Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 68 (2013) 736 – 742

Procedia Engineering

www.elsevier.com/locate/procedia

The Malaysian International Tribology Conference 2013, MITC2013

Wear mechanisms map of CNT-Al nano-composite

U. Abdullahi[a], M.A. Maleque[a]*, and U. Nirmal[b]

[a]Department of Manufacturing and Materials Engineering
Kulliyyah of Engineering, International Islamic University, Malaysia
P.O.Box 10, 50728 Kuala Lumpur, Malaysia. Email: maleque@iium.edu.my
[b]Faculty of Engineering & Technology, Multimedia University, Malaysia

Abstract

Carbon nanotube reinforced aluminium nano-composites were produced using powder metallurgy route with different weight percent of CNT into the Al matrix. The wear behaviour of pure aluminium (Al) and carbon nanotube reinforced aluminium (CNT-Al) nano-composite with different CNT content were studied with a pin-on-disc tribometer, sliding against AISI52100 steel disc. Experiments were conducted using different sliding velocities of 0.5, 0.65 and 0.79 m/s and a normal load of 5.5, 7.2 and 10 N. From the wear map it is observed that, during dry sliding wear an increase of any of the operating condition such as normal applied load, sliding velocity, or duration of rubbing leads at some stage to a sudden change in the wear rate (weight loss per sliding distance). The simplest categories of wear exhibiting at different wear rates are mild and severe wear. Mild wear marks a smooth surface that often is smoother than the original surface, with minimum plastic deformation and oxide wear debris. CNT-Al nano-composite shows lower wear rate than pure aluminium and wear rate of all the tested materials increases with increasing normal applied load. Wear rate decreases with increasing CNT content from 0-1.5 wt% and increase slightly from 1.5-2 wt%, then increase rapidly after this range of CNT content. A distinctive abrasive and adhesive type of wear were observed from the morphological image of the worn surface.

Keywords: Wear map, carbon nanotube, Aluminium, Tribological property

1. Introduction

Aluminium in its pure form is very soft and cannot withstand excessive wear and friction during operation. Recently, there is a high demand to improve its mechanical properties, wear and frictional resistance due to the high demand of lightweight, energy servings and efficient material. The uses of aluminium alloys in some industries such as automotive have been limited by their substandard strength, rigidity and wear resistance, compared aluminium based composite especially nano-composite materials [1-3]. Aluminium nano-composites, however, offer reduced mass, high stiffness and strength, and improved wear and frictional resistance. From the wear map it is observed that, during dry sliding wear an increase of any of the operating condition such as normal applied load, sliding velocity, or duration of rubbing leads at some stage to a sudden change in the wear rate (weight loss per sliding distance). The simplest categories of the types of wear exhibiting these different wear rates is mild wear and severe wear. Mild wear marks a smooth surface that often is smoother than the original surface, with minimum plastic deformation and oxide wear debris [4, 5]. Severe wear results in a rough surface that is typically rougher than the original surface, with large plastic deformation and flake-like metallic wear debris [6, 7]. Today many

doi:10.1016/j.proeng.2013.12.247

researchers had introduced advance materials as a substitute to the traditionally used materials as these modified materials are light weight and excellent in wear and friction resistance, as well as improved life span [8, 9]. Scientific ideology and calculating methods of creating new materials/composites and estimation of its wear resistance of friction nodes as well as physical simulation of friction and wear processes on a small-sized laboratory test machine need to be carried out experimentally before a future material/composite is commercially introduced in the market. Before the advent of the proposed composite material, a suitable type of wear test equipment should be used together with a suitable parameters selected which reflect the real time application of the composite. Examples of this parameters are testing techniques, type of counterface used against the test samples, sliding velocities, sliding distances, applied loads, contact conditions and orientations of the test specimen with respect to the sliding direction of the counterface. Based on this idea the present authors proposed CNT-Al nano-composite material to be used for brake disc application and to be tested before introduce in to the commercial sector. The main aim of this study is to present a wear map as a tool to analyse and identify the wear regime for CNT-Al nano-composite developed using powder metallurgy route with the data generated by wear and friction test using pin-on-disc machine.

