TRIBOLOGICAL BEHAVIOR PREDICTION FOR AN EPOXY ARAMID SYSTEM BASED ON MECHANICAL AND THERMAL PROPERTIES ANALYSES

I. G. Birsa†, I. Roman, S. Ciortan
Department of Mechanical Engineering, Dunarea de Jos University, Romania

Abstract: Taking into account that the tribological processes are a combination of many other processes the aim of this paper is building a neural network model based on mechanical and thermal properties for prediction of the tribological behaviour of an Epoxy- Aramidic composite system. The created epoxy based composites with aramidic powders, were tribological tested with diverse parameters in order to obtain follow properties: wear rate and friction coefficient. Bending and compression tests were performed for obtain main mechanical properties. Thermal tests were performed in order to obtain follow properties: specific heat, thermal conductivity and thermal expansions. With all the studied properties was created an Artificial Neural Network (ANN) model. The created ANN model can perform prediction for tribological behaviour of studied composites.

Keywords: tribological properties, mechanical properties, thermal properties, artificial neural network

1. INTRODUCTION

Nowadays there are no branches of technology that don’t use the effect of polymers development discoveries and researches. The complexity of filled polymers leads to more researches for understanding the changing character of their properties. There are a lot of mathematic models which are based on theoretical and practical studies; unfortunately there is no one general rule describes that the behaviour of amorphous composite materials. These studies give the possibilities to predict the properties of a composite material, even if the created material doesn’t work in real applications [1, 2].

Due to their mechanical, chemical and electrical characteristics, the epoxy resins represent 72 % of the used thermosetting composites; there are unsaturated polyester resins (12 %) and phenolic resins (9 %) [3].

Different modifiers (additives) were used in order to obtain optimal performances with minimal expenses [4]. At the beginning, some powders were added to the composites for lowering the final product’s price. The observation that the composite properties are improved by some of these materials, today led to the sophisticate additivation procedures having the aim to improve the properties like dimensional and thermal stability, elasticity modulus, abrasion resistance, frictional coefficient etc. [5, 6]. Based on their source the powders can be classified: organic or inorganic; based on particles dimensions: nano, micro and macro particles. It is known that some powders are easier to obtain and to include in the composite matrix. The most common used powder materials in industrial researches are carbon nanotubes, clay, starch, carbon black, talc, aramidic, aluminium etc.

The main role in composite materials forming process is played by the resin matrix - filler interface. The best performances of the composites are obtained when the adhesion between the phases is optimal [4]. Often some pre-treatments are applied to the components (in order to obtain chemical compatibility), that leads to an improved adhesion [3]. This kind of treatments are expensive and time consuming, leading to an increase of the filling materials price, and also offering the possibility to increase their weight ratio for the final composite without decreasing its properties values.

Usually, a Neural Network is described as an interconnected assembly of simple processing elements, units or nodes, whose functionality is loosely based on the animal neuron. The processing ability of

† Author for contacts: Prof. Iulian-Gabriel Birsan
E-mail: igbirsan@ugal.ro

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the network is based on the inter-unit connection strengths (weights) obtained by a process of adaptation to, or learning from, a set of training patterns [7-9].

Currently, there are a lot of specialized software packages for simulating neural networks that allow to design and to use of artificial neural networks which provide multiple facilities [10-12]. One of this software is EasyNN. The aim of this research is to create high resistance epoxy composites for tribological applications by identifying how different volume ratios of fillers change their tribological behaviour. A neuronal network model was created in order to solve a highly nonlinear problem.

2. MATERIALS AND METHODS

2.1. Composite material

The RE 4020 - DE 4020 epoxy system, filled with Aramidic powder, was used to create the composite material. The obtaining of epoxy resin was by reacting the epichlorohydrin (propylene chloride) with bisphenol A, in two steps. First was formed the component A - diglycidyl ether bisphenol A (DGEBA) - then, in second step, the cycloaliphatic amine type nonylphenol (component B) was added, as strengthening factor.

The Aramidic powder (Twaron) was mixed in three concentrations as follows: 5, 15 and 25%. It is generally used to improve tribological properties of the composites. As known, the tribological processes are very complex and it is important to improve them without losing other material properties. The aramidic powder used for this composite was the p-phenylene terephthalamide (PpPTA), a form of AABB para-paraaramide. The PpPTA is a combination of p-phenylene diamine (PPD) with terephthaloyl dichloride (TDC). As solvent for the aromatic polymer, the N-methyl pyrrolidone (NMP) and calcium chloride were used. The conversion of monomers into a polymeric powder was obtained. The thermal and chemical properties of the aramidic powder are not appropriate to be used as reinforcement but can be used as improvement factor for tribological properties of a composite material.

