Neural Network Based Analysis of Tribological Behaviour for an Epoxy-Aramid System

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The aim of this paper is based on neural network model for tribological analyses of an Epoxy composite system. The created epoxy based composites with aramidic powders, were tribologically tested with diverse parameters in order to obtain the following properties: wear rate and friction coefficient. With all the studied tribological properties was created a Neural Network (NN) model. The created NN model can perform optimisations for concentration of aramidic powder in final used composites for different domains of applications.

Keywords: epoxy composites, bloc on ring, friction coefficient, neural network analysis, optimisations

It can surely be said that nowadays there are no branches of technology that don’t use the effect of polymers development discoveries and researches. The anisotropic character of filled polymers leads to more research as for understanding the changing character of the properties. There are a lot of mathematic models which are based on theoretical and practical studies. These studies give the possibilities to predict the properties of the composite material, even if the created material does not work in real applications [1, 2].

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.

Due to their mechanical, chemical and electrical characteristics, the epoxy resins represent 72% of the used thermosetting composites. On the second place there are unsatured polyester resins (12%) followed by phenolic resins (9%), [3].

There are used different modifiers (additives) [4] in order to obtain optimal performances with minimal expences. At the beginning, some powders were added to the composites for lowering the final product price. The observation that the composite properties are improved by some of these materials, led today to the sophisticate additivation procedures having the aim to improve the properties like dimensional and thermal stability, elasticity modulus, abrasion resistance etc. [5, 6]. Comparing to fibers, the powders are easier to obtain and to include in the composite matrix. The powders can be classified, based on their source: organic or inorganic; or based on particle dimension: nano, micro and macro powders. The most used materials are carbon nanotubes, clay, starch, carbon black, talc, aluminum etc.

The main role in composite materials forming process is played by the resin matrix - reinforcing material interface. The best performances of 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 lead 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.

Experimental part

Materials and methods

Epoxy – Aramidic composite system

The RE 4020 – DE 4020 epoxy system, filled with Aramidic powder, was used for the creating composite material.

The epoxy resin has been obtained by reacting epichlorohydrin (propylene chloride) with bisphenol A. The reaction proceeds in two steps, first step forming diglycidyl ether bisphenol A (DGEBA), named component A, and second one was the strengthening of the component A (DGEBA) with cycloaliphatic amine type nonylphenol named component B [3, 4]. The Aramadic powder (Twaron) was mixed in three concentrations as follows: 5, 15 and 25%. Used aramidic powder is actually a *p*-phenylene terephthalamide (PpPTA), the simplest form of the AABB para-polyaramide. PpPTA is a product of *p*-phenylene diamine (PPD) and terephthaloyl dichloride (TDC). To dissolve the aromatic polymer, it was used a co-solvent N-methyl pyrrolidone (NMP), and an ionic component (calcium chloride CaCl). In the first stage, the monomers were converted into a fine-grained powder polymer. This material has thermal and chemical properties typical for a para-aramid, but still has not acquired properties as a yarn or paste for reinforcement. The material in this state can be used to improve the properties of the composite materials. The Aramidic powder (Twaron) is generally used to improve tribological properties of the composite. As known, the tribological processes are very complex and it is important to improve them without lossing other material properties.

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, at different sliding velocities and applied forces, in order to identify their influence on friction coefficient and linear wear.

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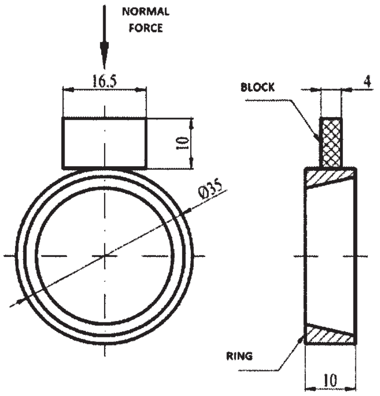

Fig. 1. Shape and dimensions of linear contact friction couple (Timken type)

Table 1
TRIBOLOGICAL TESTING PARAMETERS

Sliding speed [m/s]	Rotation speed [rot/min]	Loading force [N]		Time [min]	Sliding distance [m]
0.75	413	7.5	15	33	1500
1.11	620	7.5	15	22	

Tribological method of testing

Tribological tests were performed on UMT-2 (CETR , USA) device, using a block-on-ring module, with those block made by composite material and the ring made by 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 16.5mm x 10mm x 4mm (fig. 1). The second triboelement of the couple is exterior ring of roller bearing KBS 30202 (DIN ISO 355.720) with dimensions ∅35mm × 10mm. The material of the ring is DIN 100Cr6 steel (60-62 HRC), with the roughness in contact area: Ra=0.8μm.