2. Experimental details

2.1 Materials

The composite were fabricated using pure aluminium (Al) (99.7%), with particle size of 78 µm which has nearly spherical shape with some satellite sub-particles obtained from Innovative Pultrusion Sdn Bhd, a local supplier for the aluminium powder was used as a matrix material. The multi walled carbon nano tubes (MWCNTs) with a nominal diameter of 10 nm, length of 5-15 µm, and surface area of 230-280 m^2g-1 was also obtained from the same supplier in Malaysia and used as a reinforcement. Ethanol was used as a process control agent (PCA) during the ball milling of CNT and Al powders. The composition of CNT-Al nano-composite is presented in Table 1.

2.2 Fabrication of nano-composites material

The composite was made based on the percentage composition of CNT in to the Al powder. High energy planetary ball mill machine with 250 ml stainless steel jar, steel balls of 10mm diameter was used for the fabrication of CNT-Al nano-composite powder, and to ensure the effective dispersion of CNT in to the Al matrix. The jar was filled with argon gas and the ball mill operations was performed using planetary mill (FRITSCH pulverisette 5 05.5000/00409) at constant speed of 300 rpm for three different milling time of 1, 2 and 3 hours. Samples were extruded from each batch at regular interval of 1 hr for analysis using a FESEM in order to investigate the dispersion of the CNTs in the Al matrix and also to analyze the nano-composite particle morphology and shape. Each composition was compacted using cold unidirectional pressing machine at the pressure of 48 MPa for each sample. The mould for the sample compaction was 10 x 10 x 20 mm to make the standard size for pin-on-disc machine sample. The samples were sintered using hot isostatic press (HIP) machine (HP630) at 500 ^{o}C and the argon gas was supplied at the pressure of 17 MPa for 60 min to control the atmosphere in the process.

2.3 Wear test

Pin-on-disc machine was used to conduct the experiment based on ASTM G99 standard. It has the same working principle with the commonly used pin on ring. However, the test specimen with size of 10mm x 10mm 20mm subjected to the counterface exhibits a unvarying contact area all through the test. The test specimen is set perpendicular and horizontal to the counterface. A load cell is directly included in the load lever of the machine to capture frictional forces during the test. A counter weight balancer is incorporated at the end of machine's load lever to balance the lever arm before starting the testing. This is step has to be done when no load is applied. The counterface material depend on the nature of the test, it can be of various types (i.e. metal, cast iron, titanium, aluminium, stainless steel, etc). Commonly, this test is simulated for applications such as sliding wear of various materials where constant contact area of interest. When the machine and sample setting is done, then the experiment started for a period of 12 min.

Table 1. Percentage composition of CNT-Al nano-composite

CNT Powder (wt%)	Al Powder (wt%)	Ethanol (mL)	Vickers Micro Hardness (VH)
1.0	99.0	1.0	92
1.5	98.5	1.0	103
2.0	98.0	0.85	100
2.5	97.5	0.85	60

3 Result and discussion

3.1 Wear mechanism characterization

Fig. 1 shows SEM morphologies of the worn surfaces of the CNT-Al nano-composite at different load of 5.5, 7.2, and 10 N. The worn surface of Al (0 wt %) shows a distinctive characteristic of abrasive and adhesive wear due to the confirmation of adhesion and ploughing on the worn surface. During the experiment the counterface disc seized three times at 5.5 and 7.2 N loads and once at 10 N loads, it may be as a result of weld which makes contact with surface metal that stick out from a surface at some point. This problem only occurred for Al, whilst no such predicament was experienced for CNT-Al nano-composite throughout the experimental time. This is due to the self lubrication effect of CNT as earlier mentioned. Al wear debris on the worn surface is coated by the disc on the contact area forming slow progress. This is because wear debris contain some aluminium oxide, leading to the oxidative wear mechanism of the composites [10]. However, based on the SEM morphologies of the worn surface of the composite and the delamination theory of wear, it can be deduced that, the delamination wear is the wear mechanism. Dislocations at the surface, subsurface crack and void (Fig.1b) are induced due to repeated plastic deformation of the surface layer of the composites. This phenomena is from the load applied which cause the displacement of atom of the metal from the base unit cell, creating a defect and the atom will not return to the original position even after the release of the applied load and the generated energy cannot be recovered. Afterward the cracks expand and cause break and split of the hardened surface layer by shear deformation of the surface.