The manufacturer technical specification require that all mechanical mixing operation to be done before polymerization starting (typically 30 minutes). So, the mixing and molding in shapes were performed within recommended time interval. The polymerization require five stages: partial polymerization in molding shape for 24 hours, removing from molding shapes and keeping for 14 days and three thermal treatments (8 hours at 60 °C; 2 hours at 90 °C and 2 hours at 120 °C).

According to the testing standards several sample shapes were prepared: blocs for tribological, thermal expansion and bending tests, cylindrical shape for compression, thermal conductivity and heat specific tests. The samples sizes are coherent with each testing procedure specification.

2.2. Tribological assets

For tribological properties assessment, it was used the block-on-ring module on Universal Tribotester UMT2 (CETR®). The tests were done for 1500 m of sliding (general sliding distance for thermosetting composite material), at different sliding velocities and applied forces, in order to identify their influence on friction coefficient and linear wear.

Tribological tests were performed, using a block-on-ring module, with those blocks made of composite material and ring made of stainless steel. Through device software loading force, the rotation speed and testing time are controlled; the friction force and linear wear are recorded.

The composite sample block dimensions are 16.5 mm x 10 mm x 4 mm. The second triboelement of the couple is the exterior ring of roller bearing KBS 30202 (DIN ISO 355.720) having the dimensions Ø35 mm × 10 mm. The material of the ring is DIN 100Cr6 steel (60-62 HRC), with the roughness in the contact area: Ra=0.8 μm.

The testing parameters are presented in Table 1. For each type of composite were tested three samples, and the results were averaged.

The anisotropic character of filled polymers makes more difficult the understanding of the properties changing processes, requiring more researches on their behaviour. There are a lot of mathematical
models, based on theoretical and experimental studies. Even these models allow predicting the composite material properties, the results are with low precision. The preliminary studies are as expensive and time consuming as high is the required prediction precision.

Table 1. Tribological testing parameters.

<table>
<thead>
<tr>
<th>Sliding speed [m/s]</th>
<th>Rotation speed [rot/min]</th>
<th>Loading force [N]</th>
<th>Time [min]</th>
<th>Sliding distance [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>413</td>
<td>7.5</td>
<td>15</td>
<td>33</td>
</tr>
<tr>
<td>1.11</td>
<td>620</td>
<td>7.5</td>
<td>15</td>
<td>22</td>
</tr>
</tbody>
</table>

2.3. Bending and compression assets

The bending and compression assets were performed according to the ASTM D 790, ISO 178 and SR EN ISO 14125 standards, on a Testometric M 350 5K tester. The loading speed in bending tests was 1mm/min with the distance between the supports of 22 mm. Three parameters were recorded: the bending modulus, the breaking energy and the breaking strength. In order to minimize the errors, the results were computed as the average of five samples of each material test.

In compression test case, the loading speed was 1 mm/min. There were used cylindrical samples with equal diameters and heights. Two parameters were recorded: compression modulus and compression yielding point. Also, the averaged results of five samples of each material were taken into account.

2.4. Thermal assets

All formed composite materials were thermally tested by determining the coefficient of thermal expansion, specific heat and thermal conductivity.

Through the idea that created composite is bulk, the linear thermal expansion was determined, according ASTM E 831 [10], using TMA-SDTA 840 (Mettler Toledo). The samples were heated from 30 °C to 150 °C with a heating rate of 10 °C/min. Temperature range for the expansion coefficient determination was the linearity area after vitreous transition temperature (90 °C - 140 °C). Three samples of each material were tested, the averaged results being taken into account.

Specific heat assets were provided using DSC measuring equipment (Mettler Toledo). The samples were heated from 30 °C to 160 °C with a heating rate of 15 °C/min and cooled at the same rate. The linear region for specific heat determination was between 100 °C and 60 °C on the thermogram of the cooling curve. For each concentration were tested three samples, the specific heat value being considered the average of these results.

DSC gives the possibility to determine the thermal conductivity of the polymer using a simple method with an accuracy of ± 10 % to ± 20 %. This method was published by van Reijen in Hakvoort, and consists of measuring the melting temperature of the pure metal, which is placed on the upper surface of the cylindrical sample [6]. The average values of the thermal conductivity are higher than that of pure epoxy resin.