The testing parameters are presented in table 1. For each composite three samples were tested and results were averaged.

Results and discussions

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

For F=7.5N and v=0.75m/s (fig. 2) the lowest friction coefficient value was obtained for 5% aramidic powder composite, followed by pure epoxy resin and 25% aramidic powder composite, with a very similar evolution. The highest value was obtained for 15% aramidic powder composite.

For linear wear case, the lowest value was for pure epoxy resin and the highest value for 25% aramidic powder composite (fig. 3).

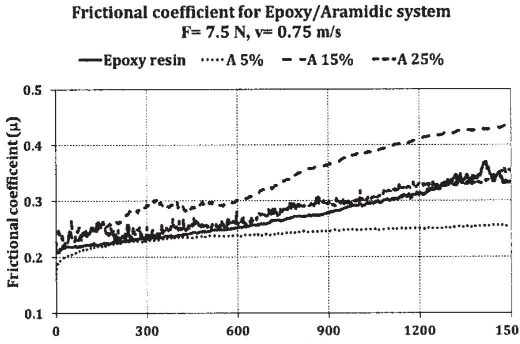

Fig. 2. Frictional coefficient for Epoxy/Aramidic system F=7.5N, v=0.75m/s

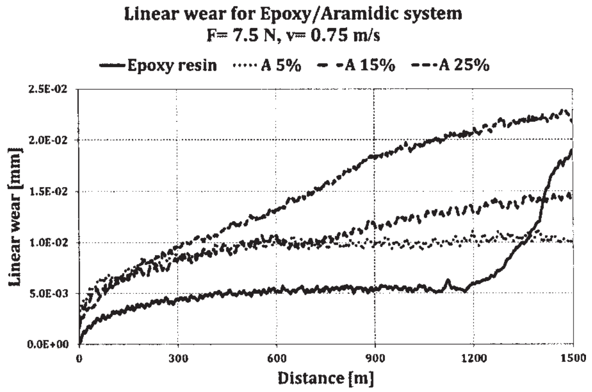

Fig. 3. Linear wear for Epoxy/Aramidic system F=7.5N, v=0.75m/s

For F=7.5N and v=1.1m/s (fig. 4, 5) the lowest friction coefficient value was obtained for 25% aramidic powder composite, but with the highest linear wear value. The highest friction coefficient value was recorded for pure epoxy resin and the lowest linear wear value for 5% aramidic powder composite. For 5% aramidic powder composite the friction coefficient value is higher than that of 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 that way, to a lower linear wear. For 15 and 25% aramidic powder composites, due to lower resin volume, the composite stability is lower, leading to a higher linear wear. Due to the detached aramidic particles, during the wear processes, the friction coefficient values are lower than those of pure resins.

