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Process parameters selection for friction surfacing applications using intelligent decision support

V.I. Vitanov[a,*], I.I. Voutchkov[b,1]

[a] School of Industrial and Manufacturing Science, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK
[b] Computational Engineering and Design Centre, School of Engineering Sciences, Mechanical Engineering,
University of Southampton, Southampton SO17 1BJ, UK

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Abstract

Friction surfacing is an advanced manufacturing process, which has been successfully developed and commercialised over the past decade. The process is used for corrosion and wear resistant coatings and for reclamation of worn engineering components. At present the selection of process parameters for new coating materials or substrate geometries is by experiment requiring lengthy development work. The major requirement is for flexibility to enable rapid changes of process parameters in order to develop new applications, with variations of materials and geometries in a cost effective and reliable manner. Further improvement requires development of appropriate mathematical models of the process, which will facilitate the introduction of optimisation techniques for efficient experimental work as well as the introduction of real-time feedback adaptive control. This paper considers the use of combined artificial intelligence and modelling techniques. It includes a new frame of a neurofuzzy-model based decision support system—*FricExpert*, which is aimed at speeding up the parameter selection process and to assist in obtaining values for cost effective development. Derived models can then be readily used for optimisation techniques, discussed in our earlier work.

Keywords: Surfaces and interfaces; Metals and alloys; Materials engineering

1. Introduction

During the past decade the friction surfacing process has become well established with a number of commercial applications. However, the existing models explaining the major relationships between process parameters are still generic. They are based on empirical rules and theoretical assumptions that account for a limited number of cases of current commercial interest. Many of these assumptions are implicit and have not been tested by using appropriate analysis and design of experiments. Consequently there is no method of determining the accuracy and sensitivity when changes in the process parameters are made [1,2]. Research so far [3–5] has revealed that in friction surfacing the mechtrode™ force (F), mechtrode rotation speed (N) and substrate traverse speed (V_x) are of critical importance for the final quality of the coating and bond. In the present study, three state variables that reflect coating quality were considered as a subject for optimisation and in this context a target for process parameter selection. These are coating thickness (C_t), coating width (C_w) and coating bond strength (C_bs). The optimisation procedure considered in this study involved:

- Development of a methodology for in-process precision measurement of temperature, torque, bonding time, spindle rotation speed and force.
- Development of an empirical model involving process parameters V_x, F, N and coating quality state variables C_bs, C_t, C_w.
- Development of a FricExpert decision support system to utilise force (F), mechtrode rotation speed (N) and substrate traverse speed (V_x) as well as temperature (T), torque (M), and bonding time (t_bt) to achieve the desired values for coating thickness (C_t), coating width (C_w) and coating bond strength (C_bs).

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* Corresponding author. Tel.: +44-1234-754757.
E-mail addresses: v.vitanov@cranfield.ac.uk (V.I. Vitanov), iiv@soton.ac.uk (I.I. Voutchkov).
[1] Tel.: +44-23-80-597662.

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2. Experimental method

2.1. Materials and geometry

The importance of torque, temperature and bonding time for obtaining coatings with desirable quality parameters is identified in [5]. The significance of these factors has also been confirmed through performing more than 2800 friction surfacing screening experiments, using different materials and geometries for the mechtrodes and substrates. Several different types of stainless steel mechtrodes were used (303, 304, 316, 416, 431), ranging in diameter from 3 to 8 mm.

2.2. Temperature and bonding time

Because of the nature of the in-process measurements of the coating and the mechtrode/coating/substrate interface temperatures, a non-contact IR pyrometer, manufactured by IMPAC Electronic, was used. The accuracy of measurement is approximately 0.3% of the measured value. Two lenses were used, with focus distances of 80 and 250 mm, and a spot size diameter of 0.3 and 0.5 mm, respectively. The sampling rate was 1000 measurements/s enabling accurate determination of bonding times for each coating cycle. No evidence has been found for any previous use of this technique in this area.

Bonding time is defined as the duration when the diameter of the heat generation area (bonding area) passes entirely over a given point on the substrate. As shown in Fig. 1(a), the bonding area is less than the surface specified by the mechtrode diameter. It has been estimated experimentally and using a close focused photography that the axial diameter of the bonding area is approximately 6/7 of its tangential diameter, which is equal to the mechtrode diameter, so that

$$d_{\mathrm{b}} = 0.875 M_{\mathrm{d}},$$

where M_{d} is the mechtrode diameter. The bonding time is then defined as

$$t_{\mathrm{b}} = \frac{0.875 M_{\mathrm{d}}}{V_x},$$

where V_x is the substrate speed.

