioxide particles is confirmed by EDAX analysis as shown in Fig.5.2. EDAX analysis of nickel coated TiO$_2$ indicates the presence of both nickel and phosphorous.

(a) Uncoated TiO$_2$ powder  (b) Nickel-coated TiO$_2$ Particles

Fig.5.1 SEM photographs of uncoated and nickel coated TiO$_2$ powder

Fig.5.2 EDAX pattern of Ni-P coated TiO$_2$ particles
5.2 Microstructure Studies

5.2.1 Optical Microstructure Studies.

Fig. 5.3 Optical Microphotographs of hot forged Al6061 alloy and Al6061-TiO$_2$ Composites

(a) Forged Al6061 Alloy
(b) Forged Al6061 - 4wt% Composite.
(c) Forged Al6061 - 6wt% Composite.
(d) Forged Al6061 - 8wt% Composite.

Fig.5.3 shows the optical microphotographs of hot forged Al6061 alloy and Al6061-TiO$_2$ composites. It is observed that there is homogeneity in the distribution of the reinforcement in the matrix alloy. There exists a good bond between the matrix and the reinforcement as shown in Fig. 5.4

Fig.5.4 Optical Microphotographs of hot forged Al6061-TiO$_2$ composite indicating good bond

Microstructures of hot forged Al6061-TiO$_2$ composites after heat treatment are shown in Fig. 5.5. It is observed that fine intermetallics of Mg$_2$Si are formed within the
matrix alloy on heat treatment. Ageing duration do dictate the extent of formation of these intermetallics. 6hrs of ageing has resulted in higher extent of formation of these intermetallics. The extent of formation of these intermetallics can be attributed to the fact that on ice quenching the rate of cooling during quenching process is very high which enhances the ageing kinetics[163].

Fig. 5.5 Optical Microphotographs of Unheat treated and heat treated Al6061-4wt% TiO₂ Composites after ageing at 175°C
Fig. 5.6 shows the microstructure of the material after homogenization treatment. Mg$_2$Si phases are indicated in the micro photograph.

Mg$_2$Si secondary phases do increase the critical deformation rate by acting as obstacles for dislocation motion [164]. Thus, presence of greater extent these intermetallic phases do result in improved hardness of the composites [94].

5.2.2 Scanning Electron Micrographs Studies

Fig.5.7 shows the microphotographs of hot forged matrix alloy and its composites. Microstructure clearly indicates the homogeneity in the distribution of reinforcement in the matrix alloy. The distribution of titanium dioxide particles in the matrix alloy is highly influenced by good wettability of Ni-P coated TiO$_2$ particles in molten metal. The reinforcements get oriented along the forging direction. Further, a good bond exists between the matrix and the particle. It is also observed that there is no pull out of the particle reinforcement from the matrix even after forging although they experience damage. This fact supports good bond between the matrix and the reinforcement. Fig.5.8 shows SEM with EDAX pattern of the interfacial region confirming the presence of TiO$_2$ particles.
Forged A16061 Alloy

Forged A16061 - 4wt% Composite.

Forged A16061 - 6wt% Composite.

Forged A16061 - 8wt% Composite.

Fig. 5.7 SEM Micrographs of forged Al6061 alloy and Al6061-TiO$_2$ composites

(a)

(b)

Fig. 5.8 Hot forged Al6061-TiO$_2$ composite and its EDAX pattern
Fig. 5.9 shows the SEM and EDAX pattern of the intermetallic precipitates. Presence of Mg and Si elements is confirmed indicating the formation of intermetallic precipitates of Mg$_2$Si within the composite after heat treatment.
5.3 Mechanical properties:

5.3.1 Microhardness

5.3.1.1 Effect of Reinforcement

Fig. 5.10 shows the variations of microhardness of forged Al6061-TiO$_2$ composites in as forged and heat treated conditions. It is observed that microhardness increases with increase in percentage of TiO$_2$ particles in the matrix alloy, in both as forged and heat treated conditions. A maximum of 20.00% improvement is noticed in as forged Al6061-8wt% TiO$_2$ composite when compared with as forged matrix alloy.

Increased microhardness with increase in percentage of TiO$_2$ particles in matrix alloy can be attributed to following reasons.

1. Higher hardness of TiO$_2$ particles. Hard reinforcement in a soft and ductile matrix always enhances the hardness of the matrix alloy in general [138].

