International Journal of Technology (2015) 3: 471-479
ISSN 2086-9614

WEAR RESISTANCE AND INTERLOCKING PROPERTIES OF AISI 5200 STEEL BALL BEARINGS COATED BY NANOCOMPOSITES

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(Received: July 2014 / Revised: June 2015 / Accepted: July 2015)

ABSTRACT

The performance of ball bearings is strongly influenced by the lubrication system. In this research, the development of a lubrication system was performed by the formation of an interlocking system through a composite coating, i.e. $Zn_3(PO4)_2$ / MoS_2 / MWCNT / nanographite / Na_2SiO_3 prepared by chemical immersion. The coating was applied through the one-mixing-layer and multi-layer techniques. The results showed that the one-mixing-layer technique has the ability to form an homogeneous thin layer with a surface roughness index that varies between 1.00 µm and 1.35 µm, whereas the thickness of the composite layers was found to be in the range from 5 µm to 6 µm. The multi-walled carbon nanotube (MWCNT) technique increased the interlocking capabilities of the coating and the solid lubricant. The one-mixing-layer technique indicated better results than that of multi-layer coated balls in terms of distribution and uniformity of elements on the coating surface, good interlocking between the composite compounds, and the thickness of the layer formed. The performance of nanocomposite coatings on the friction of the steel balls also showed that the ball bearings with a one-mixing-layer composite coating have a higher wear resistance than that of both the uncoated and the multi-layer coated ball bearings.

Keywords: Ball bearings; Carbon nanotubes; Interlocking; Lubricant; Nanocomposite

1. INTRODUCTION

Ball bearing service life depends on the suitability of the lubrication system. Many efforts have been made in order to improve the service life for ball bearings, especially because more than 50% of the ball bearing failures are generally caused by poor lubrication systems (Mowry, 2011; Radu, 2010). One of the efforts is to improve the surface quality of the ball bearing materials by coatings using diamond-like (DLC) (Zhang, 2015) or nanocoatings such as carbon nanotube (CNT) (Gao, 2001). Both methods show superior properties and corrosion resistance, however, coating by using CNT could be a good choice due to its relatively low cost compared with DLC.

It has been reported that the addition of 1 wt.% of CNT nanomaterial into a polymer matrix resulted in a 42% increase in tensile modulus and a 25% increase in tensile strength (Barbour, 1999), and with the addition of a 0.5 wt.% CNT nanomaterial into polyethylene significantly reduced the wear surface of the composite (Zoo, 2004). This CNT nanomaterial has also been used for solid lubricants because it has a smooth atomic surface, strong bonding structure, and the ability to withstand a compressive stress (Cai, 2004). In addition, this CNT nanomaterial has

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Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v6i3.433

also been proven to be a good adsorbent for organic material because of its huge surface area, van der Waals bonding, π-π electrons bonding, as well as the possibility of hydrogen bonding between the CNT composite coating and the lubricant resulting in a strong adsorption interaction (Lu, 2007; Joselevich, 2004; Sun, 2001; Star, 2003; Chin, 2010).

The correct combination of coating and lubricant is expected to provide an interlocking between the binding matrix and the lubricant. Therefore, it will produce a durable and efficient solid-lubrication system. In this research, coating development of the CNT nanomaterial and nanographite-reinforced nanocomposite to produce a high friction resistance system is discussed. Furthermore, the combination of this composite coating with a MoS_2-solid lubricant to increase the friction resistance of the ball bearings is examined. The main purpose of this research is to study the wear resistance and interlocking properties of CNT nanomaterial and nanographite-reinforced nanocomposite coated AISI 5200 steel ball bearings in a MoS_2-solid lubricant.

2. EXPERIMENTAL METHOD

2.1. Materials and Preparation

The material used was AISI 5200 steel ball bearings with a diameter of 0.5 inch supplied by NSK Indonesia. The chemicals used were MoS_2 powder with a purity $\geq$ 98%, Na_2SiO_3 (SiO_2: 46-52%; Na_2O: 47–53%), Zn_3PO4 with a purity $\geq$ 98%, nanographite (Ketjenblack with a particle size ranging from 30–40 nm), and multi-walled carbon nanotube (MWCNT, Flotube 9000 with purity 97.5%; surface area 234 m^2/gr; diameter 11 nm; and length 10 μm). The ball bearing samples were prepared in a beaker glass and soaked with heptane or benzene before dipping them into an ultrasonic bath. Ultrasonic cleaning was performed at low frequencies for 5–10 minutes and followed by airstream drying for 2 minutes.