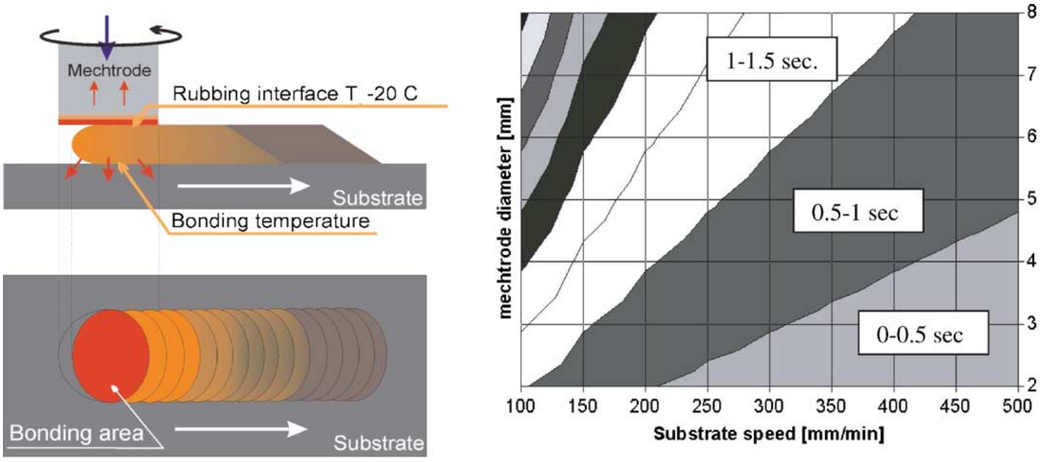
Fig. 1(b) shows the recommended bonding times that have been obtained for the most popular mechtrode diameters and substrate speeds. Longer bonding time would logically mean, better bonding, since there is more time for the process to occur and complete. However, the heat energy flux, which is generated during this bonding time, has to be balanced, because when increased or decreased outside the recommended boundaries, the quality of coating deteriorates. The most direct approach to control this energy flux is by altering the bonding time.

2.3. Torque and force

Torque was measured using a piezoelectric sensor manufactured by Kistler Instruments with a measuring range for force of 0–14,000 N and ±20,000 N cm for torque. The sensitivity of the equipment is pC/N, −2.03 and pC/N cm, 1.66. The acquired sets of data were stored into a database by using multifunction I/O board (AT-MIO-16E-10) from National Instruments capable of data acquisition at a rate of 100 kS/s. LabVIEW application software was used to automate the data acquisition process.

2.4. Bond metallography and strength

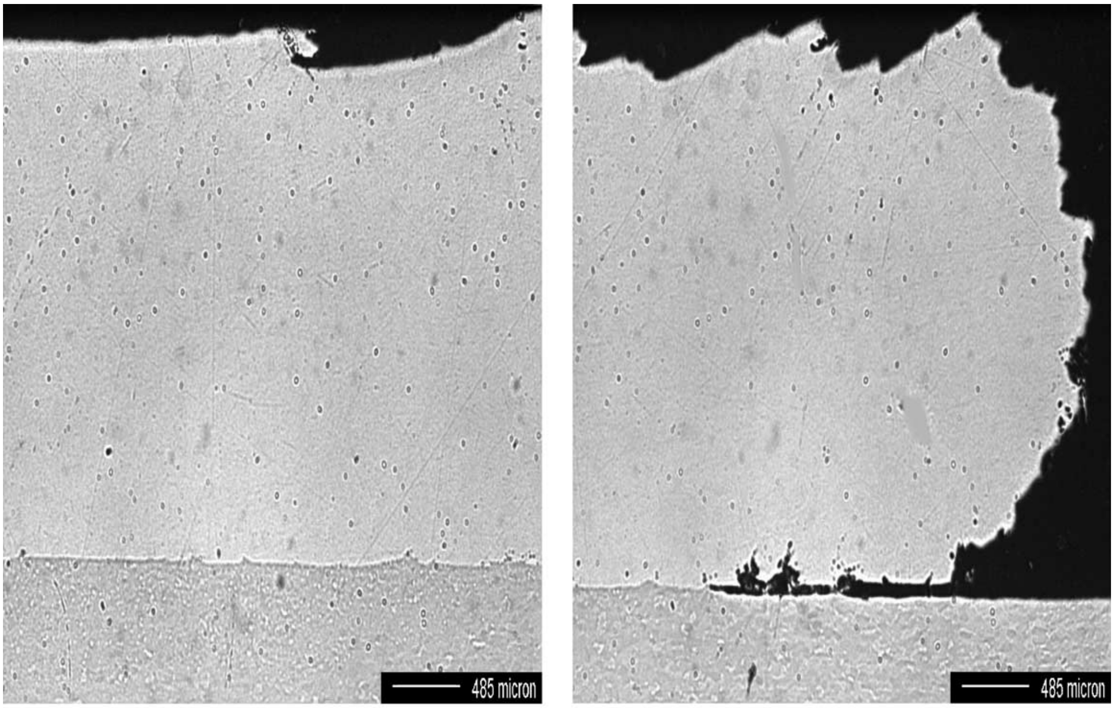
Cross-sections of coatings were examined in the as-polished state to determine the quality and width of the bond and the amount of unbonded undercut at the edges of the coating. Bond strengths were determined by a simple push-off test. The technique used involves drilling a 4 mm



