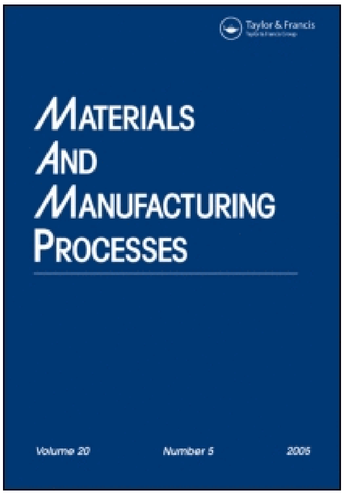

Materials and Manufacturing Processes

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597284

Prediction of Critical Load and Wear Rate of Coatings by Fuzzy Theory

Zhenfang Zhang[a]; Liangchi Zhang[a]; Yiui-Wing Mai[a]
[a] Centre for Advanced Materials Technology Department of Mechanical and Mechatronic Engineering, University of Sydney, Sydney, Australia

To cite this Article Zhang, Zhenfang , Zhang, Liangchi and Mai, Yiui-Wing(1997) 'Prediction of Critical Load and Wear Rate of Coatings by Fuzzy Theory', Materials and Manufacturing Processes, 12: 2, 345 — 357

To link to this Article: DOI: 10.1080/10426919708935145

URL: http://dx.doi.org/10.1080/10426919708935145

Materials and Manufacturing Processes Vol. 12, No. 2, 345-357, 1997

Prediction of Critical Load and Wear Rate of Coatings by Fuzzy Theory

Zhenfang Zhang, Liangchi Zhang, and Yiu-Wing Mai
Centre for Advanced Materials Technology
Department of Mechanical and Mechatronic Engineering
University of Sydney
Sydney 2006, Australia

Abstract

This paper proposes a new method of rule-based fuzzy modelling to predict the critical loads and wear rates of some typical ceramic coating systems. Coating hardness, thickness and friction coefficient were used as the input variables. Experimental results from a number of research laboratories confirmed the feasibility of the fuzzy approach. The proposed method showed its unique advantage to deal with complexity associated with the wear of surface coatings.

1.0 Introduction

Surface coating is an advanced technology to improve tribological performance of components. A good coating system requires an appropriate coating thickness, matched hardness and sufficient bonding strength between the coating and substrate, since wear occurs only within the coating layer unless catastrophic failure occurs. Common failure modes in a coating system under sliding conditions are interface debonding, fracturing of coating and plastic deformation of coating and substrate (1). Coating fracture often occurs when the substrate is not hard enough to carry the load, and therefore elastic and plastic deformation take place in the substrate underneath the contact (2). Ploughing as a wear mechanism happens in the wear process of the coating system (3). This is true even for a hard and brittle coating. Abrasive wear is another typical wear mechanism when a hard slider contacts a hard coating. The entrapped particles will have a scratching effect on both surfaces. The concentrated stresses caused by the abrasives (4-6) may well be the origin of crack nucleation in the coating, thus leading to a significant wear due to fracture. Moreover, adhesive wear is

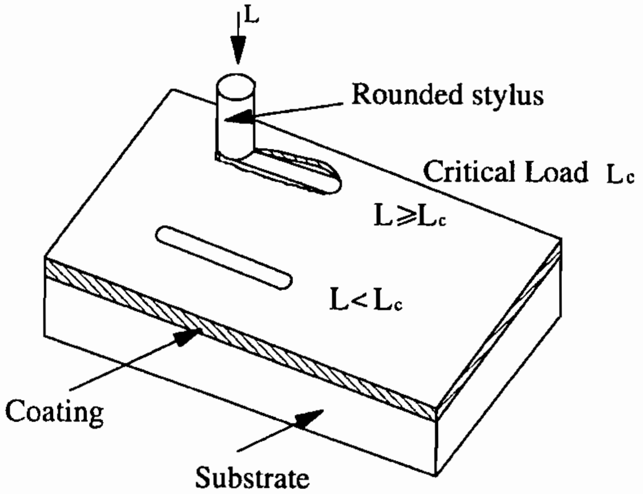

Figure 1: Schematic of failure of a coating when a normal critical load L_c is reached.

present in most cases when a hard slider moves on a hard coating or on a hard substrate covered with a thin soft coating, although it is not a catastrophic wear mode. Figure 1 shows a schematic illustration of the failure of the coating when a normal load reaches a critical load L_c.

