Tribology International 122 (2018) 133–142

Contents lists available at ScienceDirect

Tribology International

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

Shear properties under the starved condition of polyisobutylene lubricant for use in screw tightening-effect of operating condition on lubrication properties

Takefumi Otsu [a,*], Kyoichi Komatsu [b], Shinji Hashimura [c], Keiji Imado [a]

[a] Division of Mechatronics, Department of Innovative Engineering, Faculty of Science and Technology, Oita University, 700 Dannoharu, Oita, 870-1192, Japan
[b] Tohnichi MFG. Co., Ltd., 2-12 Omori-kita 2 Chome, Ota-ku, Tokyo, 143-0016, Japan
[c] Faculty of Engineering, Shibaura Institute of Technology, 7-5 Toyosu 3-chome, Koto-ku, Tokyo, 135-8548, Japan

ARTICLE INFO

Keywords:
Lubricant
Screw tightening
Polyisobutylene
Starvation
Shear properties
Shear stress
Solidification
Elasto-hydrodynamic lubrication
Optical interferometry

ABSTRACT

This paper describes that shear properties of polyisobutylene (PIB) lubricant under the starved condition using in-situ observation in order to understand the lubrication mechanism in the screw tightening process. Specifically, the study focused on the effect of operating condition (sliding speed and contact pressure) on the lubrication performance. In the test at various sliding speed, the film thickness decreased with expansions in the starved area, however, the thickness was thicker than the surface roughness of the specimens even in the full starvation condition. The shear stress under fully starved condition at 15 N did not depend on shear rate and was a constant value corresponded to almost 50 MPa in all the speeds. In the test at various contact pressure conditions, the film was formed in the contact area at the full starvation condition and the value was higher than the surface roughness. It was also found that shear stress at fully starved condition increased with increases in contact pressure. These results suggest that the solidification film was formed on the contact area in the starved condition and the film formation with high limiting shear stress inhibits direct contact and wear. This lubrication performance offers a stable value of friction coefficient in the tightening process and facilitates precise control of the clamping force.

1. Introduction

With respect to the screw tightening of the bolt-nut joints, the clamping force is affected by friction that occurs on the thread surfaces and the bearing surfaces. In the case of torque control method [1] (in which tightening torque is given as Eq. (1)), the clamping force is given by Eq. (2) [1,2]. This implies that the force depends on the torque coefficient (as shown in Eq. (3) [2]) when a constant tightening torque is applied. As shown in Eqs. (2) and (3), the clamping force is affected by the friction coefficient (μ_s, μ_w), and thus it is not possible to precisely control the clamping force if the friction coefficient is widely changed [3]. For example, a simple calculation using Eqs. (2) and (3) reveals that the clamping force of M10 bolt (metric bolt with a nominal diameter of 10 mm) is scattered in the range of ±30% for the target value if the friction coefficient changes in the range between 0.1 and 0.2 (the detail of calculation method is shown in appendix A). Furthermore, previous study suggest that it is only possible to control the clamping force with a scatter of ±10% - ±30% by using the torque wrench [4–6]. The expressions are as follows:

$$T = KFd \tag{1}$$

where T is tightening torque, F is clamping force, K is torque coefficient, d is nominal diameter

$$F = \frac{T}{Kd} \tag{2}$$

$$K = \frac{d_2}{2d}\left(\frac{\tan\beta + \mu_s \sec\alpha'}{1 - \mu_s \tan\beta \sec\alpha'}\right) + \frac{d_w}{2d}\mu_w \tag{3}$$

where d_2 is mean diameter, β is helix angle of thread, μ_s is friction coefficient between thread surfaces, α' is flank angle, d_w is mean bearing diameter, μ_w is friction coefficient between bearing surfaces.

The friction coefficient is related to geometrical and surface

* Corresponding author.
E-mail address: ootsu-takehumi@oita-u.ac.jp (T. Otsu).

https://doi.org/10.1016/j.triboint.2018.02.021
Received 22 November 2017; Received in revised form 19 February 2018; Accepted 19 February 2018
Available online 23 February 2018

properties [4], such as the geometrical error (such as squareness and parallelism tolerance) [7], surface profile [8] and lubrication [8–11]. Previous study [7] indicate the absence of uniformly in the geometrical errors due to the decreased processing accuracy. Therefore, the friction coefficient in the screw widely changed at each tightening process [3], and this implies that it is not possible to precisely control the clamping force. Hence, this is an important issue that should be resolved to accomplish safety with respect to the machine design of screw tightening to precisely control the friction coefficient. A method to enable this is the use of lubricant for screw tightening [12]. The lubrication film potentially protects the surface from direct contact and wear, and therefore the friction coefficient does not widely change. Recently, Croccolo et al. reported that ceramic paste lubricant showed highly effective for reducing friction coefficient and preventing wear in re-tightening operations [10, 11]. In this study, polyisobutylene (PIB) lubricant [13,14] is targeted as the lubricant for screw tightening. Currently, PIB is expected to correspond to the lubricant with high control ability of the clamping force [12]. However, there is a paucity of studies that explore the detail of the mechanism by which the PIB lubricant film aids in the uniform friction coefficient.

