

Finding Rules for Reinforced Composites with FormRules

Background

Strength and wear resistance are important properties of metals in a wide range of technological applications. Recently a new family of zinc-aluminium alloys has found use in replacing cast iron, aluminium and copper alloys because of their superior mechanical and tribological properties. Reinforcement using short fibres of δ -Al₂O₃ (trade name Saffil) improves the strength, modulus of elasticity, creep and wear resistance.

It is known that the wear resistance of a composite is mainly related to the fibre volume fraction, the morphology of the fibres, the fibre orientation and the strength of the metal-fibre interface. Load, speed of sliding and humidity also affect the wear performance. Understanding the nature of the interactions can be complicated.

One new technology that can be applied is neurofuzzy logic - a technique that combines the learning and adaptive capability of neural networks with the ability of fuzzy logic to express conclusions based on vague, ambiguous, incomplete and imprecise information. This technique is rapidly gaining acceptance in data mining applications - including formulation data sets - and is the underpinning technology in the **FormRules** program.

Formulation & Processing Variables

Fibre orientation

- N (Normal) or P (Perpendicular)

Fibre Volume Fraction

- 0%, 10%, 15%, 20%, 25%, 30%

Load

- 5N, 10N, 20N, 40N

Alumina-fibre reinforced composites

Genel, Kurnaz and Durman, publishing in *Materials Science and Engineering A363* 203-210 (2003), have reported studies in

which load, fibre volume fraction and orientation affected the mass loss rate and the coefficient of friction. The mass loss rate of course relates directly to the wear properties of the material.

Their studies were carried out with two different fibre orientations - parallel and normal to the wear surface respectively. They considered six different fibre volume fractions (0%, 10%, 15%, 20%, 25% and 30% respectively) at four different loads. The loads ranged from 5 to 40N. This gave 44 different experiments.

The published data given in their paper were imported directly into **FormRules**, and the default parameters were used for "training" the neurofuzzy system. Excellent models were obtained, with R² values in excess of 99%. We had expected to get good models, since Genel *et al* had successfully used neural networks to model the relationships in their data.

Rules for Reinforced Composites

FormRules immediately showed that all three inputs played a role in determining both properties.

For the mass loss rate, there were two sets of rules. In the first, an interaction between fibre orientation and fibre volume fraction was discovered:

- IF Load is LOW AND Fibre volume is LOW THEN Mass Loss Rate is LOW (0.75)
- IF Load is LOW AND Fibre volume is HIGH THEN Mass Loss Rate is LOW (0.97)
- IF Load is HIGH AND Fibre volume is LOW THEN Mass Loss Rate is HIGH (1.00)
- IF Load is HIGH AND Fibre volume is HIGH THEN Mass Loss Rate is LOW (0.87)

Values in parentheses are the 'confidence levels' for the rules. The Mass Loss Rate was high when the load was high, and the fibre volume fraction was low. The fact

that the Mass Loss Rate was much lower when the volume fraction increased shows clearly that adding the fibres improves the wear performance.

However, the fibre orientation did not play a significant role in the Mass Loss Rate, as illustrated by the second rule set:

- IF Direction is N AND Load is LOW THEN Mass Loss Rate is LOW (0.95)
- IF Direction is N AND Load is MID THEN Mass Loss Rate is LOW (0.89)
- IF Direction is N AND Load is HIGH THEN Mass Loss Rate is HIGH (0.56)
- IF Direction is P AND Load is LOW THEN Mass Loss Rate is LOW (0.92)
- IF Direction is P AND Load is MID THEN Mass Loss Rate is LOW (0.81)
- IF Direction is P AND Load is HIGH THEN Mass Loss Rate is HIGH (0.73)

Here, the orientation (direction) does not affect the overall finding that the mass loss rate is low when the load is low. However, it does affect the confidence levels. We conclude that when the fibres are parallel to the surface, the mass loss rate is increased (reflected in the higher 'confidence' for the HIGH values, and lower 'confidence' for the LOW ones), but this is secondary to the effect of a change in the load.

For the coefficient of friction, we find the following rules:

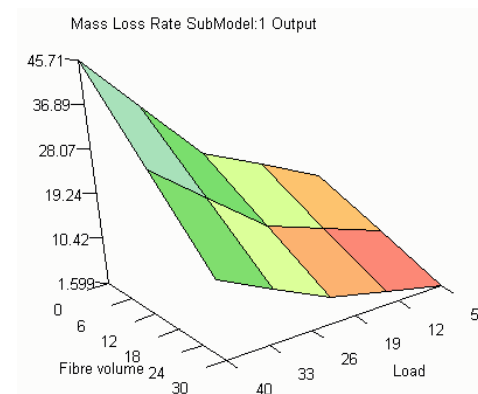
- IF Direction is N AND Fibre volume is LOW THEN Coefficient of Friction is LOW (1.00)
- IF Direction is N AND Fibre volume is MID THEN Coefficient of Friction is LOW (1.00)
- IF Direction is N AND Fibre volume is HIGH THEN Coefficient of Friction is HIGH (1.00)
- IF Direction is P AND Fibre volume is LOW THEN Coefficient of Friction is LOW (1.00)
- IF Direction is P AND Fibre volume is MID THEN Coefficient of Friction is LOW (1.00)
- IF Direction is P AND Fibre volume is HIGH THEN Coefficient of Friction is HIGH (1.00)

The coefficient of friction does not depend on the orientation of the fibres to a significant effect, but depends on the fibre volume. The coefficient of friction is low unless the fibre volume fraction is high. The coefficient of friction does not depend significantly on load, and the two rules obtained are:

- IF Load is LOW THEN Coefficient of Friction is HIGH (0.64)
- IF Load is HIGH THEN Coefficient of Friction is HIGH (0.51)

Here, only the confidence level is affected, and the results can be interpreted that the coefficient of friction is slightly higher when the load is low.

To confirm that the orientation of the fibres plays only a minor role, we re-trained the model, using only the two inputs Load and Fibre Volume Fraction. Without using orientation as an input, the ANOVA statistics were 98.5% and 97.5% for Mass Loss Rate and Coefficient of Friction respectively, showing that excellent models can be developed with only these two inputs. The relationship is shown in the figure below.



Conclusions

FormRules has generated models that are at better than those from the neural network used by Genel *et al.* The high values for the ANOVA statistics (in excess of 99%) show that the problem can be well represented by the three inputs chosen.

FormRules has been able to extract the underlying relationships and rules governing the properties of fibre-reinforced composite. These show clearly that orientation of the fibre plays a secondary role both for the mass loss rate and the friction coefficient, while fibre volume fraction and the applied load are important variables. In fact, excellent models can be developed without reference to fibre orientation as an input parameter.

With this information, it is clear which inputs affect specific properties, thereby enabling development of new formulations with better tribological and mechanical properties.