Previous studies have focused on the measurement and determination of the thickness, hardness, bonding strength or critical load, and friction and wear (1-10). Of these the critical load and wear rate are much more difficult to evaluate. Theoretical models are particularly lacking due to the complexity of the problem.

The main difficulties in the study of the tribological behaviour of a coating-substrate system are that the wear mechanisms are not clear and there is limited understanding of the roles of the constituents, i.e., coating, substrate and interface. In addition, the residual stress and the bonding strength between coating and substrate are very difficult to measure. Overall, the relationships between the tribological behaviour and the properties of coating, substrate and interface are far from understood. Nevertheless, one is able to describe verbally, based on experience and analogies, the behaviour of a system studied. Therefore, linguistic statements can be easily used to describe the causes and effects. On the other hand, many material parameters are non-crisp or fuzzy like. Fuzzy set theory (11) which uses linguistic terms to describe a process is an effective tool to deal with such kind of problems. Recent successful studies on various engineering problems, such as roughness prediction (12), wear (13-15), tool wear recognition (16-17), design techniques (18), fuzzy advisory systems for grinding (19-23) and general applications in complex systems (24), have demonstrated the feasibility of this approach to study the complex wear

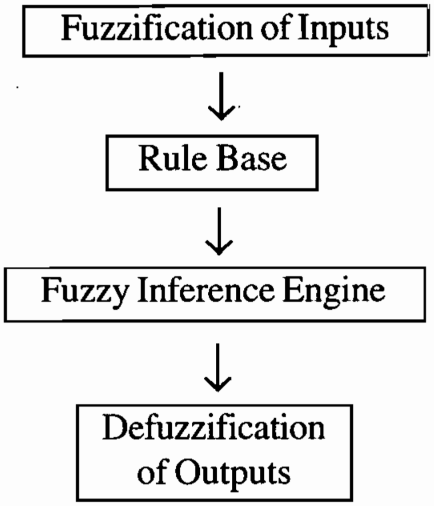

Figure 2: The architecture of the rule-based fuzzy modelling.

systems of surface coatings. This paper aims to propose a fuzzy model to predict the critical load and wear rate of ceramic coatings on a metal substrate.

2.0 Rule Based Fuzzy Modelling

2.1 Basic Structure

The basic structure of the rule based modelling for engineering applications consists of four parts: fuzzification of inputs, rule base, fuzzy inference engine and defuzzification of outputs, see Figure 2. The role of the fuzzification is to convert the input parameters to grades of their corresponding memberships. Rule base is given by a finite set of conditional sentences, in the form of "*If X Then Y*", where X and Y are fuzzy sets in the forms of linguistic variables, such as "small", "high" and so on. The function of the inference engine is to determine the rules which apply to a given condition and to obtain the level of certainty by minimum operations. Defuzzification is to produce a nonfuzzy value, as a representation of the outcome on its output axis, by calculating the results which are obtained from different rules. A typical defuzzification method which will be described later is the technique of "Centre of Area" (COA) (25).

By these four steps, results of a specific problem can be obtained based on sufficient knowledge from experiments. The details of each step will be described in the following sections.

2.2 Fuzzification and Membership Function of Linguistic Variables

In this paper, five linguistic variables are used to describe each contributing parameter such as coating hardness, H_v, coating thickness, T, and friction coefficient, f. Figures 3a to c show the membership function of these five linguistic variables, where *VS* means "Very Small", *S* "Small", *M* "Medium", *B* "Big" and *VB* "Very Big". By considering

Table 1. Data Summarised from Figure 5 (a-c) (1) and Fuzzification of the Data from UH