2.2. Formation of Rough Surface

A total of 40 samples of AISI 5200 steel balls were used for each batch of the shot peening process. Shot peening was performed by using silicon carbide (SiC) powder with diameter of 0.3 mm at a pressure of 0.5 MPa for 15 minutes. After shot peening, the samples were washed with heptane or benzene in an ultrasonic bath for 5 minutes.

2.3. Nanocomposite Coating

The suitable coating method was firstly sought at the beginning of the experiment. In this event, nanocomposite coating was applied by using two different techniques, i.e. the multi-layer technique through layer-by-layer coating and the one-mixing-layer technique. An illustration of the coating technique is shown in Figure 1.

Layer-by-layer coating was performed through a gradual immersion. Shot peened ball bearings were heated at 50^{o}C before the immersion process. The first soaking was performed with 10 shot peened ball bearings and immersed into 100 mL of $Zn_3(PO_4)_2$ 6% at a temperature between 50°C and 60°C for 15 minutes. Samples were rinsed with distilled water and then airstream dried. The second phase was followed by soaking the balls at a temperature between 50°C and 60°C for 15 minutes in a 50 g mixture of MoS_2, nanographite, MWCNT and Na_2SiO_3 with a weight ratio of 1 : 2.60 : 0.25 : 0.05, respectively. The balls were removed and heated at a temprature of 135°C for 2.5 hours.

The one-mixing-layer coating technique was performed in one main stage. A total of 10 shot peened ball bearings had been heated at a temperature of 50°C and then they were immersed into a mixture composed of 100 mL $Zn_3(PO_4)_2$ 6%, MoS_2, nanographite, and MWCNT and homogenized for 5 minutes in an ultrasonic bath. The ball bearings were soaked in the mixture at a temperature between 50°C and 60°C for 15 minutes. After soaking, the balls were rinsed and airstream dried and then they were immersed in 100 mL sodium silicate solution (4.6 g of Na_2SiO_3 in 100 g of distilled water) at a temperature of 50°C. After that, the samples were heated in an oven at a temperature of 100°C during the first hour and 135°C for the remaining 1.5 hours.

The final step for both methods was burnishing by using a 3 mm Al_2O_3 ceramic ball at 200 rpm until the coating thickness reached 5 μm (using a coordinate measuring machine Crysta plus M-443). Finally the ball bearing surfaces were cleaned from any debris and ready for characterization.

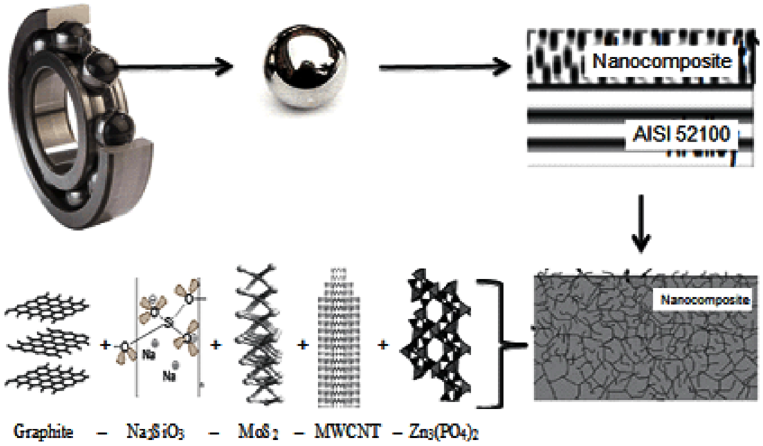

Figure 1 Schematic of nanocomposite coating on the steel ball bearing

2.4. Characterization

The surface roughness was characterized by using a Nikon Measuring Microscope MM-40. Physical topography and chemical properties of the nanocomposite coating were characterized by using a scanning electron microscope (SEM/EDX, FEI Inspect F50/EDAX). The surface hardness of the coating was examined by using a Vickers microhardness device. Friction testing was performed by using a four-ball wear method (NSK) and a Daphne ISO VG-10 lubricant with loading of 3 kg at 4000 rpm and torsion limit at 6 kgf at room temperature. The friction testing performed on both one-time lubrication and periodic lubrication (at time intervals of 4 min) was automatically recorded using a Keyence equipped with Wavethermo 1000 software.

