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Influence of surface modification on friction coefficient of the titanium–elastomer couple

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This paper presents the results of a study of the friction coefficient of titanium–elastomer couple. The study was carried out with a view to potential future utilization of its results for constructing retentive elements of implanted prostheses. Changes in the friction force were recorded while removing titanium specimens placed between two silicone counter specimens made of Ufi Gel. The influence of the titanium specimen movement speed in relation that of to the counter specimens and the influence of clamping force on the friction force were assessed. Additionally, the surface roughness of titanium specimens differed; in one case, titanium was coated with polyethylene. The effect of introducing artificial saliva between the cooperating surfaces on the friction force and friction coefficient was analyzed as well. Based on the characteristics recorded, the possibilities of shaping the friction coefficient have been assessed, since it is the friction coefficient that determines effective operation of a friction couple through increasing the titanium specimen roughness. The artificial saliva being introduced between the specimens reduces considerably the friction coefficient through a change of the phenomenon model. An increase in the pressure force for the specimens of high roughness entails a reduction of the friction coefficient. The study carried out allows us to identify the roughness parameters, which in turn will enable obtaining the prescribed retention force for friction/membrane couplings.

Key words: friction coefficient, friction force, titanium, silicone, saliva, implant prosthesis, retention

1. Introduction

In spite of a continuous improvement of overdenture structures and a considerably higher patient satisfaction level when compared to traditional dental prostheses [1]–[4], the inconveniences caused by implant or prosthesis damage are still present along with problems connected with the changes in the prosthetic base tissues [5]–[7].

A reduced number of posts necessary to retain complete implant overdentures in the case of the existing methods of the suprastructure connection with an implant results in a significant increase in load imposed on a single implant [8]. Such a situation is conducive to bone tissue atrophy progression and often leads to mechanical destruction of implants or prostheses, or to pathological changes of tissues in their anchoring zones. Endeavours made to minimize the above-mentioned unfavourable phenomena have led to a new conception of friction–membrane couplings serving to retain complete dentures on implant posts, an idea that is the subject of patent application no. P369856. The retentive element in the solution proposed is an elastic ring placed in a seating and working with a titanium implant (figure 1). After seating the denture on posts, the ring acts as a membrane spring, in accordance with mucous membrane resilience. Tests show that proper

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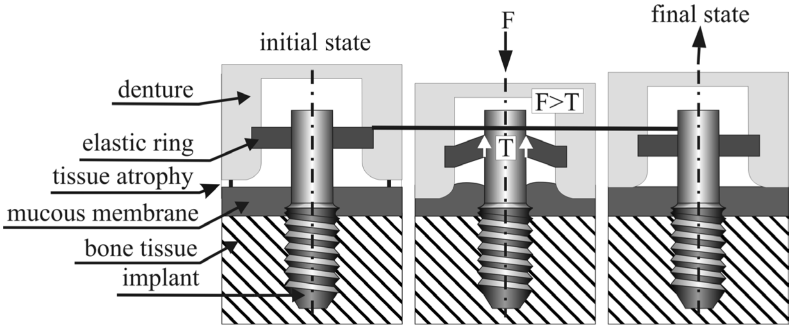


Fig. 1. Operation principle of a friction-membrane coupling enabling the adjustment of denture position to prosthetic base atrophy and the coupling's movements consistent with mucous membrane resilience

profiling of the seating itself will result in major benefits consisting in a reduction of load imposed on the mucous membrane [9], [10].

Another advantage of the design proposed is that the denture will be able to follow the disappearing base in the case of significant alveolar atrophy or the changes in mucous membrane thickness. In the zone of contact between the ring and the titanium implant, a friction coefficient should be selected in such a way that in the case of alveolar atrophy, the pressures on the alveolar arch would exceed the friction force, thus making the ring shift along with the denture plate according to the implant position, and lowering the denture's rest position. The role of the implant–coupling pair in the solution proposed is to stabilize the denture, whereas the occlusal forces should be largely transferred by the denture saddle onto the bone base.

