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Abstract: Polyetheretherketone (PEEK) was investigated using a modified version of the four-ball tester in which the upper forth ball was replaced by a cone in such a way that kinematics of the four-ball configuration were fully preserved. In this apparatus, a polymer cone was spinning against three nested ceramic balls in a cup with polymer side walls and bottom. Rotation of the cone enforced orbiting and rolling of the ceramic balls around the polymer cup. The results produced some unexpected peculiarities in the wear of ceramic balls which, in principle, should not take place. It is postulated that the wear of ceramic balls was due to the viscoelastic nature of the PEEK.

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Dear Editor-in-Chief,

2 June 2014

On behalf of my co-author, I submit the manuscript of our paper entitled “Peculiarities associated with testing polyetheretherketone (PEEK) in a model rolling contact” with the hope that you will be kind enough to consider it for publication in Tribology International.

Please let me know the outcome of the assessment in due time.

Yours sincerely,

T A Stolarski

Brunel University

***Statement of Originality**

Novelty Statement

I, on behalf of my co-author, declare that the work described in the manuscript "Peculiarities associated with testing polyetheretherketone (PEEK) in a model rolling contact" has not been published previously in any other journal and neither is under consideration for publication in any other journal.

T A Stolarski, PhD, DSc(Eng)
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***Highlights (for review)**

Highlights

The paper reports experimentally observed phenomenon of direct contact between three lower ceramic balls in the four-ball configurations when in contact with polyetheretherketone (PEEK) elements of the assembly. This is rather unprecedented as it is well known that direct contact between lower three ball normally does not take place when nominally elastic materials are tested. It is argued that the viscoelastic nature of the polymer is responsible for the occurrence of direct contact between three lower ceramic balls. A caution is recommended when testing viscoelastic materials in the four-ball configuration.

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Peculiarities associated with testing polyetheretherketone (PEEK) in a model rolling contact

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Abstract

Polyetheretherketone (PEEK) was investigated using a modified version of the four-ball tester in which the upper forth ball was replaced by a cone in such a way that kinematics of the four-ball configuration were fully preserved. Rotation of the cone enforced orbiting and rolling of the ceramic balls around the polymer cup. The results produced some unexpected peculiarities in the wear of ceramic balls which, in principle, should not take place. It is postulated that the wear of ceramic balls was due to the viscoelastic nature of the PEEK.

Key words: polymer, viscoelastic, fatigue wear, rolling contact

1. Introduction

One of the promising applications of engineering polymers seems to be in rolling contact bearings. In practical circumstances, the contact between the rolling elements and the outer and inner rings consists more of sliding than of actual rolling. The condition of no interfacial slip is seldom achieved because of material mechanical properties and factors pertinent to geometric configuration. Moreover, inherent to the state of loading on rolling elements and inner and outer rings is a fluctuating load, although the external load applied to a bearing treated as a system is static.

The fatigue life of a rolling contact bearing is a function of a number of factors which are interwoven in a highly complex manner [1]. The effect of increasing speed on the fatigue life, for instance, is mainly manifested in the operating load due to the centrifugal force, with a corresponding reduction in the loading zone. The contact angles also change, that at the inner raceway increasing and that at the outer ring decreasing with rising speed.

Polymeric materials subjected to strong mechanical and environmental excitation show, like many other materials, gradual deterioration in their performance including eventual failure. Polymers and their composites exhibit a much more complex

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behaviour when subjected to fatigue loading than ferrous materials. The net effect of the several competing processes depends on a number of factors, which include the temperature, time, environment, and basic molecular properties of the polymer. The most important factors determining the fatigue behaviour of a polymer are [2, 3, 4]: thermal effects during the loading-unloading cycle; morphological changes within the polymer; transition phenomena; molecular characteristics; chemical changes leading to degradation of bonds; mechanical deformations.

Although, at first sight, polymers may seem to be rather unlikely materials for rolling contact applications because of the generally accepted premise that polymers are weak and soft. However, modern engineering polymers and their composites have physical and mechanical properties that can be considered as very attractive for rolling contacts. The main benefits resulting from using polymers in rolling contacts are [5]: corrosion resistance; ability to operate without lubrication or lubrication with process fluids; lower price comparing to bearing steel; ease of processing; cost of manufacture. All these benefits can be readily obtained provided that the application is characterised by light loads and low to moderate speeds.

