CHAPTER 4

RESULTS AND DISCUSSION

4.1 WEAR AND FRICTION

4.1.1 Wear Resistance

The wear test results of pure epoxy and epoxy/MWCNTs nanocomposites are presented in Figure 4.1, 4.2 & 4.3 with variation in the weight of 30N, 60N and 90N. To find out the wear resistance phenomena of pure epoxy and MWCNTs reinforced epoxy composites were produced in 5 different compositions. The investigation clearly depicts that an addition of considerable amount of MWCNTs to the epoxy matrix dramatically reduces the wear rate. A gradual wear is taken place in the pure epoxy and the proposed nanocomposites with the sliding load of 30N in the entire journey of 942m. During the course of study, the pure epoxy exhibits the wear loss of 0.196 x10^-6 mm³/Nm.

Similarly, the epoxy/MWCNTs nanocomposites containing the weight fraction 0.1wt.%, 0.5wt.% and 1.25wt.% of MWCNTs in the pure epoxy exhibits the improved wear resistance of 11%, 28% and 92% compared with host matrix. The weight fraction 2.5wt.% and 5wt.% of MWCNTs reported improvement in wear resistance than pure epoxy but poor performer is compared with epoxy/MWCNTs nanocomposites with weight fraction of 1.25wt.% of MWCNTs.
Furthermore, when the sliding load was increased to 60N, a steady wear is taken place in the pure epoxy at a sliding distance of about 785m. At this stage, specific wear rate was reported $0.235 \times 10^{-6}$ mm$^3$/Nm, and the wear rate was found to drastically increase due to continuous pressure and shear force between sample and rotating steel disc. The pure epoxy is failed to complete the entire journey of 942m due to the material removal being brittle and the wear taking place in adhesive manner.

It is clear that an addition of 0.1wt.% MWCNTs to the epoxy matrix significantly improved the wear resistance. It was found that further addition of 0.5wt.% and 1.25wt.% MWCNTs significantly improved the wear performance. The 1.25wt.% MWNCTs exhibited good wear resistance than pure epoxy and showed a gradual wear on the entire journey of sliding distance of 942m with the specific wear rate of $0.092 \times 10^{-6}$ mm$^3$/Nm. The wear resistance of proposed nanocomposites of 0.1wt.%, 0.5wt.% and 1.25wt.% MWCNTs was 22%, 35% and 61% respectively which were greater than that of pure epoxy.

![Graph showing wear rate vs sliding distance](image)

**Figure 4.1** Specific wear rate of pure epoxy and epoxy/MWCNTs nanocomposites. Pin on disc machine: Speed:200rpm; load 30N; time: 30min.
Figure 4.2 Specific wear rate of pure epoxy and epoxy/MWCNTs nanocomposites. Pin on disc machine: Speed: 200rpm; load 60N; time: 30min.

Figure 4.3 Specific wear rate of pure epoxy and epoxy/MWCNTs nanocomposites. Pin on disc machine: Speed:200rpm; load 90N; time: 30min.
In dry sliding wear behavior of epoxy/MWCNTs nanocomposites and pure epoxy, the wear rate is the function of applied load, sliding speed and time. The present investigation was carried out at 60N load with the disc speed of 200rpm. The wear was studied in pure epoxy and MWCNTs reinforced composites. It was observed that the weight loss of MWCNTs reinforced composites is lower than that of pure epoxy. The reinforcement particles act as load bearing elements in the nanocomposites and it will bring down the wear. Moreover, the self-lubricating property of CNTs in 0.1wt.%, 0.5wt.% and 1.25wt.% lowers the contact with disc and further reduces the friction co-efficient and wear rate.

It is believed that excessive additions of MWCNTs adversely affect the homogeneous dispersion in the epoxy matrix. Further observation revealed that the excessive content of MWCNTs formed a bundle and was exposed in composites worn surface. The exposed bundles of MWNCTs act as solid lubricant between nanocomposites and steel rotating disc. The resulting 2.5wt.% of MWCNTs composites exhibits considerable wear resistance than pure epoxy but it is a poor performer than 1.25wt.% MWCNTs nanocomposites.

Furthermore, rising of MWCNTs content to 5wt.% resulted in abrupt variation of wear rate of the nanocomposites and lead deterioration of the wear resistance with the development of fracture on the contact surface before completing the sliding distance of 785m. This is attributed to continuous pressure and shear force induced by the rotating of the steel disc which results in brittle fracture. Figure 4.3 graph shows that the variation in the specific wear rate of pure epoxy and epoxy/MWCNTs nanocomposites with the load of 90N. Resulting unexpected variation in the wear was recorded. However, the weight fraction of 1.25wt.% MWCNTs holds quite considering wear resistance.
The improvement in wear resistance was calculated from the specific wear rate of pure epoxy and proposed nanocomposites.

\[
\text{Improvement in wear resistance} = \left( \frac{A - B}{A} \right) \times 100
\]

where \( A \) = specific wear rate of pure epoxy (mm\(^3\)/Nm), \( B \) = specific wear rate of proposed nanocomposites (mm\(^3\)/Nm).

