A fuzzy logic based model to predict surface hardness of thin film TiN coating on aerospace AL7075-T6 alloy

E. Zalnezhad · Ahmed A. D. Sarhan · M. Hamdi

Received: 21 December 2011 / Accepted: 4 January 2013 © Springer-Verlag London 2013

Abstract Aerospace applications and energy-saving strategies in general raised the interest and study in the field of lightweight materials, especially on aluminum alloys. Aluminum alloy itself does not have appropriate wear resistance. Therefore, improvement of surface properties is required in practical applications, especially when aluminum is in contact with other parts. In this work, first titanium nitride (TiN) is coated on aerospace Al7075-T6 in different conditions using PVD magnetron sputtering technique, and the surface hardness of TiN-coated specimens is measured using a micro hardness machine. Second, a fuzzy logic model is offered to predict the surface hardness of TiN coating on AL7075-T6 with respect to changes in input process parameters, direct current (DC) power, DC bias voltage, and nitrogen flow rate. Four membership functions are allocated to be connected with each input of the model. The predicted results achieved via fuzzy logic model are compared to the experimental result. The result demonstrated settlement between the fuzzy model and experimental results with 96.142 % accuracy. The hardness of titanium nitride-coated specimens is increased significantly up to 720 HV, while the hardness of uncoated specimens was 170 HV.

Keywords AL7075-T6 alloy · TiN coating · Surface hardness · PVD magnetron sputtering · Fuzzy logic model

1 Introduction

Aluminum alloy, which has superior mechanical properties, low cost, light weight, and reliability, has been widely used for aircraft engines, fuselage, and automobile parts. However, aluminum alloy is not above problems as it suffers from surface damage due to its softness and corrosion. Therefore, advances of surface properties are required in practical applications [1]. Aluminum 7075-T6 alloy which is used in this research work has low specific weight and high strength to weight ratio and also high electrical and thermal conductance. This alloy is widely used in industry and in particular in aircraft structure and pressure vessels, however, subjecting to different working conditions. Wear and fretting normally begin when the substrate is in contact with other surfaces and rubbing each other under normal load, causing share force to act on the surface. Fretting fatigue is a phenomenon which occurs when the substrate is in contact with other parts subjected to cyclic loads and sliding movements at the same time [2]. The result of fretting in engineering components under cyclic load is the reduction of life by premature initiation and propagation of cracks within the contact area.

The advent of new technologies and materials has also attracted attention as with the advent of new technologies, such as vacuum processing, high power laser, and advances in materials, such as ceramics and composites; the surface...
modification techniques based on new technologies have attracted more attentions with respect to the traditional surface modifications ranging from glazing and painting to gas carburizing and electroplating over the past decade [3–5]. Vacuum coating techniques have the potential of applying coating that has higher hardness than any metal, and they find use in these systems that cannot tolerate even microscopic wear losses. Physical vapor deposition (PVD) is one of the vacuum coating processes in which the film material is usually deposited atom by atom on a substrate by condensation from the vapor phase to the solid phase. Now, this technology permits coating deposition at temperatures as low as 200 °C (390 °F) allowing materials to be coated without distortion, loss of hardness, or reduction in corrosion resistance, and the PVD coatings have no performance loss compared to those deposited at higher temperatures. This technology also improves durability; higher surface hardness and increased service temperatures can be achieved from less expensive things [5]. There are three main techniques for applying PVD coatings: thermal evaporation, ion plating, and sputtering.

Many of the coatings that can be applied by thermal evaporation, sputtering, and ion plating are coatings used for some physical property, but the coatings that have importance in tribological systems are relatively few. Table 1 is a tabulation of some of the vacuum coatings that have been used to enhance the tribological properties of sliding system. Disadvantages of thermal evaporation and ion plating are deposits which may have poor adhesion. Deposition of alloys requires special evaporate compositions (to maintain stoichiometry of deposit), cannot deposit compound unaltered, and complex process control [6, 7]. PVD magnetron sputter coating is a vacuum coating process that is used in this investigation because of its flexible coating technique that can be used to coat virtually any material. Sputtering is basically the removal of atomised material from a solid by energetic bombardment of its surface layers by ions or neutral particles [6, 8]. Prior to the sputtering coating process, a vacuum of less than one millionth of an atmosphere must be achieved. Once the appropriate pressure has been reached to a controlled flow, an inert gas such as argon is introduced. This raises the pressure to the minimum needed to operate the magnetrons, although it is still only a few ten thousandth of atmospheric pressure.