Laboratory	UH	THD	VTT
Coating A	T = 4.5 = 0.25S/0.75 M H_v = 3100 = VB f = 0.65 = 0.5S/0.5M L_c = 97 = (B/VB) w = 8.8 (VS)	T = 4.6 H_v = 2400 f = 0.70 L_c = 99 w = 13.65	T = 4.2 H_v = 2500 f = 0.74 L_c = 98 w = 14.5
Coating B	T = 8.5 = 0.75B/0.25V H_v = 2900 = 0.2B/0.8V f = 0.52 = 0.6VS/9.4S L_c = 57 = (S/M) w = 8.7 = (VS)	T = 8.3 H_v = 2600 f = 0.70 L_c = 62 w = 9.3	T = 8.2 H_v = 2700 f = 0.90 L_c = 68 w = 17.7
Coating C	T = 2.6 = 0.3VS/0.7S H_v = 2100 = 0.8M/0.2B f = 0.66 = 0.4S/0.6M L_c = 40 = (S) w = 24.0 = (M)	T = 2.5 H_v = 1800 f = 0.70 L_c = 50 w = 54.24	T = 2.4 H_v = 2100 f = 0.89 L_c = 52 w = 35.8

(Coating Thickness T, (μm), Vickers Hardness H_v, ($\mathrm{kgfmm^{-2}}$), Critical Load L_c, (N), Wear Rate w, ($10^{-15}\ \mathrm{m^3N^{-1}m^{-1}}$)).

characteristics of these input parameters, triangular shapes of membership distributions are used except at upper and lower limits of the variables where trapezoid shapes are applied.

From the experimental point of view, values of input parameters can be easily obtained. however, the generation of the output parameters such as wear rate are often expensive and time-consuming. Extensive experimental results on three different coatings have been presented by three laboratories (7). The data from each laboratory are designated as (UH) as for the University of Hull, (THD) for the Technische Hochschule Darmstadt and (VTT) for the Technical Research Centre of Finland. These values were obtained under the fixed test conditions such as counterpart, sliding speed and testing environment. Detailed experimental methods, test conditions and coating techniques can be found in reference 7. Table 1 summaries the data which are obtained from Figures 4a to c and Figures 5a and b. This data is used to build up the rule base for fuzzy modelling. It should be noted that the Vickers hardness value obtained in Table 1 for coating C are for an applied load of 20 g because

