TRIBOLOGICAL PERFORMANCE OF BIODEGRADABLE LUBRICANTS UNDER DIFFERENT SURFACE ROUGHNESS OF TOOLS

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***ABSTRACT**: In this paper, the lubrication performance of four biodegradable lubricants is evaluated under various surface roughness of tools by ring compression test. Rapeseed oil, palm oil, boric acid and palm stearin were considered as biodegradable lubricants. Three pairs of tools were manufactured with different roughness of the surface at the contact interface with the ring specimen. Finite element simulations of ring compression test under different values of the friction factor were conducted in order to obtain a calibration diagram. The result shows that the performance of lubricants is sensitive to the change in the surface roughness of the tools.*

***KEYWORDS**: metal forming, biodegradable lubricants, ring compression test.*

1 INTRODUCTION

The role of the lubricant in the metal forming processes is to decrease the friction and energy consumption, to prevent the abrasion and wear of the tools and workpiece surfaces and to prevent adherence of the workpiece material to the tool surfaces. Therefore, the lubricant is vital, especially for bulk metal forming processes.

Nowadays, the substitution of existing conventional petroleum based lubricants, with biodegradable and nontoxic lubricants has become an important necessity in order to meet the requirements of environmentally sustainable development of the production process. Literature reveals important research works in the application of biodegradable lubricants in the field metal forming industry. Most studies have focused on the analysis of the lubrication performance of some environmentally friendly lubricants, such as: boric acid (Rao et al., 2001), (Rao et al., 2011); combination of boric acid and canola oil (Lovell et al., 2006); palm pressed fibre (Hafisa et al., 2013); BRD palm olein, palm stearin and palm oil (Syahrullail et al., 2012) and vegetable oils (Carcel et. al., 2005).

The aim of this study is to evaluate the lubrication performance of rapeseed oil, palm oil, boric acid and palm stearin under different surface finishes of the tools using the ring compression test of AA 6060-T5 aluminum alloy.

2 THE RING COMPRESSION TEST

The ring compression test (RCT) was firstly introduced by Kunogi in 1956 (Kunogi, 1956) as a qualitative method for the comparison of different friction conditions. Nowadays, the RCT has become a widely used method for the evaluation of lubricants, especially for bulk metal forming processes.

Figure 1 illustrates the principle of the ring compression test.

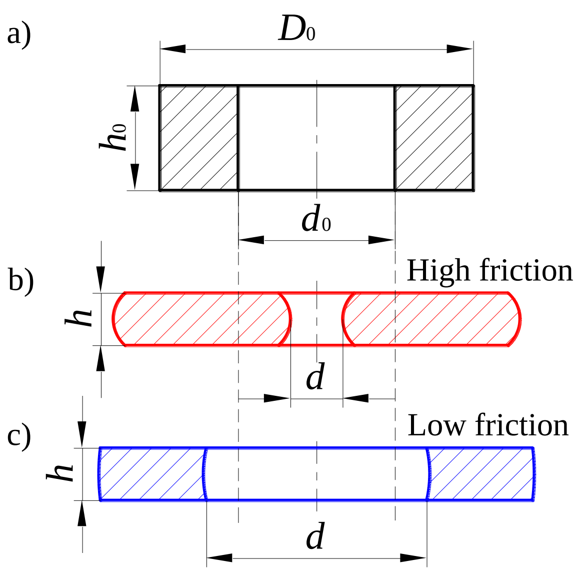


Fig. 1 Material flow during the ring compression test under different friction conditions

This test consists in the compression of a flat annular specimen (Fig. 1.a) between two flat dies. As a result of this action, the material will flow in the radial direction. The inward flow of the material is a consequence of a high friction between the specimen and the die. This will cause a decrease in inside diameter (Fig. 1.b). In the case of a low friction, the material will flow outward, which will involve an increasing in both the inside and the outside diameters of the specimen (Fig. 1.c).

Based on the relationship between the friction and the inner diameter, the calibration curve can be generated. This is a graphical representation of the pairs of points: the percent reduction in height (Eq.1) versus the percentage reduction in inner diameter (Eq.2).

$$\Delta h = \frac{h_0 - h}{h_0} \times 100 \quad [\%] \tag{1}$$

and

$$\Delta d = \frac{d_0 - d}{d_0} \times 100 \quad [\%], \tag{2}$$

where, Δh is the reduction in height;

h_0 – the initial height of specimen;

h – the current height of specimen;

Δd – the decrease in internal diameter;

d_0 – the initial inner diameter;

d – the current internal diameter.