Based on the experimental investigation and wide variation in the wear results of epoxy/MWCNTs in the various composition, it is evident that epoxy with 1.25wt.% MWCNTs showed remarkable wear resistance. The similar results were reported by Dong et al (2005) in that the weight fraction of epoxy with 1.5wt.% MWCNTs nanocomposites exhibits improved wear rate and when the addition of MWCNTs in the nanocomposites exceeds 1.5wt.% the wear rate of epoxy/MWCNTs increases slightly. In the same way Cirino et al (1988) concludes that the lower wear rate achieved, the beneficial effect of the carbon fiber reinforcement with the host matrix. Xue et al (2006) reported that the addition of only 0.5wt.% CNTs to UHMWPE/HDPE blend caused about 50% reduction in the wear rate compared with the host matrix. Wetzel et al (2002) from his discussion Nano-particles and micro-particles stated that both are able to enhance the wear resistance of the epoxy matrix.

Similarly, he reported that numerous wear-reduction mechanisms come into action: on the one hand, nanocomposites undergo a transition from severe abrasive wear to a mild abrasive wear caused by the formation of a crushed wear debris layer that temporarily protects the composite worn surface from excessive wear. According to some reports, the noticeable friction and wear mechanisms of epoxy/MWCNTs nanocomposites in dry sliding against a plain carbon steel counterpart may be attributed to the
following two factors: firstly, the incorporation of MWCNTs in epoxy helps to significantly improve the mechanical properties of the nanocomposites, hence the epoxy/MWCNTs nanocomposites show much better wear resistance than pure epoxy.

Secondly, during the course of wear and friction, MWCNTs dispersed uniformly in the epoxy/MWCNTs nanocomposites may be released from the nanocomposites and transferred to the interface between then nanocomposites and the steel counter face. Thus MWCNTs may serve as spacers preventing the close touch between the steel counter face and the nanocomposites block, which slows the wear rate and reduces the friction coefficient. Moreover, the self-lubricate properties of MWCNTs also result in reduction of the wear rate and the friction coefficient. The morphology of the worn surface of the pin material was analyzed by field electron scanning electron microscopy.

### 4.1.2 Friction Coefficient

The variation of the friction coefficient of pure epoxy and epoxy/MWCNTs nanocomposites with the load of 30N, 60N and 90N under dry sliding condition against steel counter face is shown in figure 4.4, 4.5 & 4.6. Compared to pure epoxy, epoxy/MWCNTs nanocomposites exhibited lower value of friction coefficient under all loading condition in this work. This implies that the friction coefficient of pure epoxy was reduced by the addition of MWCNTs.

The pure epoxy initially exhibited high wear coefficient and then decreased with increasing sliding distance and reached a steady state behavior after 5min. However, at low sliding load of 30N, the drops frictional coefficient was observed 26%, 27% and 47% and in moderate load of 60N, 7%, 11% and 15% was reported in 0.1wt.%, 0.5wt.% and 1.25wt.% of
epoxy/MWCNTs nanocomposites respectively, when compared with pure epoxy.

**Figure 4.4** Variation in friction co-efficient of epoxy and epoxy/MWCNTs nanocomposites at 30N

**Figure 4.5** Variation in friction co-efficient of epoxy and epoxy/MWCNTs nanocomposites at 60N
Figure 4.6 Variation in friction co-efficient of epoxy and epoxy/MWCNTs nanocomposites at 90N

Furthermore, addition of MWCNTs in 2.5wt.% and 5wt.% exhibited negligible difference in coefficient of friction than pure epoxy in both the loading conditions. For high sliding load of 90N, drastic variation in the coefficient of friction was observed in pure epoxy and epoxy/MWCNTs nanocomposites. The pure epoxy and 0.1, 0.5, 2.5 and 5wt.% of MWCNTs get fractured during the course of wear and not complete the entire sliding time of 30min due to continuous shear force acting on the surface. The 1.25wt.% nanocomposites complete the sliding time of 30min without fracture and its recorded high coefficient of friction. For other composites once the fracture occurred the new faces coming to the action and the coefficient of friction was recorded as low when compared with 1.25wt.% MWCNTs nanocomposites.

Under dry sliding, the friction coefficient of pure epoxy and epoxy/MWCNTs, nanocomposites increased with the increasing normal load. From the above discussion, it can be seen that MWCNTs was an efficient reinforcement for epoxy. The epoxy/MWCNTs composite had higher tensile
strength. Young’s modulus, than pure epoxy therefore resulted in a higher load-carrying capacity of epoxy/MWCNTs composites because tribology components must be reliable to provide low friction with minimal wear and deformation, and its carries large normal stresses reported by Burris & Sawyer (2006).

Under dry sliding, the temperature of the pin surface was increased due to the accumulation of frictional heat, which resulted in the sudden increase of the adhesive friction. However, it can be found that the temperature rise of the epoxy/MWCNTs composites surface lower than that of epoxy, because MWCNTs had higher thermal conductivity than epoxy and improved the dissipation of accumulated frictional heat. In addition, MWCNTs can act as solid lubricant to reduce the friction of pure epoxy. All of these contributed to reduce the friction coefficient of epoxy/MWCNTs nanocomposites.