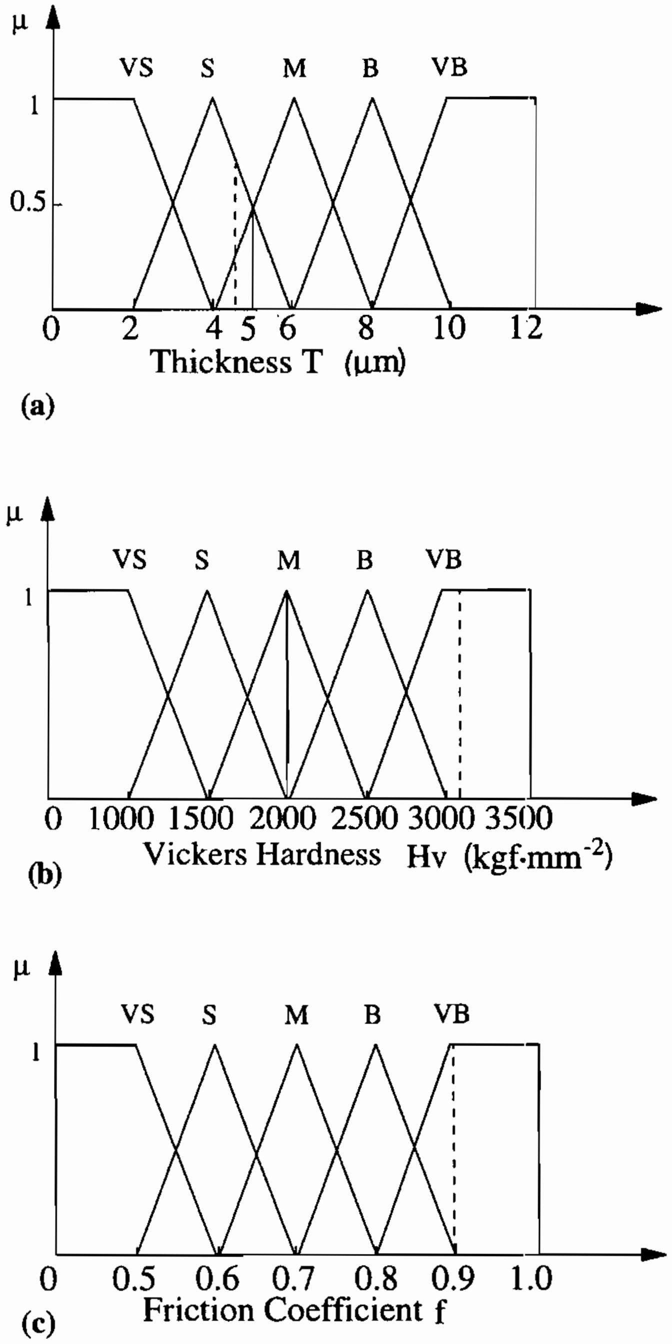

Figure 3: Membership function of input parameters: (a) coating thickness *T*, (b) Vickers hardness H_r and (c) friction coefficient *f*.

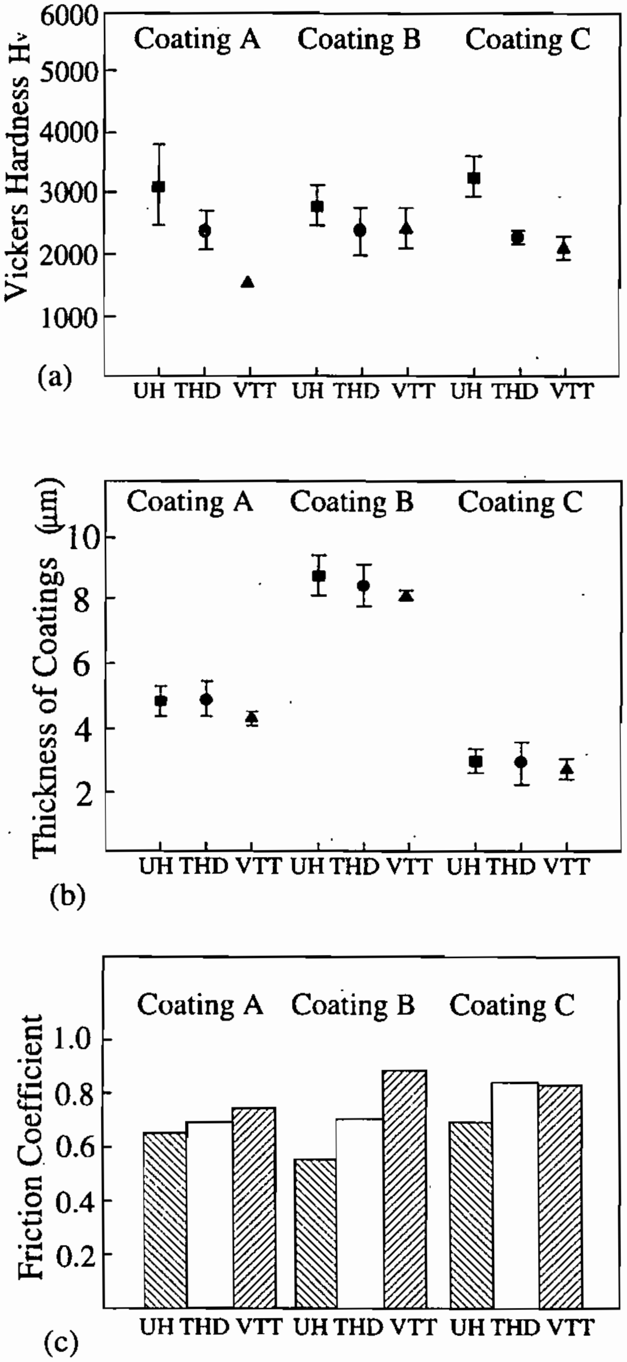

Figure 4: The measurement of input coating parameters: (a) Vickers hardness of coatings, (b) coating thickness *T*, and (c) friction coefficient *f*.

