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ORIGINAL ARTICLE

Fretting fatigue life evaluation of multilayer Cr–CrN-coated Al7075-T6 with higher adhesion strength—fuzzy logic approach

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Abstract In this research work, an experimental evaluation was conducted to explore the fretting fatigue life of multilayer Cr–CrN-coated AL7075-T6 alloy specimens with higher adhesion strength to substrate as the coating adhesion strength is one of the most critical issues in magnetron sputtering technique. Physical vapor deposition (PVD) magnetron sputtering technique was used for coating purpose, and a fuzzy rule-based system was established to investigate how to achieve higher adhesion of Cr–CrN coating on AL7075-T6 with respect to changes in input process parameters, direct current power, nitrogen flow rate, and temperature. Close assent was obtained between the experimental results and fuzzy model predicted values. Experimental result analysis was performed with Pareto–ANOVA variance as an alternative analysis. The fretting fatigue lives of coated AL7075-T6 alloy were improved 70 % and 22 % at high and low cyclic fatigue, respectively, compared with uncoated specimens.

Keywords AL7075-T6 · Fretting fatigue · Magnetron sputter technique · Cr–CrN coating · Fuzzy logic

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1 Introduction

As light-weight, high-strength, and high-conductivity materials, aluminum alloys are becoming more and more important, particularly in the aircraft and automobile industries for both economic and technical reasons [1]. Dispersion hardening through solution and ageing heat treatments are usually used to induce high-static mechanical properties in aluminum alloys. However, these alloys are always subject to different working conditions. Wear and fretting normally originate when the substrate is in contact with other surfaces, and they rub each other under normal load, causing share force to act on the surface [2–5]. When two contacting components experience a vibratory motion of small amplitude, it is termed fretting. If these mating components are then subjected to cyclic load, the process is known as fretting fatigue. Fretting fatigue increases the shear and tensile stresses at the contact surface, creating surface flaws which can act as stress concentration sites [6]. For this reason, aluminum alloys are often subjected to surface modifications. Material with proper coating should reveal different properties for working effectively in a given tribological application. Vital coating properties are high adhesion strength to the substrate, low tendency to adhere to the mated material, good wear resistance (high hardness), high fracture toughness, and superior chemical and thermal stability. Nowadays, the hard coatings of metal nitrides are used in several tribological applications [7, 8]. The hard coatings are generally deposited via physical vapor deposition techniques such as ion plating, magnetron sputtering, and thermal evaporation, permitting the creation of dense adhesive thin films at low temperatures, which is one of the most important advantages of these sorts of coatings [9]. In the past few decades, transition metal nitride coatings, mostly based on titanium and chromium, have attracted significant attention due to their beneficial

potential applications in several fields such as electronics, optical, decorative, and magnetic coatings [10, 11]. Cr–CrN thin film coating is particularly appropriate to serve as wear and corrosion protection because of its fine mechanical properties (wear resistance, low friction coefficient, and high hardness). Cr–CrN coating using magnetron sputtering technique has the main specific advantages of easily controlled deposition rate and low impurities. Furthermore, this method allows the creation of thin films of numerous crystallographic and morphology structures [12]. Multilayer Cr–CrN coatings are made by changing coating parameters which help the construction of thin films over the crystalline, i.e., lower deposition rate and lower substrate temperature [13, 14]. The traditional method of attaining high strength and hardness at different coating parameters is to use the experimental trial and error approach, which is very time-consuming due to the large number of experiments. Hence, a reliable systematic approach for predicting surface hardness at different parameter conditions is required to cover all the parameter ranges in a low number of experiments [15–17]. Soft computing techniques are useful when exact mathematical information is not available. In contrast to traditional computing, these techniques suffer from approximation, partial truth, met heuristics, uncertainty, and inaccuracy. One of the soft computing techniques with a significant role in input–output parameter relationship modeling is fuzzy logic system. Compared with other artificial intelligence methods, development of fuzzy logic is moderately easier, and it does not need many software and hardware resources. Fuzzy logic was introduced by Zadeh [18] and is the victorious application of theory of the fuzzy set, as an extension of the set theory by the characteristic function replacement of a set through a membership function whose values range from 0 to 1. A considerable amount of studies have focused on the prediction and measurement of coating surface integrity [19–21].

In this study, Al7075-T6 substrate was coated with Cr–CrN at different parameter conditions. Each parameter has four levels, namely: substrate temperature, nitrogen percentage, and DC power. The fuzzy rule-based method was proposed to investigate surface adhesion of multilayer Cr–CrN coating on AL7075-T6 alloy. The fretting fatigue life of Cr–CrN-coated specimens with high adhesion was investigated. Experimental results were analyzed using Pareto-ANOVA variance analysis as an alternative analysis.

2 Experimental details

2.1 Material

The material investigated in this work is 7075-T6 aluminum alloy with the following chemical composition (in weight percent)—4.6 Zn, 1.8 Mg, 1.85 Cu, 0.06 Mn, 0.47 Si, and 0.28 Cr. The ultimate strength and yield stress of Al7075-T6 were attained via a number of tensile tests, and they are: σ_{ut}= 590 MPa and σ_y=520 MPa, respectively.

2.2 Coating procedure

In order to make the films adhere well to the substrates, surfaces must be carefully cleaned before film deposition. At the beginning, all substrates were polished with SiC paper of 800–2000 grit and were surface mirrored with diamond liquid. The substrates were ultrasonically cleaned in alkali and alcohol baths, respectively, and thoroughly rinsed with distilled water. The samples were then inserted into the chamber for in situ cleaning. The chamber was evacuated to a pressure of 3.7×10^{-5} Torr, and the substrates were heated to 350 °C for 1 h. This process mainly removed water molecules, which were absorbed on almost all surfaces. During the last step of cleaning, called ion-etching or Ar^+ sputtering, Ar^+ ions were accelerated by applying substrate bias potential V_s (−200 V) onto the substrates. In the ion-etching process, oxides or chemisorbed nitrogen and/or carbon atoms were removed. A magnetron sputtering machine (SG Control Engineering Pte Ltd) was utilized in order to deposit thin film on the metal. DC generators were selected to facilitate the sputter metals. Sputtering pressure was adjusted to around 5.2×10^{-3} Torr. Table 1 presents the coating parameter conditions used in this experiment, in an investigation of how to increase sputtered CrN thin film adhesion to the substrate. A pure chromium 99.95 % target was selected for exploring the sputtering parameters condition for Al 7075-T6 alloy. Pure chromium was initially coated onto the substrate as an interfacial layer for 1 h to improve adhesion between the substrate and second layer of coating (chromium nitride). The deposition time for the second layer was adjusted to 3 h.

In the design of experiments to reduce the number of experiments, the coating procedure was planned using Taguchi's orthogonal array shown in Table 2. Adhesion of coating to substrate is the most essential factor to be investigated. The layers were characterized by scanning electron microscopy (FE/SEM-FEG) and focused ion beam technique (Quanta FEG250). Substrate adhesion was measured using micro-scratch force equipment (Micro Material Ltd, Wrexham, UK). Each experiment was

Table 1 Parameters and levels used in experiment

Parameters		Levels			
		1	2	3	4
A	DC power (W)	200	300	400	500
B	Temperature (°C)	150	200	250	300
C	Nitrogen low rate (%)	3	6	9	12