The stress in polymeric materials used for rolling contacts is influenced by the rate of strain and, therefore, the contact stress and deformation will depend upon the speed of rolling. The characteristic feature of polymeric materials that largely defines their fatigue behaviour is that they, unlike metals, are inhomogeneous on a gross scale and anisotropic. They tend to accumulate damage in a general rather than a localised way. Moreover, failure does not usually occur by propagation of a single macroscopic crack. The mechanisms of damage accumulation, including fibre and matrix cracking, de-bonding, transverse cracking, and delamination, occur sometimes independently and sometimes interactively. The predominance of one or other of them may be strongly influenced by both the material variables and the testing procedure and conditions.

This complex picture of competing failure processes when a polymer is subjected to a cyclic loading is clear evidence that experimental testing is the only reliable way to assess suitability of a given polymer for rolling contact application. PEEK is a promising polymer for the production of precision-machined custom bearing expected to suit special market needs. Due to its self-lubrication ability, high impact durability, high corrosion resistance, low specific gravity, high melting temperature of 340 °C and high glass transition temperature of 143 °C, PEEK is considered a high performance polymer material [6, 7].

Polyetheretherketone (PEEK) was tested in a model contact simulating operation of a rolling contact ball bearing in order to ascertain the prevailing mode of failure under dry contact conditions. The findings of this study are reported in this paper.

2. Analyses of model rolling contact

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A widely used four-ball configuration [8, 9, 10] was suitably modified to simulate, as closely as possible, operation of a rolling contact ball bearing. Figure 1 shows, schematically, the layout of the test apparatus used.

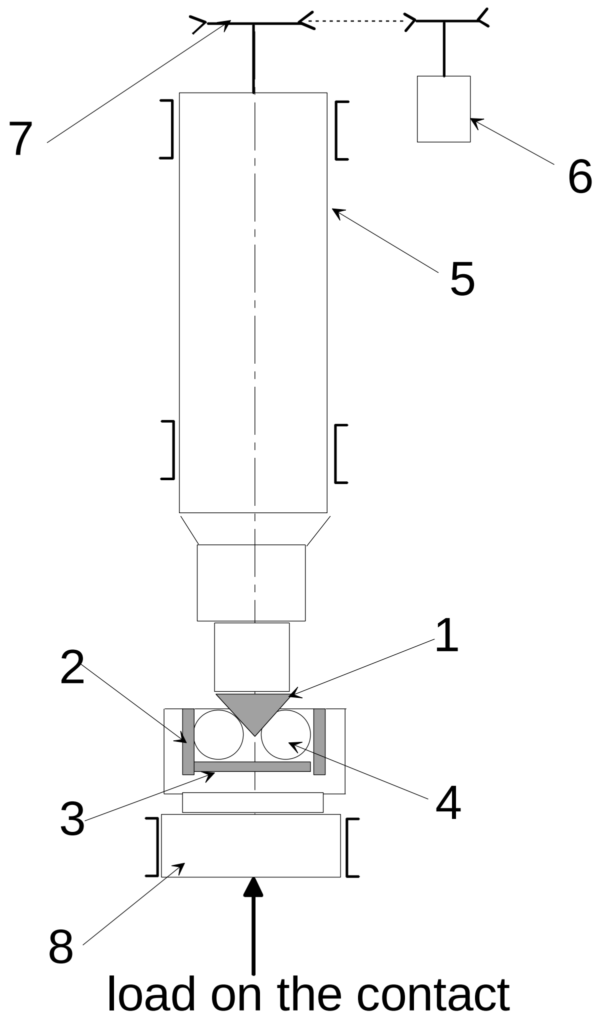

Figure 1. General layout of the test apparatus.

(1) Polymer cone; (2) polymer ring; (3) polymer bottom disc; (4) ceramic balls; (5) spindle; (6) electric motor driving the spindle; (7) belt drive.

It consists of three ceramic balls in contact with a polymer cone, which replaced the fourth ball normally present in the four-ball configuration. Such a change does not alter kinematics of the original four-ball configuration and this point is elaborated on later. The balls are also in contact with the cup consisting of the ring and the bottom disc both made of the same polymer as the cone.

It is known that the contact region between the balls and the cone is characterised by a degree of slip resulting from a complex motion of the balls. The magnitude of the slip within the contact region depends, among other things, on the elastic properties of the contacting materials. The slip contributes to heating, softening of cone's

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surface, and, eventually, to sliding wear which must be distinguished from the wear produced by surface fatigue due to rolling motion.

