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Lowering friction of ball screws made of different steel grades through ultrasonic impact treatment

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ABSTRACT

Ball screws made of SCM445H, NF42CD4 and SAE4150 steel grades were treated by ultrasonic nanocrystal surface modification (UNSM) technique to boost their performance by improving the surface integrity and lowering the friction. It was found that the friction of the UNSM-treated ball screws reduced successfully thanks to the improvement in surface integrity, transformation of tensile residual stress into compressive residual stress. Suggested mechanisms concerning lowering the friction of ball screws were discussed. Consequently, the feasible possibility of adopting the UNSM technique to a ball screw in order to improve its performance and reliability through lowering the friction was systematically investigated. Accordingly, the application of UNSM technique is a crucial approach to determine the replacement of those three different steel grades.

1. Introduction

A ball screw is a mechanical linear actuator that converts rotational motion to linear one (or vice versa) with a very low friction [1,2]. This mechanism associated with a combination of screw and nut, which operate similarly to bearing components between spiral raceway of screw and nut [3]. The spiral raceway of a screw serves as an inner race, while a nut serves as an outer ring. In the last decades, demand on ball screws, which installed in various machines, with the requirements of higher accuracy and better performance is increased. However, there are still a lot of issues related to their friction, wear, fatigue life and dimension tolerance, which directly provide a vibration-induced fracture. Most of the previous studies considered mostly improvement the quality of ball screws through developing new designs and lubrication optimization for minimizing the friction coefficient and reducing stress to the nut housing [4,5]. Wei and Lai presented a new model that was adopted for wear resistance of a ball screw [6]. Fleischer also developed a new method to minimize the friction and to extend the lifespan of a ball screw by lubrication supply [7]. An alternative simulation approach was made to investigate the frictional behavior of a ball screw in the previous study [8]. Moreover, Drossel presented a new approach to adjust a preload loss in a ball screw to improve the accuracy [9]. In order to investigate the rolling parts of a ball screw the correlation between friction and offset (displacement) needs to be balanced since it may lead to an error in motion [10].

In ball screw, there are usually three types of friction may occur: a solid friction can be derived when there is no lubrication between rolling balls and ball grooves; an elasto-hydrodynamic friction can be derived when there is always an oil between rolling balls and ball grooves; a mixed friction can be derived when there is some oil acting as a lubricant but also some direct dry contact between rolling balls and ball grooves. Ball screw moves much faster than before under the abrasion and adhesion wear regimes, where the abrasive wear is caused by contamination inside the ball-screw nut, while the adhesive one stems from a result of the oil-film breakdown. The effect of two wear regimes is premature failure from loss of preload. Therefore, one of the easiest way to improve the reliability and to extend the lifespan of a ball screw is a surface engineering. Much effort has been made to meet the higher accuracy and better performance requirements of a ball screw with low friction and wear by surface engineering and lubrication science [11,12]. For example, Brecher et al. investigated the role of oil additives to increase the wear resistance of a ball screw clarifying the possibility of adjusting the preloading by supplying oil additives that led to a low wear in comparison with the non-additived oils [13]. Corradi and Marchetti deposited a tungsten (W) coating onto a ball screw with the aim of lowering friction derived at the contact interface between the balls and grooves [14].

In this study, three different ball screws, namely made of SCM445H, NF42CD4 and SAE4150 steel grades, were treated by ultrasonic nanocrystal surface modification (UNSM) technique. The surface integrity and frictional behavior of those UNSM-treated ball screws were compared and discussed with the untreated ones. The main goal of the present study is to lower the friction of aforementioned ball screws with the aim of replacing high-hardness ball screw steels with another low-

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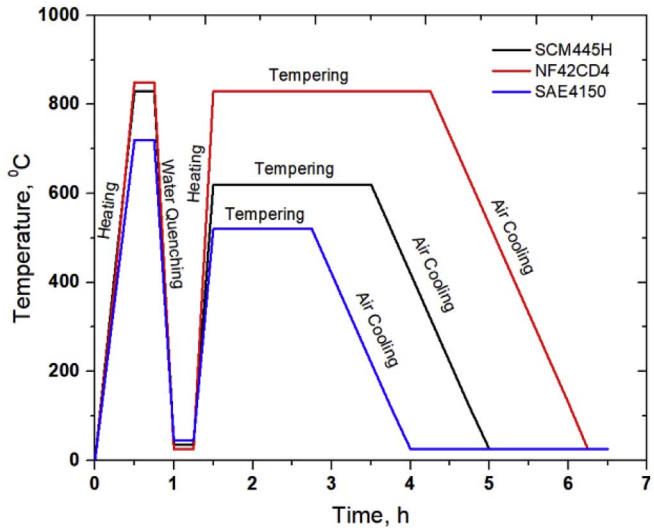

Fig. 1. Typical heat treatment process diagram for SCM445H, NF42CD4 and SAE4150 ball screw steel grades.

hardness ball screw steel by improving the surface integrity of the latter one by means of UNSM technique. Such material selection and replacement is very beneficial from an aggregate economic point of view. Another benefit is that some challenges and issues related to ball screw can be reduced by UNSM technique.