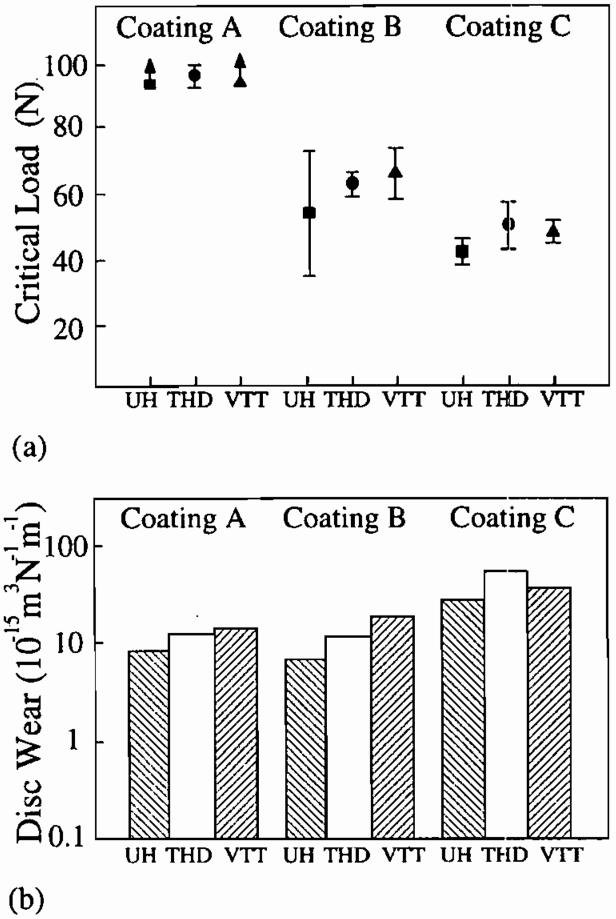

Figure 5: Membership function of output parameters: (a) critical load L_c and (b) wear rate w.

of the very thin film thickness (2.5 μm), hardness values for coatings A and B, are obtained under a load of 100 g, see Figure 4a. According to reference 7, the upper critical loads determined by direct observation (3) are used as the nominal critical load in this paper.

To determine a membership function, a range of input values needs to be specified based on the data available. For example, the range of hardness for the present coating systems is selected from 0 to 3500 kgfmm^{-2}, Figure 3b, while the ranges of coating thickness and friction coefficient are from 0 to 12 (μm) and 0 to 1.0, respectively, see Figure 3a and c.

Similarly, the output parameters of the critical load L_c and the wear rate w also use five linguistic variables, as shown in Figure 6. Triangular membership

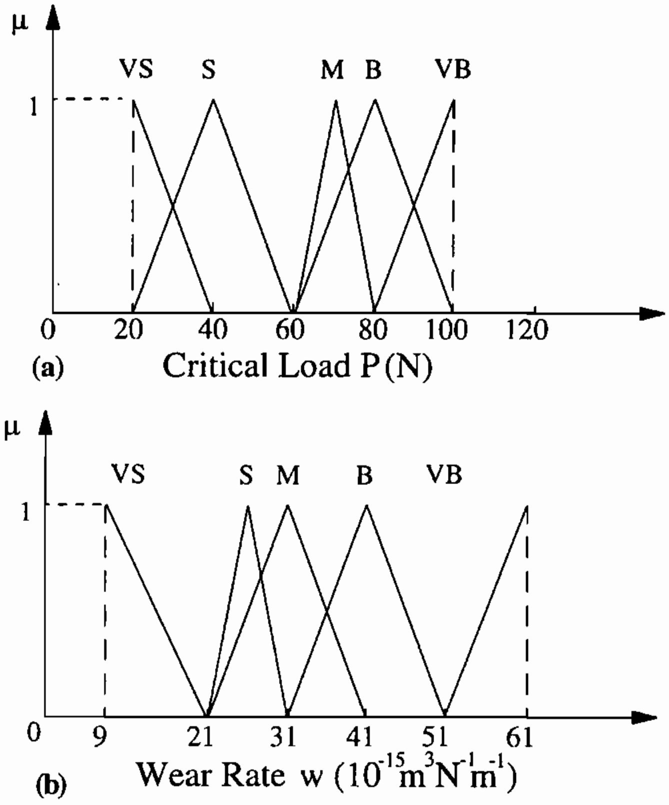

Figure 6: Experimental results on the output parameters: (a) upper critical load assessed by direct observations, and (b) the mean values of the wear rates.