a) The arrow indicates the bonded area

b) Bonding time

Fig. 1. (a) and (b) Bonding parameters.



(a) Middle section in µm (b) Undercut in µm

Fig. 2. (a) and (b) Cross-sections showing coating/substrate interface, as-polished (50×).

hole, in the substrate, just under the deposit. The depth of the hole is accurately controlled to be exactly equal to the thickness of the substrate, i.e. the hole goes through the substrate and reaches the bonding area of the deposit. As the whole substrate is being clamped, a 3.95 mm pin is pushed into the prepared hole. Force and elongation are recorded as the deposit is being pushed away from the substrate. The repeatability of the result as measured by the variance is above 95%. More sophisticated testing based on a fracture mechanics approach is currently under development.

The metallography of a cross-section of a well-formed friction surfaced coating is shown as in Fig. 2(a) and (b). This clearly illustrates the undercut at the edge, which is an inherent feature of the process. Stages 2 and 3 of the optimisation process essentially extend the width of good bond and minimise the undercut at the edges. Materials used in these illustrations are 316 stainless steel coatings on mild steel.

3. General concept of FricExpert decision support system

The development process of FricExpert decision support system comprises the following key stages:

- Development of the empirical model based on controllable, observable and quality parameters.
- Development of the inference mechanism engine logic.

3.1. Empirical relationship between process parameters and coating state variables

Fig. 3 is a schematic representation of the adopted experimental approach and indicates dependencies between process parameters V_x, F, and N and coating state variables C_{bs}, C_{t} and C_{w}.

Groups 1–3 represent the process itself. In most of the processes, the state variables can be monitored and observed during the process. However, in friction surfacing, the state variable can only be evaluated after the process has finished, and the coating has undergone various mechanical and thermal transformations. Hence, evaluation of the state variables is useful for gathering information about the process in its steady state, while the parameters of the second group can indicate various dynamical events during the coating itself. Dynamic modelling and real-time control, which are represented in Fig. 3 in groups 2 and 4, have also been developed and the work on this matter will be published in the near future.

The work discussed in this paper, aims to represent the relationship between groups 1 and 3, and to show how this knowledge can be embedded into group 5—the knowledge based decision support system. These results form a foundation for reverse process designs.

When considering the spindle speed experiments have shown that for a given material, spindle speed effect on its own over the state variables is insignificant in comparison to the other two parameters—traverse speed and force. Fig. 4 represents this. Coating width is not plotted because there is

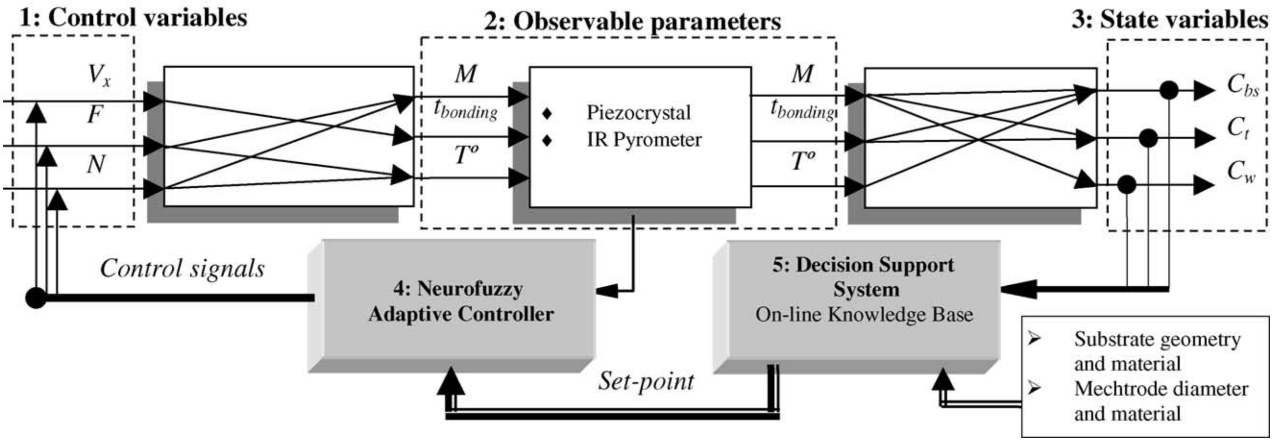


Fig. 3. Schematic representation of the experimentally established relationships, between controllable, observable and quality parameters in the friction surfacing process.