2. Increased content of reinforcement in matrix alloy leads to increased dislocation densities during solidification due to thermal mismatch between 6061 alloy and TiO$_2$ particles leading to retardation in plastic deformation [165, 142].

3. Excellent bond between matrix alloy and reinforcement and minimum micro porosities as a result of metallic coating of TiO$_2$ particles [166, 167].
4. During hardness test of the composite, the indentation pressure is partially accommodated by plastic flow of material and largely by localized increase in concentration of TiO₂ particles [168].

A maximum of 33.98% improvement is noticed in heat treated forged Al6061-8wt% TiO₂ composite when compared with as forged matrix alloy. It is also observed that, heat treatment has profound influence on microhardness of forged Al6061 alloy and Al6061-TiO₂ composites. All the heat treated samples exhibit higher microhardness values when compared with as forged alloy and its composites. This can be attributed to the formation of intermetallic precipitates namely Mg₂Si from super saturated solid solution.

5.3.1.2 Effect of Ageing duration

Fig. 5.11 Effect of ageing duration on microhardness of Al6061 alloy and Al6061-TiO₂ composites (Ageing temperature 175°C).

Fig. 5.11 shows the variation of microhardness of hot forged Al6061 and Al6061-TiO₂ composites with increase in ageing duration. It can be observed that, increase in ageing duration has resulted in increased microhardness for both matrix alloy and its composites. It is also observed that all the composites and matrix alloy exhibit maximum hardness at 6hrs of ageing duration. A maximum improvement of 51% is noticed in forged Al6061–8wt% of TiO₂ composite aged for 6 hrs duration. The increased microhardness with increased ageing duration can mainly be attributed to the formation of larger extent of intermetallic precipitates in a fine state of dispersion. Finer the precipitates, greater will be the obstruction to the motion of dislocation there by leading to increased microhardness. However, slight decrease in microhardness has been noticed in both the matrix alloy and composites on ageing for 8hrs. This may be due to fact that,
very long ageing duration will result in coarsening of intermetallic precipitates. Presence of coarser intermetallic precipitates results in reduced hardness [169].

5.3.2 Ultimate Tensile Strength:

5.3.2.1 Effect of Reinforcement

Fig.5.12 shows the variation of ultimate tensile strength of forged Al6061 alloy and Al6061-TiO$_2$ composites. An increase in ultimate tensile strength is observed with increased percentage of TiO$_2$. Use of TiO$_2$ in developing the composite has significantly increased the ultimate tensile strength. This can be attributed to the fact that TiO$_2$ results in lowering the surface tension and thereby promotes better wettability of the reinforcements with the molten metal matrix. Wettability is one of the dominating factors to ensure good bond between matrix and reinforcement [170]. A good bond between the matrix and reinforcement always favours an improvement in the ultimate tensile strength of metal matrix composites. Further, dispersion of hard ceramic particle in the soft ductile matrix results in improvement in strength. The hard ceramic particle obstructs the advancing distraction front, thereby strengthening the matrix [171]. This may be attributed to large residual stress developed during solidification and to mismatch of thermal expansion between hard ceramic particles and soft Al matrix [172-175].

A similar behaviour has been reported for AA2618/20 vol% Al$_2$O$_3$ composite after forging, hot extrusion hot rolling the improvement in the material strength was explained with effect of declustering of particles induced by the plastic deformation. The
improvement in the composite strength can also be attributed to the synergetic effect of microstructural changes in the matrix, such as grain refinement, porosity reduction and particle break down of the reinforcement during forging process. The high compressive stresses during forging do result in large degree of reduction in TiO₂ particle sizes. Smaller the size of the reinforced particles and higher its homogeneity in its distribution within the matrix alloy result in significant improvement of strength of the composites. This behaviour has been reported by other researchers [130, 173]. Further, heat treatment has a profound influence on the ultimate tensile strength of both matrix alloy and its composites. A maximum improvement of 28.87% is noticed in forged Al6061-8wt% of TiO₂ composite aged for 6hrs duration.

5.3.2.2 Effect of Ageing duration.

Fig. 5.13: Tensile strength of Al6061 & its composites with varying percentage of reinforcement with different ageing duration.