2.1. Kinematic analysis of model rolling contact

The analysis of motion taking place in the cup assembly can help a better understanding of the fatigue mechanism. To determine the velocity relationships the balls together with the cone, outer ring and bottom disc should be considered as a planetary gear train. In this way, the number of stress cycles to which the driving cone is subjected, may be computed.

Geometric relationships are important as ball diameters and cup dimensions affect the kinematics and contact loads. Figure 2 shows the geometry of the assembly; angle θ is the basic contact angle, and is a function of ball and cup dimensions. In the present analysis the cone, which was actually used in testing, is replaced by the equivalent ball with radius R_A (see Figure 2 for details). This was done in order to analyse kinematics of the testing arrangement used in the same way as that usually applicable to the four-ball configuration.

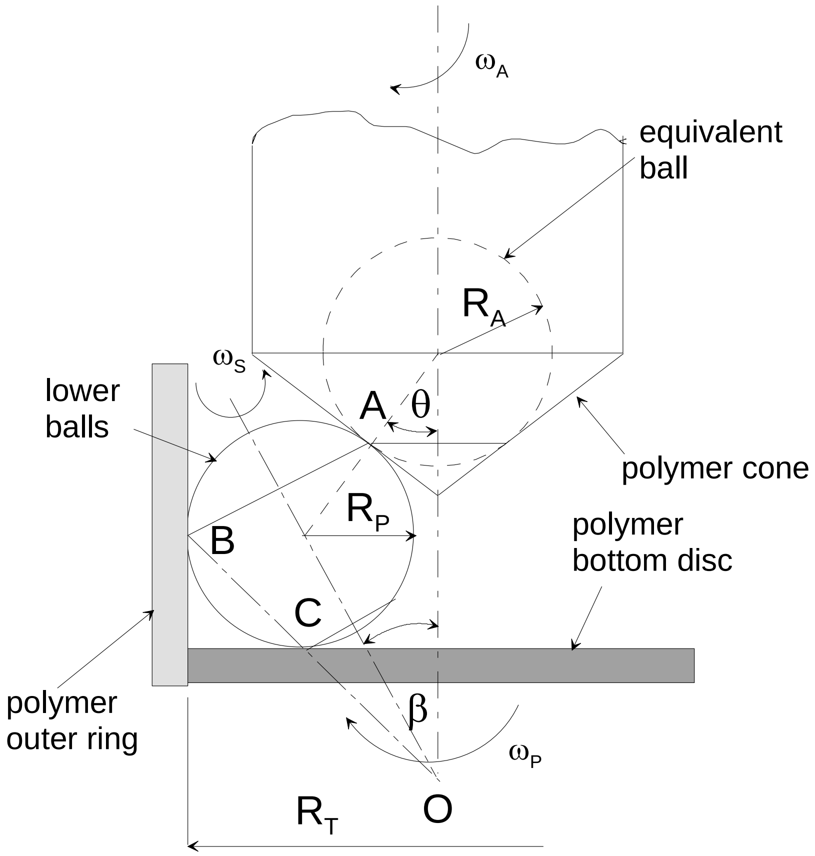

Figure 2. Geometry relationships characteristic for the rolling four-ball machine configuration. Please note that the equivalent ball replaces the cone.
ω_s-spin angular velocity, ω_p-rotational (orbital) velocity, ω_A- cone rotational velocity

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Trigonometric relationships may be used to find the angle θ:

$$\theta = \arcsin\frac{R_T - R_P}{R_P + R_A} \text{ [deg]}$$

Angle β is the angle between the lower ball centroid and the vertical axis and is a function of equivalent upper and lower ball dimensions and the contact angle theta.

$$\beta = \arctan\frac{R_T - R_P}{R_T} \text{ [deg]}$$

Upper and lower ball linear and angular velocities are found by considering instantaneous motion. The equivalent upper ball drives the three lower balls around the cup, which in the study presented here was formed by the outer ring and the bottom disc. Linear and angular velocities for upper ball are defined by the spindle's velocity and the contact angle because the upper ball (or cone) is fixed to the spindle directly.