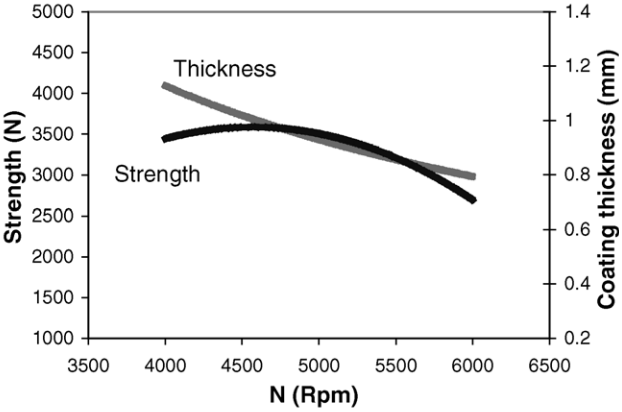


Fig. 4. The effect of spindle speed over thickness and strength.

no indication that spindle speed has effect on this variable. It is shown that variation of spindle speed can slightly affect the bond strength and the coating thickness. The following two logic rules can be derived:

- Increasing the spindle speed reduces the coating thickness slightly.
- Spindle speed is in weak second-order relationship with the bond strength.

Spindle speed becomes an important parameter when using different mechtrodes or substrate material. It has been found that V_x and F have much greater effect on the state variables. The following models were derived to represent the relationship between them and the state variables:

$$C_\mathrm{t} = b_0 + b_1 V_x + b_2 F + b_{11} V_x^2 + b_{22} F^2 + b_{12} V_x F,$$

$$C_\mathrm{w} = b_0 + b_1 V_x + b_2 F + b_{11} \frac{V_x}{F} + b_{22} F V_x + b_{12} \frac{F}{V_x},$$

$$C_\mathrm{bs} = b_0 + b_1 V_x + b_2 F + b_{11} V_x^2 + b_{22} F^2 + b_{12} V_x F,$$

where the values of the b coefficients are shown in Table 1. Fig. 5(a)–(c) illustrates graphically the above equations.

The correlation coefficient r_{xy}^2 represents the accuracy of the model. The closer to 1, the better the approximation. Such values for each model are shown also in Table 1. Inaccuracies occur due to measurement errors that also include information about the uniformity of the variable in relation to the parameters. It is seen that the bond strength data has most measurement errors, while the thickness has least errors

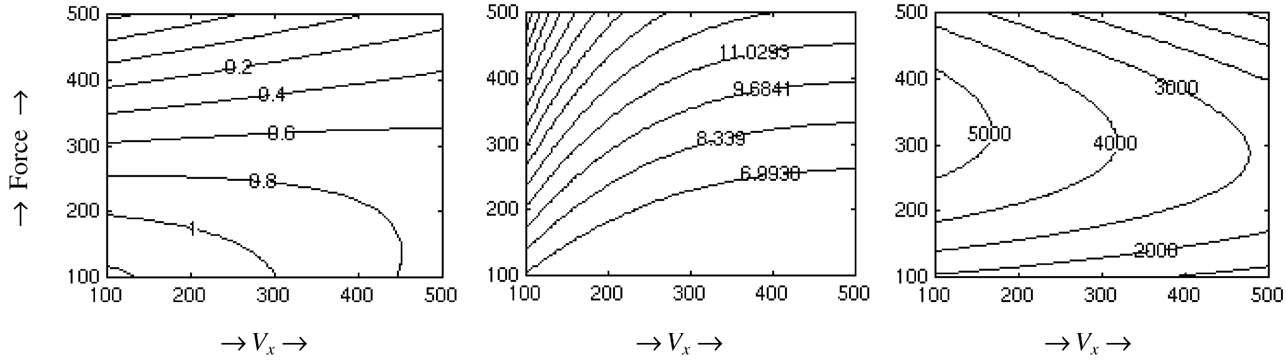


Fig. 5. (a) Coating thickness, C_t; (b) coating width, C_w; (c) bond strength, C_bs.