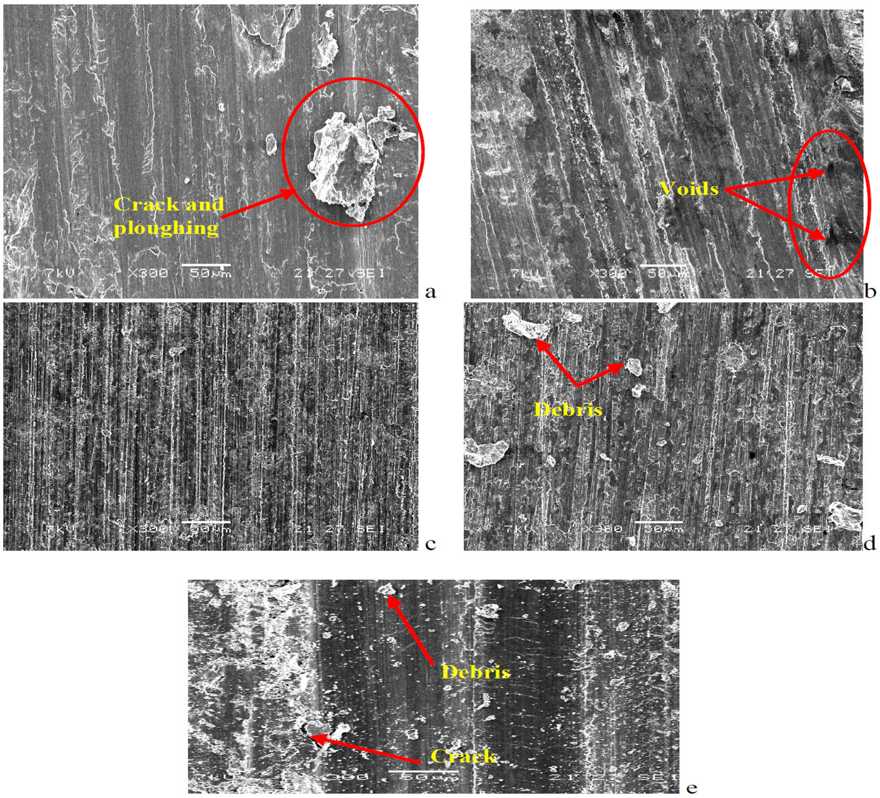

Fig. 1. SEM Image of the worn surface of (a) 0 wt% , (b) 1 wt%, (c) 1.5 wt%, (d) 2 wt% and (e) 2.5 wt% CNT-Al nano-composite materials.

As a result of the uniform and homogeneous dispersion of CNT in to the Al matrix, the plastic deformation of Al is restricted, which prevents the progressive development of the micro-cracks and continues movement of the dislocations. It is also observed that, the flake like scars on the worn surface of the nano-composite gradually became smaller and the confirmation of ploughing became shallower comparing the images (a) and (e) in Fig. 1. It is postulated that the abrasive and adhesive wear of the nano-composites is less predominant when compared with pure Al due to the extraordinary and excellent features of CNT that shows an affirmative effect on the Al matrix. Fig. 2 presents the FESEM image of the worn surface of CNT-Al nano-composite under 5.5 N loads showing the CNT dispersion in to the Al matrix, and it is assume that the dispersion of CNT is uniform and homogeneous in Al matrix and the achievement can be as a result of the use of appropriate quantity of ethanol as a process control agent and preliminary mixing of CNT and Al via manual hand shake before milling operation. The homogeneity of CNT in to the matrix ensures the improvement in wear resistance of the CNT-Al nano-composite. From Table 1 it is deduced that hardness of CNT-Al nano-composite increase with the loading of CNT content.

