A fuzzy logic predictive model for better surface roughness of Ti–TiN coating on AL7075-T6 alloy for longer fretting fatigue life

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**Abstract**

In this study, the fretting fatigue resistance of AL7075-T6 alloy is investigated using surface treatment Ti–TiN multilayer coating by physical vapor deposition (PVD) magnetron sputtering technique. A fuzzy logic model was established to forecast the surface roughness of Ti–TiN coating on AL7075-T6 with respect to changes in the input process parameters of DC power, temperature, DC bias voltage, and nitrogen flow rate. The results indicate an agreement between the fuzzy model and experimental results with 95.349% accuracy. The fretting fatigue lives of Ti–TiN-coated specimens with the lowest surface roughness resulting from fuzzy logic were enhanced by 18% at low cyclic fatigue, while at high cyclic fatigue the result was reversed.

**1. Introduction**

Light-weight and high-strength aluminum alloys such as 7075 are widely utilized in aircraft engines, fuselage and automobile parts. Aluminum alloys themselves do not provide adequate mechanical strength for structural parts. Therefore, enhancing surface properties is vital in practical applications, particularly when aluminum is in contact with other components [1]. Ceramic coatings like TiN, CrN, and SiC are possibly effective in raising surfaces hardness, corrosion and wear resistance. However, coatings used for aluminum alloys via old-fashioned techniques such as hard anodizing, glazing and thermal spraying, are provided with little support from the underlying material besides the inadequate adhesion strength, decreasing their durability [2,3]. Fretting fatigue is a phenomenon which occurs when two components are in contact with each other and one or both are subjected to a cyclic load, often resulting in damage which may cause premature component failure.

Ti–TiN coating applied by PVD technique is a method of improving the hardness of AL7075-T6 surface by reducing wear and extending fretting fatigue service life [4–6]. The formation of TiN coating on the surface of materials is among the most effective techniques of improving material wear resistance. However, the characterization of surface topography is imperative in applications including abrasion, wear, and lubrication. Surface hardness and roughness are important when identifying the performance of a coated surface [7,8]. High surface quality is essential in achieving lower surface roughness, which affects the practical characteristics such as friction, fretting fatigue, wear, and light reflection [9]. The surface rough-
ness of hard materials coated using PVD magnetron sputtering technique is mostly affected by the selecting of various coating parameters including DC bias voltage, nitrogen percentage, temperature, and DC power. Hence, for investigating and predicting the best surface roughness at different Ti–TiN coating parameters, a reliable systematic approach is required. Soft computing techniques are useful when exact mathematical information is not available. The techniques differ from customary computing in that they are tolerant of uncertainty, imprecision, approximation, partial truth and meet heuristics. Fuzzy logic is a soft computing method that plays a significant role in imputation, partial truth and heuristics. Fuzzy logic is useful when exact mathematical information is not available. The techniques differ from customary computing in that they are tolerant of uncertainty, imprecision, approximation, partial truth and meet heuristics. Fuzzy logic is a soft computing method that plays a significant role in imputation, partial truth and heuristics. Fuzzy logic is ideal in predicting the coating characterization of surface topography based on the input variables due to the nonlinear condition in the coating process [13]. Fuzzy logic was established to develop the rule model for predicting the surface roughness value in Ti–TiN coating on Al7075-T6 alloy based on parameter and performance interaction.

The goal of this study is to evaluate the fretting fatigue life of Ti–TiN coated Al7075-T6 alloy with different surface roughness.

In this present work, multilayer Ti–TiN was coated on Al7075-T6 substrate at different parameter conditions. Each parameter comprises four levels, namely nitrogen percentage, power (DC), substrate temperature, and DC bias voltage. A fuzzy rule-based method was proposed to predict the surface roughness of Ti–TiN coating on Al7075-T6 alloy, after which the fretting fatigue lives of coated specimens with better surface roughness were investigated.

2. Experimental details

2.1. Surface treatment and measurement

Aluminum 7075-T6 alloy was employed in this research work. The material’s composition was attained by Energy-dispersive X-ray spectroscopy (EDX) apparatus (Table 1). The ultimate strength and yield stress of Al7075-T6 were obtained by performing a number of tensile tests ($\sigma_{ut} = 590$ MPa and $\sigma_y = 520$MPa, respectively). All samples were polished with SiC paper of 800–2000 grit, and were surface-mirrored by diamond liquid. The substrate was cleaned with acetone in an ultrasonic bath for 14 minutes, and then thoroughly rinsed with distilled water. An SG Control Engineering Pte Ltd. series PVD magnetron sputtering machine was used to experimentally deposit thin films of metal. DC generators were designed to facilitate metal sputtering. The chamber was evacuated to below $2.67 \times 10^{-3}$ Pa ($2 \times 10^{-5}$ Torr) before the argon gas for sputtering was introduced. A constant sputtering pressure of $6.9 \times 10^{-1}$ Pa ($5.2 \times 10^{-3}$ Torr) was maintained. Table 2 shows the parameters and levels throughout the experiment. The DC bias voltage, substrate temperature, nitrogen percentage and DC power as coating parameters, were arranged according to the experimental array provided in Table 3, to learn how to develop the sputtered Ti–TiN thin film roughness.