3. RESULTS AND DISCUSSION

3.1. Surface Roughness

Figure 2 shows the surface roughness of the ball bearings before and after shot peening. As can be seen in Figure 2, variations in the height of the surface relative to a reference plane form asperities and valleys. These variations in the forms of asperities and valleys are the results of SiC collision with the surface of the AISI 52100 steel. A negative value indicates that the surface is made up of valleys, whereas a surface with a positive skewness is said to contain mainly peaks and asperities. This roughness will serve as the onset of interlocking so that the resistance of the composite coating adhesion to the shear force will increase (Jiang, 2007). A negatively skewed surface is good for lubrication purposes because it produces homogeneous interlocking better than the shape of a wide large valley or a short blunt (Sadeghi, 2010).

The increase in surface roughness from 0.005 μm to 0.200 μm is enough to increase the interlocking surface for subsequent coatings. The level of surface roughness can significantly affect the performance of the interface with the increase of roughness and surface area so that the adhesive contact will also increase. The asperities and valleys will lock the composite layer formed thereon in which the composite will not be easy to shift.

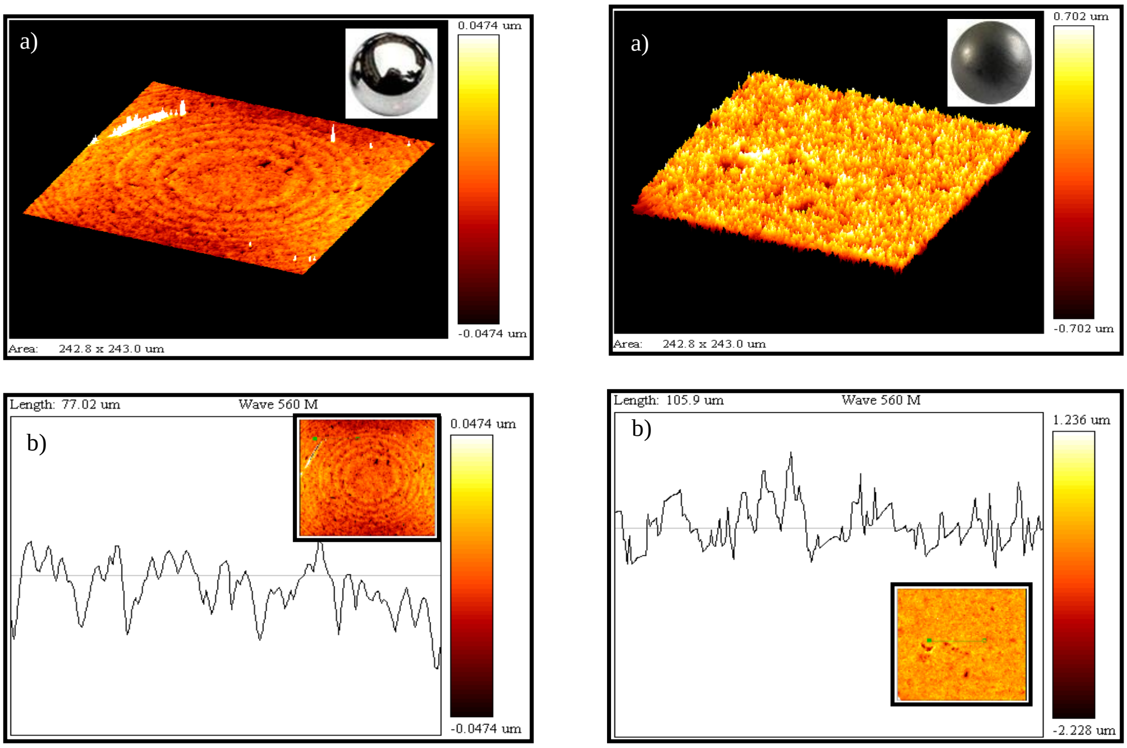

Figure 2 Surface roughness of the ball bearing before (left side) and after (right side) shot peening treatments: a) 3D surface roughness topography and b) Surface roughness profile

3.2. Nanocomposite Coatings

Subsequent modifications to strengthen the composite coating were performed using $Zn_3(PO_4)_2$ as an adhesive layer, which increases the contact surface area. Zinc phosphate forms a microporous crystalline layer that is attached to the surface of the AISI 5200. This phenomenon is utilized to increase the surface adhesion by enhancing surface interlocking. The surface topography of the composite coating can be seen in Figure 3. Micro-cracks are visible on the surface area of the phosphate crystal, whereas there is no visible crack on the surface area of MoS_2 crystals.