Fig.5.13 shows the tensile test results of hot forged Al6061 alloy and varying wt% of TiO₂ composites with different ageing duration. It can be observed from the figure that the strength is increased to 220Mpa. From the figure it is evident that, the heat treatment on the composite developed has a major influence on ultimate tensile strength further it is evident that 6hrs heat treated specimens showing improved tensile strength for the entire wt% studied. Further it is observed that the tensile strength of the Al matrix alloy & the composites decrease aged for 8hrs duration. The improved tensile strength for 6hrs heat treated samples may be due to significant strengthening effect with heat treatment.
5.3.3 Ductility

5.3.3.1 Effect of Reinforcement

Fig. 5.14: Variation of ductility of hot forged Al6061 alloy and Al6061-TiO$_2$ composites

Fig. 5.14 shows variation of ductility of hot forged Al6061 alloy and Al6061-TiO$_2$ composites. It is observed that addition of Ti$_2$O leads to the drastic reduction in ductility of hot forged Al6061–TiO$_2$ composites. The reduced ductility of Al6061–TiO$_2$ composites with increased content of TiO$_2$ particles can be attributed to the stress concentration effects at the matrix and the TiO$_2$ interface [176]. The presence of intrinsically brittle phases and presence of additional secondary or intermetallic phases serves as a potential sites for early crack nucleation resulting in reduction in ductility under quasi-static loading [6, 142]. Ramchandra et al [177] have reported this kind of reduction in ductility with an increased content of reinforcement in soft ductile matrix.

5.3.3.2 Effect of Ageing duration

Fig. 5.15 Variation of ductility of hot forged Al6061 alloy and Al6061-TiO$_2$ composites.
Fig. 5.15 shows the variation of ductility of Al6061 matrix and its composites with reinforcement content. On heat treatment there is further decrease in ductility of hot forged composites. An area reduction of 69.11% and 81.46% are observed for forged Al6061 alloy and forged Al6061- TiO₂ composites respectively. This can be attributed to the fact that Al6061 and Al6061- TiO₂ composites posses highest hardness and tensile strength for a given reinforcement on heat treatment. Higher the hardness and strength, lower will be the ductility. S. Das et al [178] have observed the effect of SiC particles on the ductility of aluminium alloys in both peak and under age conditions. It is reported that there is lowering of ductility with peak aged matrix.

5.3.4 Compressive Strength

Fig. 5.16: Variation of compressive strength for different TiO₂%

Fig. 5.16 shows variation of compressive strength with increase in percentage of Ni-P coated titanium dioxide particles. The compressive strength of the composite material increase by an amount as content Ni-P coated titanium dioxide particle increase from 0 to 8wt%. The trend is similar to results of other researchers [179]. The addition of hard titanium dioxide particles induced strength to matrix alloy there by causing increased resistance to compressive stresses. Resulting in enhanced compressive strength.
5.3.5 Fractography Studies.

Fractured surfaces of the forged Al6061 and TiO$_2$ reinforced Al6061 composites tested at room temperature are shown in Fig. 5.17. The particle have not got detached from the matrix alloy, however, they appear to have got damaged as shown in Fig. 5.17c. The EDAX pattern of the cracked particle is shown in Fig. 5.18. It confirms that the cracked particle is TiO$_2$. 

Fig. 5.17 Factrographs of Forged Al 6061 alloy and Al6061-TiO$_2$ Composites.

Fig. 5.18 EDAX pattern of TiO$_2$ particle.
The fracture surface of MMC’s at room temperature, are generally characterized by a modal distribution of large voids associated with the particle reinforcement debonding, due to high localized stress concentration at the interface and small dimples [180, 155, 181]. It is evident from the micrograph that the base matrix alloy shows larger voids indicating the ductile fracture, where as Al6061 hot forged T\textsubscript{02} composite shows voids of size smaller than that of base alloy, indicating macroscopically brittle fracture and microscopically ductile fracture. However, the test result shows that even though the material exhibits ductile characteristics, there is a drop in ductility as the percentage of reinforcement is increased, which leads to differences in deformation mechanisms hence causing a tri-axial stress state in the soft and ductile metal matrix. This favours the initiation and growth of voids in the matrix as well as debonding at the particle matrix interface [182]. It can be observed from the micrographs that the sizes of voids have decreased on heat treatment in both Al6061 matrix & Al6061 T\textsubscript{02} composite.
5.4. Friction and Wear studies

5.4.1 Coefficient of friction

5.4.1.1 Effect of Reinforcement

Fig. 5.19 shows the effect of incorporation of titanium dioxide in Al6061 matrix on coefficient of friction. Increased content of TiO₂ results in decrease in coefficient of friction. A maximum of 17% reduction of coefficient of friction is noticed in Al6061-8wt% TiO₂ composite. This reduction in coefficient of friction of composites with increased content of nickel coated titanium dioxide particles can be attributed to improvement in antifrictional behaviour of reinforced particles which acts as load bearing elements [183, 184].