The TiN coating’s surface roughness was determined using micro-roughness equipment (MAHR). The layers were characterized by scanning electron microscopy (SEM), focused ion beam technique (Quanta FEG250) and atomic force microscopy (AFM-NANOSCOPE DIMENSION D13000).

2.2. Fretting fatigue

All specimens for the fretting fatigue test were machined at an initial surface roughness of $R_s = 0.6 \pm 0.1 \mu m$ by lathe turning (CNC LATHING MACHINE, Miyano, BNC-42C5). The round shape samples utilized in this experimental work were prepared in accordance with ISO standard [14]. Fretting fatigue pads were fabricated from AISI 4140 steel plate with Vickers hardness of 346HV. Substrate material (179HV) is softer than the pads but Ti–TiN coating (540HV) is harder. Illustrations of the fretting fatigue samples and friction pads can be found in Fig. 1. A bridge-type friction pad and ring-type load cell were designed and manufactured to simulate the fretting fatigue conditions. Fig. 2 shows a schematic view of the fretting fatigue test setup used in this study.

The samples were loaded rotationally in a rotating bending fretting fatigue test apparatus (Fig. 2). The fretting fatigue tests were performed at a constant contact pressure of 100 MPa, while the samples comprised uncoated and Ti–TiN-coated Al7075-T6. Plain and fretting fatigue testing were carried out at laboratory temperature (25 °C) in a two-point loading rotating bending machine.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experimental condition levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A DC power (w)</td>
<td>300 350 400 500</td>
</tr>
<tr>
<td>B Temperature (°C)</td>
<td>150 180 200 220</td>
</tr>
<tr>
<td>C Nitrogen low rate (%)</td>
<td>3 4 5 6</td>
</tr>
<tr>
<td>D Substrate bias voltage (v)</td>
<td>25 50 75 100</td>
</tr>
</tbody>
</table>

Table 1 Chemical composition of AL 7075-T6.

<table>
<thead>
<tr>
<th>Al</th>
<th>Cu</th>
<th>Si</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td>1.85</td>
<td>0.47</td>
<td>1.8</td>
<td>0.28</td>
<td>4.6</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 2 Parameters and levels used in the experiment.
The tests were stopped if the samples did not fail after $1 \times 10^7$ cycles. The amount of friction coefficient ($\mu$) between pads (AISI 4140 steel) and AL7075-T6 was calculated to be around 0.607. Friction force could be found from the equation $F = \mu N$, in which $N$ is the contact load calculated by a ring-shaped load cell (Fig. 2(a)) and $F$ is the friction force measured from the friction test machine.

### 3. Ti–TiN multilayer coating results

The coated specimens’ surface roughness was measured with micro-roughness equipment. Each roughness measurement was repeated three times and the calculated averages are tabulated in Table 4. A typical Ti–TiN multilayer coating on Al7075 is depicted in Fig. 3(a), which reveals under SEM that the coat’s structure is columnar. As demonstrated in Fig. 3, there are two portions to the coating, pure titanium as an interfacial layer and titanium nitride. Fig. 3(b) presents the diffusion rate of titanium and nitrogen, chemical composition of AL 7075-T6 and the interfacial layer of titanium and TiN and aluminum. The thicknesses of TiN coating at different parameter conditions are illustrated in Table 5.

TiN coating surface morphology was also studied using atomic force microscopy (AFM). Fig. 4(a) and (b) show typical examples of high and low surface roughness of Ti–TiN coating under different parameter conditions.

### 4. Fuzzy logic-based model to investigate the effects of Ti–TiN multilayer parameters on substrate surface roughness

The relationship between the input parameters (sputtering DC bias voltage, substrate temperature, nitrogen percentage and DC power) with the output parameter (surface roughness of Ti–TiN coating on Al7075-T6) was
referred to for rule construction. Fuzzy linguistic variables and fuzzy expression for input and output parameters are presented in Table 6. Four membership functions were utilized for each variable as input: Low (L), Medium (M), High (H), and Very High (VH). The output variable (Roughness) also comprises four membership functions, Excellent, Good, Average, and Bad. The Input and Output variable characteristics are given in Table 6.