Titanium nitride (TiN) coating using PVD technique is a method used to improve the hardness of Al7075-T6 at different coating parameters condition for less wear and longer fretting fatigue service life. The creation of a titanium nitride coating on the surface of the substrate material is one of the most effective methods of enhancing the wear resistance of materials. This coating is also promising from the standpoint of the possibility of achieving high hardness and strength in achieving longer service life in fretting fatigue application and simultaneously good protective-and-decorative surface properties [9–11]. The conventional method helps to achieve high hardness and strength at different coating parameters with a view to using the experimental “trial and error” approach. However, “trial and error” approach is very time-consuming due to the large number of experiments. Hence, a reliable systematic approach to predict the surface hardness at different parameters condition is thus required to cover all the parameters’ range in a few numbers of experiments [12–14]. Soft computing techniques are useful when exact mathematical information is not available, and these differ from conventional computing in that it is tolerant of imprecision, uncertainty, partial truth, approximation, and met heuristics. Fuzzy logic is one of the soft computing techniques that play a significant role in input–output matrix relationship modeling. It is used when subjective knowledge and suggestion by the expert are significant in defining objective function and decision variables. Fuzzy logic is preferred to predicting coating performance based on the input variables due to nonlinear condition in coating process [15–19]. This paper applies the fuzzy logic to develop the rule model in order to predict the surface hardness performance of TiN based on parameter and performance interaction.

Dr. Lotfizadeh, an Iranian professor at the University of California in Berkley, pioneered in introducing the concept of fuzzy logic not only as a control methodology but also as a way to process data based on authorizing the use of membership in a small group instead of making use of membership in a cluster group [16]. Fuzzy logic is a simple rule based on: If X and Y, then Z. Fuzzy mathematics is a metaset of Boolean logic and denotes relative correctness. The fuzzy theory is still a prominent theory, although sometimes it describes uncertain and indefinite phenomena having the following structure as shown in Fig. 1:

Table 1 Thin film coatings for tribological and surface integrity applications

<table>
<thead>
<tr>
<th>Thermal evaporation</th>
<th>Sputtering</th>
<th>Ion plating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>SiO</td>
<td>Cr</td>
</tr>
<tr>
<td>Ag</td>
<td>SiO2</td>
<td>Mo</td>
</tr>
<tr>
<td>MCrAlY’s</td>
<td>Cr</td>
<td>TiC</td>
</tr>
<tr>
<td>Cr</td>
<td>Mo</td>
<td>TiN</td>
</tr>
<tr>
<td>Mo</td>
<td>Au</td>
<td>Au</td>
</tr>
<tr>
<td>TiC</td>
<td>Ag</td>
<td>Si3N4</td>
</tr>
<tr>
<td>TiN</td>
<td>Si3N4</td>
<td></td>
</tr>
<tr>
<td>Al2O3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WS2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MoS2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si3N4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTFE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiB2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. Fuzzification: making something fuzzy.
2. Fuzzy rule base: in the rule base, the if–then rules are fuzzy rules.
3. Fuzzy inference engine: produces a map of the fuzzy set in the space entering the fuzzy set and in the space leaving the fuzzy set, according to the rules if–then.
4. Defuzzification: making something nonfuzzy [19].

In this present work, TiN is coated on Al7075-T6 substrate in different parameters condition. Each parameter has four levels which include the direct current (DC) power, substrate temperature, the nitrogen flow rate, and DC substrate biases voltage. Fuzzy rule base method is proposed to predict surface hardness of TiN coating on AL7075-T6 alloy.

2 Design of experiments

The most important stage in the designing of an experiment lies in the selection of parameters and identifying the experimental array. In this experiment with four parameters and four levels each, the fractional factors design used is a standard L₁₆ (₄⁴) experimental array. This array is chosen due to its capability to check the interactions among parameters. The parameters and levels are assigned as in Table 2. The 16 experiments with the details of combination of the experimental levels for each parameter (A–D) are shown in Table 3.