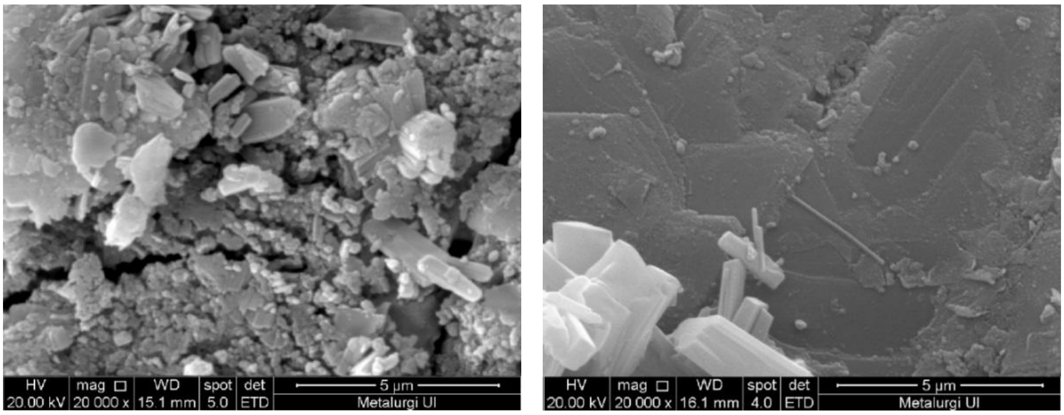

Figure 3 Surface topography of the composite coating. Microcracks are visible on the surface area of the phosphate crystal from layer-by layer examination (left), whereas there are no visible cracks on the surface area of MoS_2 crystals

The cracks are expected to occur due to the growth of phosphate crystals in which the crystals grow and tend to form aggregates and then blend together resulting in cavities. These cavities are then formed around the aggregates to form cracks (Phuong, 2013). On the other hand, the surface area of MoS_2 crystals is characterized by a regular layered structure that results in a smooth surface.

The layer-by-layer technique indicates that a mixture of composite layers is difficult to form into phosphate crystals because of the strong mix of the composite layers and the small pore size of crystalline phosphate. Two-dimensional EDS mapping images of the surface layer coated as a layer-by-layer technique and one-mixing layer technique is shown in Figure 4. As can be seen in Figure 4, there are separations between Zn and Fe that illustrate the presence of pores in the inner layer of the phosphate crystals. These pores, however, cannot be penetrated by the composite layer. The introduction of a burnishing process will then erode the outer layer of the film and open the pores in the inside layer.

The structure of the composite layer produced by the one-mixing layer coating technique has a better result when compared to the one produced by the layer-by-layer technique as can be further evidenced in the friction test simulating periodic lubrication conditions. In term of thickness, a ball bearing was set to a maximum thickness coating of 10 μm on the application. This was done to ensure the movement of the ball bearing in order to avoid friction with the retainer. Coating thickness can be controlled by the burnishing process in which the initial thickness of about 20 μm was reduced to 5-6 μm after burnishing.