(i) Cone (equivalent upper ball):

$$\omega_A = \frac{2\pi N_A}{60} \text{ [rad/s]}$$

Where N_A is the rotational velocity of the upper ball or cone

(ii) Lower ball:

a) Motion about upper ball vertical axis

$$\frac{\omega_A}{\omega_P} = 1 + \frac{R_T}{R_A}\left(1 + \frac{\tan\beta}{\tan\theta}\right)$$

$$\omega_P = \frac{\omega_A}{1 + \frac{R_T}{R_A}\left(1 + \frac{\tan\beta}{\tan\theta}\right)} \text{ [rad/s]}$$

b) Motion about axis at the angle beta to vertical axis

$$\frac{\omega_S}{\omega_P} = \frac{R_T}{R_P} \cdot \frac{1}{\cos\beta}$$

$$\omega_S = \omega_P\left(\frac{R_T}{R_P}\frac{1}{\cos\beta}\right) \text{ [rad/s]}$$

The ratio of ω_s/ω_p (spin/roll) denotes the amount of sliding motion.

Using geometry of the three balls and the cone (equivalent ball) and kinematic relationships one can find out the number of load cycles corresponding to one full revolution of the cone,

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$$N = z\left[1 + \frac{R_A/R_T}{1 + \left(\tan\beta/\tan\theta\right)}\right]^{-1}$$

where z = 3 represents the number of lower balls.
Taking into account specific dimensions of the balls, cone and the inside diameter of the ring, the following can be calculated.
$R_A = R_P$ = 6.35 mm is representing radius of the equivalent ball traced within the cone and equal to the radii of three lower balls (see Figure 3).
R_T = 13.68 mm represents inside radius of the outer ring.
Therefore, using the above data one can calculate,

$$\theta = arcsin\frac{R_T - R_P}{R_P + R_A} = 35^o 16'$$

and

$$\beta = arctan\frac{R_T - R_P}{R_T} = 28^o 11'$$

Now, taking into account the expression for the number of load cycles per one full revolution of the cone, it is easily found that N = 2,37 loadings/1 cone's revolution. If the experiment is run at a specific rotational velocity, say n [rev/min], then the number of load cycles is given as,

$$N_n = N \times n \ \left[\frac{cycles}{min}\right]$$

2.2 Load distribution in the model rolling contact

Distribution of an external load on the contact, W, between constituent components of the assembly, i.e. cone, ring, bottom disc and ceramic balls is schematically depicted in Figure 3.

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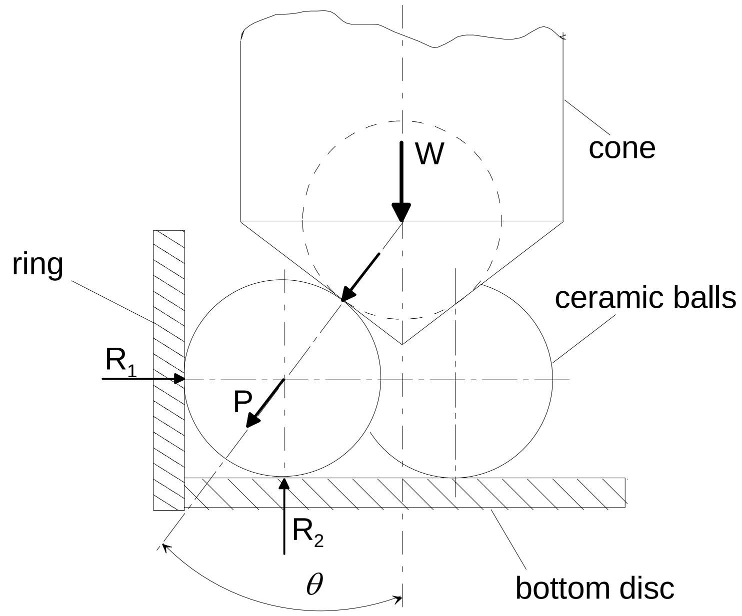

Figure 3. Schematic showing distribution of external load, W, on constituent components of the rolling contact assembly.

Force P acting on a single ceramic ball is given by:

$$P = \frac{W}{3cos\theta}$$

Forces acting at the points of contact of a ceramic ball with the ring, R_1, and the bottom disc, R_2, can be found from:

$$R_1 = Psin\theta$$
$$R_2 = Pcos\theta$$

Using expression derived earlier for the angle θ and substituting for P expression given above the following equations for R_1 and R_2 are arrived at:

$$R_1 = \frac{W}{3cos\theta}sin\theta = \frac{1}{3}Wtan\theta = \frac{1}{3}Wtan\left(arcsin\frac{R_T - R_P}{R_P + R_A}\right)$$

and

$$R_2 = \frac{W}{3cos\theta}cos\theta = \frac{1}{3}W$$

All the symbols used in the above equations were introduced earlier on (see Figure 2).