Table 2 Parameters and levels used in the experiment

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experimental condition levels (i)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>A DC power (W)</td>
<td>300</td>
</tr>
<tr>
<td>B Temperature (C)</td>
<td>150</td>
</tr>
<tr>
<td>C Nitrogen low rate (%)</td>
<td>3</td>
</tr>
<tr>
<td>D Substrate biases voltage (v)</td>
<td>25</td>
</tr>
</tbody>
</table>

3 Test specimens and coating preparation

Aluminum alloy 7075-T6 is used in this research work. The material’s composition obtained using EDX is given in Table 4. The surface of all samples was polished with SiC papers grit 800–2,000; after that, all samples were surface mirrored by diamond liquid, and the substrate was ultrasonically cleaned in acetone for 14 min, thoroughly rinsed with distilled water, and dried using nitrogen gas to avoid contamination. A SG Control Engineering Pte Ltd series magnetron sputtering system is used to experimentally deposit thin films of metal. This system contained 600 W RF and 1,200 W DC generators with 4″ × 12″ electrodes 15 cm away from the target. To easily sputter metals, we design DC generators. The substrate carrier was circular and rotatable at various speeds for required co-sputtering deposition. The chamber is evacuated to below 2 × 10⁻⁷ Torr before the argon gas for sputtering was introduced. Here, the constant sputtering pressure 5.2 × 10⁻³ Torr is used. The substrate temperature, DC bias voltage, nitrogen flow rate, and DC power as coating parameters are arranged according to the experimental array shown in Table 3 to learn how to improve the hardness of the sputtered TiN thin film. The layers were characterized using scanning electron microscopy (FE/SEM-FEG), focused
ion beam techniques (Quanta FEG250). In addition, the hardness of the layers is determined using micro-hardness equipment (HMV Micro Hardness Tester Shimadzu).

4 Experimental result

The hardness of the surface layers is measured using micro-hardness equipment. Each measurement was repeated three times, and the averages are calculated and summarized in Table 5. Figure 2 shows a typical example of a TiN coating; it can be seen under SEM that the coating structure is columnar. The diffusion rate of Ti and nitrogen, chemical composition of AL 7075-T6, and the interfacial layer of titanium and TiN and aluminum have been shown in Fig. 2 as well.

5 Fuzzy logic-based model to predict surface hardness

The relationship between input parameters which are sputtering DC power, substrate temperature, nitrogen flow rate, and DC bias voltage with the output parameter which is surface hardness of TiN coating on AL7075-T6 was referred to construct the rules. Fuzzy linguistic variables and fuzzy expression for input and output parameters are shown in Table 6. For each variable, four membership functions were used which are low, medium, high, and very high for inputs. The output variable (hardness) also used four membership functions, ranging from bad, average, good, and excellent, and the characteristics of the inputs and output variables are shown in Table 6.

5.1 Membership functions for input and output fuzzy variables

In choosing the membership functions for fuzzification, the event and type of membership functions are mainly dependent upon the relevant event [17]. In this model, each input and output parameter has four membership functions. Gauss shape of membership function is employed to describe the fuzzy sets for input variables. In output variables fuzzy set, triangular shape of membership functions is used. Triangular membership function is generally used and possesses gradually increasing and decreasing characteristics with only one definite value [17]. The input variables have been partitioned according to the experiment parameter ranges. Membership functions for fuzzy set input DC power, temperature, nitrogen flow rate, and DC bias voltage variable are shown in Fig. 3a, b, c, and d, respectively. Moreover, Fig. 4 shows the membership functions for hardness fuzzy set.

