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Citation	Biosurface and Biotribology (2019), 5(1): 24-27
Issue Date	2019-01-24
URL	http://hdl.handle.net/2433/242852
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Type	Journal Article
Textversion	publisher

Biosurface and Biotribology

Research Article

Destruction energy index (DEI) of vitamin E blended UHMWPE for artificial joints

ISSN 2405-4518
Received on 24th August 2018
Revised on 6th November 2018
Accepted on 29th December 2018
doi: 10.1049/bsbt.2018.0027
www.ietdl.org

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Abstract: Destruction resistance such as start-up wear resistance characteristics of vitamin E (dl-α-tocopherol) blended ultra-high molecular weight polyethylene (UHMWPE) were evaluated using the destruction energy index (DEI). The DEI is used to evaluate wear-like destruction, by minimising the effects of viscosity at the sliding interface, and is estimated using newly designed friction testers. In this experiment, silicone oils of different viscosities were used to determine micro displacement up to a start-up point, and the DEI of the UHMWPE was changed from 17.48 to 1.84 μJ by adding vitamin E. The results suggest that the blending with vitamin E reduces destruction of UHMWPE at start-up friction in silicone oils.

1 Introduction

Total joint replacement is an effective treatment for severe arthritis. Ultra-high molecular weight polyethylene (UHMWPE) has been used for more than 50 years, a bearing material for total joint replacement of artificial joints [1]. However, the wear debris of UHMWPE causes osteolysis, which leads to aseptic loosening [2].

Vitamin E blended UHMWPE (dl-α-tocopherol) has been developed as the bearing surface for total joint replacement. Vitamin E blended UHMWPE offers an artificial joint replacement with good mechanical properties, oxidation resistance and wear resistance. The vitamin E added UHMWPE was also reported to prevent crack initiation at subsurface grain boundaries of UHMWPE [3], and the wear volume examined by the knee joint simulator was reduced to 30% compared to that of virgin UHMWPE [4]. On the other hand, Okubo *et al.* evaluated the tribological performance of the vitamin E blended UHMWPE, and reported that the friction force was higher than that of virgin UHMWPE [5]. The wear volume does not always correlate with friction forces when viscoelastic bodies, such as UHMWPE, are in contact with viscous fluids. The influence of viscosity must be taken into account to evaluate the wear.

On the other hand, in day-to-day dynamics, the kinetic friction is predominant over the start-up friction. At start-up, implants may cause direct local contact after sustained standing position and may drastically increase the wear-like destruction. Therefore, we focused on static friction of start-up friction and proposed a new index for wear-like destruction at a sliding interface, named destruction energy index (DEI). The DEI is expressed as a bristle model [6–8], using irreversible viscoelasticity in the presence of micro displacement before start-up [9].

Fundamentally, the DEI and dynamic friction are different concepts. However, we assume that the lower wear of vitamin E blended UHMWPE was caused by the increased contact viscosity of the UHMWPE or the material–fluid interaction. In this study, the effects of vitamin E blending on the contact viscosity were investigated using the DEI.

2 Materials and method

2.1 DEI model

The phenomenon of friction at the sliding interface of artificial joints is difficult to analyse because of complex interactions between destruction and viscoelasticity of the material, the viscosity of lubricant, molecular cleavage, adsorption and/or immersion of lubricant at the interface, and so on. This complex phenomenon at the sliding interface is analysed with a simple irreversible bristle model [6], on which the theory of DEI is based, as shown in Fig. 1. The bristle has deflection x_0 (micro displacement up to a start-up point), and the sum of the elastic element and the viscous element is observed as the friction force. k is the elastic modulus and λ is the viscosity of this system. DEI is defined that the dissipated energy due to viscosity corresponds to, e.g. thermal energy, while the elastic energy released from the system contributes to 'destruction' such as molecular scission, abrasion, and loss of adhesion.

The DEI is expressed as the product of f_k (an elastic component of starting friction force) and the half value of x_0.

$$\mathrm{DEI} = \frac{1}{2} f_k x_0 \tag{1}$$

The start-up friction force is correlated to the load increase rate. We estimated f_k by extrapolating load increase rates to zero for start-up friction [10].

2.2 Experimental apparatus and procedure

The vitamin E blended UHMWPE block was manufactured using a direct compression moulding from UHMWPE GUR1050 resin powder, blended with vitamin E (dl-α-tocopherol, 0.3 wt%). The virgin non-crosslink UHMWPE block, which was used as the control specimen, was manufactured similarly, but without the addition of vitamin E. Prior to machining of the final shape, these blocks were machined to flat-ended cylindrical shape ($\varphi 5 \times 10$ mm) by a turning machine. After ultrasonic cleaning in isopropanol for 5 min, three specimens were installed so that they protruded more than 2 mm to the sample holder. Finally, the sample stage was placed on the turning machine; the specimen was machined to protrude 2 mm and cleaned in isopropanol for 5 min (Fig. 2).