Under the action of external load, W, the balls are pushed by the cone outwards to make direct contacts with the ring and bottom disc. Consequently, balls become permanently separated from each other which means no direct contact between them (see Figure 4). It is certainly true for hard, elastic materials, such as steel or ceramics.

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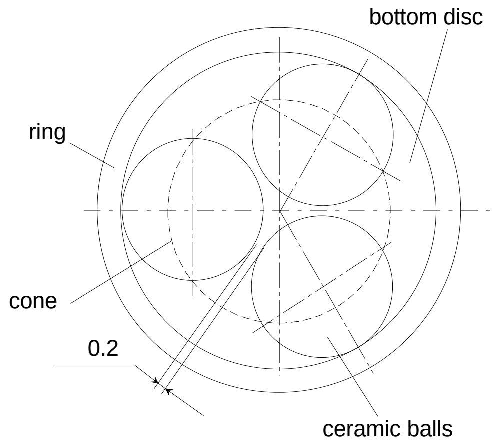

Figure 4. Top view of the rolling contact assembly.

For the geometry and dimensions utilised in the study reported here, the gap between adjacent ceramic balls was only 0.2 mm. Such small a separation between balls together with the viscoelastic properties of the polymers tested could create conditions for occasional and random direct contact of the balls. This rather unusual phenomenon was observed during testing and is elaborated on later in this paper.

2.3 FE analysis of model contact

Replacement of the cone by the equivalent ball is fully justified and enables kinematic analysis to be carried out in exactly the same way as for the original four-ball configuration. However, this is not allowed when contact loads are calculated because of the entirely different contact conditions between the cone and three lower balls (configuration actually used) and that encountered when the upper ball is in contact with the three lower balls (original four-ball configuration). For that reason finite element method was used to estimate the contact loads within the assembly used during testing.

2.3.1 Geometry of numerical model

Geometry of the model contact was used to create its numerical model. Figure 5 depicts complete test assembly with its elements meshed.

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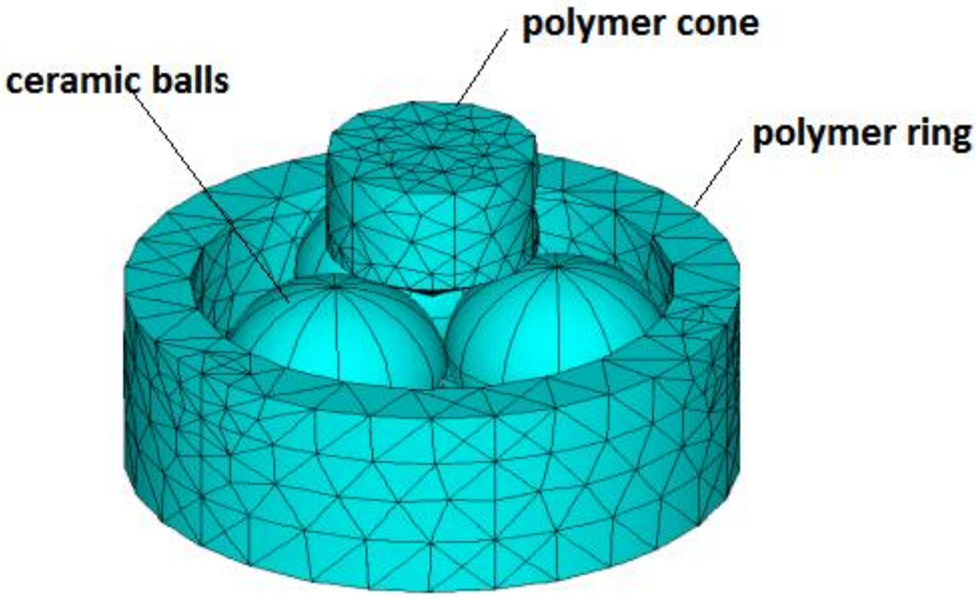

Figure 5. Complete test assembly with constituent elements meshed.

Elements of the contact had the following dimensions:
- three balls with 12.7 mm diameter,
- outer ring with inside diameter of 27.5 mm and outside diameter of 35 mm,
- bottom disc with 35 mm diameter and thickness 4 mm,
- cone with diameter 12 mm, length 18 mm, and apex angle of 109 deg.