distributions are also applied for five linguistic variables of the output. The ranges of the critical load and wear rate are 0-120 (N) and 0-71 (10^{-15} $m^3N^{-1}m^{-1}$) respectively. The locations of centre of area of different linguistic variables for the critical load (*N*) are $L_{c1} = 20$, $L_{c2} = 40$, $L_{c3} = 70$, $L_{c4} = 80$ and $L_{c5} = 100$, and the wear rates (10^{-15} $m^3N^{-1}m^{-1}$) are $w_1 = 9$, $w_2 = 26$, $w_3 = 31$, $w_4 = 41$ and $w_5 = 61$.

Examples of defuzzification are given as shown in Figures 3a and b. A crisp input value, H_{20}=2000, corresponds to the grade of membership of "Medium" of 1 (Figure 3b), which means that the hardness value of 2000 fully belongs to the linguistic variable "Medium". Similarly, giving input value of thickness, T_{10}= 5 μm, (Figure 3a), the grades of corresponding memberships are 0.5 S & 0.5 M.

2.3 Establishment of Rule Base

The rule base which is essential for evaluating the critical load and wear rate is established based on the information of the scratch and wear behavior presented by Ronkainen et al. (1). The rule base for evaluating the critical load uses coating

Table 2. Rule Base Associated with the Input of Coating Thickness, *T* and Coating Hardness H_v for an Output of the Critical Load L_c

Rule No.	Input *T*	Input H_v	Output L_c
1	S (0.75)	VB (0.8)	VB (0.75)
2	M (0.25)	VB (0.8)	B (0.25)
3	B	B	S
4	B	VB	M
5	VB	VB	S
6	VB	B	S
7	VS	M	S
8	VS	B	S
9	S	M	S
10	S	B	S
11	VS	S	M
12	M	M	VB

(Number in brackets is the grade)

thickness, *T*, and hardness of coating, H_v, as input; and that for evaluating the wear rate uses three input parameters, *T*, H_v and friction coefficient *f*. The rule base covers the most possible combinations of the fuzzy sets. We assume that the rules are proper and the number of the rules are complete (to a certain degree).

There are 25 rules if 2 input parameters are used. Table 2 gives 12 rules to represent the present input-output relationships. Take the first rule in Table 2 as an example. It is given as:

"If T is small AND H_v is very big THEN L_c is very big".

Similarly, the first rule in Table 3 states that

"If T is small AND H_v is very big AND f_v is small THEN w is very small".

Using these rules together with the inference engine to be described below, the correlation between the causes and effects can be obtained.

2.4 Inference Engine

The output can be obtained in linguistic variables according to the rule base. The membership grade of the output, however, is calculated by the minimising operation. For the critical load, it is

$$h_j = T(X_{10}) \wedge H(X_{20}), \qquad (1)$$

while for the wear rate, it is given by

$$h_j = T(X_{10}) \wedge H(X_{20}) \wedge f(X_{30}) \quad (2)$$

Table 3. Rule Base Associated with the Input of Coating Thickness, *T*, Coating Hardness, H_v and Friction Coefficient, *f* for Output of Wear Rate, *w*