Experiments were conducted with the static friction tester shown in Fig. 3. The experimental conditions are listed in Table 1. Each UHMWPE specimen was in contact with the optical prisms with contact stress of 5.3 MPa on the lubricant of silicone oil of different viscosities (10, 100, 1000 cSt). The sample holder and weight were connected and pulled by the automatic stage via the spring. The load increase rate was controlled by driving the automatic stage at a constant speed and the statics period before the experiments was constant [11]. Friction forces and micro displacements at each load increase rate were measured by the load cell and the laser displacement sensor.

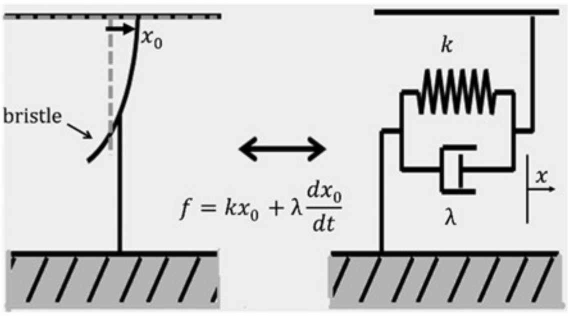

Fig. 1 *Schematic of the bristle model*

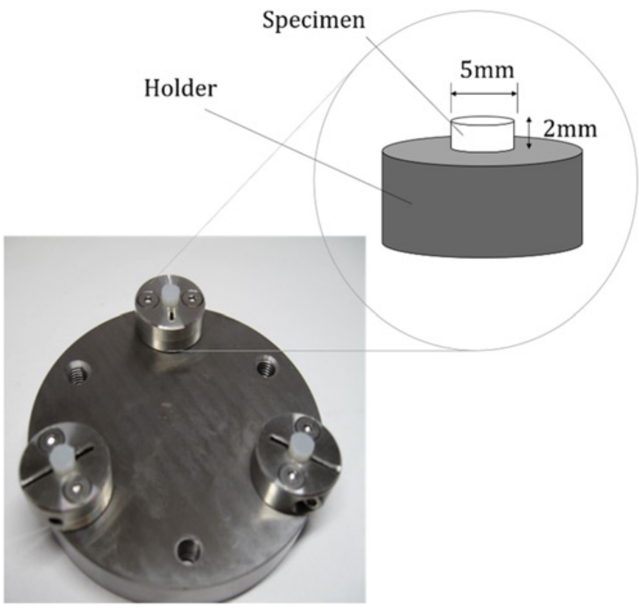

Fig. 2 *Appearance of specimens and sample holder*

2.3 Data processing

Estimation of DEI requires the measurement of x_0 (micro displacement up to starting point) and f_k (an elastic component of starting friction force).

The estimation was made assuming the viscosity of the lubricant to be affected only by the viscosity term. Therefore, DEI is considered to be consistent in the lubricants of different viscosities in the model. As the measured DEI does not completely match in each viscosity of lubricant, the approximate value of x_0 that represents the minimum value of the coefficient of variation of DEI, was adopted in this experiment.

The coefficient of variation was calculated with the following formula:

$$V_c = \frac{\sum (\mathrm{DEI_M} - \mathrm{DEI_R})^2}{\mathrm{DEI_M^2}}, \tag{2}$$

where V_c, $\mathrm{DEI_M}$, and $\mathrm{DEI_R}$ represent, respectively, the coefficient of variation, the mean of DEI, and the DEI at each viscosity.

3 Results and discussion

An example of the measurement results is shown in Fig. 4, where the horizontal axis x_0 is changed from 0.5 to 20 µm in a unit of 0.5 µm. There is a micro displacement until start-up. The optimal solution of x_0, which represents the minimum value of the coefficient of variation, was chosen for the calculation.

Fig. 5 shows the DEI for different values of x_0, from 0.5 to 20 µm, at each viscosity. The coefficient of variation was determined from these results, as shown in Fig. 6. The minimum value of the variation coefficient for the vitamin E blended and the virgin specimens are 1.0 and 3.0 µm, respectively. Therefore, these values are defined as an approximate value of x_0. The DEI of the vitamin E blended and the virgin UHMWPE were 1.84 µJ ($x_0 = 1.0$ µm) and 17.48 µJ ($x_0 = 3.0$ µm), respectively.