Materials used for the elements had the following mechanical properties: Polyetheretherketone (PEEK), (used for outer ring, bottom disc, and cone) had Young's modulus $E_1 = 3.6x10^3$ MPa, Poisson's ratio $v_1 = 0.4$, and tensile strength = 80 MPa.

Balls were made of silicon nitride (Si_3N_4) with Young's modulus $E_2 = 324x10^3$ MPa, Poisson's ratio $v_2 = 0.27$, and tensile strength = 524 MPa. Because of significantly larger Young's modulus of silicon nitride in comparison with that of PEEK it was justifiably assumed that the balls could be treated as undeformable bodies. Moreover, it was taken that friction coefficient between ceramic balls and polymer elements during a slip motion is $\mu = 0.1$.

In FE analysis elements SOLID92 were used to mesh polymer constituents of the contact and CONTA174 elements together with TARGE170 were utilised to mesh the direct contact region. Ceramic balls were also meshed with TARGE170 elements. An average size of elements in the contact regions was 0.1 mm. For regions outside direct contacts larger elements were used to reduce computing time.

2.3.2 Presentation of results

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Numerical results, obtained with the help of FE computer programme ANSYS, are presented in the form of stress maps for various loads acting on the contact. For each case of loading two types of stresses were considered, namely contact pressure and tangential stress due to friction within the direct contact zones between interacting elements of the assembly.
Figure 6 shows contact pressure, given in MPa, between the bottom polymer disc and a ceramic ball at the load on the contact of 30 N.

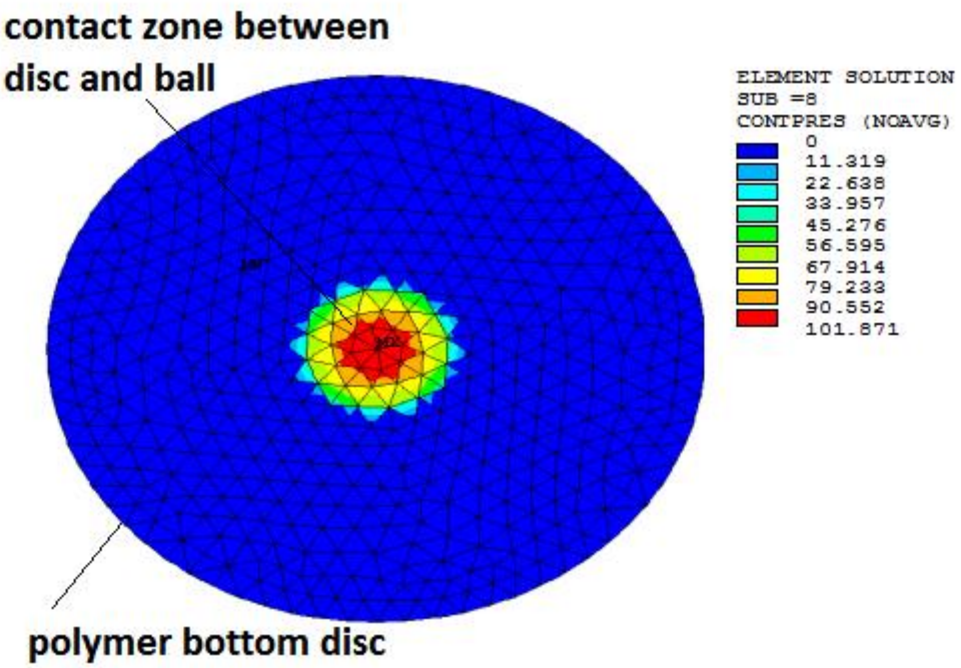

Figure 6. Element solution for contact pressure [MPa] between ceramic ball and polymer bottom disc under the load on the contact of 30 N.

Different stress situation exist in the contact region between ceramic ball and polymer ring. Figure 7 presents element solution for contact pressure under the load of 30 N. As anticipated both contact pressure and tangential stress are clearly lower compering to those generated under the same load in the contact zone between ceramic ball and polymer bottom disc.