4.1. Fuzzy logic variables membership function for input and output

The event and type of membership function are mainly dependent on the relevant event in which the membership functions are chosen for fuzzification. There are four membership functions for each input and output parameter. For input and output variables, the Gaussian and triangular forms of membership function were used to describe the fuzzy sets. The triangular form of membership function with only one definite value has progressively increasing and decreasing characteristics [10,11]. The input variables were partitioned according to the experimental parameter ranges. Membership functions for fuzzy set input DC bias voltage, nitrogen percentage, temperature, and DC power variable are found in Fig. 5(a)–(d) respectively, while a membership function for a roughness fuzzy set is illustrated in Fig. 5(e).
4.2. Structure of fuzzy rules

A set of 16 rules was constructed based on the actual experimental surface roughness of Ti–TiN coating on AL7075-T6, as shown in Tables 3 and 5. Experimental results were simulated in Matlab software according to Mamdani Fuzzy Logic as follows:

1. IF (A is L) and (B is L) and (C is L) and (D is L) then (Roughness is Good)
2. IF (A is L) and (B is M) and (C is M) and (D is M) then (Roughness is Good)
3. IF (A is L) and (B is H) and (C is H) and (D is H) then (Roughness is Good)

Table 6

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Linguistic variables</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A – DC power (W)</td>
<td>Low (L), medium (M), high (H), very high (VH)</td>
<td>300–500</td>
</tr>
<tr>
<td>B – Temperature (°C)</td>
<td>Low, medium, high, very high</td>
<td>150–220</td>
</tr>
<tr>
<td>C – Nitrogen flow rate (%)</td>
<td>Low, medium, high, very high</td>
<td>3–6</td>
</tr>
<tr>
<td>D – DC bias voltage (V)</td>
<td>Low, medium, high, very high</td>
<td>25–100</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roughness (μm)</td>
<td>Excellent, Good, Average, Bad</td>
<td>0.035–0.289</td>
</tr>
</tbody>
</table>

Fig. 5. Membership functions for the input and output parameters.
4. IF (A is L) and (B is VH) and (C is VH) and (D is VH) then (Roughness is Bad)
5. IF (A is M) and (B is L) and (C is M) and (D is M) then (Roughness is Good)
6. IF (A is M) and (B is L) and (C is L) and (D is VH) then (Roughness is Bad)
7. IF (A is M) and (B is H) and (C is H) and (D is M) then (Roughness is Excellent)
8. IF (A is M) and (B is VH) and (C is H) and (D is M) then (Roughness is Good)
9. IF (A is H) and (B is L) and (C is H) and (D is VH) then (Roughness is Bad)
10. IF (A is H) and (B is M) and (C is VH) and (D is H) then (Roughness is Bad)
11. IF (A is H) and (B is H) and (C is L) and (D is M) then (Roughness is Bad)
12. IF (A is H) and (B is VH) and (C is M) and (D is L) then (Roughness is Bad)
13. IF (A is VH) and (B is L) and (C is VH) and (D is M) then (Roughness is Average)
14. IF (A is VH) and (B is M) and (C is H) and (D is L) then (Roughness is Average)
15. IF (A is VH) and (B is H) and (C is M) and (D is VH) then (Roughness is Bad)
16. IF (A is VH) and (B is M) and (C is L) and (D is H) then (Roughness is Bad)

4.3. Defuzzification

Defuzzification is the conversion of a fuzzy quantity to a precise value, just as fuzzification is the conversion of a precise value to a fuzzy quantity [15]. There are several methods that researchers utilize for defuzzifying, including center of largest area, first (or last) of maximum method, center of sum, centroid, weight average, mean of max, etc. [16]. Selecting the method is essential as it greatly influences the model's speed and accuracy. In the current model, the centroid of area (COA) defuzzification method is used due to its wide acceptance and capability to produce more accurate results compared to the others. The resultant membership functions in COA are developed by considering the union of each rule's output, which means that the fuzzy output set's overlapping area, is counted as one, providing more results [17,18].

