Vacuum 150 (2018) 1–7

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Improved the elevated temperature mechanical properties of Al-Si alloy deposited with Al-Si coating by magnetron sputtering

Feng Xu [a, b], Dongmei Gong [a, *]

[a] School of Mechanical and Vehicle Engineering, West Anhui University, Lu'an 237012, Anhui, China
[b] School of Mechanical Engineering, Hefei University of Technology, Hefei 230009, Anhui, China

A R T I C L E I N F O

Article history:
Received 9 December 2017
Received in revised form
30 December 2017
Accepted 8 January 2018
Available online 11 January 2018

Keywords:
Al-Si alloy
Elevated temperature
Surface defect
Friction coefficient
Wear

A B S T R A C T

Compact and uniform aluminum silicon (Al-Si) coatings with different Si contents were deposited on Al-Si alloy by magnetron sputtering. The structure and mechanical properties of the Al-Si alloy covered with Al-Si coating were characterized. The results indicate that the introduction of Al-Si coating on Al-Si alloy surface can increase the mechanical properties of Al-Si material. Hardness and elastic modulus of the Al-Si coating with 25.2 at % Si reach about 23.6 GPa and 178.0 GPa, respectively, which are obviously higher than those of Al-Si bulk. The Al-Si coating with 25.2 at % Si exhibits the lowest friction coefficient of 0.231 and lowest wear rate of 0.9-1.4 $\times$ 10^{-6} mm^3/Nm. The low friction coefficient of Al-Si coating is attributed to the Al and Si debris which react with thermal moisture to form aluminum and silicon oxide, serving as a lubricant between two contact counterparts.

1. Introduction

Recent years, the development of electronic packaging materials has resulted in remarkable improvements in comparison to traditional Me materials in terms of their increased mechanical performance, which make these packaging materials suitable for electronic applications [1–6]. Among these electronic packaging materials, due to their unusual properties, such as low coefficient of thermal expansion (CTE), high thermal conductivity (TC) and excellent mechanical properties, Al-Si alloy containing high fraction Si content has attracted more and more attention which make it viable for the heat dispersal applications [7–10].

As one kind of packaging material, Al-Si materials are usually exposed to the conditions of vibration, wear, oxidation and fatigue under elevated temperature atmosphere. The continuous contact with other electronic carrier and in relative motion can lead to the deformation or the failure of the Al-Si material components [11–13]. On the other hand, although Al-Si material shows the certain extent wear and corrosion resistance, the intrinsic surface defects, such as lower density, crack and a certain degree of porosity and voids, could become a key source of wear debris and lead to the local damage [14–17]. To break through this disadvantage, lots of researchers are focused on regulating manufacture process. Up to now, many technologies such as the powder metallurgy, spray deposition, suspension casting and semi-solid thixoforming, have been explored [18–20]. Most of those studies mainly investigate the regulating of chemical composition, mechanical properties, CTE and TC of Al-Si alloy in order to confirm whether the prepared alloy is the products of mixture of Al and Si fraction [21–25]. Little attention has been paid to the effect of evolution of surface state and Si content on the mechanical properties. Furthermore, detailed studies of the relationship between the structure and the tribological properties of Al-Si coatings under elevated temperature atmosphere have not been extensively reported in literature.

Actually, the hard coating such as Al-Si coating can be deposited onto bulk Al-Si material and improve its density and tribological behavior, which makes the design promising. Some outstanding advantages such as high density, high hardness, excellent wear resistance and superior elect-compatibility have kept driving working force to be contributed into various functional coating in past years [26–31]. Thus, the effective method to overcome the previously mentioned problems may be the creation of Al-Si coating with compact density on the surface. In this case, the inner part of the Al-Si alloy substrate provides the strength and modulus, while the outer part Al-Si coating can guarantee wear

* Corresponding author. School of Mechanical and Vehicle Engineering, West Anhui University, West to YunLu Brigde, Lu'an 237012, Anhui, China.
E-mail address: gongdmwxc@gmail.com (D. Gong).

https://doi.org/10.1016/j.vacuum.2018.01.013
0042-207X/

Table 1
Experimental parameters of the Al-Si coatings during deposition.

Process	Detailed parameter	Value	
		Al	Al-Si
Film deposition	Bias voltage (V)	30	60 ± 5
	Base pressure (Pa)	$3.5 \pm 2 \times 10^{-3}$	$3.5 \pm 2 \times 10^{-3}$
	Ar flow rate (sccm)	20	30
	Current of Al target (A)	0.5 ± 0.02	0.5 ± 0.02
	Current of Si target (A)	~	3–5
	Work pressure (Pa)	0.52 ± 0.022	0.65 ± 0.022
	Rotation speed (R/min)	8	8
	Temperature (°C)	200 ± 10	220–240 ± 10

resistance in contact and relative motion under elevated temperature atmosphere. In addition, previous study have confirmed that the modified Al-Si coating contained special diffusion barrier structure can primly restrain the degradation of the coating. However, in the high temperature environment, especially the environment rich in the high temperature oxidation and wear resistance of Al-Si coating was still not ideal [32]. Consequently, in this study, Al-Si coating with different Si content were fabricated on Al-Si alloy by the magnetron sputtering, and the elevated temperature tribological behaviors (friction coefficient, wear rate and adhesive) of the Al-Si coatings were investigated qualitatively and quantitatively.