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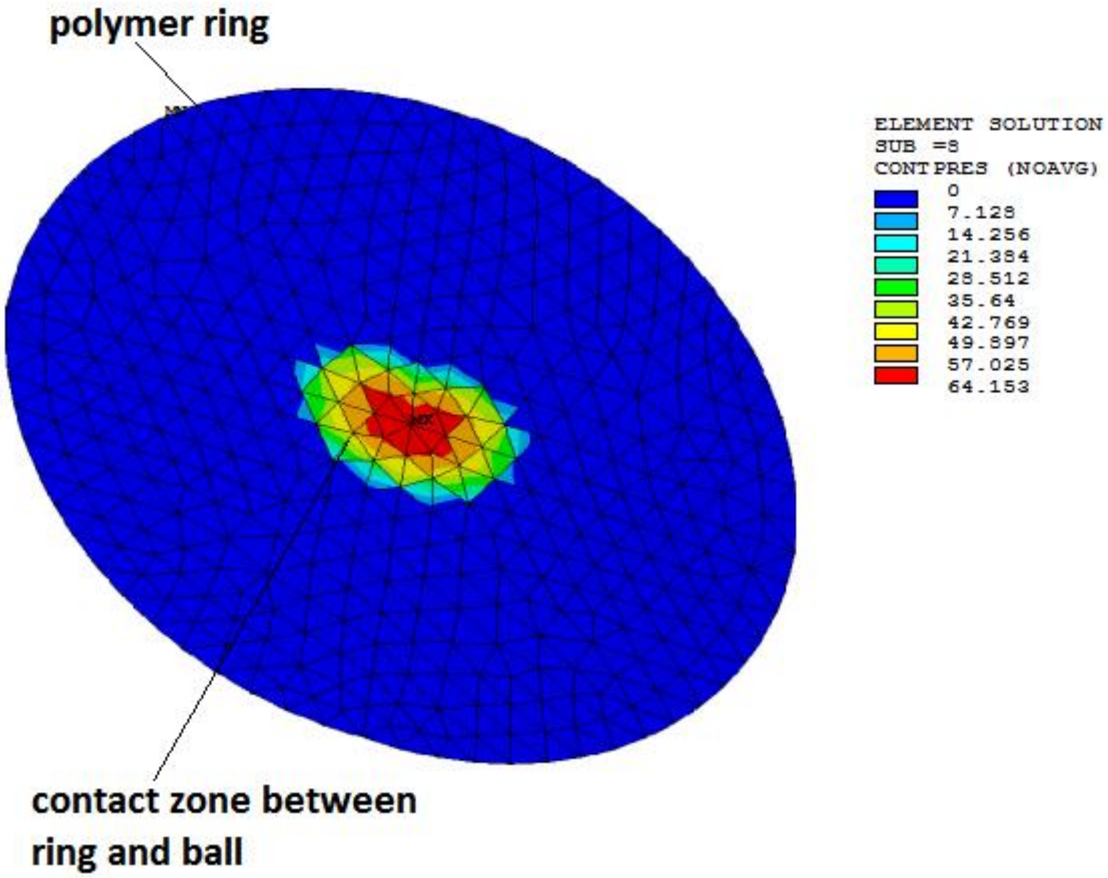

Figure 7. Element solution for contact pressure [MPa] between ceramic ball and polymer ring under the load on the contact of 30 N.

The third contact zone in the assembly tested exists between polymer cone and ceramic balls. This contact zone is characterised by highest contact pressure and tangential stress due to friction. Figure 8 shows element solution for contact pressure existing between the polymer cone and ceramic balls under the load of 30 N.