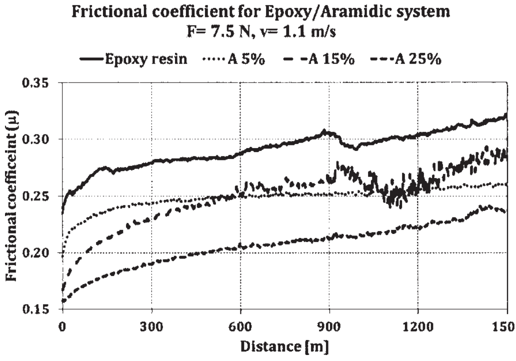

Fig. 4. Frictional coefficient for Epoxy/Aramidic system F=7.5N, v=1.1m/s

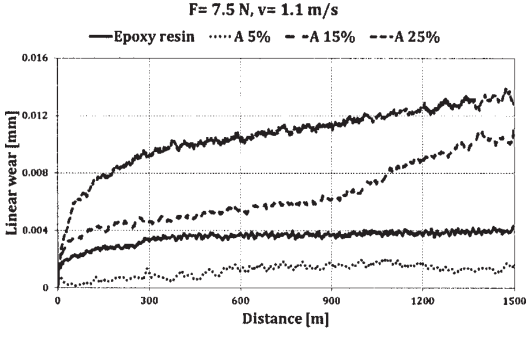

Fig. 5. Linear wear for Epoxy/Aramidic system F=7.5N, v=1.1m/s

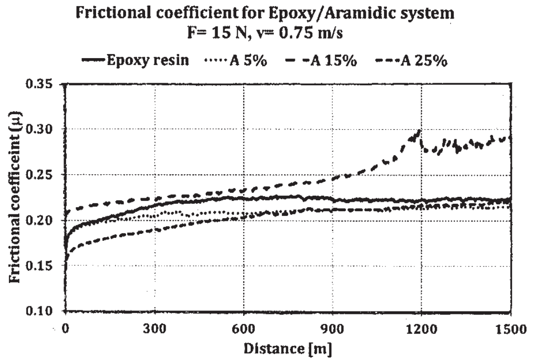

Fig. 6. Frictional coefficient for Epoxy/Aramidic system F=15N, v=0.75m/s

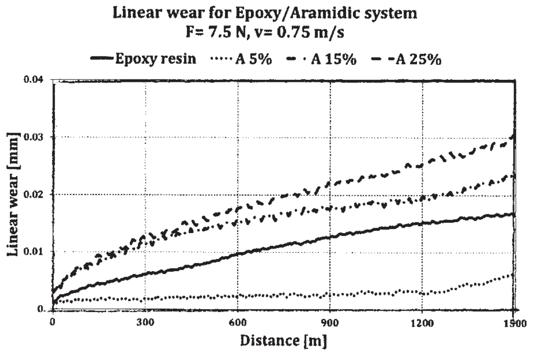

Fig. 7. Linear wear for Epoxy/Aramidic system F=15N, v=0.75m/s

For F=15N and v=0.75m/s, the friction coefficient evolution (fig.6, 7) was very similar with that of pure epoxy resin and 5 and 25% aramidic powder composite. In 15% aramidic powder composite the friction coefficient value was with 0.1 higher. A difference occurs for 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 behaviour in this case is similar with that for F=7.5N and v=1.1m/s.

The last set of testing parameters (F=15N and v=1.1m/s) the lowest friction coefficient value was measured for 5% aramidic powder composite (fig. 8, 9). The pure epoxy resin friction coefficient value was with 0.1 higher than that of 5% aramidic powder composite. The slopes of friction coefficient evolution for 15 and 25% aramidic powder composites are very similar, with a minor difference of 0.1. The same similarity is obtained also in linear wear case, with difference of 0.03mm.

In figure 10 is presented the worn surfaces of 15% aramidic powder composite for F=15N, v=0.75m/s. In figure 11 is presented the worn surfaces of 15% aramidic powder composite for F=15N, v=1.1m/s. In both cases can be observed the abrasive wear tracks with thermally degraded particles (brown color).