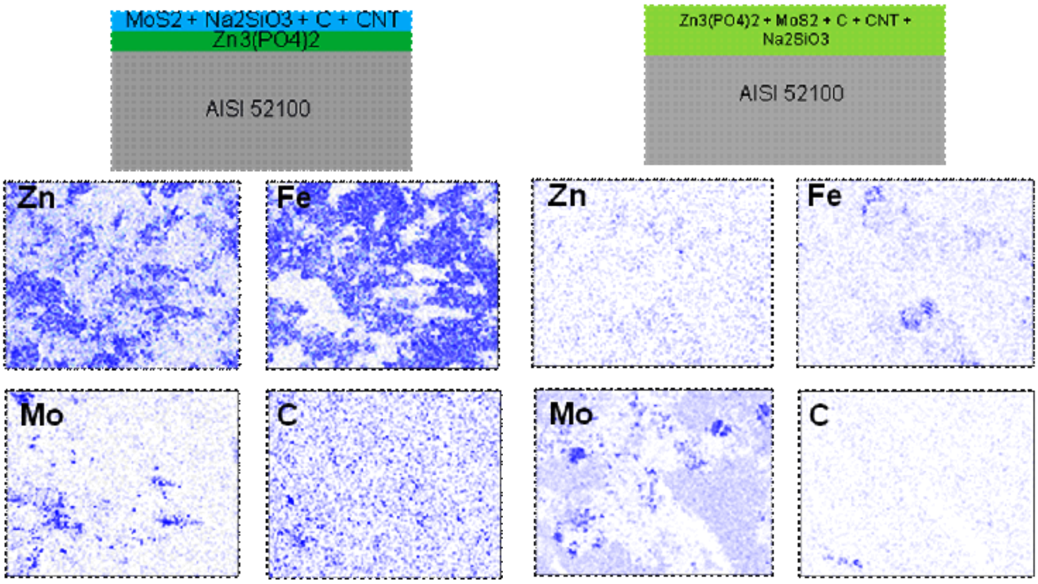

Figure 4 Two-dimensional EDS mapping images of the surface layer on the composite coating made by the layer-by-layer technique (left) and by the one-mixing layer (right) technique after burnishing

3.3. Hardness Test

The surface hardness of the composite coating was qualitatively characterized by using a Vickers microhardness gauge. Figures 5a and 5b show the difference between the indentation of the steel ball bearing and the composite layer, respectively. As can be seen from the figures, the indentation on the composite surface is larger than that of the steel surface. This is expected to be due to the fact that the composite layer is composed mostly of a crystalline phosphate matrix that is not as hard as AISI 5200.

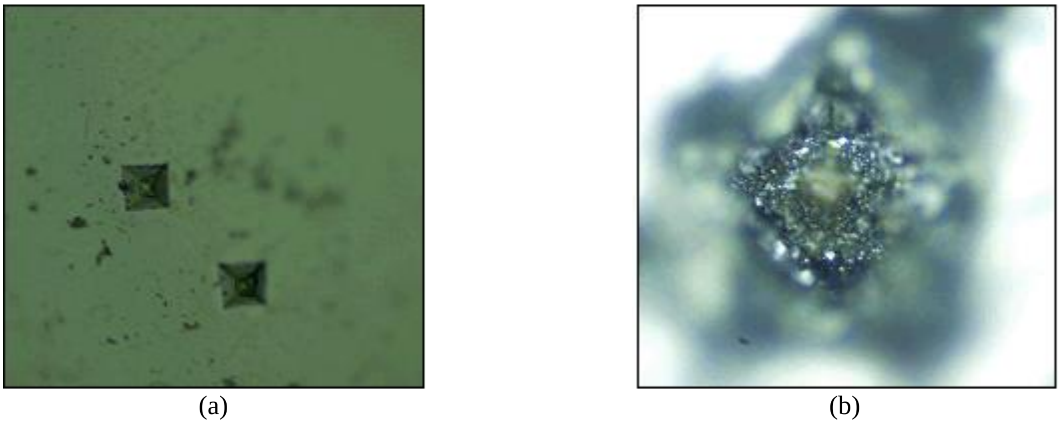
(a) (b)

Figure 5 Photograph of Vickers microhardness indentation on the surface of: a) steel ball bearing; b) composite layer

3.4. Friction Test

The friction test was performed through one-time and periodic lubrication conditions by using four-ball bearings (Figure 6). Friction test results of the composite coated ball bearings by using one-layer-mixing and layer-by-layer techniques can be seen in Figure 7. The results show that the friction resistance of the composite with one-layer-mixing technique is better than that of the composite with a layer-by-layer technique. It was found that some of porous structures were not occupied by the solid lubricants (MoS_2) and the strengthener materials (MWCNT and graphite) on the composite produced by layer-by-layer coating technique, results in less resistance during the friction stage. The elastic modulus index of the coating composition decreased with a corresponding increase in the pore size, and hence, this will affect the compression resistance when the friction test is loaded.