3. RESULTS AND DISCUSSIONS

All obtained data were analyzed through the influence of testing parameters and through the concentration of aramidic powder.

3.1. Tribological properties

For F=7.5 N and v=0.75 m/s the lowest friction coefficient value was obtained for 25 % aramidic powder composite, followed by pure epoxy resin and 5 % aramidic powder composite, with a very similar evolution. The highest value was obtained for 15 % aramidic powder composite (see Figure 1).

In linear wear case, the lowest value was obtained for 5 % aramidic powder concentration and the highest value for 25 % aramidic powder composite (see Figure 2).
In case of \( F=7.5\, N \) and \( v=1.1\, m/s \) (see Figure 1) the lowest friction coefficient value was obtained for 25% aramidic powder composite, but with the highest linear wear value (see Figure 2). The highest friction coefficient value was recorded for pure epoxy resin. For 5% aramidic powder composite the friction coefficient value is higher than that of 15% and 25% aramidic powder composite but the linear wear is lower, thus indicating that the composite stability is higher at lower aramidic powder concentrations, due to higher epoxy resin volume. Yet, the friction coefficient value is lower than that of pure epoxy resin due to the lubricating properties of aramidic particles, leading this way, to a lower linear wear. For 15% and 25% aramidic powder composites, due to the lower resin volume, the composite stability is lower, leading to a higher linear wear. Based on the detached aramidic particles, during the wear processes, the friction coefficient values are lower than those pure resins.

![Figure 1](image1.png)

**Figure 1.** Average frictional coefficient for epoxy composites filled with aramidic powder.

In the case of \( F=15\, N \) and \( v=0.75\, m/s \), the friction coefficient evolution (see Figure 1) was very similar with that of pure epoxy resin and 5% and 15% aramidic powder composite. For 25% aramidic powder composite the friction coefficient value was higher. Difference occurs for the linear wear case. The lowest value was observed for 5% aramidic powder composite, followed in order by pure epoxy resin and respectively 15% and 25% aramidic powder composites. The explanation of tribological behavior in this case is the fact that for loading at \( F=15\, N \) at \( v=1.1\, m/s \), aramidic particles are detached during the friction process and acting like a solid lubricant.

![Figure 2](image2.png)

**Figure 2.** Average of linear wear rate for epoxy composites filled with aramidic powder.

The last set of testing parameters at \( F=15\, N \) and \( v=1.1\, m/s \) the lowest friction coefficient value was measured for 5% aramidic powder composite (see Figure 1). The pure epoxy resin friction coefficient value was more than 0.1 higher than that of 5% aramidic powder composite. It is observed that for epoxy resin deviation bars have very high value, that indicate the limit of testing parameter, opposite results are for 25% aramidic powder, concluding with a gripping wear presses with lower abrasive resistance. Also it can be concluded for 15% aramidic composite.

The analysis of loading force influence on friction coefficient evolution also can be analyzed through Figure 1. Can be observed that, for a 0.75 m/s sliding speed value, the increase of loading force leads to the decrease of the friction coefficient. This can be explained by wear detached particles, acting as a solid lubricant. For 1.1 m/s sliding speed value, can be observed an increase of friction coefficient.
value with loading force for pure resin and for composites with 15 % and 25 % aramidic powder. For 5 % aramidic powder composite case, the evolution of friction coefficient shows a very low dependency with loading force.

By analyzing the sliding speed influence on friction coefficient evolution, it can be observed a decreasing tendency with sliding speed increasing, for 7.5 N loading force. In case of 15 N loading force value, the friction coefficient values increase with sliding speed.

Looking to the average of linear wear rate evolution (see Figure 2), a hierarchy can be observed for first three sets of parameters. For pure epoxy resin, the wear intensity is higher than that of 5 % aramidic powder composite, increasing with the powder concentration.

3.2. Mechanical properties

In the case of bending tests the values of bending modulus are between of 1250-1450 MPa. The bending modulus increases as the epoxy resin is more filled, behaviour that can be explained in terms of strong elastic properties of the filler agent into the matrix (see Table 2).

Table 2. Mechanical properties of Aramidic composite materials.