2. Experimental procedures

Magnetron sputtering deposited system was used to fabricate the Al-Si coatings with the total thickness of 4 μm on aluminum silicon alloy substrates (Al- 60 vol % Si). Surface finish of Al-Si alloy was significantly improved by mechanical-polishing. Prior to deposition, Al-Si alloy substrates ($20 \times 20\ mm^2$) were cleaned with 8–10 vol % dilute HF and distilled water in ultrasonic cleaner. During deposition, the base pressure of chamber was kept at less than 3.5×10^{-3} Pa. High purity Ar (99.99%) was introduced into the chamber at a fixed flow (30 sccm) and the total work pressure was kept at 0.65 Pa. A 20 nm Al transitional was deposited on Al-Si substrate by sputtering Al target through process parameter regulation, the details parameters of the Al interlayer during deposition were listed in Table .1. Subsequently, the Al-Si coatings were deposited on Al underlayer by co-sputtering of aluminum target (0.5 A) and silicon target. One series of Al-Si coating with different Si contents were fabricated by varying the current of silicon target (CT-Si = 3, 4, 5A) respectively. The applied bias voltage for all the coatings was 60 V. The details parameters of the Al-Si coatings during deposition were also listed in Table .1.

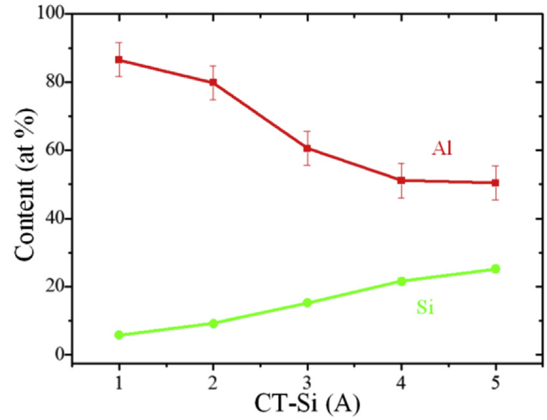

Fig. 2. Si and Al content distributions of the Al-Si coatings as a function of silicon target current (CT-Si). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Optical microscope (OM) and Scanning electron microscope (SEM, Hitachi S-4700, GENENIS 4000 EDAX director) were used for the observations of surface and cross-sectional morphology of Al-Si coating and Al-Si bulk. The thickness of Al-Si film was were both about 4 μm. Phase composition and the microstructure of the Al-Si coating were analyzed using X-ray photoelectron spectroscopy (XPS, ESCA 220i-XL, using Al $K_{\alpha X}$ rays and the power of 300 W). The BE (binding energies) was referenced to the C 1s line at 284.6 eV from adventitious carbon. Decomposition of chemical bonding states of Si element was performed using Gaussian curve fitting. Indentation experiments were carried out on the nano-indenter (G-200, Agilent technologies) at Al matrix zone of Al-Si alloy and Al-Si coating surface. A Berkovich indenter, a three-sided pyramid, was used in all the experiments. Multiple indentations were carried out for 5 times at one sample, at the load of 10 mN. Hardness (H) and indentation modulus, E/(1-ν2), (E is Young's modulus, ν is Poisson's ratio) were calculated by the average of data from the five load vs displacement curves. The indentation depth values were at least nearly 5 times the roughness and also below 10% of the samples thickness, to avoid the effect of substrate. Elevated temperature wear tests were performed using ball-on-disc at 400 °C. The wear tests were carried out at the load of 5.0 N. A standard Si_3N_4 ball with 3 mm diameter was used. The wear scares of Al-Si coatings were analyzed through SEM. Al-Si coatings used for tribological characterization were made into discs (Ø = 20 mm), while the Al-Si coating samples used for structure characterization were made into slices ($10 \times 10\ mm^2$). All test dates were collected

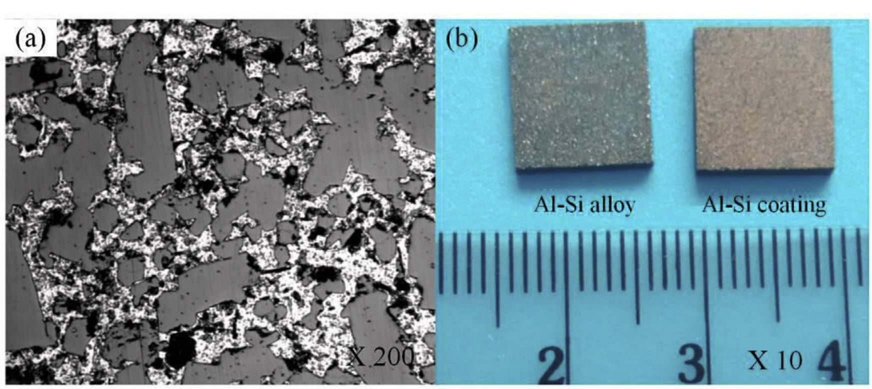

Fig. 1. Optical micrographs of (a) Al-Si bulk material and (b) Al-Si coating.