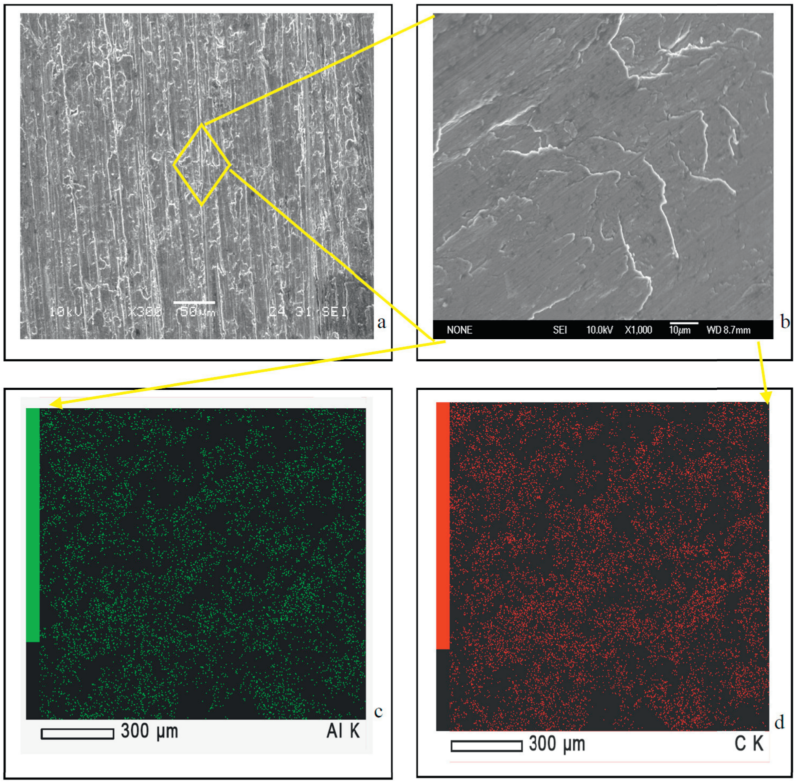

Fig. 2 (a) Worn surface of CNT-Al nano-composite at 5.5 N normal applied loads, (b) a portion of worn surface for mapping, (c) elemental mapping displaying Al in the nano-composite, (d) elemental mapping displaying CNT in the nano-composite.

3.2 Wear mechanism map for CNT-Al nano-composite

From the wear map and the SEM image of wear track both mild wear and severe wear have been identified. Wear maps of wear rate and CNT weight percentage against sliding velocity is plotted whereby the various sections related to diverse wear mechanisms and the transitions from mild to severe wear can be identified as shown in Fig. 2. Each section is defined in terms of wear rate, disc contact surface appearance, metallographic features of disc sections and wear debris. It was found that mild wear dominated at lower operating condition (load and sliding speed) which later remain steady with increase in duration of rubbing for CNT-Al nano-composite material, but for pure Al material severe wear was clearly occurred. For CNT-Al nano-composite with higher CNT wt% the wear rate at that point is not mild it is in between the two type of wear, or can be classified as moderate. In the mild system, wear seems to be dominated by surface oxidation and while in the severe and mixed system of wear, it is dominated by surface cracking and ploughing. The boundary line between the mild and the transition to mixed wear indicate the safe operating region of both material and the counterpart, whilst the boundary line between the moderate wear and the severe wear indicate the service life span of both material and the counterpart as well. From the map it is deduced that CNT-Al material exhibited most of the wear within the safe region. When comparing the two tested material that is Al and CNT-Al nano-composite, from the experimental results presented it is evidently shown that, wear rate of the material (Al) increases with the introduction of CNT as reinforcement. Finally it can be said that wear rate of CNT-Al nano-composite material lower than that of pure Al.