Fig. 6(a) and (b) are examples that demonstrate the suitable assent between parameter change and Ti–TiN coating surface roughness values predicted by the fuzzy-based model. Fig. 6(a) shows that with increasing the DC power from 300 to 400 W there is no remarkable increase in surface roughness, but with further increase from 400 to 500 W, surface roughness drastically mounts. Fig. 6(a) indicates that increasing the nitrogen flow rate from 3% to 5.5% significantly lowers surface roughness, while by again increasing the amount of nitrogen, surface roughness is slightly increased slightly goes up. Temperature is yet another element with effects on the surface roughness quality of thin film Ti–TiN. Surface roughness diminishes with increasing the temperature from 150 to 220 °C, as revealed in Fig. 6(b). The figure is manifests that the ideal substrate DC bias voltage to achieve excellent roughness is amplitude of 60–70 V; when raising DC bias up to 100 V, surface roughness is extremely increased. After creating the fuzzy rules, five additional, new, separate experiments were performed while the proposed fuzzy model was used to predict surface roughness under the same conditions (Table 7) to explore fuzzy model accuracy and error. The comparison between the fuzzy model prediction values and experimental results is depicted in Fig. 7(a) and (b). According to these figures, the experimental and fuzzy values are in very close assent to each other; hence the fuzzy logic technique can be efficiently utilized for predicting Ti–TiN coating surface roughness from magnetron sputter coating technique. Fig. 7(b) and (c) portray the accuracy and error graphs, also indicating that the proposed model can satisfactorily predict the surface roughness of Ti–TiN multilayer-coated AL7075-T6.

5. Fretting fatigue test results

In order to examine the fretting fatigue life of Ti–TiN-coated specimens with low surface roughness investigated in the fuzzy logic section, some experiments were executed and the results are illustrated in Fig. 8. Fig. 8(a) shows a comparison of the number of cycles to failure versus bending stress for fretting fatigue and plain fatigue of uncoated specimens. Clearly, the fatigue life of uncoated specimens lessened with increased bending stress. Moreover, it can be deduced that fretting has a destructive effect
on fatigue life. The reduction in percentage of the fretting fatigue life of uncoated specimens vs. stress compared to plain fatigue is illustrated in Fig. 8(b). This figure proposes that a drop in fretting fatigue life takes place when the applied bending stress is increased. For example, the reduction percentage is nearly 57% at a stress of around 150 MPa, while at 300 MPa it is roughly 32%. Fig. 8(c) presents the fretting fatigue S/N curve of uncoated and coated specimens with lower surface roughness. By studying Fig. 8(c) and (b), it can be understood that the fretting fatigue lives of Ti–TiN-coated specimens with low surface roughness improved by only 18% at high bending stress, while at low bending stress, the results are reversed. Fig. 9 shows the tested specimens’ fracture surfaces examined using optical microscopy, suggesting that the fracture surface contains two different areas: a fatigue region generated by crack propagation and a tensile zone which triggers specimen fracture when it is sufficiently weakened by distinct crack development. Fig. 10 shows the cracked and shattered thin film Ti–TiN coating at a bending stress of 300 MPa and $5.7 \times 10^4$ cycles caused by fretting pads. The cracks occurred far from the fretting pads. Fig. 11 demonstrates the fractured Ti–TiN-coated specimen at a bending stress of 250 Mpa and $1.2 \times 10^5$ cycles. The SEM image indicates that the fracture of coated specimen contains cracks and pits inside the specimen and around the coating. A crashed region can be seen in the image as well which is resulted from friction pads during fatigue test.

6. Discussion

6.1. The effect of Ti–TiN coating parameters on surface roughness

The experimental and fuzzy model prediction results indicate that the surface roughness of Ti–TiN-coated specimens does not enormously increase when DC power is raised from 300 to 400 W; however, surface roughness significantly increases if DC power is further raised to 500 W (Fig. 6(a) and (b)). When DC power gets increased up to 400 W, the sputtered and ionized elements become more energized while sputtering rate improves, a phenomenon that may cause the distance between energized atoms to decrease and makes the surface denser. When power is increased more from 400 to 500 W, the surface becomes denser and rougher. Besides, nitrogen is also a key parameter in Ti–TiN coating in helping to achieve good surface roughness.
The Ti–TiN multilayer coating roughness was also measured as a function of nitrogen content in the argon-nitrogen gas mixture [19,20]. It is noteworthy that without nitrogen doping, the pure Ti coating is rough (0.37 μm), while the nitrogen mix is effective in reducing surface roughness. The coating’s surface roughness diminishes when nitrogen is raised from 3% to 5.5%, and when nitrogen is further increased to 6%, surface roughness escalates (Fig. 6(a)). This may be due to the fact that the surface becomes more brittle. Fig. 6(a) also shows the best surface roughness value of Ti–TiN coating, at which point DC power is between 300 and 400 W and nitrogen is at 5.5%. DC power has an important role in coating thickness. Table 6 shows the list of coatings thickness at different parameter conditions. From the study of this table can be understood that the coatings thickness are increased with increasing of DC power which this phenomenon is due to increasing in the deposition rate. It means that more DC power can separate more atoms from the target. Therefore more atoms or molecules can stick to the surface during sputtering. Beside that vacuum pressure also has a significant effect on coatings thickness. The film thickness im-
proves at high vacuum pressure. In this study, the vacuum pressure was kept constant. With inserting the nitrogen flow rate the film thickness changes due to change in vacuum pressure. With increasing the nitrogen flow rate, the vacuum pressure decreases and therefore the coatings thickness decrease. The best thickness was obtained at low nitrogen flow rate and high DC power.