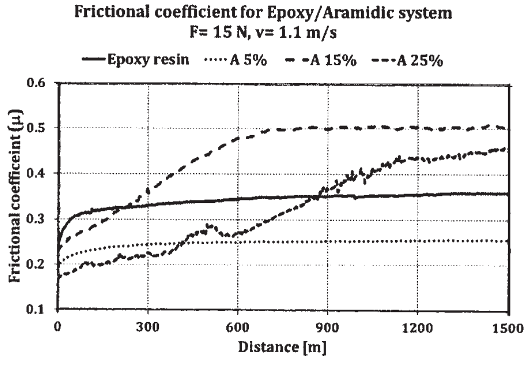

Fig. 8. Frictional coefficient for Epoxy/Aramidic system F=15N, v=1.1m/s

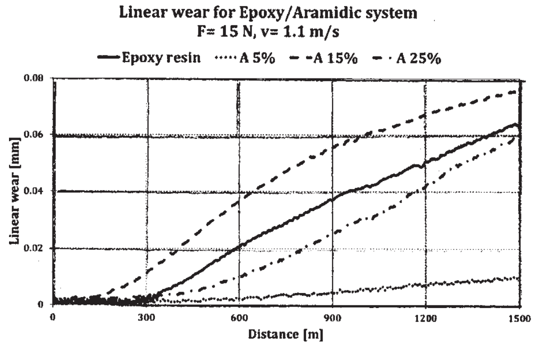

Fig. 9. Linear wear for Epoxy/Aramidic system F=15N, v=1.1m/s

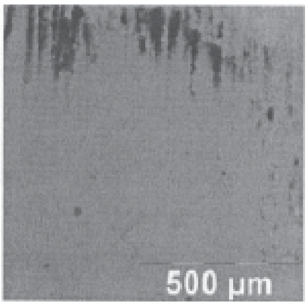

Fig. 10. Worn surface for 15% aramidic powder composite at testing parameter F=15N, v=0.75m/s F=15N, v=1.1m/s

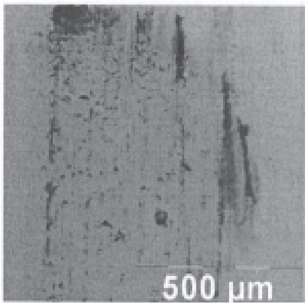

Fig. 11. Worn surface for 15% aramidic powder composite at testing parameter F=15N, v=1.1m/s

The analysis of loading force influence on friction coefficient evolution is presented in figure 12. It be can observed that, for 0.75m/s sliding speed value, the increase of loading force leads to a decrease of the friction coefficient. This can be explained by wear detached particles, acting as a solid lubricant.

For 1.1m/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, a decreasing tendency can be observed with sliding speed increasing, for 7.5N loading force.

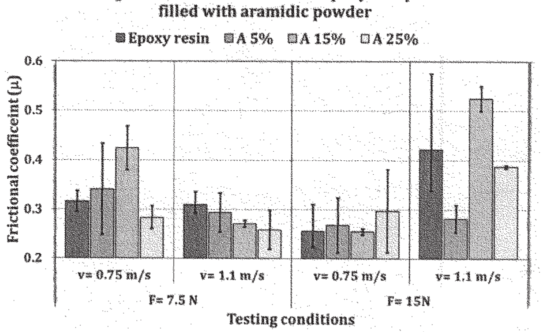

Fig. 12. Average frictional coefficient for epoxy composites filled with aramidic powder

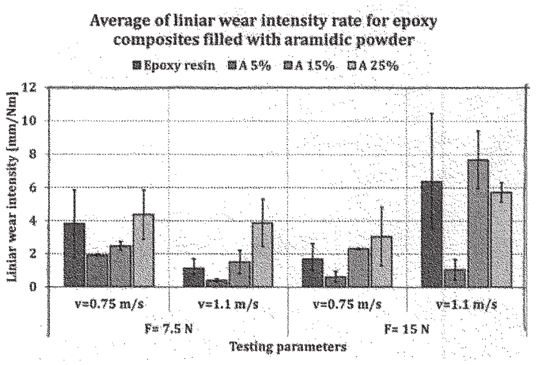

Fig. 13. Average of linear wear rate for epoxy composites filled with aramidic powder

In 15N loading force value, the friction coefficient values increase with sliding speed.

Looking to the average of linear wear rate evolution (fig. 13), 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.

Neural Network Modeling

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 [3, 4] the preliminary studies are as expensive and time consuming as high is the required prediction precision.

The neural networks based modeling methodology, wide used in case of processes with non-linear behaviour modeling [9], can be applied for both prediction and analyzing of the properties evolution of the composite polymers [10]. As consequence, it was created a neural network model, in order to identify the relative influence on composite tribological properties of aramidic powder volume ratio, and to predict the properties values. As inputs values were used: aramidic powder concentration (C), loading force value (L) and sliding speed (S). As outputs values were used: friction coefficient (FC) and linear wear rate (WR). The numerical values used for training and validating the model were experimentally acquired. The chosen neural network was feed-forward back-propagation type.