In addition to this, reduced coefficient of friction of composites can also be attributed to improved dispersion of titanium dioxide particles, excellent bond and clean interface between matrix alloy and reinforcement and also smaller particle sizes of TiO₂. These factors favour the antifriction properties of the composites as reported by other researchers [182, 183]. The excellent antifriction behaviour of composites can also be attributed to formation of tribolayers consists of oxides of metals such as Al₂O₃, Fe₂O₃ during solidification process. Presence of such tribolayers has been reported by other researchers also [185, 186].

![Graph showing variation of coefficient of friction with content of TiO₂ particles in matrix alloy](image)

Fig. 5.19 Variation of coefficient of friction with content of TiO₂ particles in matrix alloy

5.4.1.2 Effect of Load.

Fig. 5.20 shows the variation of coefficient of friction of both matrix alloy and its composites with load. A reduction in coefficient of friction for both the matrix alloy and developed composites has been observed. However, at all the loads studied, Al6061-TiO₂ composites exhibit reduced coefficient of friction with increased content of TiO₂ particles...
when compared with matrix alloy. The reduced coefficient of friction at higher loads can be attributed to change of wear mechanism due to thermal softening beneath the worn surface as a result of increased temperature [187].

Further, with increase in loads there is more probability of the squeezing out of the reinforcement and forming a thin film which may act as a lubricant there by lowering the coefficient of friction [188].

![Graph showing the variation of coefficient of friction with load and sliding velocity.](image)

**Fig.5.20 Variation of coefficient of friction of Al6061 and its composites with Load**

### 5.4.1.3 Effect of sliding velocity

The variation of coefficient of friction of hot forged matrix alloy and its composites with sliding velocities are shown in Fig.5.21. It is observed that coefficient of friction increases with increase in sliding velocity up to a certain value, reaches maximum and then with further increase in sliding velocity not much variation in coefficient of friction is noticed. However, as the sliding velocity is increased, the solid lubricating film gets thickened and may fragment and results in higher coefficient of friction. Further, thermal softening due to increased sliding velocities is also responsible for higher coefficient of friction [188]. On the other hand, increased temperature at higher sliding velocities can cause severe plastic deformation of mating surfaces leading to more asperity junctions as a result of which, coefficient of friction increases [189]. The initial decrease in coefficient of friction with increased sliding can be attributed to the fact that the brittle particulate reinforcements in the composites gets cracked [190].
5.4.1.4 Effect of Ageing duration

Fig. 5.22 shows the effect of ageing duration on co-efficient of friction of hot forged Al6061 alloy and its composites. Ageing duration has a profound influence on co-efficient of friction of both matrix alloy and its composites. As the ageing duration increases a decrease in coefficient of friction is observed and a minimum value coefficient of friction is observed for 6 hrs of ageing. However, at all the ageing duration studied composites posses lower coefficient of friction when compared with matrix alloy. The improvement in antifrictional behaviour of composites and matrix alloy with increased ageing time can be attributed to improved mechanical properties with increased ageing time as discussed in previous section.
5.5 Wear studies

5.5.1 Adhesive wear

5.5.1.1 Effect of Reinforcement

Wear rates plotted against weight fraction of reinforcement are shown in Fig.5.23. It illustrates the influence of reinforcement percentage on wear rates of Al6061-TiO₂ MMCs worn against a steel counterface. It is observed that for the composites studied the wear rate of the composites decreases with increased contents of the reinforcement in the matrix alloy. It is obvious that the reinforcements effectively prevent wear, the reinforcements act as load carrying elements at the beginning of rubbing, and additionally act as inhibitors against plastic deformation and adhesion of the matrix material [191]. However, for a given reinforcement content, the composites possess lower wear rates than the matrix alloy. The improvement in the wear resistance of the composites with increased contents of reinforcement can be attributed to the improvement in the hardness of the composites [192]. An improved hardness of composites on incorporation of TiO₂ which is a hard phase, results in improvement of wear resistance.