3 EZPERIMENTAL PROCEDURE

3.1 Biodegradable lubricants

In this study, four biodegradable lubricants were chosen to evaluate theirs lubrication performance under three conditions of tool surface roughness during the ring compression test: rapeseed oil, palm oil, boric acid and palm stearin. A degummed rapeseed oil with a cinematic viscosity of 32 mm^2/s at 40 ˚C was used. The palm oil considered in this study is cold pressed and typically used in the food industry. The boric acid (H3BO3) and the palm stearin are in the form of white powder.

3.2 Material characterization

The material used in this study for the test specimen preparation was an AA6060-T5 aluminum alloy.

The stress strain response of the investigated material was measured in the uniaxial compression tests of five cylindrical specimens with 20 mm diameter and 20 mm height. During the compression tests, the load versus stroke curves were recorded continuously. The recorded data were used to calculate engineering stress - engineering strain curves and subsequent the true stress – true strain curves, based on the formulas presented in the paper (Bucur et al., 2018). The resulted stress – strain curve are shown in Figure 2. The compression test were carried out using a universal material testing machine Instron, model 1343. The test speed was 2 mm/min.

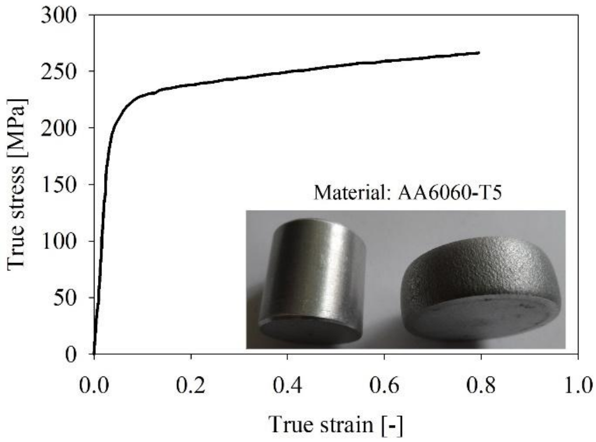


Fig. 2 Stress-strain curve of AA 6060 – T5 aluminum alloy

3.3 Preparation of ring specimens

The as received AA6060-T5 aluminum alloy bars with 25 mm diameter were machined into annular test specimens of 20 mm outer diameter, 10 mm inner diameter and 6.66 mm height in proportions of 1 x 1/2 x 1/3, as shown in Figure 3. The surface roughness of specimen (Ra) 0.60 μm and was measured using a digital surface roughness tester — TIME TR220.

Fig. 3 Example of a ring specimen before the test

3.4 Preparation of die insert

In order to investigate the lubrication performance of the four biodegradable lubricants under different surface roughness of the tools, three pair of insert die were prepared. The insert dies were manufactured from AISI D3 (X210Cr12) tool steel and subsequent hardened at 60-62 HRC. Three sets of dies were used, each set having a different roughness of the work surface. All work surface of dies were first prepared by wet grinding method. The working surfaces of the first die set were subsequent polished, the working surfaces of the second die set were maintained as resulted after the grinding process, while the working surface of the third die set where sandblasted. Figure 4 shows the insert dies used in this study.

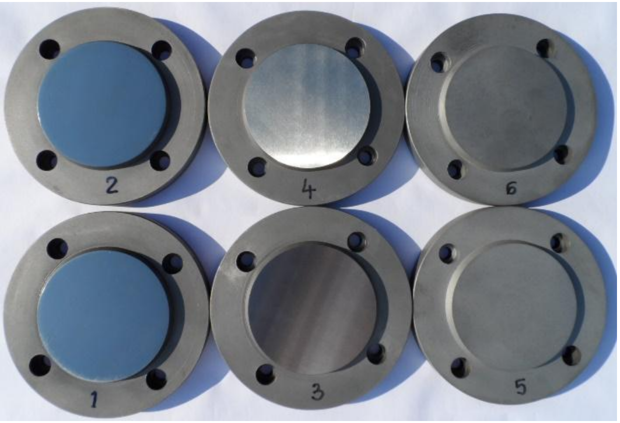


Fig. 4 Insert dies for ring compression test: 1-2 Set I; 3-4 Set II and 5-6 Set III

The surface roughness measurement was performed in order to characterize the work surface of the dies. In this regard, the same digital surface roughness tester — TIME TR220, as in the case of ring specimens, was used. The measurements were performed on two perpendicular directions on the tools surfaces and the mean value of each die set was calculated. These values are shown in Table 1.