Variations in the volume loss were also observed in the moderate load of 60N as shown in Figure 4.7. A reduction in weight loss was observed with considerable addition of MWCNTs when tested at a specific sliding load of 60N. Reduction in weight loss was observed to be 38%, 55% and 82% for nanocomposites containing 0.1wt.%, 0.5wt.% and 1.25wt.% MWCNTs respectively, compared with the pure epoxy tested under similar experimental conditions.

Furthermore, additions of MWNCTs with 2.5wt.% and 5wt.% exhibited almost equal in weight loss to the pure epoxy. The coefficient of friction does not show any relationship with total weight loss, but exhibits close correlation with calculated weight loss of CNT in total wear particles. This result strongly proposed that increased CNT content in wear debris will
Figure 4.7 Volume losses of pure epoxy and epoxy/MWCNTs nanocomposites at 60N

lower the coefficient of friction. Lower coefficient of friction with nanocomposites specimen could be expected if CNT somehow decreases the friction by either the action of rolling or sliding.

4.1.3 Contribution of the MWCNTs on wear of Nanocomposites

The primary goal of this investigation is to provide experimental information on the wear properties of epoxy/MWCNTs nanocomposites. MWCNTs have good self lubricating property and could make a direct involvement in improving the wear resistance because graphite sheets are rolled like $sp^2$ bonded. The inter shell interactions are predominately controlled by Van Der Waals force, so that MWCNTs walls can freely slide or rotate with each other, leading to the emphasis of self lubrication property.

The presence of MWNCTs only not improves the tribological property. The interfacial adhesion, internal strength and the homogeneous dispersion in the host matrix play a major role in the improvement of tribological
properties of nanocomposites. However, the uniform dispersion of MWNCTs in the matrix depends on the functional group of MWCNTs, in which the interfacial adhesion and the internal strength of the nanocomposites structure have a close relationship with the concentration and functionalized MWCNTs.

The MWCNTs could make a direct contribution to improve the wear resistance and reducing the friction coefficient in the nanocomposites. In pure epoxy, cracks generated during the wear process resulted in pull-out of the epoxy grain and led to the higher wear rates. In the epoxy/MWCNTs nanocomposites, MWCNTs appeared at the grain boundaries protected the crack propagation and also strengthened the grain structures via a pinning mechanism. Furthermore, the existence of MWCNTs within the grains also acted as a barrier for cracks developed at worn surfaces, terminating further crack propagation inside the grains, through a crack bridging phenomenon Corral et al (2008).

It is most likely that the exposed part of the MWCNTs may act as a solid lubricant between the nanocomposites samples and the counterpart due to their inherent lubrication properties, and act as a rolling medium between the two surfaces decreasing the wear reported by Boris and Susan (2001) and Zhang (2006). Well-dispersed MWCNTs lead to nanocomposites with higher densities while agglomerated resulted in lower one was demonstrated by Ahmad et al (2010). It is believed that too high additions of MWCNTs adversely affected these two important parameters such as dispersion and led nanocomposites to lower densities.

The high weight loss of 2.5 wt.% and 5 wt.% MWCNTs nanocomposites at 60N load can be associated with the lower density and mechanical properties caused by the MWCNTs agglomerates that is formed as localized bundle. Some of the MWCNTs agglomerates, although pull out from the matrix, could remain embedded in matrix and act as lubricants
therefore reduce the friction coefficient. It is remarkable property that even under such severe conditions, the MWCNTs maintain their tubular morphological characteristics, due to their unique tubular structure, nanoscale and outstanding mechanical properties particularly the elasticity (Treacy et al 1966), (Wichmann et al 2008).

It is possible that hard particles spoiled the matrix and left the scratch, but leaving the MWCNTs unharmed. To make use of such unique lubrication characteristics of MWCNTs, a strong interfacial connection between the matrix and the MWCNTs is necessary in this context. As a weak interface link with matrix will be ended up with MWCNTs being dragged out of the worn surface during wear, and losing their lubrication features and becoming debris. Our recent study has shown that the desired strong interfacial connection makes it practical for the MWCNTs direct contribution towards the improved wear rates and reduced coefficient of friction.

4.1.4 Influence of Friction co-efficient

Friction co-efficient describes the whole tribological system which consists of sample material, counterpart, magnitude of load and testing environment. It is evident from the present investigation that friction co-efficient of the samples decreases with increasing sliding time. However, the friction co-efficient of 1.25wt.% sample was considerably low at the initial stage and further decreased with increasing sliding time.

This is attributed to MWCNTs which are uniformly dispersed in pure epoxy. These MWCNTs come into action in order to reduce friction co-efficient by providing solid lubrication between nanocomposites and steel disc thereby serving as an effective reinforcement of epoxy. The sliding wear of polymer against metallic counterpart was well known that the friction component resulting from adhesion equalled the product of the real contact and the shear strength of the polymer (Chang et al 2007).
4.1.5 Morphology of Wear Surface

The morphologies of the worn surface of the specimens were observed using FESEM. The FESEM image of the pure epoxy and five nanocomposites under same testing condition are discussed. From figure 4.8 (a) it can be seen that the worn surface of pure epoxy reveals that the material removal was brittle in nature which was characterized by smooth surfaces area, large hyperbolic markings, and fractured steps revealing that pure epoxy has relatively poor wear resistance in sliding against the steel disc. Furthermore, 0.1wt.% and 0.5wt.% MWCNTs reinforced epoxy nanocomposites worn surface is smooth and displays many inter particle cracks and grooves as in Figure 4.8 (b and c).