Table 1
State variables model coefficients

	C_t	C_w	C_{bs}
b_0	1.5398	1.7576	−1731.3
b_1	−0.0015769	−0.0084871	−1.554
b_2	−0.0015117	0.0059518	46.023
b_{11}	−6.6242E−07	3.8045	5.6577E−05
b_{22}	−5.6456E−06	2.6256E−05	−0.067033
b_{12}	6.7868E−06	1.3044	−0.016273
Correlation coefficient, r^2_{xy}	0.87594	0.83866	0.75928
Logic rules drawn as a conclusion	Increasing force reduces proportionally the coating thickness Increasing traverse speed reduces proportionally the coating thickness The higher the mechtrode force the lesser the undercut The faster the substrate movement the lesser the bonded area, the greater the undercut	Low values of V_x make the coating thicker An increase of coating thickness weakens the bond	Increasing force increases proportionally the bond strength Increasing traverse speed decreases the bond strength by reducing the bonding time

and further more is most consistent throughout the whole length of the run.

3.2. Inference mechanism

The above conclusions have been developed further into fuzzy logic rules that are built into FricExpert's inference engine. In the current approach, the decision support module selects appropriate values of the process parameters, traverse speed and force, in order to obtain a desired value for the coating strength and thickness (Fig. 6).

Using the knowledge of previously recorded runs (now more than 2800), the system is capable of giving expert advice for the next set of experiments, in order to meet various requirements for various quality variables. The value of this system is in reducing the lead time and hence cost for determining the optimum parameters for a given coating material on a given substrate geometry. This is an important feature when developing the process for new applications because the optimal process parameters depend on the thermal system, which will vary when materials, mechtrode diameters and substrate geometries are changed. The range of commercial applications currently includes the manufacture of machine knives for the food and pharmaceutical processing and packaging industries. Other applications include hard facing of valve seats with satellite.3, the repair and manu-

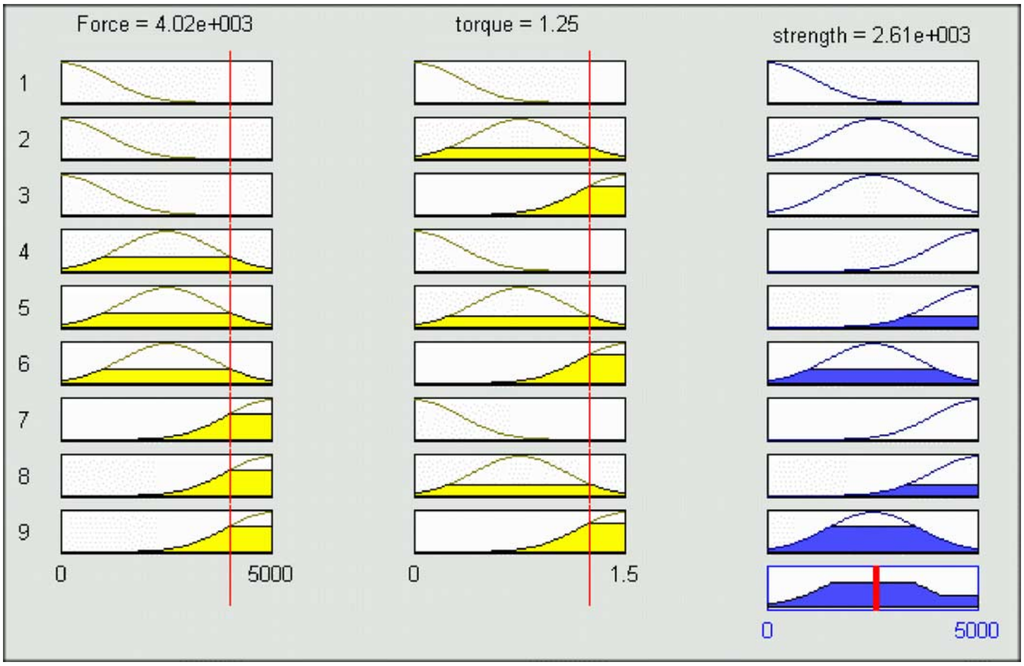


Fig. 6. Fuzzy logic based decision support system.

facture of parts for the gas turbine industry, notably gas turbine blades, and various types of tooling such as punches and drills.

4. Conclusions

(1) Measurement and data analysis techniques have been successfully developed for the friction surfacing process.
(2) The introduction of the decision support system has shown to be promising for process parameter selection.
(3) Fuzzy rules and membership functions have been established between quality state variables and process parameters such that they allow for reverse engineering of the optimum friction surfacing process parameters.

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