Table 1. Surface roughness of inserts dies

Die set / Roughness	Set I	Set II	Set III
Ra [µm]	0.06	0.42	0.97

3.5 Experimental setup

The ring compression tests were performed using a universal material testing machine Instron, model 1196. The test speed was set at 2 mm/min. Figure 5 shows the tools used in the experiments. For each lubricant used in this study, five ring compression tests were performed, each at different reduction in height. After the tests, the inner diameter of deformed specimens was measured and Δd was calculated using the formula (2). The measurement of inner diameter were performed based image processing technique using a Werth Scope Check measuring machine, with a maximum length measurement error of 0.0018 mm. The specimen height was measured utilizing a digital micrometer with a measuring accuracy of 0.005 mm.

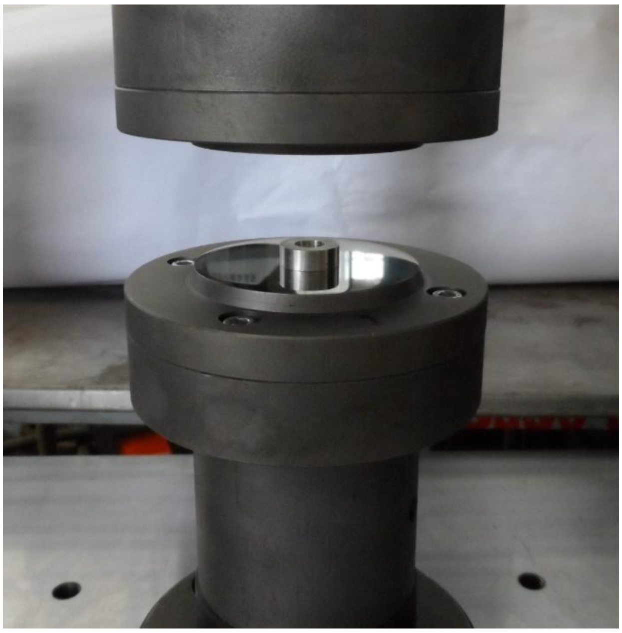
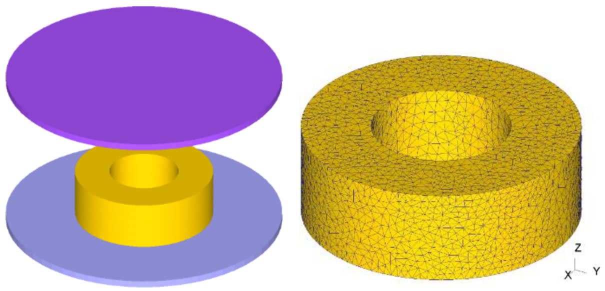


Fig. 5 Tool system for ring compression test

4 GENERATION OF FRICTION CALIBRATION CURVES

The friction calibration curves were determined based on the finite element (FE) simulation of ring compression test using different values of friction factor. The calibration diagram serves to estimation the friction factor of each lubricant considered in this study by overlapping the experimental points on this diagram. The DEFORM 3D software (Def, 2011), was used for the modelling and simulation of the RCT. The FE model includes the upper and the lower dies and the annular specimen. Figure 6 illustrates the FE model and the meshed annular specimen. During the test, the lower die was kept stationary and the upper die was movable with a constant speed of 2 mm/min. The dies were modeled as ridged bodies, while the specimen as a deformable body using 27979 mesh elements and 6406 nodes.