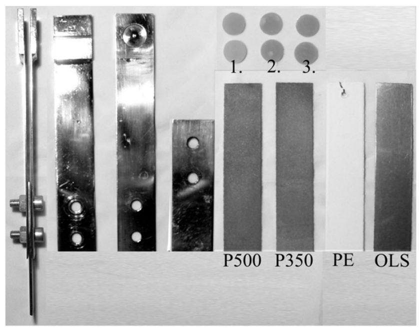
Based on model studies, geometric properties of the coupling were preliminarily identified and the desirable mechanical properties of the material intended for the elastic ring were determined. Analysis shows that in most cases the present requirements are satisfied by typical elastic polymer materials applied in dental prosthesis for relining. In so far as properties normally measured for these materials, such as absorbability, solubility, colour stability, microhardness, the number of incongruities occurring during polymerization, or adhesion to the denture plate material [11]–[14], are known, no research has been conducted so far into the friction phenomena in the titanium–elastomer couple because of primary intentions for which these materials were created.

The friction phenomena of soft polymer materials (such as silicone rubbers) differ in many aspects from the friction properties of other solid bodies. There are many reasons for this. First of all: a low elasticity modulus and high internal friction of these materials [15]–[18]. Due to the primary purpose of the silicone materials investigated, there are no studies regarding friction phenomena in the titanium–elastomer couple. The present study aims to analyze the influence of certain factors on friction characteristics, and the factors may serve in practice to shape the retention force of dentures and influence the amount of load imposed on a prosthetic base.

2. Research methodology

Testing was performed using a Zwick strength tester with an affixed holder, enabling application of symmetric pressure of elastomer counter specimens on titanium specimens (figure 2).

a)



b)

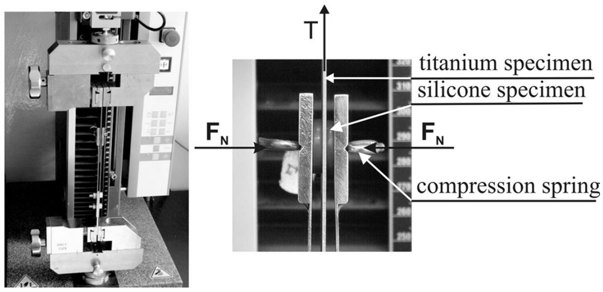


Fig. 2. Holder for counter specimens, counter specimens and titanium specimens (a)
view of a system ready for operation (b)

During measurements, the force necessary to extract a titanium specimen from the holder equipped with silicone discs was recorded. The prescribed pressure force values of: 5 N, 15 N and 30 N (figure 2b) were achieved by using calibrated springs. The speed of titanium specimens was 2 mm/min, 20 mm/min and 60 mm/min, respectively.

In order to take into account the influence of the oral cavity's environment on friction coefficient and friction force values, measurements were carried out both in dry conditions and after introducing artificial saliva between the friction elements.

Elastomer counter specimens, 15 mm in diameter and 2.5 mm thick, were created in a specialist prosthetic laboratory by using a silicone material, namely the Voco company's Ufi Gel. Flat titanium bars with a cross-section of 2 × 21 mm were cut out from a special sheet made of Ti6Al4V alloy, then they were subjected to surface modification through:

- sanding with abrasive material of 350 μm under pressure of 5 bar (P350),
- sanding with abrasive material of 500 μm under pressure of 5 bar (P500),
- application of a polyethylene layer in a fluidized bed (PE),
- treatment with a loose abrasive (OLS).

Designations used later in the paper are provided in brackets to identify particular specimens.

Three-dimensional measurements of the surface roughness of the modified titanium elements were performed using a Form Talysurf Series 50 from Taylor Hobson Ltd. Areas of 2 mm × 2 mm were examined and analyzed with 0.01 mm resolution on the *Y*-axis, by taking 201 measurements in 10 μm intervals. In this study, the parameter marked as *Sa* was adopted as a criterion for roughness evaluation, described as the mean arithmetic deviation of surface irregularities' heights from the reference plane [19], [20].

3. Results and discussion

On the basis of the research it can be concluded that the lowest roughness is characteristic of the surface subjected to treatment with loose abrasive (OLS), $Sa = 0.42$ μm. The polyethylene coating allowed almost twofold increase in this parameter. Sanding enabled the generation of a surface with much higher roughness and a high degree of development. The obtained values of *Sa* amount to 2.81 μm (P350 μm) and 4.68 μm (P500 μm), respectively. Surface maps, profiles and values of the parameter *Sa* for the surfaces investigated are presented in figure 3.