In the present study, a fundamental friction test that simulated the contact surface of screw tightening was conducted, in which the in-situ observation system was used to understand the film formation and breakdown. With respect to the lubrication of the screw surfaces, the lubrication regime is suggested as thin film lubrication or boundary lubrication regime. In the study, these conditions were simulated at the sliding friction test under the starved condition. Previous studies [15,16] on the starved elasto-hydrodynamic lubrication (EHL) reported that the film formation was observed, and the film thickness was measured by using the optical interferometry method. The results in the starved condition revealed that the film thickness reduced due to decreases in the amount of oil at inlet, which is related to the inhibition of generation of hydrodynamic pressure with respect regarding to the wedge effect. Additionally, the formula for calculating minimum inlet length (meniscus length) to prevent the starved condition was given by hydrodynamic theory [15,17]. Previous studies [18,19] involved proposing the oil replenishment model in the starved condition and examining oil reflow to the contact area that is related to the surface tension as well as the circulation flow [20] that affects the formation of film. Numerical simulations [21,22] using the replenishment model showed that the simulated film thickness at the starved condition corresponded to the experimental results. Conversely, Kingsbury [23,24] reported that the adequate film thickness was maintained in the long term and the direct contact on the surface was prevented by the film (this is termed as parched lubrication). The measurement of film thickness by using the spacer layer method showed that a film with a thickness of tens of nm was formed during 20 min–30 min from the start in the parched lubrication [25,26].

A previous study [27,28] examined the fundamental tribological properties of PIB by using point contacted spinning friction test and a point contacted EHL test. These results demonstrated that the friction coefficient of PIB exceeded the value of the other lubricant, although the wear was smaller than that obtained by using the other lubricant. The results reveal that PIB lubricant inhibits the direct contact between the surfaces due to the formation of lubrication film with high shear strength. In the EHL test under the starved condition, the film thickness corresponded to over tens of nm, and this exceeded the surface roughness of the specimens. Moreover, the shear stress of the film did not depend on the share rate, and the value was greater and almost corresponded to 50 MPa. This revealed that the film changed to a solid like film and the limiting shear stress of the film was 50 MPa. This corresponds to the results in the spinning test, meaning that the film with high shear strength was formed on the sliding surface. The formation of solidification film in PIB aids in inhibiting the direct contact and wear on the surfaces. Therefore, the use of PIB for the screw tightening can lead to stable film formation on the screw surfaces, and this implies that friction coefficient is precisely controlled as uniform value.

This study describes the shear properties and the film formation of PIB under the starved condition in order to understand the detail of solidification film formation mechanism. Specifically, the study focused on the relationship between the lubrication performance and the operating conditions (sliding speed and contact pressure). In the test, an in-situ observation for the point contact EHL film was conducted and the film thickness was measured using the spacer layer method [29]. In addition, the shear stress of the film on the sliding surfaces was also simultaneously measured to understand the solidification properties of PIB.

2. Experimental

2.1. Test apparatus

Fig. 1 shows a schematic of the test apparatus employed in this study, that is typically used for a point contact, pure-sliding EHL tests. The observation in the contact area is performed by using a microscope.

In the system, a disc was fixed on the plate part, and a ball was connected to a rotating shaft. The ball was pressed against the disc by a lever mounted on a fixed plate, and the ball was rotated by a motor such that it slides on the disc. The plate part was fixed on a linear guide and could move in the sliding direction. The friction force generated on the contact area was measured by a load cell fixed in front of the plate part. The lubricant was applied to the disc surface prior to the start of the test.

A ball specimen was made of JIS SUJ2 bearing steel, which is equivalent to AISI 52100. The radius of ball was 19.05 mm. A BK7 glass disc coated with a semi-reflective chromium layer and a silica spacer layer [29] (thickness is 300 nm) was used to measure the film thickness by using the optical interferometry method with a spacer layer. The root mean squared surface roughness of the ball and the disc were 10 nm and 5 nm, respectively.

2.2. Test conditions

The tests were conducted under a normal load of 15 N, 28 N and 48 N in which the corresponding average Hertzian pressures were 320 MPa, 393 MPa and 470 MPa to simulate the contact pressure in the thread surfaces and the bearing surfaces at the actual tightening condition. Based on previous research conditions [28], the sliding speeds were selected, that were 112 mm/s, 168 mm/s and 224 mm/s, respectively.

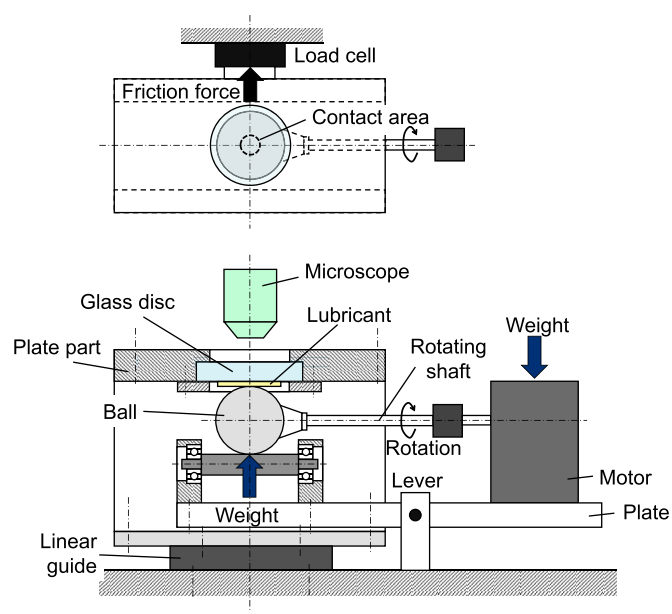

Fig. 1. Test apparatus.