The friction is modeled based on the constant friction law, described by eq. (3)

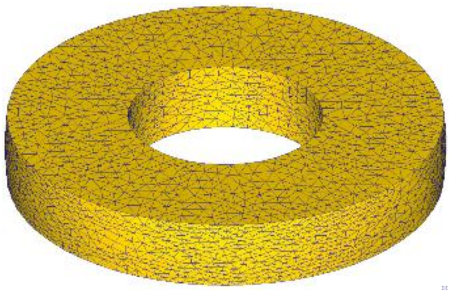


a) b)

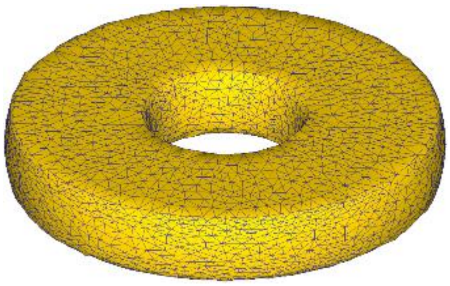
Fig. 6 FE simulation of the ring compression test: a) – the model; b) – undeformed mesh

$$\tau = m \cdot k\,, \tag{3}$$

where τ is the friction stress, m is the friction shear factor and k is the yield shear stress.
Figure 7 shows an example of FE result illustrating the deformed ring specimen under different friction factor in the case of a reduction in height of 45%.



a) m =0.1



b) m = 0.4

Fig. 7 FE simulation compressed rings at 45% reduction in height and two values of friction factor

5 RESULTS

5.1 Evaluation of lubricants

In order to evaluate the lubrication ability of the four lubricants, the experimental points, determined under three surface roughness of the tools, were overlapped on the calibration diagram, Figures 8-10. The results from these figures show that the palm stearin provides the lower friction factor (m), followed by the boric acid, palm oil and rapeseed oil. This hierarchy remains valid in all three cases of surface roughness of tools considered in this study.

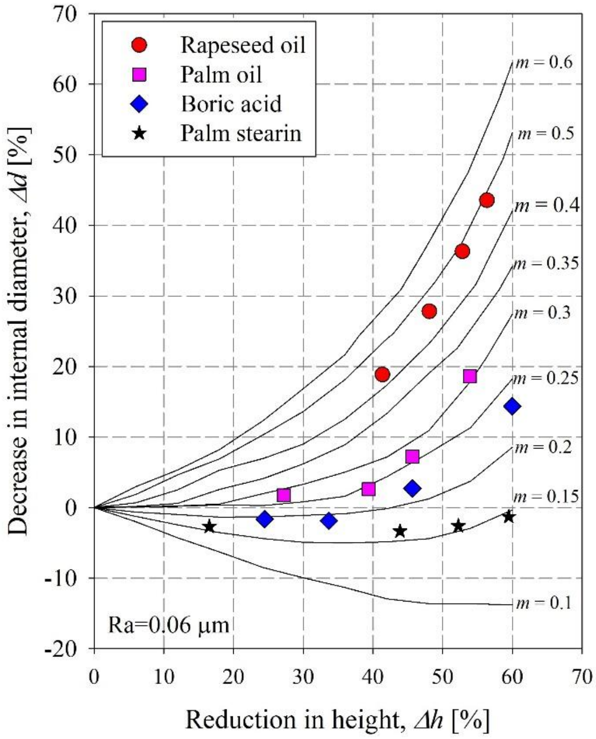


Fig. 8 Theoretical friction calibration curve and experimental results for Ra = 0.06 μm

In the case of a surface roughness of the tool of 0.06 μm (Fig. 8), one can observe that the friction factor for the palm stearin is almost near 0.15. A friction factor between 0.2 and 0.25 corresponds to the boric acid.

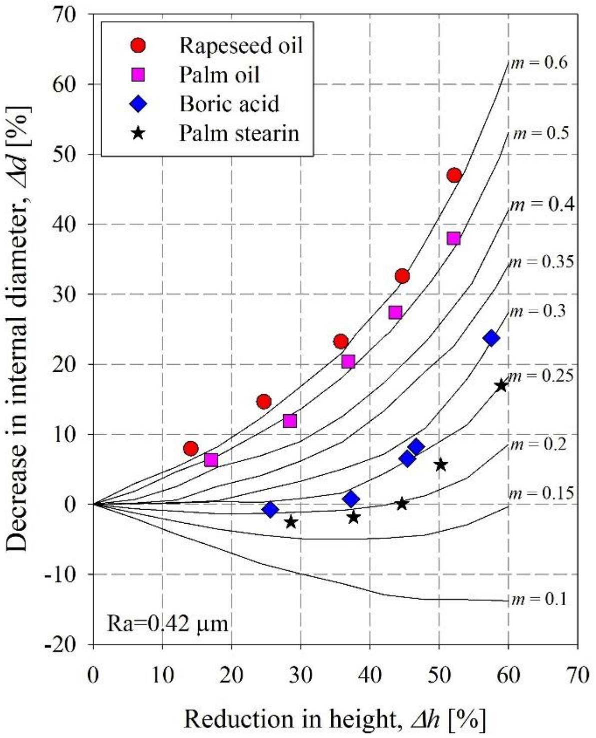


Fig. 9 Theoretical friction calibration curve and experimental results for Ra = 0.42 μm