![Figure 4.8 (a) SEM images of worn surface of epoxy](image_url)
Figure 4.8(b) SEM images of worn surface of epoxy/0.1wt.% MWCNTs nanocomposites

Figure 4.8(c) SEM images of worn surface of epoxy/0.5wt.% MWCNTs nanocomposites
Especially, the worn surface of 1.25wt.% MWCNTs reinforced epoxy displays relatively smooth and fewer micro cracks as shown in Figure 4.9 (a). It indicates that the MWCNTs are pulled out from the host matrix and then further rolled and moved to cracks and filled due to their size. A closer look at the surface topography did not perceive any fragmentation on the worn surface Figure 4.9 (b) which seems to suggest that the mechanism of material removal was ductile.

This composition predominantly shows a considerable increase in wear resistance of nanocomposites comparing with pure epoxy. However, the excessive load of MWNCTs cannot provide any wear reducing effect in the host matrix.

![SEM images of worn surface of epoxy/1.25wt.%MWCNTs nanocomposites](image)

Figure 4.9(a)  SEM images of worn surface of epoxy/1.25wt.%MWCNTs nanocomposites
Figure 4.9 (b) SEM images of worn surface of epoxy/1.25wt.% MWCNTs nanocomposites smooth surface topography

Figure 4.10 (a) SEM images of worn surface of epoxy/2.5wt.% MWCNTs nanocomposites
Figure 4.10(b) SEM images of worn surface of epoxy/5wt.% MWCNTs nanocomposites

Figure 4.11 SEM image of undispersed CNT bundles in pure epoxy

As a result, the adhesive wear takes place on the 2.5wt.%MWCNTs nanocomposites like wave of the sea shown in figure 4.10 (a). Epoxy pull outs shown in figure 4.10 (b) exhibit weak Van Der Waals force effect in high
load fraction of 5wt.% MWCNTs reinforced matrix. The FESEM image of
Figure 4.11 revealed that MWNCTs were not well embedded and dispersed in
localized bundles in the pure epoxy.

4.2 EROSION TEST

4.2.1 Effect of Impingement Angles

The erosion behavior polymer depends on whether the material is
thermoplastics or thermosetting. The mechanism of erosion failure can be
grouped into ductile, brittle and semi-ductile ones. In general ductile
behavior will occur on thermoplastic and thermosetting polymer exhibits
brittle behavior. The angle of impingements is usually described as the angle
between the eroded surface and the trajectory of the impact particle. It is well
known that the important factor influencing the erosion is impingement
angles, impact velocity, size of the eroding particle and shape and hardness of
the sample materials.

On the whole, all these have important effects on erosive weight
loss. The erosion weight loss was measured as a function of impingement
angle of ductile and brittle material has shown difference in their response.
Taking these factors as a reference, the experiments have conducted
generally. It shown that the maximum erosion rate of ductile materials occurs
at impingement angle of 15-30°, whereas maximum erosion rate of brittle
materials occurs at 90° impingement angle. The maximum erosion rate of
semi-ductile material was found to occur at impingement angle of 45 - 60°.
Figure 4.12 Weight loss as a function of impingement angles

Figure 4.12 shows the influence of impingement angle of erosive wear on pure epoxy and epoxy/MWCNTs nanocomposites with various weight fraction of 0.1, 0.5, 1.25, 2.5 and 5wt.% MWCNTs. In the present investigation the erosive weight loss was found maximum at 60° impingement for all the composition. The morphology analysis of eroded surface revealed that the material removal is mainly caused by the damage mechanism as micro cracking, pinch hole due to the impact of silica sand particle. It is stated that MWCNTs as reinforcement of epoxy matrix are a typically semi ductile materials so that the maximum weight loss is occurred at 60° impingement angle.

4.2.2 Effect of Exposure Time

Exposure time is defined as it is a measure of accumulation of exposure to material surface to remove the material in erosion environment. Figure 4.13 (a & b) shows the schematic representation of erosion diagram as a function of exposure time and impingement angle (Barkoula et al 2001). In case of brittle material, the material removal rate increases linearly with
increasing time, in ductile material the erodent particle embedded in the target surface causing weight gain. This period is generally known as incubation period. At the end of incubation period, material removal usually proceeds at a constant rate. The maximum weight loss can be found at $60^\circ$ impingement angles, it is demonstrated as semi-ductile material.

![Diagram](image)

**Figure 4.13** Schematic representation of ductile and brittle type of erosive wear (a) based on time (b) based on impingement angle.

The Figure 4.14 (a, b & c) shows weight losses as a function of exposure time at different weight fraction of MWCNTs nanocomposites at various impingement angles of $30^\circ$, $60^\circ$ and $90^\circ$. The erosive wear increases linearly with increasing exposure time for pure epoxy and 5wt.% MWCNTs nanocomposites, whereas 0.1, 0.5, 1.25 and 2.5wt.% MWCNTs show small incubation period, thereafter erosive wear increases linearly with time.