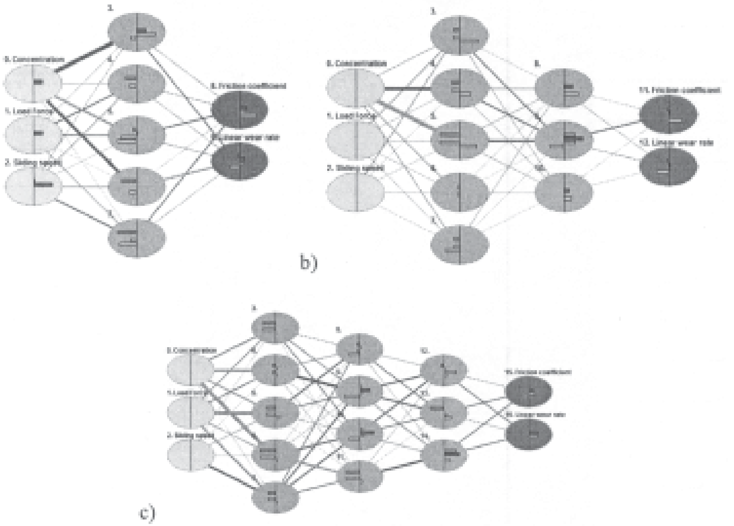

Fig. 14. Neural networks architectures

Taking into account that, in case of neural network models, the network architecture has the highest influence on model validity, being directly linked to the analyzed problem [11], three architectures were created and tested in EasyNN software framework, (fig. 14).

Analyzing the networks performances (table 2) it can be observed that the increasing of the number of hidden layers of the neural network leads to a higher training time so, from this point of view, the optimal architecture of the model is single hidden layered.

The neural model can be used both for investigate the inputs influences over outputs and for prediction of unknown output data for known input data sets.

Looking at the input importance over outputs, it can be observed in table 2, that all the tested architectures show the same hierarchy: the most influencing factor on tribological properties of the composite is aramidic powder concentration (C). On the second and third place are

Table 2
NEURAL NETWORKS PERFORMANCES

Hidden layers Parameter	1	2	3
Training cycles	405	500	3585
Input importance	C L S	C L S	C L S
Prediction error			
Friction coefficient	4.5%	5.4%	3.3%
Linear wear rate	21.4%	74.8%	33.1%

Table 3
ARAMIDIC POWDER CONCENTRATION OPTIMIZATION

Input Output			C [%]	L [N]	S [m/s]
FC	min	0.2557	5.75	15	0.75
	max	0.4880	17.75	11.77	0.91
WR	min	0.4339	7.25	15	0.75
	max	6.7069	19.25	11.85	0.91

loading force (L) and respectively sliding speed (S). This information, provided by the neural model, is in very good concordance with experimental results presented above, proofing that the neural networks succeeded to form the physical dependencies between the input-output factors.

Regarding the prediction of tribological properties of the composite based on known aramidic powder concentration, loading force and sliding speed values, the prediction error was summed by comparing the neural model outputs with the corresponding experimental acquired data. The results are different: for friction coefficient the lowest error is provided by three layered neural network while for linear wear rate the minimum error is obtained in the single layered network.

Taking into account the parameters values presented in table 2, it can be concluded that the best suitable network neural architecture for tribological properties analysis and prediction for studied aramidic powder composite is the single hidden layer one.

The neural model can also be used for optimization of aramidic powder concentration in order to obtain desired values (maximum or minimum) for friction coefficient and/or linear wear, for imposed functioning conditions (loading force and/or sliding speed), as it is presented in table 3.

In table 3, it can be observed that the lowest/highest values for friction coefficient and linear wear are obtained for identical loading forces and sliding speeds values. The aramidic powder concentration values are slightly different.

Conclusions

Based on tribological analysis of aramidic powder additivated composites, the conclusions can be drawn that in the case of the loading force influence on friction coefficient can be observed that in low speed case, the coefficient is decreasing with increase force. In higher speed case, the coefficient values are increasing with loading force values.

But in the case of the sliding speed influence on friction coefficient evolution, it can be observed a decrease with speed increasing, for low loading force values. At higher loading force values, the friction coefficient is increasing with speed increasing.

Also the neural network model can be build and trained with experimental acquired data; and it can be used for establishing which is the input that is most influencing over the outputs, for prediction of tribological values for known input data sets and for establishing optimal input data values for desired (minimum or maximum) output values.

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