In the tests conducted without artificial saliva, the lowest friction coefficients were obtained for the specimen OLS, 0.49 at a speed of 2 mm/min and pressure force of 30 N. The application of a PE specimen enabled only a slight increase in the friction coefficient by increasing the surface of real contact, whereas the application of specimens after sanding, with much higher roughness, allowed obtaining distinctly higher values of friction coefficient. The values of friction coefficient rise with the increasing relative speed of friction elements and fall as the pressure force increases (figure 4). The higher the roughness, the more stabilized the results. The influence of a change in compression speed and pressure force on the value of μ decreases as the parameter *Sa* of titanium alloys grows. The differences between the lowest and the highest recorded values of μ for different specimens were: OLS, 0.88; PE, 0.81; P350, 0.6; P500, 0.54.

A decrease in the friction coefficient with an increase in pressure force can be explained by the fact that an elastic material, already at low force values, fills in the irregularities in titanium specimens relatively well, owing to which an increase in pressure force results in a minor increase of the real contact surface only, whereas the friction coefficient falls. The differences recorded in the values of friction coefficient are also higher when a low speed of specimens' relative movement is applied. It is worth mentioning that for all types of specimens, the highest value of friction coefficient, close to 1.4, was achieved when 5 N force was applied at a speed of 60 mm/min. A supposition can therefore be made that in the case of low pressure force and a high movement speed (60 mm/min), there will not be enough time for elastomer to undergo deformation, which would otherwise allow it to penetrate into surface irregularities, whereas the silicone counter specimen will slide over the peaks of irregularities on a specimen. Thus, an increase in the surface of real contact proved to be impossible, leaving the friction coefficient unchanged.

After artificial saliva was introduced between the cooperating surfaces, a considerable decrease of the friction force and friction coefficient took place. Application of titanium PE and OLS specimens (with smooth surfaces) generated only minor friction forces. Figure 5a shows examples of friction characteristics for PE sheet. Figure 6a and 6b presents the dependence of average forces of static friction on the speed of extracting the flat bar, and the surface pressure force. The values of a friction force fluctuate between 0.3 and 0.41 N. There is no