Rule No.	Input *T*	Input H_v	Friction Coef. *f*	Wear Rate *w*
1	S	VB	S	VS
2	S	VB	M	VS
3	M	VB	S	VS
4	M	VB	S	VS
5	B	B	VS	VS
6	B	VB	VS	VS
7	B	VB	S	VS
8	VB	VB	S	VS
9	VB	B	VS	VS
10	VB	B	S	VS
11	VS	M	S	M
12	VS	M	M	VB
13	S	M	S	M
14	S	M	M	S
15	S	B	S	M
16	M	VB	B	S
17	B	B	VB	VS
18	B	VB	VB	S
19	VS	M	B	M
20	S	B	VB	B
21	VS	B	B	M
22	VS	B	VB	B
23	VS	M	VB	VB
24	S	M	B	M
25	S	B	B	M
26	S	B	VB	B
27	B	B	M	VS
28	VB	VB	M	VS

where $T(X_{10})$, $H(X_{10})$ and $f(X_{10})$ are linguistic variables with grade of membership of the i^{th} input with its input value X_{10}. Symbol stands for the *MIN* operation of the j^{th} active rule and h_j is a grade of output membership. An example for the grade of the output membership when the 1st and 2nd rules in Table 2 are active is illustrated in Figure 3(a) and (b), in which $T_1(4.5)=0.75$ S/0.25 M, $H_2(X3100)=1.0$ VB. Thus the grades of the output membership h_1 and h_2, according to the rule base in Table 2 and fuzzy operation of equation, (1) are 0.25 B & 0.75 VB.

2.5 Defuzzification of the Output

The output linguistic variables with their grades obtained from the rule base and the inference engine need to be defuzzified to a crisp value that best represents the output membership function. In this paper we use the method of Centre of Area (25) to calculate the crisp value, i.e.,

$$y = \left(\sum_{j=1}^{n} h_j y_j\right) / \sum_{j=1}^{n} h_j \qquad (2)$$

where h_j is the grade of the membership function of the output obtained by rule j, y_j is the centre of the area of the corresponding output membership function and n is the number of the active rules for the output. If only one rule is active, the crisp value of the final output y is the coordinate value at the output axis corresponding to the apex because the symmetrical triangular shape is used in the present work. A key technique in the present method is to adjust the shape and location of the output membership function to minimise error.

3.0 Discussion

An example to obtain the defuzzified value of the final output, using equation (2) and Figure 6(a), is given by

$$y = \frac{0.25x80 + 0.75x100}{0.25 + 0.75} = 95. \qquad (3)$$

Comparing this representative value with the experimental results for the nominal critical load of 97 *N*, a good agreement is clearly seen. Another example is given by applying rule Nos. 17 and 18 in Table 3, using the data on coating B from VTT in Table 1, i.e., $T_2(8.2) = 0.9$ B/0.1 VB, $H_2(2700) = 0.6$ B/0.4 VB, $f_2(0.9) =$ VB, the output result is $w =$ 0.4 VS/0.6 S. After defuzzifying using Figure 6b, we obtain $w = 19.2x10^{-15}\ m^3N^{-1}m^{-1}$, which is very close to the experimental result of $17.7x10^{-15}\ m^3N^{-1}m^{-1}$, see Table 1. These two examples indicate that the present fuzzy modelling can describe complex problems very well. A comparison of the wear rate of each evaluated result by this model and two experimental results on each coating from VTT is illustrated in Figure 7. A good agreement between the evaluation and the experimental results is clearly seen. Therefore, by using the present method, the critical load and the wear rate in such a wear system can be evaluated. The unique advantage is that one does not have to understand the mechanism of the process studied. The process can be regarded as a blackbox, if necessary input values (contributing factors) are known, the output values (results) can be obtained by the rule-base modelling.

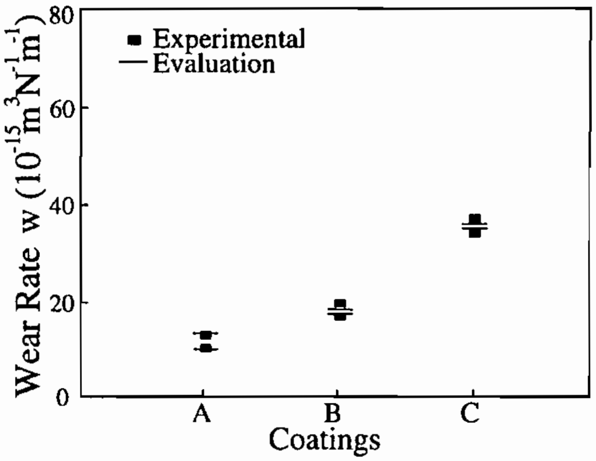

Figure 7: Comparison of evaluated wear rate and experimental results from Reference 1.