Similarly semi-ductile erosion has been observed in an 1.25wt.% MWCNTs nanocomposites and it has been attributed to homogeneous distribution and dispersion of MWCNTs in the host matrix. 1.25wt.% MWCNTs exhibited good erosion resistant which is 73% better than the pure epoxy. Whereas the 0.1, 0.5, 2.5 wt.% MWNCTs exhibits 25%, 30% and
41% improved erosion resistance than the pure epoxy respectively. The investigation clearly stated that the excessive addition of MWCNTs will not improve the erosion resistance.

Figure 4.14 (a) Weight loss as a function of exposure time and impingement angle of $30^0$

Figure 4.14(b) Weight loss as a function of exposure time and impingement angle of $60^0$
Figure 4.14(c) Weight loss as a function of exposure time and impingement angle of 90°

4.2.3 Surface morphology of Eroded Surface

In general, thermoplastic matrix composites exhibit plastic deformation, ductile tearing and plugging on eroded surface because of ductile in nature. Similarly, crack initiation and propagation of lateral surface on brittle are occurred in nature of thermosetting matrix composites. The erosion behavior of composite materials depends on matrix reinforcement, dispersion in the host matrix, experimental conditions (impingement angle, erodent etc).

The erosive particle hits the material surface at low angles and the impact force can be divided into two components: one force parallel ($F_p$) to surface of the material and other force vertical ($F_v$) the surface. The abrasive and impact phenomena are controlled by $F_p$ and $F_v$ respectively. The parallel force $F_p$ becomes marginal when the impact angle shifts towards 90°, it
exhibits micro cracking and pinch hole due to impact (Barkoula et al 2001). In the same way micro plugging and micro cutting are observed in oblique angle.

Figure 4.15 (a) shows the eroded surface of pure epoxy with impingement angle of 60° and an impact velocity of 70m/s. It can be seen that, when the hard erodent particle impact and penetrate the surface of the sample it causes the material removal by micro plugging, cutting, cracking and plastic deformation, which is the dominant wear mechanism of pure epoxy. The morphology shows the eroded surface of epoxy/MWCNTs nanocomposites at an impingement angle of 60° and an impact velocity of 70m/s. Figure 4.15 (b) shows large number crack initiation and propagation found in the eroded surface at the same time minimum level of plugging and deep holes are also found.

Similarly, 0.5wt.% MWCNTs nanocomposites exhibits localized groove on the surface shown in Figure 4.15 (c), because the eroded particle targets the surface during the incubation period. The above morphology investigation clearly exhibits the material transforming from brittle to ductile nature due to addition of MWCNTs in the pure epoxy. Figure 4.15 (d) is 1.25wt.% of epoxy/MWCNTs eroded surface, it shows large area of smooth surface and small amount of crack on the surface and it will demonstrate the good erosion resistance.

However, the excessive amount of 2.5wt.% MWCNTs cannot provide any erosion reducing effect in the host matrix. As a result, large number of multiple cracks (Figure 4.15 (e) and (f)) deep grooves, pits and pullouts exhibit weak Van Der Waals force effect in the MWCNTs reinforced matrix with high load fraction of 5wt.%. Figure 4.16 revealed that MWNCTs are not well embedded and dispersed in pure epoxy and formed localized bundles.
Figure 4.15 (a) Eroded surface SEM micrographs of pure epoxy

Figure 4.15(b) Eroded surface SEM micrographs of epoxy/0.1wt.% MWCNTs nanocomposites
Figure 4.15(c) Eroded surface SEM micrographs of epoxy/0.5wt.% MWCNTs nanocomposites

Figure 4.15 (d) Eroded surface SEM micrographs of epoxy/1.25wt.% MWCNTs nanocomposites
Figure 4.15 (e) Eroded surface SEM micrographs of epoxy/2.5wt.% MWCNTs nanocomposites

Figure 4.15 (f) Eroded surface SEM micrographs of epoxy/5wt.% MWCNTs nanocomposites
Figure 4.16 SEM image of undispersed CNT in epoxy/5wt.% MWCNTs nanocomposites

4.3 TENSILE TEST

4.3.1 Influence of MWCNTs on mechanical properties

The tensile test results of pure epoxy and epoxy/MWCNTs nanocomposites are shown in table 4.1. The investigation clearly depicts that the stress level is increased by adding considerable amount of MWCNTs. The load carrying capacity of 1.25wt.% is increased 4.42 times higher than pure epoxy as shown in Figure 4.17. However the tensile strength is also increased by considerable amount and the percentage of elongation is clearly represented that the displacement value was gradually decreased when increasing the MWCNTs content in the epoxy matrix as shown in Figure 4.18.

Moreover the nanocomposites 5wt.% also exhibit similar enhanced performance but brittle fracture occurs on the specimen due to the excessive content of MWCNTs dispersion in the matrix. The 0.1wt.%, 0.5wt.% and 2.5wt.% MWCNTs nanocomposites are also performed well and shown that
the load carrying capacity of the nanocomposites gradually increased. In addition there is a significant decrease in the displacement value and the percentage elongation of nanocomposites.