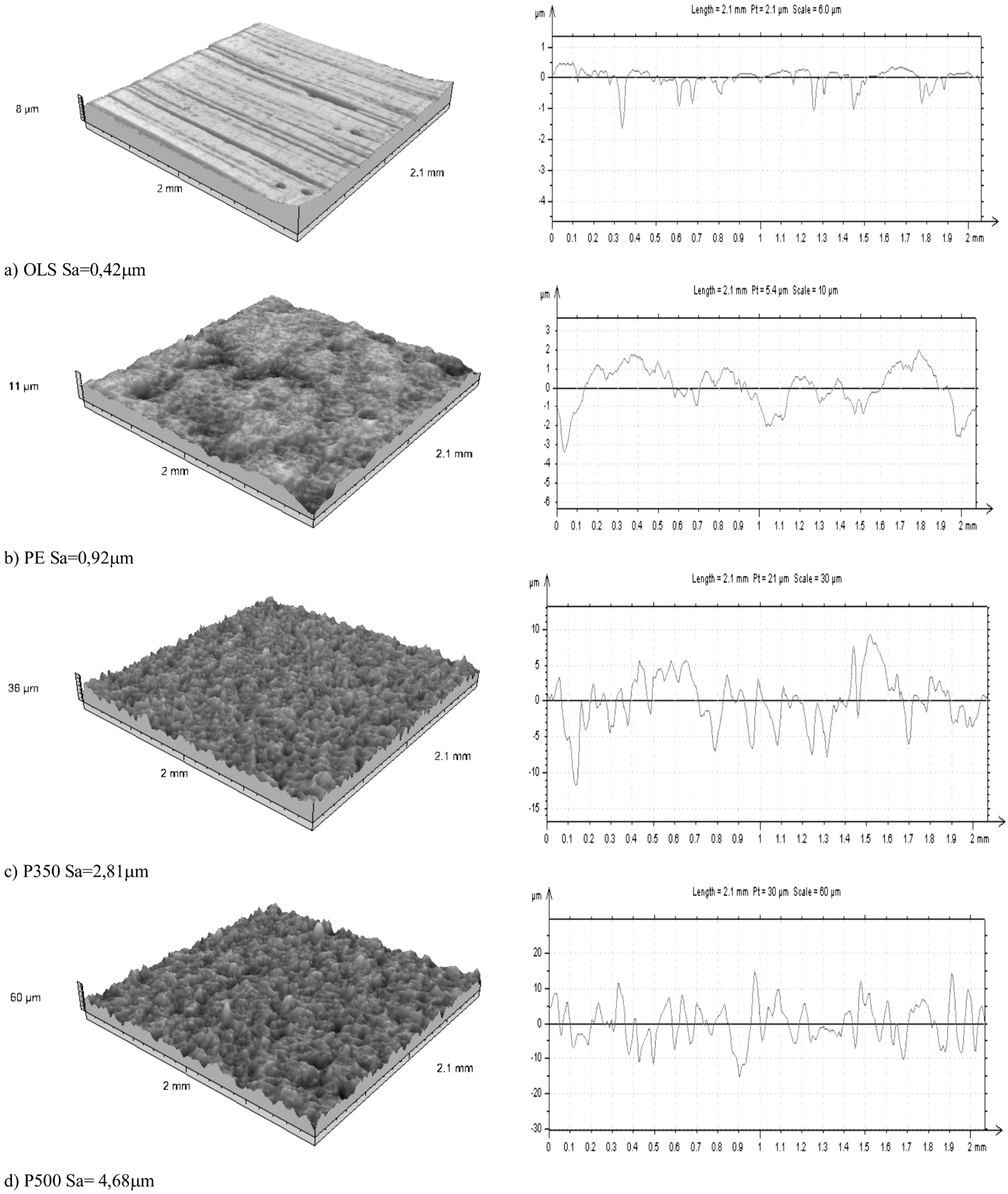


Fig. 3. Three-dimensional images of titanium specimens' surfaces along with example profiles and *Sa* parameter: OLS (a), PE (b), P350 (c), and P500 (d)

significant dependence of the friction force on the pressure force, nor the dependence of the friction force on the speed at which the flat bar is removed. The dynamic friction force is much lower and ranges within 0.15–0.28 N (figure 6c and 6d). There is an slight increase in the friction force as the relative speed of friction elements' movement and the pressure force increase.

When specimens were used after prior sanding, a seventyfold increase of friction forces in relation to