The DC bias voltage also plays a role in Ti–TiN coating regarding attaining lower surface roughness. Coated specimen roughness diminishes when raising DC bias voltage from 25 to 62 V, while it begins to increase tremendously from 62 to 100 V (Fig. 6(b)). Thus, by biasing the substrate to an optimal value (62 V) the thin film Ti–TiN coating’s uniformity is enhanced, and it was found that renucleation is initiated beyond the critical bias voltage value. The increased adatoms’ mobility along with higher nucleation density is the result of raising substrate bias voltage during magnetron sputter coating. The best substrate bias voltage value to attain the best surface roughness seems to be 62 V. When temperature goes up from 150 to 220 °C surface roughness declines, something attributed to the faster and more energized atoms which create a more homogeneous surface. Substrate temperature controls the delusions of atoms during Ti–TiN development [20]. The effect of deposition temperature on surface roughness is presented in Fig. 6(b). Finally, differences in roughness are evident where roughness declines from 0.18 to 0.085 μm at arising deposition temperature.

6.2. S/N curves and fretting fatigue life

The corresponding fretting fatigue and plain fatigue S/N curves at 100 MPa contact pressure are shown in Fig. 8(a). The figure obviously demonstrates a significant decrease in fretting fatigue life compared to the plain fatigue life, and particularly at lower bending stresses. Fig. 8(b) reveals the reduction percentage of fretting fatigue life versus stress. The lower fretting fatigue life of uncoated specimens in comparison to plain fatigue is due to the existence of stress concentration in the interface area between the friction pads and substrate. Because of locally concentrated frictional shear stress at the contact surface, fretting fatigue cracks get generated in this area. Thus, the decreased fatigue life by fretting destruction is believed to be due to the increase in crack initiation life produced by the local stress concentration from fretting as well as the acceleration of initial crack propagation from fretting [21]. Fig. 5(c) displays the S/N curve of fretting fatigue for uncoated and Ti–TiN-coated specimens with the lowest surface roughness. The fretting fatigue life of coated specimens with the lowest roughness improved 18% at low cyclic fatigue, while at high cyclic fatigue, the results are reversed. Surface roughness has very complex and even contradictory effects on fretting resistance. The plasticity index in surfaces with high roughness is higher than in smooth surfaces [22], so at the asperities’ tips on a rough surface some plastic deformation will occur. Work hardening is likely to prevent these deformed asperities from being completely flattened, so that the sharper asperities on a rough surface can accumulate more of the tangential movement by elastic deformation. During fretting, an abundance of hard oxide debris accumulates on the contact surface and can cause severe abrasion, but on a rough surface, there is a greater chance that wear-debris will escape from the contact areas into the adjacent hollows or depressions instead of ploughing the worn surfaces. However, in some cases, the increased surface roughness can result in a arising coefficient of friction, which is not beneficial for fretting fatigue resistance. A rough surface containing potential stress raisers is very dangerous, especially under fatigue conditions [23,24].

7. Conclusion

In this research work, AL7075-T6 samples were coated with Ti–TiN at varying parameter conditions. Fuzzy logic
model was used to predict the surface roughness of the coated specimens. The fretting fatigue lives of uncoated and coated specimens with low surface roughness were investigated. From the experimental and computational results the following conclusions are obtained:

1. For AL7075-T6 alloy coated with Ti–TiN by sputtering machine, 350WDC power, 200 °C, 5.5% nitrogen flow rate, and 50V substrate DC bias voltage are recommended in order to obtain the lowest surface roughness for the specific test range of 0.035 μm.

2. The fuzzy model percentages of error and accuracy were found to be 5.97% and 95.349%, respectively. This indicates that the fuzzy logic prediction model predicted the AL7075-T6’s thin Ti–TiN film surface roughness with great accuracy.

3. Fretting can decrease the fatigue life of uncoated AL7075-T6 by 57% in high cycle regions and 32% in low cycle regions (Fig. 8(b)).

4. The fretting fatigue life of Ti–TiN-coated specimens with the lowest surface roughness was enhanced by 18% in low-cycle fatigue, while in high-cycle fatigue, the results are reversed.

Acknowledgements

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