The DEIs and approximate value of x_0 of the vitamin E blended UHMWPE were lower than those of the virgin UHMWPE. It is suggested that blending with vitamin E reduces destruction at start-up. The coefficient of variation of the vitamin E blended UHMWPE was higher than that of the virgin UHMWPE.

As can be observed in Fig. 7, the relationship between the load increase rate and the frictional force shows a positive correlation. However, the gradient obtains silicone oil stained by extrapolating the load increase rate in linear shows no increase by adding vitamin E. It is unreasonable if vitamin E increases the viscous component of contact stiffness. There are possibilities that the

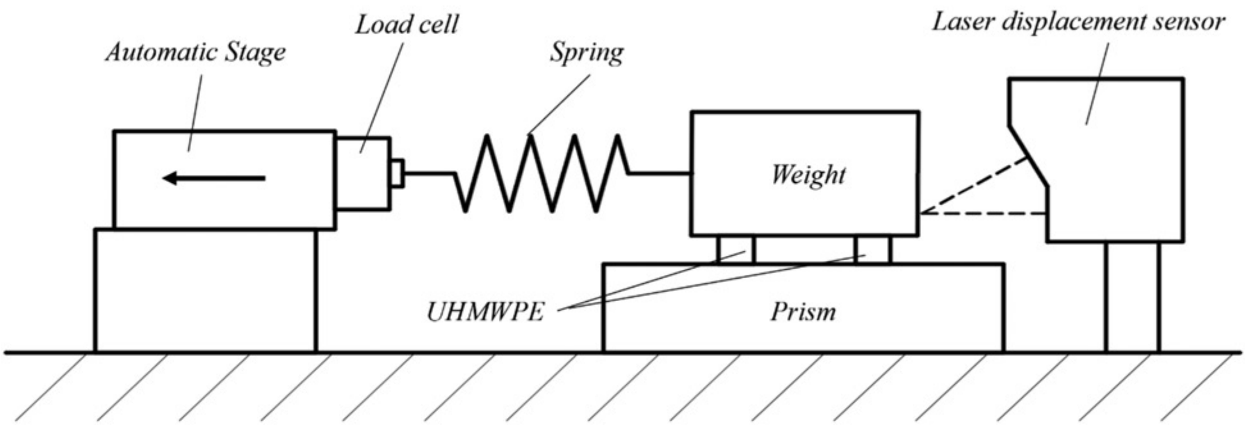

Fig. 3 *Schematic diagram of the experimental apparatus*

Table 1 Experimental conditions

Specimen	VE-UHMWPE, virgin-UHMWPE
counter surface	prism
load increase rate, N/s	1, 8, 16, 24, 30, 36
nominal contact stress, MPa	5.3
normal load, N	310
static period, s	60 ± 1
lubricant, cSt	silicone oil 10, 100, and 1000
number of samples	3

VE-UHMWPE, vitamin E-blended UHMWPE.

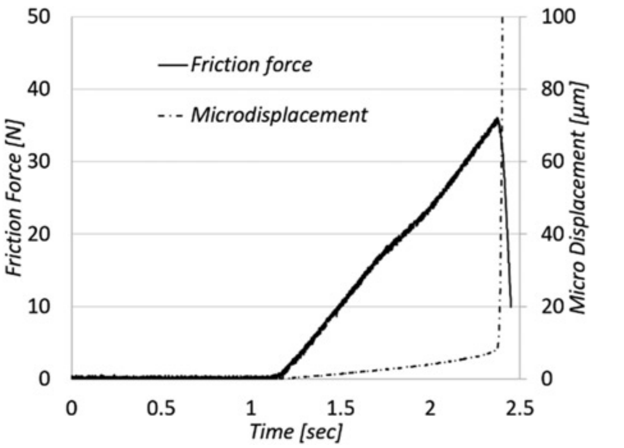

Fig. 4 *One case of the friction-time relation and micro displacement-time relation*