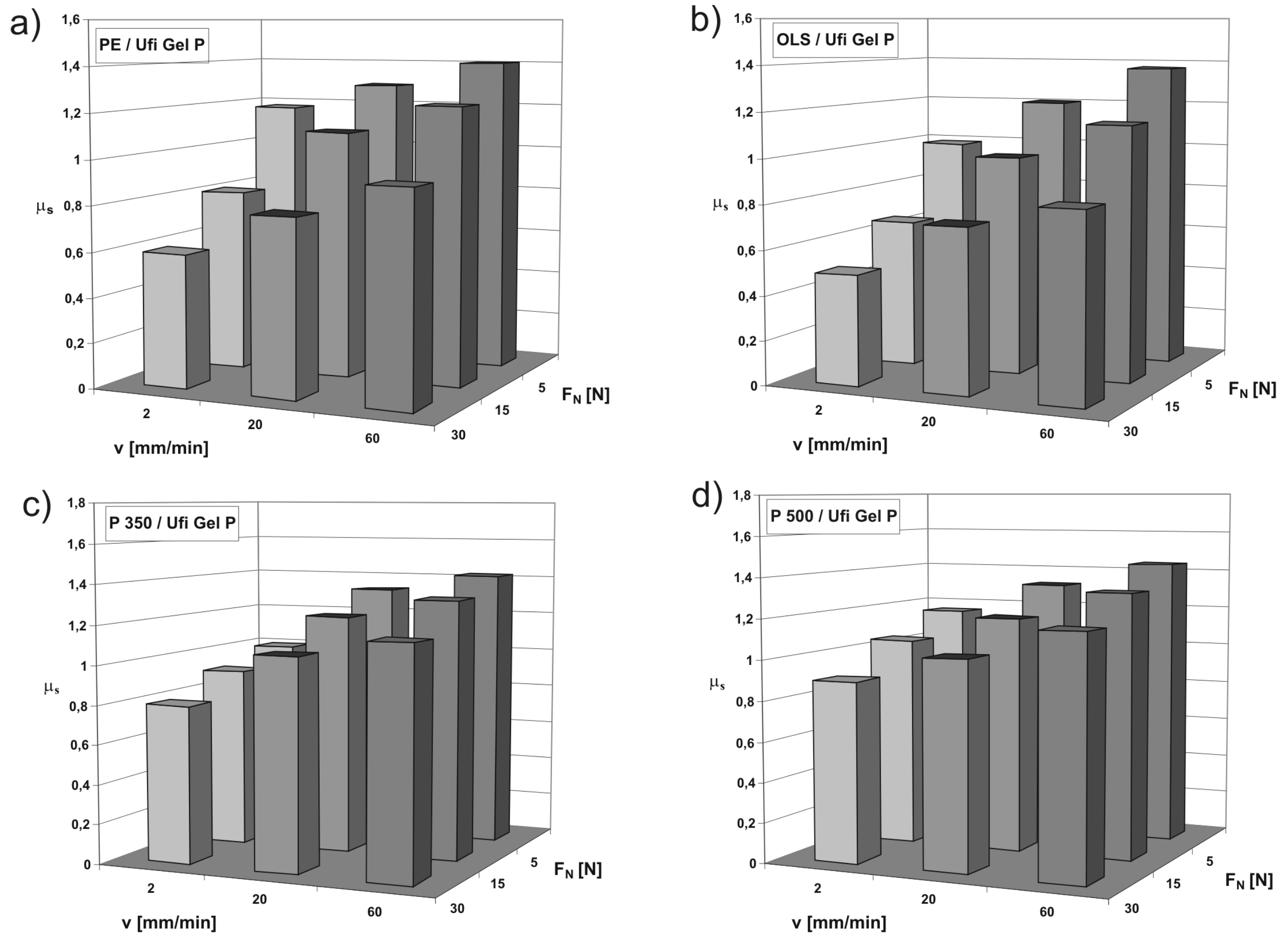


Fig. 4. Dependence of "dry friction" force on pressure force and relative speed of friction elements for specimens: PE, OLS, P350 and P500

OLS and PE specimens occurred. At the same time, the friction coefficient is even four times lower than that obtained in analogical tests conducted under "dry" conditions. Figure 8a and 8b shows the dependence of static friction coefficient on the pressure force and speed of the sheet's movement. An increased speed of the relative movement of friction elements leads to an increased static friction coefficient. This effect is much better visible where a specimen of higher roughness was used, i.e., P500. An increase in the pressure force caused in turn a decrease in the friction coefficient.

In the case of specimens PE and OLS, we have to deal with a situation where saliva introduced between two cooperating surfaces of slight undulation worked as a lubricant (figure 7a). The classical model of dry friction is not applicable in this case, as fluid or mixed friction becomes the issue here. The external friction turns into internal friction of the lubricating agent, with the friction force dependent upon the lubricant's properties, not the properties of the cooperating surfaces.

The value of the fluid friction coefficient is low and dependent on the thickness of the lubricating liquid layer, its viscosity and, sometimes, on relative speed of friction elements.

The application of titanium specimens subjected to surface modification through sanding considerably enhanced the friction force by increasing the area of the friction couple's real contact and by changing the titanium sheet surface profile. Such an effect was obtained due to a switch from a fluid friction model to a mixed one, consisting of varied types of friction within the contact zone of friction elements. Although a growth in the pressure imposed by the elastomer counter specimens on titanium specimens normally entails an increase of the real contact area of friction couple resulting from growing deformation of elastic silicone, and thereby, causing an increase of the friction coefficient (figure 7b), an opposite situation was recorded. A supposition can be therefore made that the saliva introduced between the friction surfaces got stuck in the rough irregularities of the titanium P350 and P500 sheets, thus largely