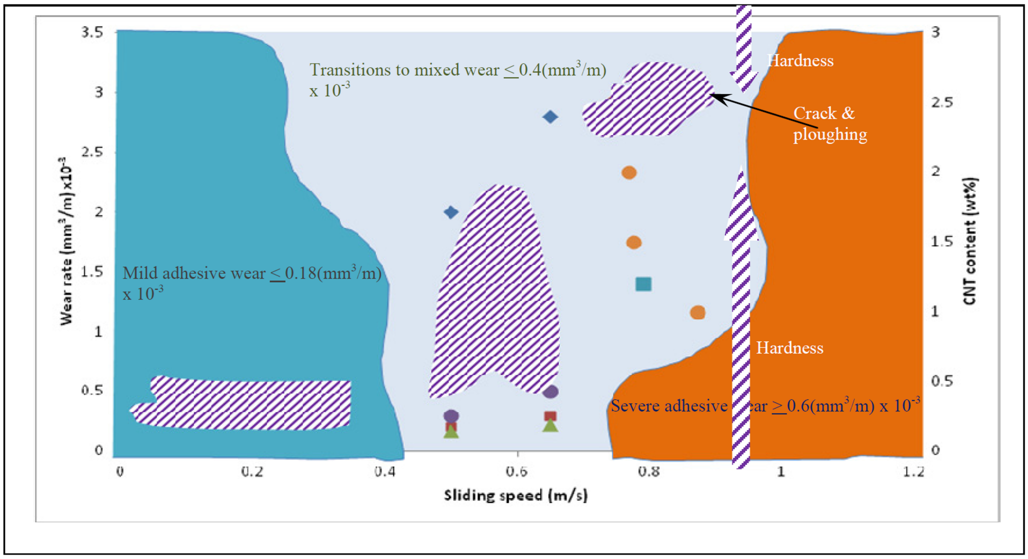

Fig. 3. Wear mechanism map of CNT-Al nano-composite material.

Conclusion

A wear map was developed and it served as a tool which identified and displayed regimes for different type of wear and the transition for CNT-Al nano-composite material. The wear data was obtained using pin-on-disc apparatus mainly for the purpose of this study. CNT-Al nano-composite shows lower wear rate than pure aluminium and wear rate of all the tested materials increases with increase in normal applied load. Wear rate decrease with increase in CNT content from 0-1.5 wt% and increase slightly from 1.5-2 wt%, then increase rapidly after this range of CNT content. A distinctive abrasive and adhesive wear were observed from the morphological image of the worn surface. Hardness increases with increase in CNT content from 0-1.5 wt% and decreased gradually from 2.0 wt%. Wear resistance increase also within the range of 0-1.5 wt% CNT and decrease subsequently with increasing of CNT content.

Acknowledgement

Authors are grateful to the International Islamic University (IIUM) fir financial support under RMGS12-007-0020 and Multimedia University which made this study possible.

References

[1] McQueen, H. J., Kassner, M. E., Evangelista, E., 2011. Hot working of aluminum alloys: Microstructures, properties and processing (Vol. 75): CRC PressI Llc.
[2] Rajesh, S., Rajakarunakaran, S., & Pandian, R. S., 2012. Modeling and optimization of sliding specific wear and coefficient of friction of aluminum based red mud metal matrix composite using taguchi method and response surface methodology. Materials Physics and Mechanics 15, p. 150-166.
[3] Umma, A., Maleque, M., Iskandar, I., & Mohammed, Y., 2012. Carbon nano tube reinforced aluminium matrix nano-composite: a Critical Review. Australian Journal of Basic and Applied Sciences 6(12), p. 69-75.
[4] Lacey, P. I., 1993. Wear with low-lubricity fuels I. Development of a wear mapping technique. Wear 160(2), p. 325-332.
[5] Kumar Mondal, A., Chandra Rao, B., & Kumar, S., 2007. Wear behaviour of AE42+ 20% saffil Mg-MMC. Tribology International 40(2), p. 290-296.

[6] Adachi, K., Kato, K., Chen, N., 1997. Wear map of ceramics. Wear 203, p. 291-301.
[7] Basavarajappa, S., Chandramohan, G., Mahadevan, A., Thangavelu, M., Subramanian, R., Gopalakrishnan, P., 2007. Influence of sliding speed on the dry sliding wear behaviour and the subsurface deformation on hybrid metal matrix composite. Wear 262(7), p. 1007-1012.
[8] Sharma, S., 2012. Abrasive Wear Study of Rare Earth Modified Coatings by Statistical Method. Journal of thermal spray technology 21(5), p. 773-781.
[9] Christensen, R. M., 2012. Mechanics of composite materials: Courier Dover Publications.
[10] Jin-long, J., Hai-zhong, W., Hua, Y., Jin-cheng, X., 2007. Fabrication and wear behavior of CNT/Al composites. Transactions of Nonferrous Metals Society of China 17, p. s113-p. s116.
[11] Maleque, M.A. and. Abdullahi U., 2013. Materials And Processing Route For Aircraft Brake System. International Journal of Mechanical and Materials Engineering (IJMME) 8(1), p. 14-20.