In case of displacement value the nanocomposites with 2.5wt.% MWCNTs contents have proven to be the best nanocomposites with 5wt.% MWCNTs which has shown the lowest percentage of elongation. The nanocomposites with 1.25wt.% MWCNTs epoxy has shown the best performance. The enhancement in breaking load, peak load and stress value of 1.25wt.% MWCNTs in comparison to base matrix of neat epoxy have been noted as 6.11, 4.42, 4.42 times respectively. Although the result is misleading towards the weight concentration of MWCNTs, the interest still comes with 1.25wt.% MWCNTs content composite because of other facets and economical point of view.

**Table 4.1 Tensile test result of pure epoxy and epoxy/MWCNTs nanocomposites**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Peak Load in KN</th>
<th>Breaking Load in KN</th>
<th>Displacement in mm</th>
<th>Stress N/mm²</th>
<th>Strain</th>
<th>Young's Modulus N/mm²</th>
<th>Elongation in %</th>
<th>Ultimate Tensile strength N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Epoxy</td>
<td>1.89</td>
<td>1.21</td>
<td>3.9</td>
<td>14.21</td>
<td>1.3</td>
<td>10.93</td>
<td>7.91</td>
<td>9.1</td>
</tr>
<tr>
<td>0.1 wt.% MWCNTs</td>
<td>3.76</td>
<td>2.42</td>
<td>4.6</td>
<td>28.27</td>
<td>1.36</td>
<td>20.79</td>
<td>8.049</td>
<td>18.2</td>
</tr>
<tr>
<td>0.5 wt.% MWCNTs</td>
<td>3.92</td>
<td>2.84</td>
<td>3.7</td>
<td>29.47</td>
<td>1.28</td>
<td>23.02</td>
<td>7.83</td>
<td>21.35</td>
</tr>
<tr>
<td>1.25 wt.% MWCNTs</td>
<td>8.37</td>
<td>7.4</td>
<td>2.96</td>
<td>62.93</td>
<td>1.23</td>
<td>51.16</td>
<td>6.21</td>
<td>55.64</td>
</tr>
<tr>
<td>2.5 wt.% MWCNTs</td>
<td>6.4</td>
<td>4.02</td>
<td>1.12</td>
<td>30.09</td>
<td>1.09</td>
<td>27.60</td>
<td>2.49</td>
<td>30.23</td>
</tr>
<tr>
<td>5 wt.% MWCNTs</td>
<td>2.41</td>
<td>2.41</td>
<td>0 (Brittle)</td>
<td>18.12</td>
<td>0</td>
<td>-</td>
<td>1.8</td>
<td>18.12</td>
</tr>
</tbody>
</table>
Figure 4.17 Variation in load carrying capacity of pure epoxy and MWCNTs nanocomposites

This study is suggestive to optimize the fabrication by taking 1.25wt.% MWCNTs content composite for futuristic development in the domain. It has been seen that optimum load capacity must be managed. The excessive load of MWCNTs causes brittleness due to agglomeration of fillers. However this can be further avoided by increasing the sonication rate and shear mixing rate. On the other hand the lower amount of MWCNTs as filler are inadequate to bear the load transfers in the matrix.
Figure 4.18 Tensile strength and % of elongation of pure epoxy and MWCNTs nanocomposites

At the breaking load, the sample has been examined by the scanning electron microscopy (SEM) [JEOL JFM 6390] suggesting the uniform distribution of MWCNTs in case of the best performer test sample (1.25wt.%). The Figure 4.19 clearly shows that the hyperbolic opens occur on the pure epoxy fracture surface and also pieces of epoxy pull out from the matrix. The morphology of the 1.25wt.% MWCNTs fracture region clearly debits that no pull out in the matrix and also the fracture initiated from bottom left to top right shown Figure 4.20.
Figure 4.19  SEM image of pure epoxy fracture surface. (1) Hyperbolic open in fracture surface, (2) Pieces of epoxy pull out from the matrix.

Figure 4.20  SEM images of 1.25wt.% of epoxy/MWCNTs fracture surface. Fracture initiate from bottom left to top right.
It has shown that acid functionalization improves the interfacial bonding properties between the CNTs and a polymer matrix. The carboxylic functional groups have been shown to give a stronger nanotube–polymer interaction, leading to enhanced values in Young’s modulus and mechanical strength. BHA causes cyclone addition reaction which leads to easy mixing with epoxy resin and that is why it has been severely used as monomer in the making of epoxy goods.

This functionalization provided stable dispersions of CNTs in a range of polar solvents, including water. An advantage of the phenolic functionalities is that they allow post-functionalization of the MWCNTs with other molecules that can be employed in preparing customized products. In fact, the functionalized MWCNTs increase the compatibility with epoxy matrix due to formation of an interface with stronger interconnections. The mechanism has probably followed because of cross linking among MWCNT-COOH, Epoxy and BHA as per the presentation in figure 4.21.

![Figure 4.21 Schematic presentations of linkages among CNT – Carboxylic – Bisphenol entities.](image-url)
4.3.2 Influence of Mechanical property to enhance the wear behavior

Wear in polymer materials is closely attributed to the mechanical properties of the polymer. Therefore we can assess the polymer nanocomposites wear performance using their mechanical properties data, in order to gain better understanding to check whether the improved wear resistance is due to the mechanical property of polymer nanocomposites. The mechanical properties of epoxy and epoxy/MWCNTs nanocomposites were collected experimentally, from that epoxy composites containing, 1.25wt.% of MWCNTs exhibited higher tensile strength and Young’s modulus than pure epoxy.