It is also reported that [193] lesser porosity in the composite materials can increase the required length of crack propagation to line up with other cracks to cause delamination and increases the wear resistance of the composite.

Further, it is observed that a good bond exists between matrix and the reinforcement even after forging. The good bond between matrix and reinforcement is a major factor that influences the wear behaviour. Further, nickel coating provided at the interface between matrix and reinforcement resulting in strong bond [194, 174] has enhanced the load transfer capability from matrix to reinforcement leading to superior wear resistance [195].
5.5.1.2 Effect of Load

Fig. 5.24 shows the effect of applied load on wear rates of Al6061-TiO₂ composites. The wear rates of both the matrix alloy Al6061 as well as Al6061-TiO₂ a composite specimen steadily increases with the increase of the applied load. It may be noted that the composite specimens exhibited significantly lower wear rates than the matrix. It is observed that the wear rates of both matrix alloy and its composites increases steadily with increase in load up to 70N after which there is a steep rise in the wear rates. Increased wear rates with increased load can be attributed to the fact that at higher loads, there is a tendency for large plastic deformation which promotes the extent of wear debris formation leading to higher wear rates. The greater the extent of plastic deformation, the higher will be the probability of subsurface cracking which in turn leads to larger material removal [196].
5.5.1.3 Effect of sliding velocity

Fig. 5.25 shows the variation of wear rates of Al6061 and Al6061-TiO₂ composites with increased sliding velocities. It is observed that the wear rate increases steadily up to a sliding velocity of 0.62m/sec. With further increase in the sliding velocity a drastic increase in the wear rates are being observed for both the matrix alloy and its composites.

However, at all the sliding velocities studied, the wear rates of the composites were much lower when compared with the matrix alloy. As the sliding velocity increases, the surface temperature increases which promotes softening of the surfaces leading to more surface damage resulting in higher wear rates. The increased rate of subsurface deformation increases the contact area by fracture and fragmentation of asperities. Therefore this leads to enhanced delamination contributing to higher wear loss [197].

Further, increased wear rate with increased sliding velocity is due to high strain rate subsurface deformation.

5.5.1.4 Effect of Ageing duration

The results of Al6061 and its composites wear rates as a function of different ageing durations for Al6061-TiO₂ composites shown in Fig. 5.26. Wear rates results of heat-treated composites and matrix alloy points to a trend of decrease with increased ageing durations. 6 hrs of ageing do results in the best wear resistance of both matrix and its composites. This can be attributed to fact that on heat treatment as discussed in
previous sections, there is a tremendous improvement in both strength and hardness of the composites, which in turn leads to improved wear resistance of the composites.

Fig. 5.26 Effect of heat treatment on wear rates of hot forged Al6061 alloy and Al6061-TiO₂ composites.

5.6 Worn surface analysis.

Fig. 5.27 shows the worn SEM photographs of Al6061 alloy and Al6061-TiO₂ composites before and after heat treatment. From the microphotographs, it is observed that the morphology of worn surfaces of composite is different from that of unreinforced alloy.

Further, it is also observed that the width and size of the grooves are less on heat treatment in both matrix and its composites indicating superior wear resistance on heat treatment. This is because of improved hardness and strength of composites and matrix alloy on heat treatment as discussed in previous section. Improved hardness and strength results in excellent wear resistance of the material. The EDAX pattern of TiO₂ (indicated in Fig. 5.27d) on the worn surface is shown in Fig. 5.28. It confirms the presence of TiO₂ on the worn surface indicating excellent bond between the matrix and the reinforcement. This promotes larger extent of spreading of TiO₂ film on the worn surfaces during sliding resulting in superior tribological behaviour of the developed composites.

However, composites exhibit better wear resistance at all ageing duration when compared with matrix alloy.
Fig. 5.27 Adhesive worn surfaces of Al6061 and its composites before and after heat treatment at load of 30N, sliding velocity of 0.620 m/sec and duration of 30 min.

Fig. 5.28 EDAX pattern of TiO$_2$ particle.
5.7 Sand abrasion test results.