5.2 Structure of fuzzy rules

A set of 16 rules have been constructed based on the actual experimental surface hardness of TiN coating on AL7075-T6. Experimental results were simulated in the Matlab software on the basis of Mamdani Fuzzy Logic which was as follows:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Measured surface hardness (HV)</th>
<th>Average surface hardness (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First</td>
<td>Second</td>
</tr>
<tr>
<td>1</td>
<td>192</td>
<td>215</td>
</tr>
<tr>
<td>2</td>
<td>208</td>
<td>203</td>
</tr>
<tr>
<td>3</td>
<td>189</td>
<td>206</td>
</tr>
<tr>
<td>4</td>
<td>181</td>
<td>229</td>
</tr>
<tr>
<td>5</td>
<td>326</td>
<td>411</td>
</tr>
<tr>
<td>6</td>
<td>290</td>
<td>305</td>
</tr>
<tr>
<td>7</td>
<td>301</td>
<td>207</td>
</tr>
<tr>
<td>8</td>
<td>617</td>
<td>581</td>
</tr>
<tr>
<td>9</td>
<td>321</td>
<td>300</td>
</tr>
<tr>
<td>10</td>
<td>192</td>
<td>198</td>
</tr>
<tr>
<td>11</td>
<td>402</td>
<td>380</td>
</tr>
<tr>
<td>12</td>
<td>699</td>
<td>713</td>
</tr>
<tr>
<td>13</td>
<td>221</td>
<td>225</td>
</tr>
<tr>
<td>14</td>
<td>590</td>
<td>501</td>
</tr>
<tr>
<td>15</td>
<td>186</td>
<td>202</td>
</tr>
<tr>
<td>16</td>
<td>258</td>
<td>216</td>
</tr>
</tbody>
</table>
1. If (A is L) and (B is L) and (C is L) and (D is L), then (hardness is bad).
2. If (A is L) and (B is M) and (C is M) and (D is M), then (hardness is bad).
3. If (A is L) and (B is H) and (C is H) and (D is H), then (hardness is bad).
4. If (A is L) and (B is VH) and (C is VH) and (D is VH), then (hardness is bad).
5. If (A is M) and (B is L) and (C is M) and (D is H), then (hardness is good).
6. If (A is M) and (B is M) and (C is L) and (D is VH), then (hardness is average).
7. If (A is M) and (B is H) and (C is VH) and (D is L), then (hardness is average).
8. If (A is M) and (B is VH) and (C is H) and (D is M), then (hardness is excellent).
9. If (A is H) and (B is L) and (C is H) and (D is VH), then (hardness is average).
10. If (A is H) and (B is M) and (C is VH) and (D is H), then (hardness is bad).
11. If (A is H) and (B is H) and (C is L) and (D is M), then (hardness is good).
12. If (A is H) and (B is VH) and (C is M) and (D is L), then (hardness is excellent).
13. If (A is VH) and (B is L) and (C is VH) and (D is M), then (hardness is average).
14. If (A is VH) and (B is M) and (C is H) and (D is L), then (hardness is good).
15. If (A is VH) and (B is H) and (C is M) and (D is VH), then (hardness is bad).
16. If (A is VH) and (B is VH) and (C is L) and (D is H), then (hardness is average).

5.3 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 [17]. Seven methods are available in literatures to be used by researchers for defuzzifying methods which include centroid, weight average, mean of max, center of sum, center of largest area, and first (or last) of maximum method. The selection of the method is important, and it greatly influences the speed and accuracy of the model. In this model, centroid of area defuzzification method is used due to its wide acceptance and capability in giving more accurate result compared to the other methods [18, 19]. In this method, the resultant membership functions are developed by considering the union of the output of each rule, which means that the overlapping area of fuzzy output set is counted as one, providing more result [20, 21]. Figure 5 shows the graphical representation of center of area defuzzification method. The shape refers to the remaining area of active fuzzy sets that is controlled by the related fuzzy rules.

Figure 6a and b are examples to demonstrate the appropriate assent between parameters change and TiN coating.
surface hardness values predicted by fuzzy based model. The close assent of surface hardness values of TiN coating obviously displays that fuzzy logic model can be used to predict hardness of TiN coating parameters under consideration. Thus, the proposed fuzzy logic model gives promising solution to predict hardness value in the specific range of parameters.

6 Investigate the fuzzy model accuracy and error

Constructing the fuzzy rules, other new five experimental tests from separated experiment were carried out while the proposed fuzzy model is used to predict the surface hardness at the same conditions to investigate the fuzzy model accuracy and error as shown in Table 7. The individual error percentage is obtained by dividing the absolute difference of the predicted and measured values by the measured value as shown in Eq. (1), where \( e_i \) is the individual error, \( H_m \) is measured value, and \( H_p \) is the predicted value [13].

\[
e_i = \left( \frac{|H_m - H_p|}{H_m} \right) \times 100\%
\]

Meanwhile, accuracy is calculated to measure the closeness of the predicted value to the measured value. The model accuracy is the average of individual accuracy as shown in Eq. (2), where \( A \) is the model accuracy and \( N \) is the total number of data set tested.

\[
A = \frac{1}{N} \sum_{i=1}^{N} \left( 1 - \frac{|H_m - H_p|}{H_m} \right) \times 100\%
\]

The error for dataset result is calculated, and the model accuracy for fuzzy logic is determined showing the experimental condition, surface hardness results, and fuzzy model predicted value in Table 7. The highest percentage of error for fuzzy model prediction is 6.09%. The low level of errors shows that the fuzzy predicted surface hardness results were very close with actual experimental surface hardness values. Table 7 also shows that the fuzzy model accuracy is...
96.142 %. The value of accuracy shows that the proposed model can predict the surface hardness of TiN coating on AL7075-t6 satisfactorily as it can be seen in Fig. 7a–c.