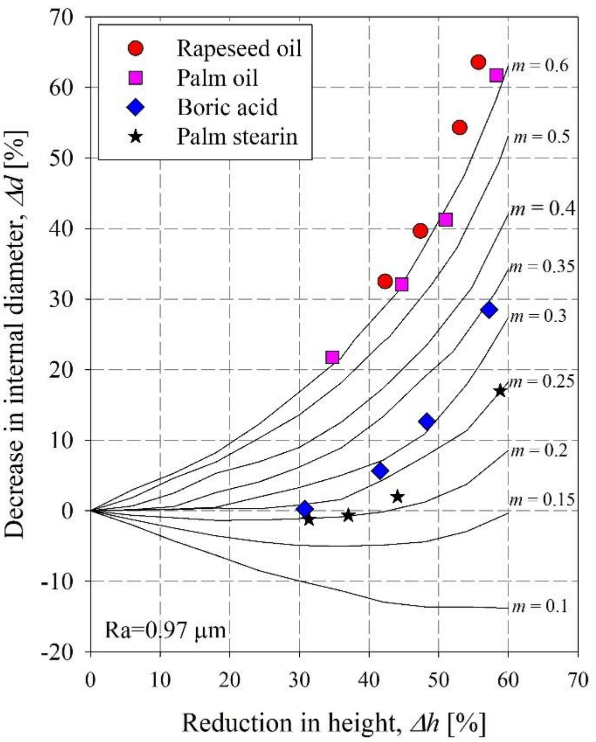


Fig. 10 Theoretical friction calibration curve and experimental results for Ra = 0.97 μm

The friction factor for the palm oil lies between 0.25 and 0.3. The higher friction factor corresponds to the rapeseed oil: between 0.4 and 0.5.

5.2 Effect of surface roughness of the tools on the performance of lubricants

In order to evaluate the influence of tools surface roughness on the lubrication properties of the four lubricants considered in this study, the experimental points resulted under different values of Ra (0.06; 0.42 and 0.97 μm), were overlapped on the calibration curves, Figures 11-14. From these diagrams it is obvious that workpiece surface roughness affects the lubrication properties of each lubricant. The increase in surface roughness determines an increasing of friction factor.

5.3 Sensitivity analysis

From Figures 11-14 one can see that the increase in surface roughness of the tools has different effects on the lubrication performance of the four lubricants. For a quantitative analysis of this influence, Table 3 and Figure 15 compare the decreases in internal diameters (*Δd*) resulted under the three surface finishes of the tools and in the case of a constant value of reduction in height of specimens (*Δh* = 50%).

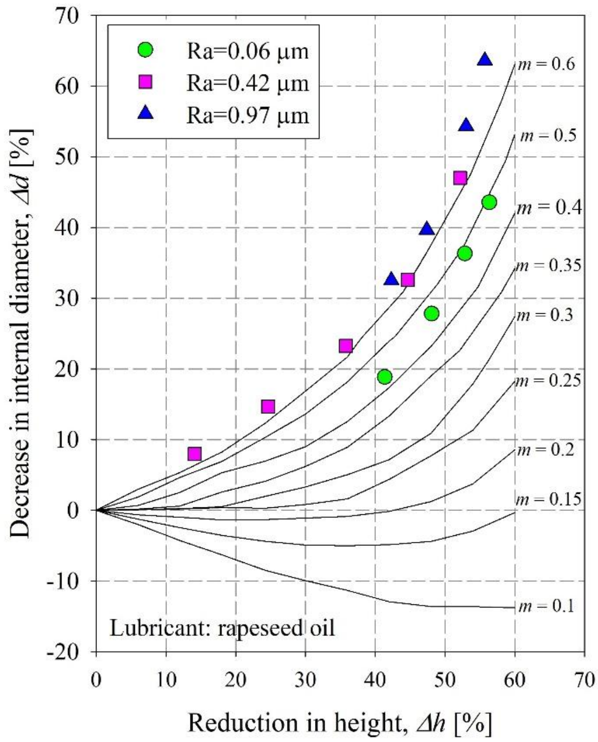


Fig. 11 Theoretical friction calibration curve and experimental points for rapeseed oil