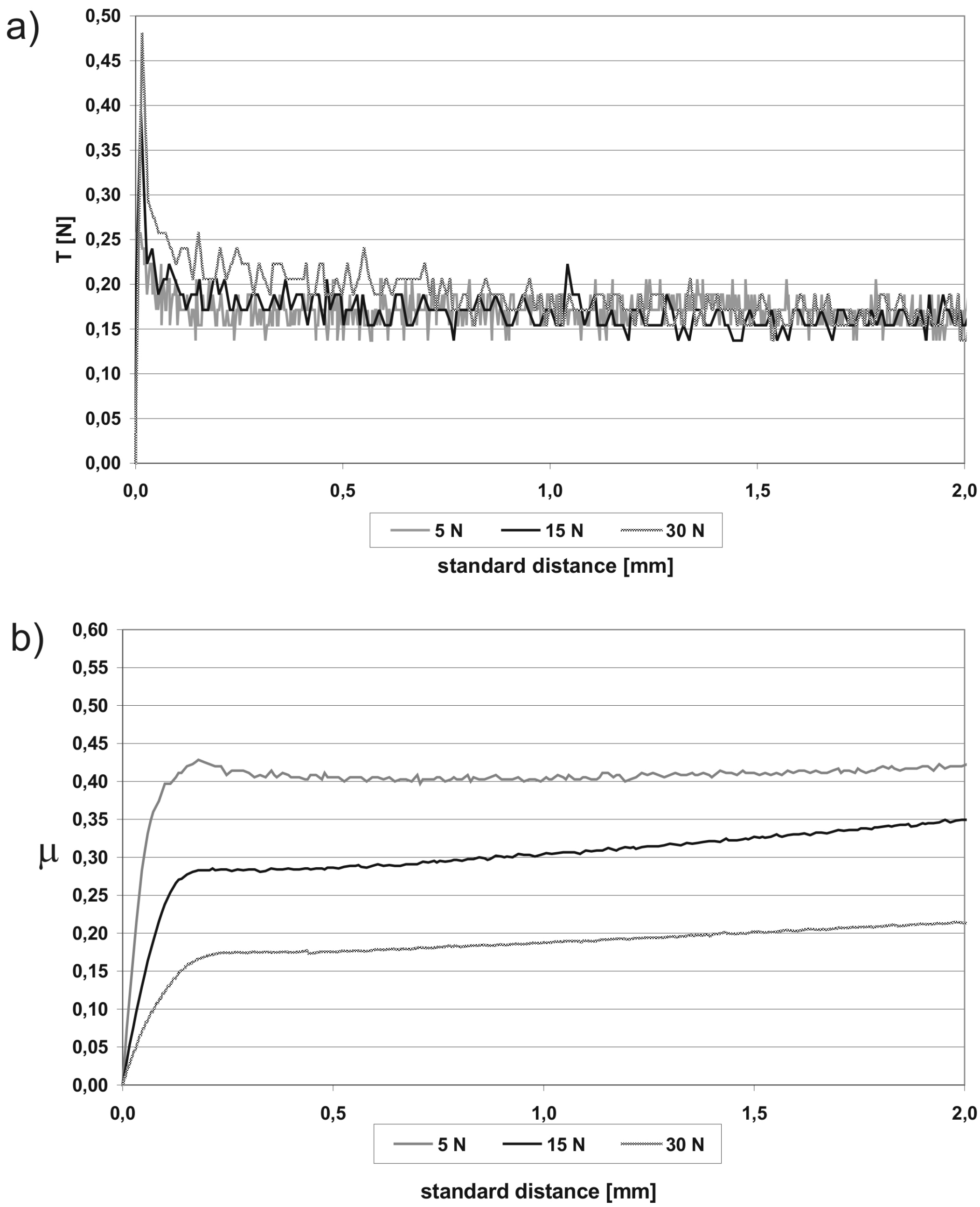


Fig. 5. Examples of friction characteristics obtained at different pressure forces after introduction of artificial saliva between silicone counter specimens and titanium specimens: PE at a speed of 20 mm/min (a), P350 at a speed of 20 mm/min (b)

reducing the viscoelastic deformation of the elastic material. The silicone counter specimens slipped in places filled with saliva, whereas in places of contact between titanium and silicone, they acted in accordance with the dry friction principles. Thus, the friction force increase observed as a result of increasing surface pressure was lower than expected. In that situation, the enhanced deformation due to the increased pressure force was based on limited possibilities of expelling the saliva from the sheet's rough irregularities outside the system as well as on minor compressibility of the fluid (figure 7c). Therefore, in spite of a distinct friction force growth (figure 8c and 8d), a decrease of the friction coefficient was recorded.

4. Conclusions

1. Application of surface modification technologies, which allow obtaining surfaces of high roughness, increases the friction coefficient value.