7 Discussion

The selection of the deposition conditions is essential for fabricating composite thin films. The most important parameters affecting the deposition rate are the DC bias voltage, temperature, DC power, and nitrogen flow rate. A pure titanium 99.995 % target is selected for investigating the sputtering conditions for Al 7075-T6 alloy. The sputtering power is varied from 300 to 500 W. The pressure is $5.2 \times 10^{-3}$ Torr during experiments. The effect of TiN coating on surface hardness is observed at different parameters condition.

From the experimental and fuzzy model prediction results as shown in Fig. 6a, b, the surface hardness of TiN-coated specimens is increased with increasing of DC power from 300 to 450 W, while with more increasing of DC power up to 500 W the surface hardness is decreased. This may because if the pressure is kept constant, with increasing power, the ion density increases. The sputtering rate increases with increasing power. If power is further increased, the sputtering rate decreases owing to back diffusion. When the DC power is increased to 300 and 400 W, the ionized and sputtered particles became more energetic, and the sputtering rate increased causing a decrease in the distance between energized atoms, and it makes the surface...
denser, so with more density, the surface is gotten harder from 300 to 450 W. On the other hand, when DC power increases more to 500 W, collisions of sputtered particles with chamber particles (argon gas and ions) increased, and the hardness of surface is decreased, as it can be seen from Fig 6a.

The DC bias voltage also plays important roles in TiN coating to get high value of hardness. The hardness of coated samples is decreased with increasing substrate bias voltage from 25 to 100 V, which is demonstrated in Fig 6b. Thus, uniformity of the TiN coating is improved with substrate biasing up to an optimal value, and the renucleation is observed to start above a critical bias value. The hardness values of the Ti interlayers were also measured as a function of nitrogen content in argon–nitrogen gas mixture. An important issue is that without nitrogen doping, the pure Ti interlayer is very soft, with hardness value around 255 HV, and nitrogen mixing is effective in enhancing the hardness and strength of the interlayer [10]. There is a general trend that the hardness of the Ti interlayer increases with increasing degree of nitrogen doping following correlation between these two. This is obviously due to the dissolution of nitrogen in the α-Ti lattice, causing solid solution hardening in the interlayer [22]. By mixing the nitrogen and titanium, the surface becomes ceramic, and the surface hardness of TiN-coated samples by increasing the nitrogen from 3 to 5 % is increased, while by increasing nitrogen flow rate up to 6 %, the hardness of the surface is decreased; this may happen because the surface was more brittle.

In addition, by increasing the temperature from 150 to 220 °C, the surface hardness is increased. This can be attributed to the movement of atoms which is fasted and energized, and this event can make the surface homogeneous. Substrate temperature is believed to control the delusions of atoms during the TiN growth [14]. The effect of the deposition temperature on the hardness is exhibited in Fig. 6b. Differences in hardness can be observed where the hardness increases from 170 to 720 HV with rising deposition temperature. The hardness of TiN is a complex issue and comprises the composition, defects, grain size, residual stresses, and texture of the material [23]. From the almost identical lattice parameters, no significant differences in composition can be expected.
8 Conclusion

In this research work, first TiN was coated on AL7075-T6 samples at different parameters condition using PVD magnetron sputtering, and hardness of all samples was measured by micro hardness machine. The parameters in this study include the DC power, substrate temperature, the nitrogen flow rate, and DC substrate biases voltage. Second, prediction of surface hardness of TiN coating on AL7075-T6 alloy was investigated at same parameters condition using fuzzy logic technique. From the result of the fuzzy logic prediction model, the following conclusions can be derived:

1. In the TiN coating on AL7075-T6 alloy by sputtering machine, use of 400 W DC power, 200 °C temperature, 4 % nitrogen flow rate, and 100 v substrate DC bias voltage are recommended to obtain the highest surface hardness for the specific test range 720 HV.

2. The hardness and strength of the interlayer are increased due to nitrogen dissolution in the α-Ti lattice. The hardness of TiN-coated AL7075-T6 samples is increased up to 720 HV, while the hardness of uncoated samples was 170 HV.

3. The fuzzy model percentages of error and accuracy were found to be 6.09 and 96.142 %, respectively. It is indicated that the fuzzy logic prediction model could be used to predict the surface hardness of the coated thin film of TiN on AL7075-T6 alloy in a very accurate manner.

Acknowledgments The authors acknowledge the financial support under the University Malaya Research Grant (grant no.: UM.TNC2/RC/AET/GERAN (UMRG) RG133/11AET) from the University of Malaya, Malaysia.

References