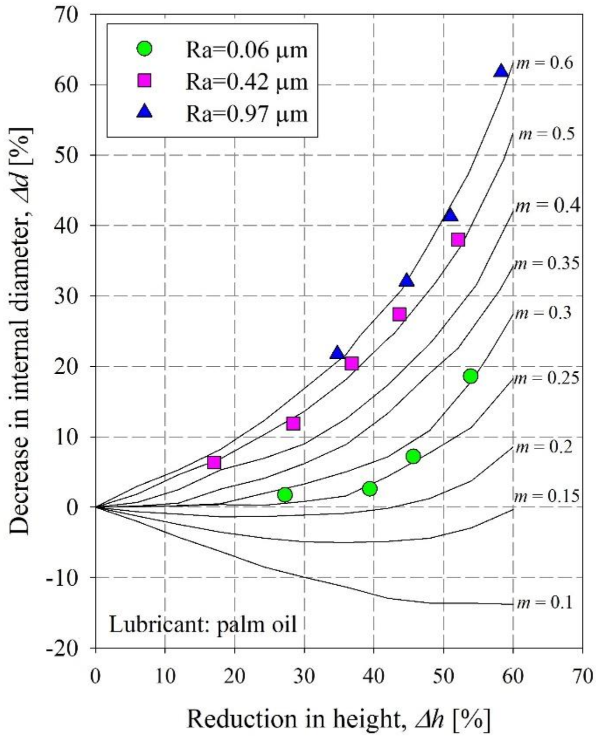


Fig. 12 Theoretical friction calibration curve and experimental points for palm oil

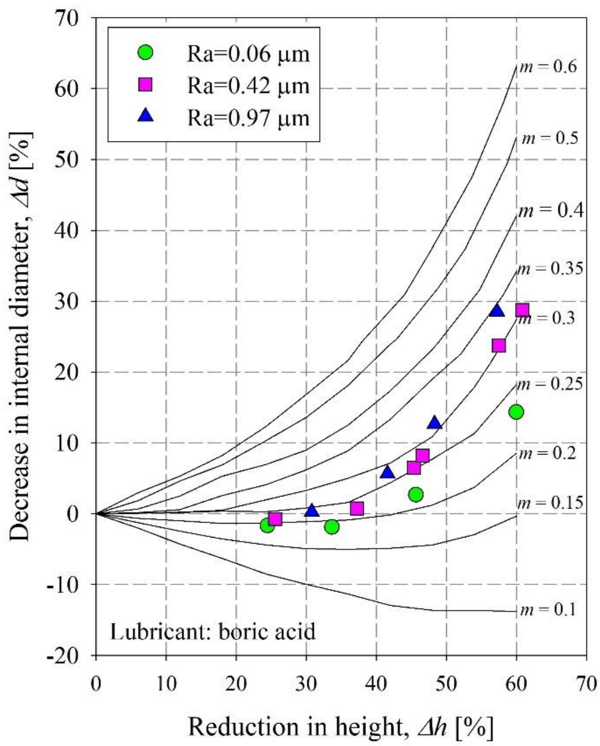


Fig. 13 Theoretical friction calibration curve and experimental points for boric acid