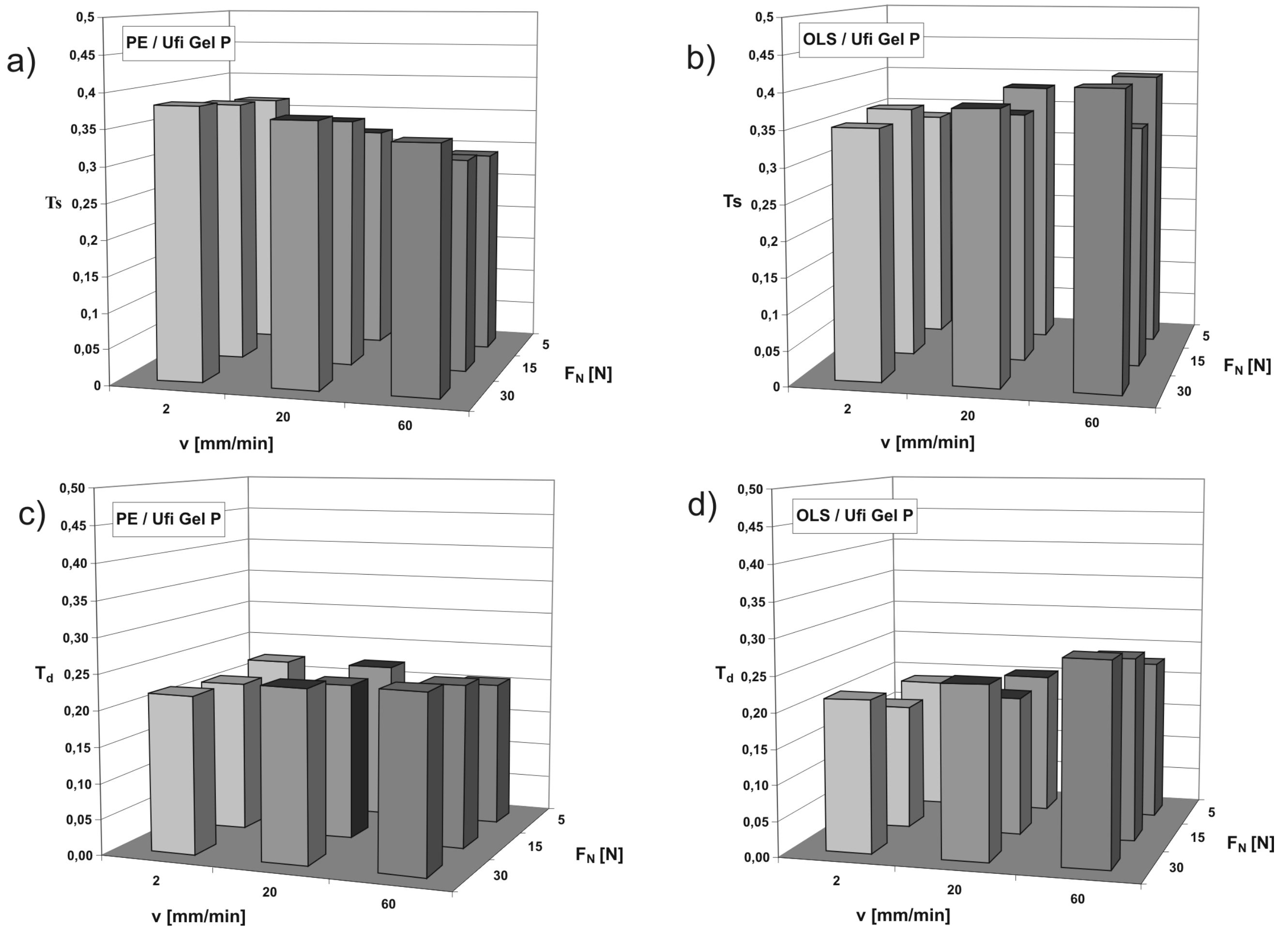


Fig. 6. Dependence of static friction force (a and b) and dynamic friction force (c and d) on pressure force and relative speed of friction elements for specimens PE and OLS

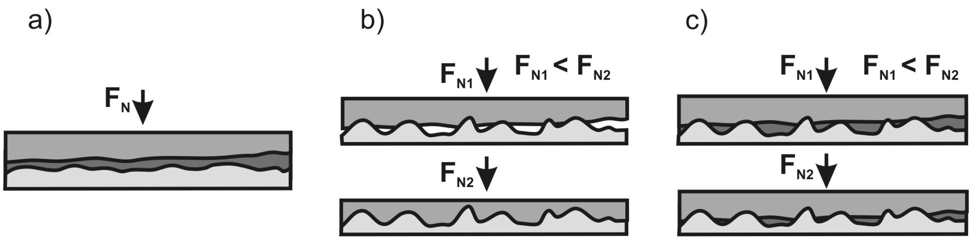


Fig. 7. Area of real contact of an elastic body with smooth surface juxtaposed with: smooth surface wetted with artificial saliva (a), rough surface of a hard body (b), and rough surface of a hard body wetted with artificial saliva (c)

2. Introduction of artificial saliva between silicone counter specimens and titanium specimens with smooth surface (PE or OLS) results in a change of the type of friction into fluid friction.

3. Introduction of artificial saliva between titanium specimens P350 and P500 and silicone counter specimens results in a considerable decrease of the friction coefficient through a transition from dry into mixed friction.