2. Experimental procedure

2.1. Sample preparation

Ball screw alloy grade is popular alloy steel used for engineering purposes, e.g. for ball screw, which works in the non-corrosive medium and temperature below 250 °C. Each ball screw steel was subjected to heat treatment in the formation of martensite, which can increase the strength together with a significant reduction in ductility. A typical heat treatment process diagram of SCM445H, NF42CD4 and SAE4150 ball screw steels is depicted in Fig. 1, where the heat treatment parameters such as heating temperature, tempering time and air cooling rate were different for ball screw steels. The chemical composition and mechanical properties of those ball screw steel grades (after heat treatment) are listed in Tables 1 and 2, respectively. Following heat treatment, the specimens ($10 \times 10 \times 5\ mm^3$) were cut off from ball screws by using a wire cutting and then were subjected to UNSM treatment. It needs to be mentioned here that the specimens were washed with an ethanol (50 ml) for 5 min.

2.2. UNSM treatment

A UNSM is a mechanical surface modification treatment that uses an ultrasonic energy to generate a surface and subsurface severe plastic deformation in the surface layer. A number of publications related to this UNSM technique improving the mechanical properties, tribological performance, corrosion resistance and fatigue strength of a wide range of materials are available in the literature [15–20]. Importantly, a thin mono- and poly-crystalline Si wafer with a thickness of 200 μm can be also treated by UNSM technique, which is the only mechanical surface treatment method that does not fracture such a thin Si wafer with no damages and cracks on the surface by mechanical impact [21]. In this special case, an oil lubrication supply that provides additional cooling at the contact point needs to be monitored carefully. Table 3 shows the optimized UNSM treatment parameters in terms of not only surface integrity, but also friction behavior. It is worth mentioning here that it was a bit of a challenge at first just to treat a ball screw by UNSM treatment because of its complex shape and form. Hence, it was required a special programming language G-code written for computer numerical control (CNC) machine. We could command the CNC machine where and how to move to various points at a desired speed by inputting a programming language code into it. A photography of a ball screw that subjected to a UNSM treatment is depicted in Fig. 2. Obviously, the features of UNSM treatment on the groove surface of a ball screw can be seen in Fig. 2(b) (shown by an arrow). In general, when the surface of a metallic material is treated by UNSM technique, a rainbow colored shiny surface can be observed reflecting to green, violet, blue purple, red, brown hues due to the surface modification features such as surface roughness, reflectance, etc. The quality of the UNSM-treated ball screw depends on the UNSM treatment parameters listed in Table 3 below, where its evaluation can be made through the intensity of light that is absorbed and reflected due to the spectrochromatic shift. The intensity of color on the UNSM-treated surface depends on the observation angle of light. However, improper UNSM treatment conditions may affect how the UNSM-treated surface refracts light.

Table 1
Chemical composition of three different ball screw steel grades (in wt.%).

Steel grades	C	Cr	Ni	Mo	Mn	P	S	Fe
SCM445H	0.22	1.1	0.25	0.25	0.7	0.03	0.03	Bal.
NF42CD4	0.4	1.0	0.25	0.25	0.85	0.01	0.02	
SAE4150	0.5	0.95	–	0.25	0.1	0.04	0.04	

2.3. Friction behavior evaluation

The effects of UNSM treatment on dry friction of three different ball screw steel grades were evaluated using a reciprocating type of tribometer (CSM Instruments, Switzerland) (see Fig. 3) under the conditions listed in Table 4. A heat treated ball made of bearing steel SAE52100 with a diameter of 12.7 mm was chosen as a counterpart specimen for simulating the closest similar working conditions. The hardness of a counterface ball was about 62 HRC.

2.4. Characterizations

The surface profilometer (SJ-210, Mitutoyo, Japan) and the Vicker hardness tester (MVK-E3, Mitutoyo, Japan) were used to measure the surface roughness and hardness of the ball screws. The change in surface morphology and wear mechanisms after friction test was observed by scanning electron microscopy (SEM: SNE-300 SEC, Korea). The chemical composition was examined by energy dispersive X-ray (EDX: XFlash®6 SDD, Bruker, USA) integrated with the SEM. The cross-sectional profiles and images of the wear tracks were obtained by laser scanning microscopy (LSM: Keyence VK-X100, Japan). X-ray diffraction (XRD: Bruker D8 Advance) was employed running at 40 kV/mA with Cr K_α radiation at a wavelength of 1.54 scanned over the 2θ range of from 30° to 90° with a scan speed of 1.0°/min to confirm the grain size refinement, to measure the full-width at half maximum (FWHM) and micro-strain and also to confirm if any phase transformation occurred after UNSM treatment. The surface was polished by an electropolisher-etcher (ElectroMet 4, Buehler, USA) to eliminate the top surface layer. The obtained residual stress measurement data with respect to depth from the top surface with a huge error bar represent the average of three measurement results.

3. Results and discussion

3.1. Surface topography

Fig. 4 shows the surface topography of ball screw steel grades showing that the surface of the untreated ball screws was modified after

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