This unique advantage is prominent if more input parameters are involved.

4.0 Concluding Remarks

Rule-based fuzzy modelling for evaluation of the critical load and wear rate is presented in this paper. The input parameters considered for predicting the critical load are coating thickness and hardness of coating, while friction coefficient is used as an additional input parameter when evaluating the wear rate. The model assumes that the membership functions of the inputs and outputs are proper, and the rule bases are established using these membership functions. The method shows its simplicity and unique advantage to deal with problems associated with surface coatings.

5.0 Acknowledgment

Z. F. Zhang is supported by an EMSS scholarship.

6.0 References

1. Bull, S. J. and D. S. Rickerby, Advanced Surface Coatings, A Hand Book of Surface Engineering, D. S. Rickerby, ed., p.9, (1991).
2. Holmberg, K., H. Ronkainen, and A. Matthews, Thin Films in Tribology, D. Dowson, eds., (1993).
3. Rosset, E. A., S. Mischler, and D. Landolt, Thin Films in Tribology, D. Dowson, ed., (1993).
4. Sue, J. A. and H. H. Troue, Surface Coating Technology, Vol.43/44, p.709, (1990).
5. Burnett, P. J. and D. S. Rickerby, Thin Solid Films, Vol.148, p.41, (1987).
6. Burnett, P. J. and D. S. Rickerby, Thin Solid Films, Vol.154, p.403, (1987).

7. Ronkainen, H., S. Varjus, K. Holmberg, K. S. Fancey, A. R. Pace, A. Matthews, B. Matthes, and E. Broszeit, Mechanics of Coatings, D. Dowson, et al., eds., Tribology Series 17, Elsevier, Amsterdam, (1990).

8. Bull, S. J., Surface Coating Technology, Vol.50, p.25, (1991).

9. Hills, A., Mechanics of Coatings, D. Dowson et al., eds., Tribology Series 17, Elsevier, Amsterdam, (1990).

10. Holmberg, K., H. Ronkainen, and A. Matthews, Thin Films in Tribology, D. Dowson, ed., (1993).

11. Zadeh, L. A., Information Control, Vol.8, No.1, p.338, (1965).

12. Fei, J. and I. S. Jawahir, IEEE International Conference on Fuzzy System, (1992).

13. Kolar, D. and M. Dohnal, Wear, Vol.110, p.35, (1986).

14. Stupka, K. and M. Dohnal, Wear, Vol.156, p.239, (1992).

15. Zhang, Z. F., L. C. Zhang, and Y. W. Mai, Tribology Letters, Vol.2, p.89, (1996).

16. Ko, T. J. and D. W. Cho, Wear, Vol.169, p.97, (1993).

17. Ko, T. J., D. W. Cho, and J. M. Lee, CIRP Annals, Vol.41, No.1, p.125, (1992).

18. Kouatli, I. and B. Jones, International Journal of Machine Tools and Manufacturing, Vol.31, p.107, (1991).

19. Nakajima, K., Journal of Japan Society of Precision Engineering, Vol.58, No.2, (1992).

20. Sakakura, M. and I. Inasaki, CIRP Annals, Vol.42, No.1, p.379, (1992).

21. Trmal, G. J., C. B. Zhu, and P. S. Midha, Journal of Materials Processing Technology, Vol.33, p.507, (1992).

22. Ali, Y. and L. C. Zhang, Proceedings to appear in 3rd Asia-Pacific Conference of Materials Processing, Hong Kong, (1996).

23. Ali, Y. and L. C. Zhang, Proceedings to appear in 3rd International Conference on Progress in Cutting and Grinding, Osaka, Japan, (1996).

24. Vachkov, G., Proceedings of the International Fuzzy Engineering Symposium, Japan, Vol.2, p.853, (1991).

25. Berenji, H. R., R. R. Yager, and L. A. Zadeh, eds., Kluwer Academic Publishers, p.69, (1992).