4. An increase in the relative speed of friction elements under “dry” conditions for specimens with high roughness (P350 and P500) in an artificial saliva environment led to an increase in the friction coefficient.

5. Increased pressure imposed on silicone counter specimens compressed to titanium specimens P350 and P500 results in a lower than expected increase of friction force in relation to pressure force and thus a decrease of the friction coefficient.

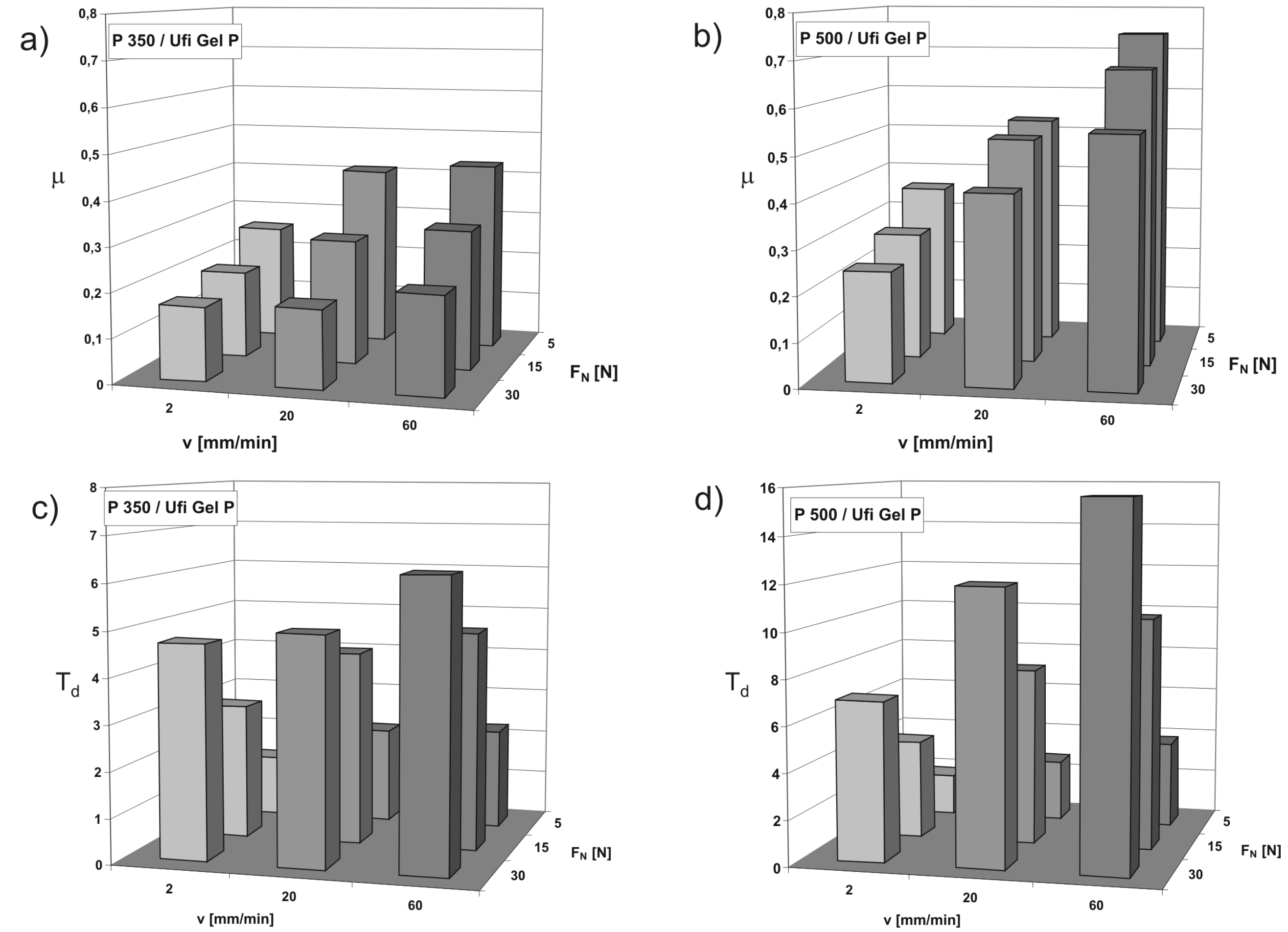


Fig. 8. Dependence of friction coefficient and friction force on pressure force and relative speed of friction elements for specimens P350 and P500

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