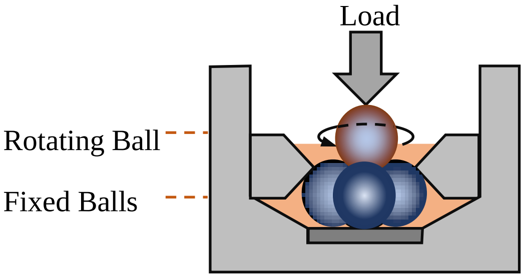

Figure 6 Schematic of the NSK four-ball wear testing equipment

The results of the NSK four-ball test on the one-time lubrication showed that the composite layer resulting from the one-layer mixing technique has better friction resistance than that of layer-by-layer technique. The ball bearings without coating and the ball bearings with Sic-shot peening do not have a good friction resistance. Although these balls have low surface roughness to avoid friction, the ball bearings do not have the lubrication retention on the surface so that in a short time these will become eroded by the friction causing a large increase in the friction index.

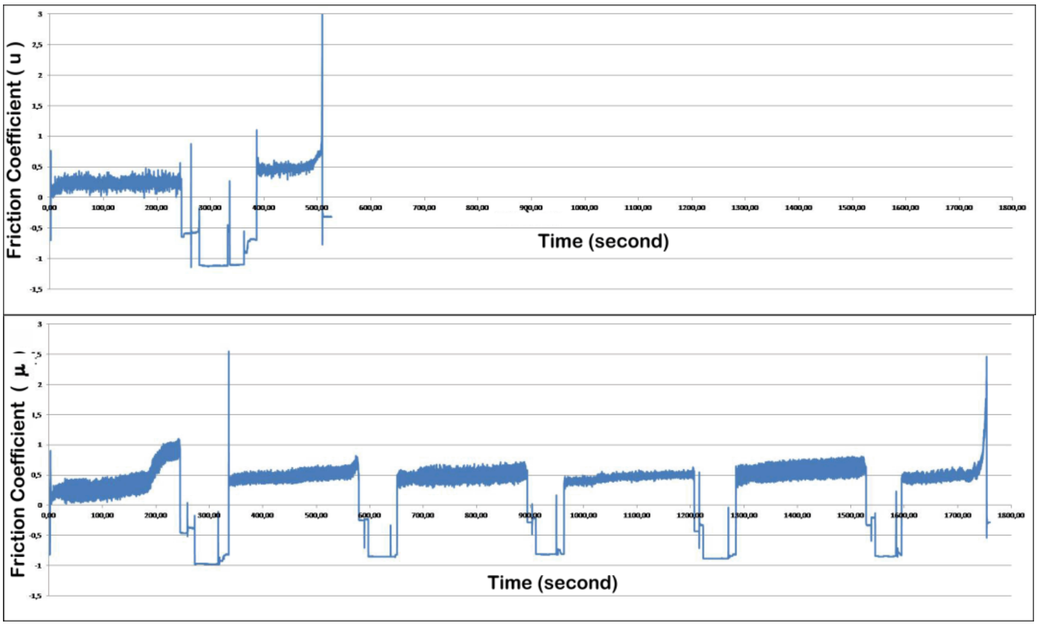

Figure 7 Friction test results of the composite coated ball bearings produced through layer-by-layer technique (top) and one-mixing-layer technique (below)

In general, friction will increase with an increase in surface roughness. On the contrary, according to Bikerman, the liquid layer on the surface would play an important role as a viscous substance and at a certain level surface roughness will act as a reservoir for lubricant (Ludema, 1996). The shot peened ball has low surface area related to roughness, however, the low friction only lasted for a short time because the surface cannot retain the lubricant and thus the layer gets eroded quickly causing an increase in friction.

Friction resistance increases with the use of MoS_2 as a solid lubricant. This can be understood because when the liquid lubricant starts to run out, the solid lubricant will take over the lubrication system. The lifetime of the MoS_2 coated ball bearings can be increased by approximately 16%, whereas for shot peening the MoS_2 coated ball bearing results in an increase of about 98%. Holmberg and Matthews explained that the MoS_2 layers are quickly compressed in the early friction stage to become a thin solid (Ludema, 1996; Winer, 1967). After many cycles, the thickness reduction will stop and film transfer on the composite surface begins, followed by a steady state stage in which the friction coefficients and the wear rates are low. Failure will take place when the surface experiences blister in which the dense layer becomes brittle and wear debris starts to form due to increasing friction. Adsorption of the lubricant on the surface seems to work quite well as wear-time increases sharply in the one-layer mixing technique for composite ball bearings. Thus, the friction test on this composite ball bearing indicates that the surface roughness has a little effect on the conjunction with the friction coefficient (Ludema, 1996).