Due to high aspect ratio of MWCNTs, well dispersed CNTs in epoxy provided a large surface area available for interaction between the epoxy resin molecules and CNTs, which facilitated better load transferring to the reinforcing phase and thus improved the strength and modulus of the composites. Obviously, MWCNTs are successful reinforcement for epoxy matrix in the present case. However, the elongation at break of epoxy decreased slightly, which indicated that the composites became somewhat brittle compared with epoxy, because MWCNTs restricted the motion of epoxy chains chemically.

The specific wear rates of epoxy and its epoxy/MWCNTs nanocomposites with the increasing normal loads under dry sliding are discussed in the previous chapter. It can be seen that the specific wear rate of epoxy/MWCNTs nanocomposites always exhibited a lower value than that of pure epoxy under all conditions in this work, which signified that the wear resistance of pure epoxy under dry sliding was improved by the addition of MWCNTs.
Moreover, it can also be found that the epoxy and epoxy/MWCNTs nanocomposites materials are exhibited under dry sliding condition and the specific wear rate increased with the increasing normal load, which was in consistence with the finding that the wear loss was proportional to the normal load. From the above discussion, epoxy/MWCNTs nanocomposites had higher strength, modulus and micro hardness than pure epoxy, which indicated high load-carrying capacity of epoxy/MWCNTs nanocomposites due to the enhancement of CNTs. Therefore, the removal of the material from epoxy/MWCNTs nanocomposites was more difficult than that of host matrix, which led to a higher wear resistance of epoxy/MWCCNTs nanocomposites under sliding against the stainless steel counterpart.

Variation of microstructure and load-carrying capacity should be considered as possible explanations for increase in tensile strength and decrease in wear loss. Thus the crystallinity of the matrix upon CNT addition was taken into the consideration. However, addition of MWCNTs makes no significant changes to the internal structure of pure epoxy and thus MWCNTs is a potential reinforcement without significant structural changes. Tensile and tribological results suggest that both applied stress during mechanical and frictional stresses is transferred to the nanotubes.

CNT addition may contribute to increase the local compressive and shear strength. Lower debris generation is expected when contact surfaces with higher strength of pure epoxy are exposed by the frictional sliding. A slight increase in the coefficient of friction is possibly due to the increase in shear strength and surface roughness by MWCNTs addition because the counterpart is faced with CNT, which has good mechanical properties.
4.4 WEAR NUMERICAL SIMULATIONS

4.4.1 Experimental Predictions

The sliding wear test to generate the experimental data were performed on pin and disc machine. In the course of experiments specific wear rate was recorded. The data base containing 80 independent wear experiments results in pure epoxy and epoxy/MWCNTs with different load and composition, which were performed in room temperature as shown in Figure 4.22 and Figure 4.23. The obtained experimental results have been used to train and test the ANN. The measured parameter includes the material compositions (epoxy with different weight fraction of MWCNTs), testing parameter of load, sliding time and the wear characteristics (specific wear rate) as output.

![Figure 4.22 Experimental measured datasets of pure epoxy and epoxy/MWCNTs nanocomposites at 30N for 30min](image-url)
Figure 4.23 Experimental measured datasets of pure epoxy and epoxy/MWCNTs nanocomposites at 60N for 30min

The wear test results of pure epoxy and epoxy/MWNCTs nanocomposites in 30N and 60N are shown in Figure 4.24 and Figure 4.25. According to these figures, the wear rate transition from mild to severe depends on the applied load. The applied load 30N, the pure epoxy and epoxy/MWCNTs showed lower wear rate compared with 60N. The experimental investigation depicts that addition of 0.1wt.%, 0.5Wt.% and 1.25wt.% of MWCNTs significantly improves the wear resistance compared with pure epoxy on both loading conditions.

Moreover, the 1.25wt.% MWCNTs exhibits good wear resistance over pure epoxy. Further addition of 2.5wt.% and 5wt.% MWCNTs into the host matrix reported very poor performance due to excessive addition of MWCNTs which affect the homogeneous dispersion in the epoxy matrix. However in 60N the pure epoxy and 5wt.% MWCNTs nanocomposites failed to complete the entire journey of 30min and the wear rate was found sudden increase after the completion of 25min due to
continuous pressure and sheer force between the sample and rotating counterpart.

**Figure 4.24** Specific wear rate of pure epoxy and different composition of epoxy/MWCNTs nanocomposites at 30N

**Figure 4.25** Specific wear rate of pure epoxy and different composition of epoxy/MWCNTs nanocomposites at 60N
4.4.2 ANN Numerical Predictions

The experimental wear rate has been preprocessed to the required format for the ANN testing method. The ANNs were constructed with three inputs as load, sliding time and MWCNTs composition, hidden layers with eight neurons and the specific wear rate is in output node. There are many ANN algorithms used for predicting the wear performance of composites. It is therefore necessary to select an appropriate ANN algorithm for the real time applications. Based on the commercially used neural network tool box of MAT Lab, the following wide spread used algorithms (Table 4.2) were studied in our training process.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFBN</td>
<td>It error-driven learning technique which works under supervised Learning process</td>
</tr>
<tr>
<td>RBNN</td>
<td>The output of the network is a linear combination of radial basis functions of the inputs and neuron parameters</td>
</tr>
<tr>
<td>PRNN</td>
<td>Operable to be mapped on to input space with output space</td>
</tr>
<tr>
<td>GRNN</td>
<td>Memory-based network it provides estimates of continuous variables and converges to linear or nonlinear surface</td>
</tr>
</tbody>
</table>