5.7.1 Effect of reinforcement

Fig. 5.29 shows the variation of wear loss of as forged and heat treated Al6061 alloy and Al6061-TiO₂ composites after sand abrasion tests. It is observed that weight loss decreases with increase in reinforcement in matrix alloy in both as forged and heat treated conditions. Heat treated samples exhibit better performance than the as forged alloy and its composites. A maximum of 61% and 69% reduction is noticed in as forged Al6061-8wt%TiO₂ composites and heat treated Al6061-8wt%TiO₂ composites when compared with their alloys. Decreased weight loss with increase in percentage of reinforcement can be attributed to higher hardness of composites. The higher the hardness, the better is the abrasive wear resistance of the materials. The presence of hard TiO₂ particles protects the soft ductile matrix by reducing the extent of penetration of the abrasive particles on the surface [198]. On the other hand there exists excellent bond between matrix and reinforcement as a result of metallic coating of TiO₂ particles. The presence of good bond between the matrix and reinforcement is a major factor that influences the wear behaviour of forged composites. In the absence of good bond, a three body abrasive wear situation does arise resulting in large wear rates [199, 200]. Also, there is no indication that the TiO₂ particles are being plucked from the matrix as a result of abrasion. This fact suggests that a strong bond exists between TiO₂ particles and the matrix. It is also reported that the wear behaviour of hard particle- reinforced composites depends primarily on the type of interfacial bonding between the Al matrix and the reinforcement [160].
5.7.2 Effect of Load.

![Graph showing variation of abrasive weight loss of Al6061 alloy and Al6061-TiO2 composites with Load](image)

**Fig. 5.30 Variation of abrasive weight loss of Al6061 alloy and Al6061-TiO2 composites with Load**

The dependence of abrasive wear loss of Al6061 matrix alloy and Al6061-TiO2 composite with load in as forged and heat treated condition is shown in Fig.5.30. In a multiphase material like metal matrix composites containing hard phases like ceramic reinforcement and softer metallic matrix, the harder one carries the major portion of applied stress and protects the relatively soft alloy matrix. The hard dispersoid particles also remain present on the specimen surface as protuberance and protect the abrasives to come in effective contact with the matrix surface. Thus, the ceramic particles can protect the matrix more effectively at lower loads [155].

Composites exhibits less wear with increase in load when compared with the alloy, indicating improved wear resistance of the composites over the base alloy. Especially at higher loads, composite exhibits significantly higher wear resistance than that of the base alloy. This may be due to increased protection offered by dispersoid particles within the matrix from the abrasive action of the abrasive particles [201,202].

The increase in weight loss with increased load of all the materials studied can be attributed to the larger extent of plastic deformation and an increased effective contact area between rubber wheel and specimen at higher loads. It is reported that the wear loss of MMCs increased with applied load since the extent of fracture of the reinforcement also increases with increased load [170].

Further, it is observed that heat treatment has a profound influence on abrasive loss of studied materials. Heat treated matrix alloy and its composites exhibit excellent abrasive wear resistance when compared with unheat treated ones. However, at all the
loads studied heat treated composites exhibit lower abrasive wear loss when compared with heat treated matrix alloy.

5.7.3 Effect of ageing duration:

![Fig. 5.31 Variation of abrasive weight loss of Al6061 alloy and Al6061-TiO2 composites with ageing duration](image)

Fig. 5.31 shows the variation of abrasive wear loss of Al6061 alloy and Al6061-TiO2 composites with increase in ageing duration. The abrasive wear resistance of the composites may be suitably altered by thermal ageing. When the composites were under-aged, the aluminum alloy matrices contain significantly less number of coherent and semi-coherent α precipitate which offer little resistance to plastic deformation and therefore lowers its wear resistances [203].

It is observed that an increase in ageing duration has resulted in reduced abrasive wear loss up to 6hrs of ageing for both forged 6061 alloy and Al6061-TiO2 composites. After 6hrs, the weight loss becomes almost stable. A maximum of 72.2% decrease in the abrasive wear loss is noticed in Al6061-8wt%TiO2 composites quenched in ice and artificially aged for 6hrs when compared with as forged Al6061 alloy. The decreased in abrasive wear loss of the composites with increase in ageing duration can be attributed to improved hardness with increased ageing duration. The increased ageing duration will accelerate the kinetics of precipitation hardening in the composites. This phenomenon will result in larger extent of formation of intermetallic precipitates in fine state of dispersion, leading to higher hardness. However, further increase in ageing duration results in coarser intermetallic precipitates, reducing the hardness as discussed earlier leading to increased weight loss. On the other hand, formation of such precipitates (Mg2Si) provides resistance to plastic deformation as the abrasive particles pass across the composite surface and lowers the material loss from the surface [203].