The addition of graphite reduces the adsorption capacity of the phosphate crystal matrix due to the reduction of a large enough volume for the introduction of graphite into the micro layer. The reduction of crystalline phosphate adsorption can be compensated by an increase in the ability of graphite and MWCNT interlocking. This can be understood since the presence of MWCNT and graphite at the grain boundaries would create crack propagation to be locked and this would strengthen the grain boundary pinning mechanism (Mowry, 2011). Graphite and MWCNT will become second phase precipitates in the pinning mechanism and thus these two materials will create physical barriers so that dislocations cannot pass through them. To get through this barrier, dislocation must have a loop or have a large energy input to deform the precipitates directly. Hence, the trapped MWCNT at the bottom of the layer will become an interlocking anchor causing an increase of shear resistance (Keshri, 2011). Low friction value and a longer lifespan occurred in the one-mixing-layer composite coating. It shows that the binding liquid lubricants are excellent compared with the other composite ball bearings. Adsorption by the matrix remains the case, but the friction is further aided by the solid lubrication of MoS_2 and graphite-MWCNT interlocking. The friction value of the nanocomposite ball bearing is reduced by a combination of liquid and solid lubricants; as well as by the interlocking mechanism, therefore the combination of effects prolongs the lifespan of the ball bearings as can be seen in Figure 8.

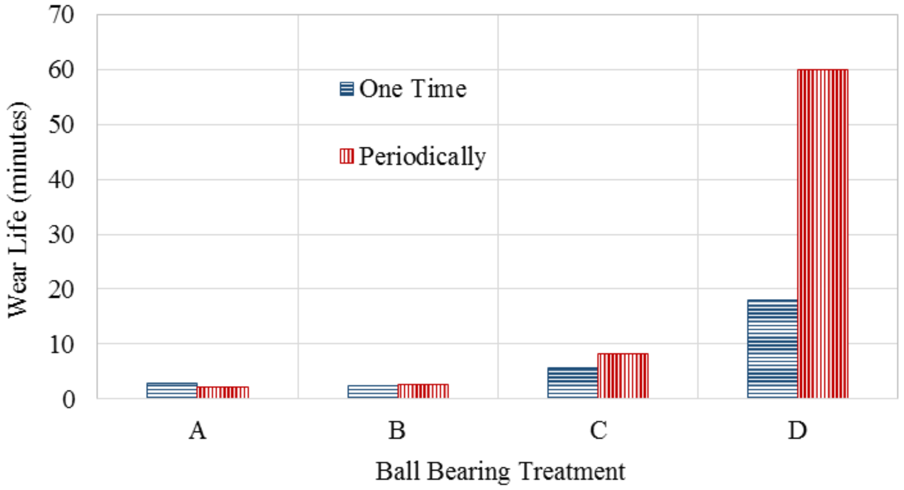

Figure 8 Wear lifetime results of the ball bearings: uncoated (A), shot peened (B), layer-by-layer coating (C), and one-mixing-layer coating (D) based on one-time and periodic lubrications

4. CONCLUSION

One-mixing-layer technique shows the ability to form a homogeneous thin layer when compared with the other multi-layer technique. One-mixing-layer technique also shows better results in terms of distribution and uniformity of elements on the coating surface, good interlocking between composite compounds and the thickness of the layer formed is in accordance with the bearing standard as compared to the other multi-layer technique. A thin layer of wear-resistant nanocomposite material can be formed chemically by interlocking reinforcement through shot peening and phosphate crystals. The ball bearings with a one-mixing-layer composite coating have a higher wear resistance when compared with both the uncoated and the multi-layer coated ball bearings.

5. ACKNOWLEDGEMENT

The authors would like to acknowledge the Directorate of Research and Public Services, Universitas Indonesia for the financial support through BOPTN Research Grant 2013.

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