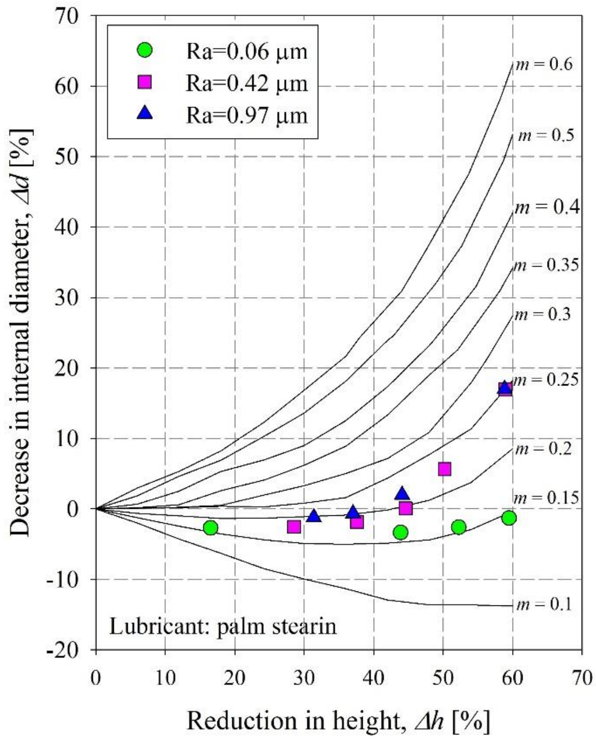


Fig. 14 Theoretical friction calibration curve and experimental points for palm stearin

One may observe in Table 3 and Figure 15 that the percentage change in the inner diameter (Δd) is most sensitive to the change in the surface finish, when palm oil is used as lubricant at the specimen/tool interface. In this case, when the Ra is increased from 0.06 to 0.97 μm, the Δd increases from 13.61 to 40.14 %; this means an increase of 20.53 % in the Δd. In the order of decreasing in sensitivity of the Δd to the change in the surface roughness, follow the lubricants: rapeseed oil (14.98%); palm stearin (10.7%) and boric acid (9.66%).

Table 2. Values of Δd (in %) for various lubricants and surface finishes of the tools (Δh = 50%)

Ra [μm] / Lubricant	0.06	0.42	0.97
Rapeseed oil	31.66	42.87	46.64
Palm oil	13.61	35.52	40.14
Boric acid	6.11	13.17	15.77
Palm stearin	-2.83	5.53	7.84

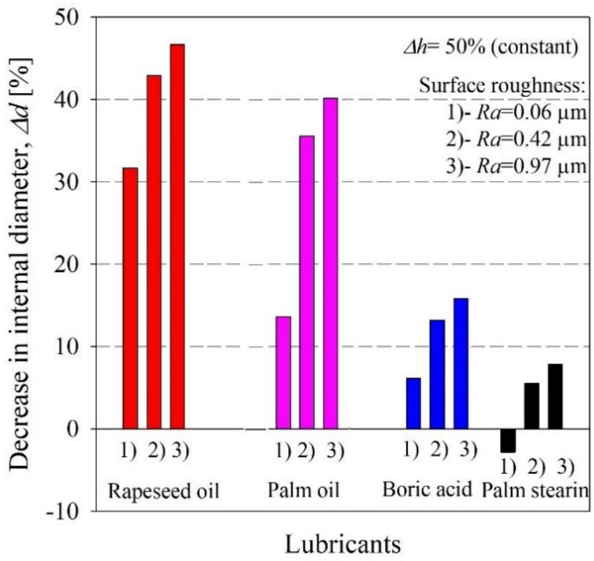


Fig. 15 Influence of surface finishes of the tools on Δd for various lubricants (Δh=50 %, constant)

6 CONCLUSIONS

The influence of surface finish of the tools on the lubrication performance of four biodegradable lubricants in the ring compression test was investigated by experiments and Finite Element simulation. The following conclusions can be formulated:

1) The best lubrication properties were observed in the case of palm stearin, followed by boric acid, palm oil and rapeseed oil. This hierarchy is not influenced by the surface roughness of the tools.

2) The performance of the biodegradable lubricants (evaluated on the basis of the friction factor) is significantly affected by the change of surface roughness of the tools. The friction factor for each lubricants, considered in his study, increases with the increase of tools surface roughness.

3) The percentage change in the inner diameter of the specimen after the test, is less sensitive to the changes in the surface roughness of the tools when boric acid was used as a lubricant; the sensitivity increases when palm stearin, rapeseed oil and palm oil was used.

4) As a general conclusion, the friction factor is slightly sensitive to the reduction in specimen height. It increases with the reduction in height. This could be attributed to the fact that when the load increases, the lubricant is pulled out from the tool/specimen interface and the two surfaces are in direct contact at the periphery of the specimen. This implies that the test should stop at a certain limit of the reduction in height of the specimen.

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