<table>
<thead>
<tr>
<th>Concentration [%]</th>
<th>0</th>
<th>5</th>
<th>15</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bending Properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength at break [MPa]</td>
<td>95.93</td>
<td>94.76</td>
<td>88.91</td>
<td>79.90</td>
</tr>
<tr>
<td>Bending Modulus [MPa]</td>
<td>1305.16</td>
<td>1345.53</td>
<td>1315.53</td>
<td>1358.65</td>
</tr>
<tr>
<td>Energy at break [N.m]</td>
<td>0.54</td>
<td>0.40</td>
<td>0.34</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>Compression Properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression modulus of elasticity [MPa]</td>
<td>973.59</td>
<td>804.30</td>
<td>986.72</td>
<td>903.61</td>
</tr>
<tr>
<td>Compression yield point [MPa]</td>
<td>100.13</td>
<td>81.76</td>
<td>99.50</td>
<td>91.66</td>
</tr>
</tbody>
</table>

For compression test there were taken into account two main properties: compression modulus of elasticity and compression yield point used cylindrical specimens with a diameter equal to the 6.2 mm height. For average values of compression modulus of elasticity it is observed the lower value in case of concentrations of 5 % and 25 % powder, and is approximately equal for 15 % than bulk epoxy.

3.3. Thermal properties

Analyses of the coefficient of linear thermal expansion indicate absolute similarity for composite with 5 % and 25 % aramid powder. Their evaluation shows that the addition of epoxy resin got the lower values of the coefficient of thermal expansion with an insignificant variation range.

Specific heat assets were provided using DSC measuring equipment. Maximum variation of 6 % compared to the epoxy resin was for composite with 25 % powder concentration. Slightly upward trend was observed with the increasing of powder concentration (Table 3).

Table 3. Thermal properties of Aramidic composite materials.

<table>
<thead>
<tr>
<th>Concentration [%]</th>
<th>0</th>
<th>5</th>
<th>15</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific heat [J/g°C]</td>
<td>1.52</td>
<td>1.46</td>
<td>1.56</td>
<td>1.62</td>
</tr>
<tr>
<td>Thermal expansion coefficient [ppm/°C]</td>
<td>205.30</td>
<td>191.47</td>
<td>197.56</td>
<td>191.90</td>
</tr>
<tr>
<td>Thermal conductivity [W/m°C]</td>
<td>0.1249</td>
<td>0.1374</td>
<td>0.1179</td>
<td>0.1249</td>
</tr>
</tbody>
</table>

4. NEURAL NETWORK MODELING

The corresponding obtained backpropagation network architecture has nine inputs - mechanical and thermal properties and four outputs - friction properties. Three hidden layers complete the network (see Figure 3).
Created neural model was twice trained, first time, in order to predict properties for composite with 5% aramidic powder and second time for 15% aramidic powder. This percentage was chosen according to the recommendation of the neural network theory. For training process were excluded successive values of the properties for 5% and 15% aramidic composites. As activation function, the sigmoidal one was chosen. The training target was settled at 0.01.

Figure 3. Neural network architecture.

Looking to the input importance over outputs, it can be observed following hierarchy: the most influencing factors on tribological properties of the composite are thermal conductivity; bending modulus and bending strength at break (see Figure 4). This information, provided by the neural model, is in direct concordance with experimental results presented above, proving that the neural networks succeeded to form the physical dependencies between the input-output factors.

Figure 4. Relative importance of neural network model.

Regarding the prediction of the tribological properties of the composite based on known mechanical and thermal properties, the prediction error was summed by comparing the neural model outputs with the corresponding experimental acquired data. The results are presented in Figure 5.
Figure 5. Relative errors for predicted value of friction coefficient.

5. CONCLUSIONS

The neural network modelling is an appropriate method for friction coefficient estimation, based on some mechanical and thermal properties. This way, the time consuming tribological tests can be overcome.

After analysing the obtained predictions it can be concluded that the higher values are on limit of the testing parameters, which shows once again that for this composites used loading force and velocities are optimal. Beyond these values the composite behaviour becomes highly non-linear, leading to wide scattered values of friction coefficient. Minimal errors were identified for the prediction of the friction coefficient for test parameters with \( L=7.5 \, \text{N} \); \( v=1.1 \, \text{m/s} \) and \( L=15 \, \text{N} \); \( v=0.75 \, \text{m/s} \) for both predicted 5% and 15% aramidic concentration. In this domain the composite behaviour is stable, the neural network model being reliable for friction coefficient prediction.

FURTHER WORK

Following the obtained results after using the created neuronal network model, it will be created another neuronal model which will show the influence of tribological test parameters on the tribological results, and correlating them into a global model, in order to obtain a more precise description of the composite behaviour.

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