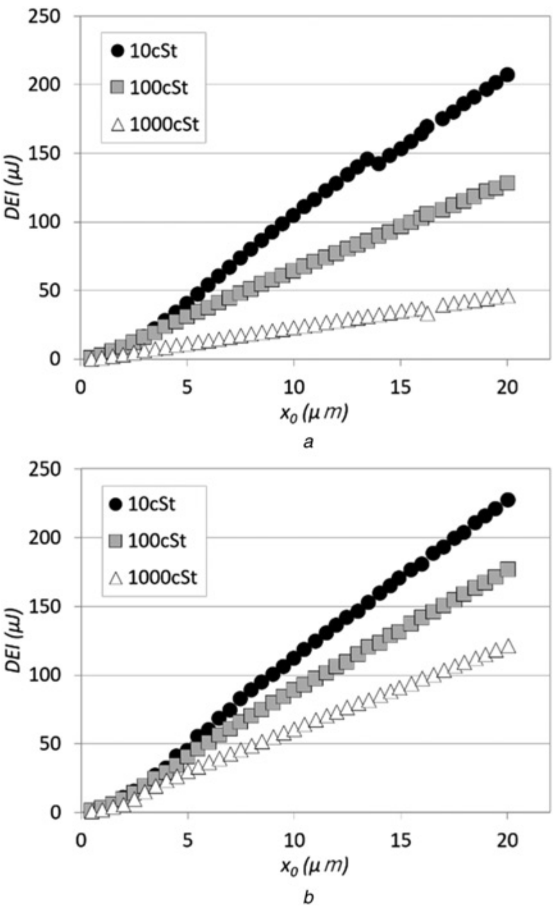

Fig. 5 *Relationship between DEI and x0 in three viscosities*

a Vitamin E blended
b Virgin

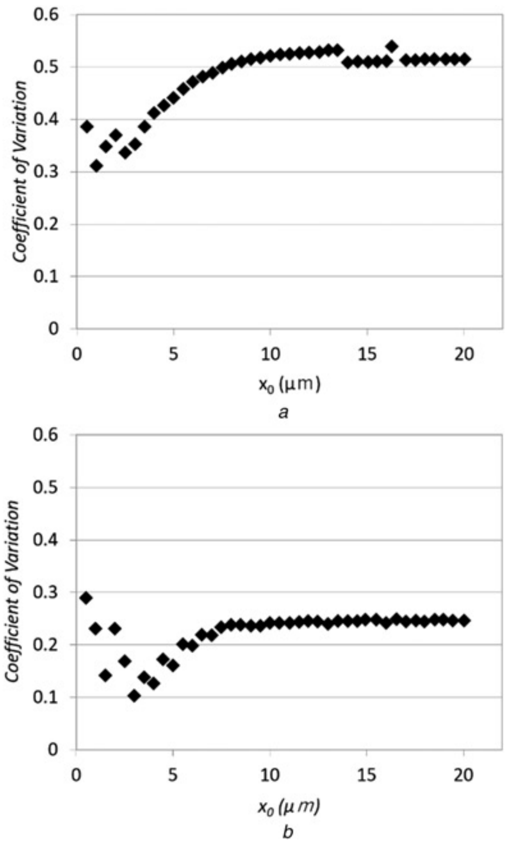

Fig. 6 *Relationship between the coefficient of variation and x0*

a Vitamin E blended
b Virgin

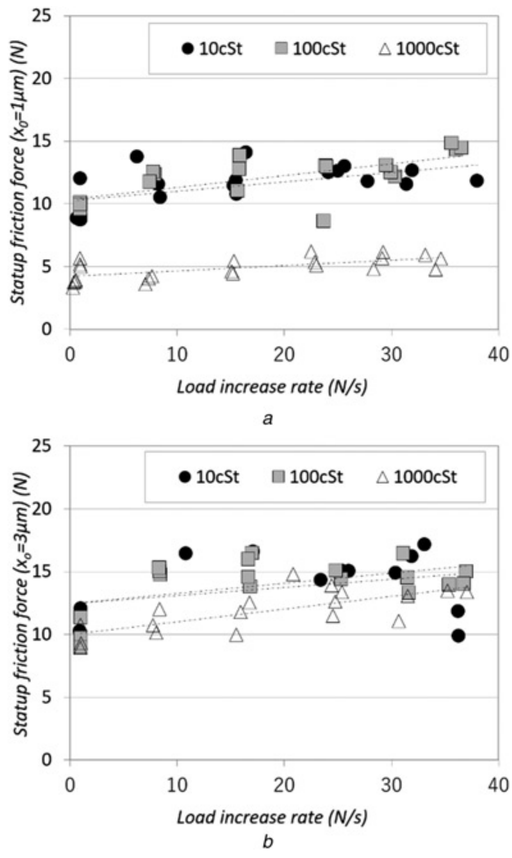

Fig. 7 *Relationship between load increase rate and start-up friction force*

a Vitamin-E blended
b Virgin

viscous component of contact stiffness was changed by sliding distance or that vitamin E changes the susceptibility to lubricants.

4 Conclusion

In this study, destruction resistance of vitamin E blended UHMWPE at start-up friction were evaluated using DEI by minimising the effects of viscosity. The results showed that the DEI and approximate value x_0 of the vitamin E blended UHMWPE were lower than those of the virgin UHMWPE. It is suggested that the blending with vitamin E reduces destruction of UHMWPE at start-up friction in silicone oils.

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