An ANN configuration of 14 – 8 – 1 was used to compare the performance of the ANN algorithm. In this network processing one hidden layer with six material compositions, six different time durations and different loading
Figure 4.26 (Continued)
Figure 4.26 Comparison of measured and ANNs predicted specific wear rate of (a) pure epoxy, (b) 0.1wt.% MWCNTs, (c) 0.5wt.% MWCNTs, (d) 1.25wt.% MWCNTs, (e) 2.5wt.% MWCNTs and (f) 5wt.% MWCNTs at 30N for 30min.
Figure 4.27 (Continued)
Figure 4.27  Comparison of measured and ANNs predicted specific wear rate of (a) pure epoxy, (b) 0.1wt.% MWCNTs, (c) 0.5wt.% MWCNTs, (d) 1.25wt.% MWCNTs, (e) 2.5wt.% MWCNTs and (f) 5wt.% MWCNTs at 60N for 30min.
The present work GRNN model is very useful for the perspective of epoxy/MWCNTs nanocomposites design. The model can be used to predict the wear rate of epoxy/MWCNTs nanocomposites with influence of applied load, sliding time and weight fraction of MWCNTs based on the input binary sliding time and weight fraction of MWCNTs. It is important to mention that the codification used in the training dataset. It is single pass learning algorithm with highly parallel structure and also it provides smooth transitions from one observed value to others. Consequently it cannot be used to predict new data with different knowledge domain. Because the major limitation of the ANN techniques is that the networks run in "shelled box" fashion. Therefore, the explicit physical phenomena will affect the experimental data, so it cannot be used to predict data accurately.

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Table 4.3 Sample experimental data and predicted output from the ANN with relative error

<table>
<thead>
<tr>
<th>Test data No.</th>
<th>Composition</th>
<th>Load (N)</th>
<th>Time (min)</th>
<th>Measured</th>
<th>FFNN Predicted</th>
<th>RBNN predicted</th>
<th>PRNN predicted</th>
<th>GRNN predicted</th>
<th>FRBN</th>
<th>RBNN</th>
<th>PRNN</th>
<th>GRNN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pure epoxy</td>
<td>30</td>
<td>30</td>
<td>0.196</td>
<td>0.185</td>
<td>0.195</td>
<td>0.189</td>
<td>0.197</td>
<td>-3.93</td>
<td>0.43</td>
<td>3.50</td>
<td>-0.29</td>
</tr>
<tr>
<td>2</td>
<td>Pure epoxy</td>
<td>60</td>
<td>25</td>
<td>0.235</td>
<td>0.225</td>
<td>0.250</td>
<td>0.178</td>
<td>0.235</td>
<td>4.16</td>
<td>-6.19</td>
<td>24.42</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>0.1wt.%MWCNTs</td>
<td>60</td>
<td>30</td>
<td>0.183</td>
<td>0.199</td>
<td>0.196</td>
<td>0.178</td>
<td>0.183</td>
<td>-8.52</td>
<td>-7.12</td>
<td>2.96</td>
<td>0.21</td>
</tr>
<tr>
<td>4</td>
<td>0.5wt.%MWCNTs</td>
<td>30</td>
<td>25</td>
<td>0.171</td>
<td>0.171</td>
<td>0.172</td>
<td>0.168</td>
<td>0.172</td>
<td>0.18</td>
<td>-0.48</td>
<td>1.88</td>
<td>-0.46</td>
</tr>
<tr>
<td>5</td>
<td>1.25wt.%MWCNTs</td>
<td>60</td>
<td>30</td>
<td>0.092</td>
<td>0.084</td>
<td>0.093</td>
<td>0.091</td>
<td>0.092</td>
<td>8.49</td>
<td>-1.55</td>
<td>0.90</td>
<td>0.14</td>
</tr>
<tr>
<td>6</td>
<td>2.5wt.%MWCNTs</td>
<td>30</td>
<td>25</td>
<td>0.167</td>
<td>0.167</td>
<td>0.167</td>
<td>0.165</td>
<td>0.167</td>
<td>-0.09</td>
<td>-0.02</td>
<td>1.49</td>
<td>0.08</td>
</tr>
<tr>
<td>7</td>
<td>5wt.%MWCNTs</td>
<td>30</td>
<td>30</td>
<td>0.143</td>
<td>0.132</td>
<td>0.143</td>
<td>0.144</td>
<td>0.143</td>
<td>7.41</td>
<td>0.32</td>
<td>0.78</td>
<td>0.24</td>
</tr>
<tr>
<td>8</td>
<td>5wt.%MWCNTs</td>
<td>60</td>
<td>25</td>
<td>0.192</td>
<td>0.191</td>
<td>0.192</td>
<td>0.195</td>
<td>0.192</td>
<td>0.74</td>
<td>-0.12</td>
<td>-1.59</td>
<td>0.08</td>
</tr>
</tbody>
</table>