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5.7.4 Worn surface analysis:

(a) Un-heat treated forged Al6061

(b) Heat treated forged Al6061 (6hrs Ageing)

(c) Un-heat treated forged Al6061-8wt% TiO₂

(d) Heat treated forged Al6061-8wt% TiO₂ (6hrs Ageing)

Fig. 5.33 EDAX pattern of TiO₂ particle.

Fig. 5.32 SEM Photographs of hot forged abrasive worn surfaces at a load of 8N.
SEM photographs of the worn surfaces of the matrix alloy and its composites in both heat treated and un heat treated conditions are shown in Fig 5.32. Extensive plastic grooving and ploughing has been observed on unheated Al6061 alloy when compared with heat treated Al6061 alloy. This may be due to the increased hardness of the matrix due to ageing. The extent of grooving in composites is minimal when compared with matrix alloy before and after heat treatment. Further, the grooves are fine with minimal plastic deformation being noticed in case of composites. It is also observed that among all the systems studied, heat treated Al6061 8wt% TiC composite exhibited the least extent of grooving as shown in Fig. 5.32(d). In case of matrix alloy the abrasive particles are capable to dig in and plough out the material owing to their lower hardness. As for as composite materials are concerned, the abrasive particles do scratch the surfaces rather than ploughing out leading to lower material removal.

The superior abrasion wear resistance of the composites especially at higher loads can be mainly attributed to the excellent interfacial bond between TiC particle and matrix alloy even after abrasion tests. This is clearly evidenced from Fig.5.32d with the EDAX (Fig. 5.33) taken on the reinforcement particle which confirms it as TiC.

The above discussion is supported by the average roughness values of the worn surfaces shown in Fig 5.34(a-d). The average peak-to-valley height (Ra) values are 3.22µm, 3.07µm for un-heat treated and heat treated matrix alloy respectively, while 8wt% TiC composite under un-heat treated and heat treated exhibited Ra values of 1.52µm and 1.44µm respectively.
Fig. 5.34 Surface roughness of hot forged abrasive worn out surfaces (a,b) un-heat treated Al6061 alloy and its composite, (c,d) heat treated Al6061 and its composites.
5.8 Corrosion in 3.5% NaCl

The variations of corrosion rates of hot forged Al6061 alloy and Al6061-TiO2 composites before and after heat treatment are shown in the Fig.5.35 The corrosion rate increases slightly with increased contents of reinforcement for hot forged composites. Further, heat treatment has improved the corrosion resistance of both hot forged matrix alloy and its composites in 3.5% NaCl solution. The deterioration in the corrosion resistance of the composites can be mainly attributed to the galvanic coupling effect between the matrix and the reinforcement. Deterioration of corrosion resistance of MMCs has been reported by several researchers [204].

Fig. 5.35 Variation of corrosion rate of hot forged Al6061 alloy and Al6061-TiO₂ composites before and after heat treatment.
5.9 Connecting Rod.

Fig. 5.36 Connecting Rod - As forged

Fig. 5.37 Connecting Rod - As Finished

Fig. 5.38 Microphotographs

(a): Optical
(b): SEM

Fig. 5.38 Microphotographs
A connecting rod for an automotive application was developed by hot forging of the developed composites. The procedure [205] used for industrial forging of aluminum alloys was adapted for developing the connecting rod. A closed die with two cavities was used for forging trial. The composite bars were heated at 500±10°C for 2h prior to forging. The process of forging was performed in six steps by closed-die forging. The forgings were obtained on a press with a capacity of 300 tonne with a deformation rate of 0.0107mm s$^{-1}$. Hot forging was followed by hot trimming.

Fig. 5.36 and Fig. 5.37 shows the macrophotographs of the developed connecting rods in as forged and as finished condition respectively. Optical and SEM micrographs on sections of connecting rod indicated in Fig. 5.37 are shown in Fig. 5.38. Both the micrographs reveal uniform distribution of Titanium dioxide within the matrix alloy indicating high quality composite material.