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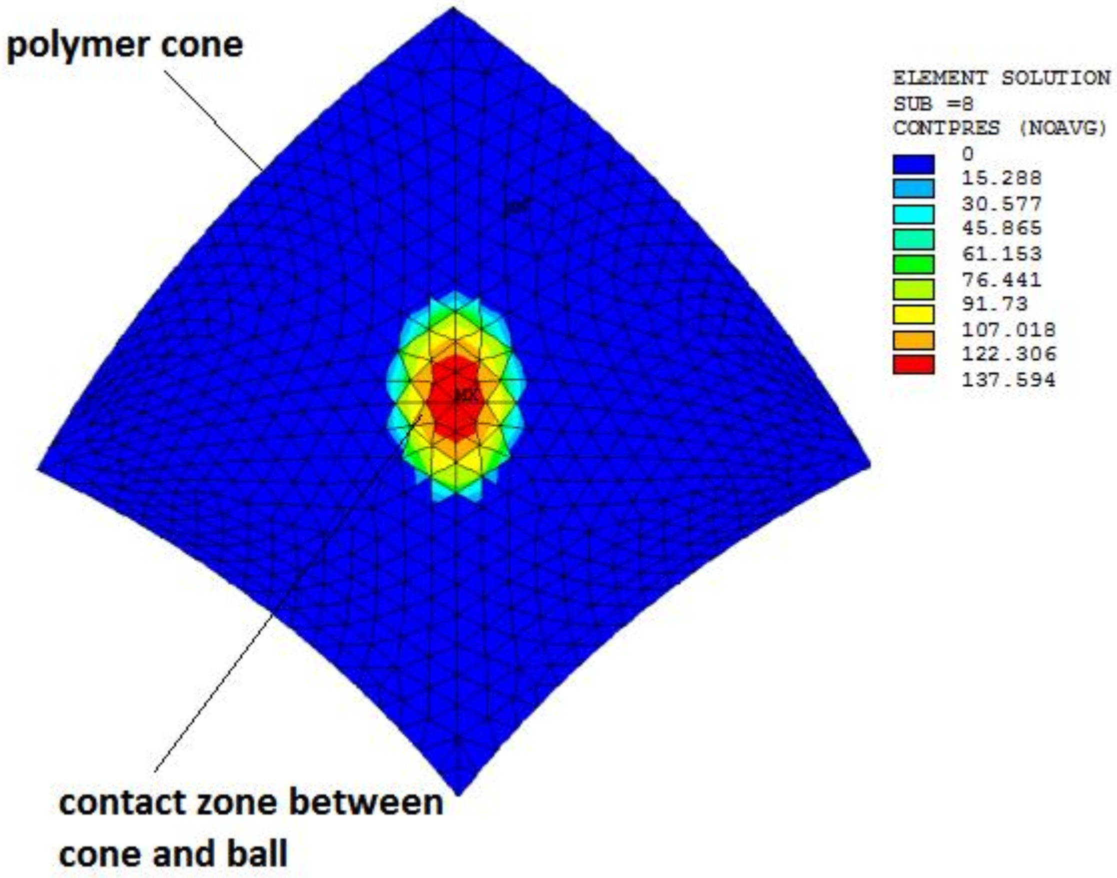

Figure 8. Element solution for contact pressure [MPa] between ceramic ball and polymer cone under the load on the contact of 30 N.

2.3.3 Discussion of numerical modelling results

Using FE method it was possible to determine the magnitude of contact pressure and tangential stress resulting from the contact between constituent elements of the assembly. Various loads were used during numerical simulation but only results generated under the load of 30 N are presented here as being typical. It has to be emphasised that results presented are only representing the initial contact between components of the assembly tested. With the passage of time and due to the viscoelastic nature of PEEK, contact pressure undoubtedly changed and decreased. Highest contact pressures and tangential stresses were found to be between the polymer cone and ceramic balls. The contact between polymer bottom disc and ceramic balls was subjected to less severe loading than that between polymer cone and ceramic balls. According to the results of numerical modelling the least sever loading was experienced by the contact between polymer ring and ceramic balls. This is understandable when the way in which the external load on the contact is distributed between components of the assembly tested is considered (see Figure 3).

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3. Experimental

3.1 Test procedure and its parameters

All tests were carried out using test apparatus shown in Figure 1. Testing was performed under dry contact condition at laboratory normal temperature 20 ±3^{o} C and relative humidity 38-50 %. Loads applied on the contact were changed stepwise as follows: 5 N, 10 N, 20 N, and 30 N. At any given load tests continued for up to 50 hours in total. This test duration, at the speed of the spindle 200 rpm kept constant, corresponds to 1422000 load cycles.

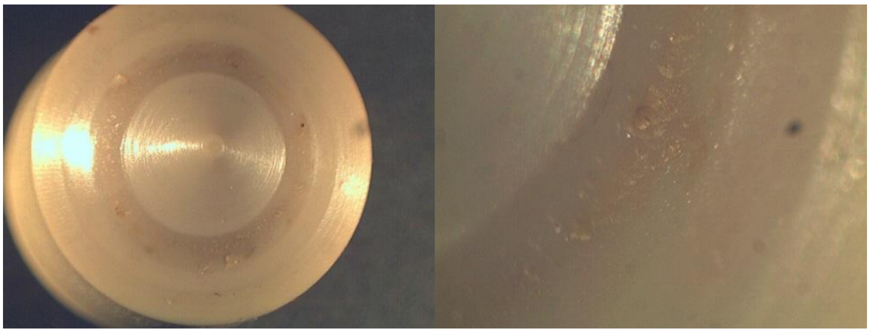
Tests were terminated when during inspection under an optical microscope a gross failure or damage of one of the polymer constituents was found. Tests were interrupted at the regular predetermined time intervals to record the appearance of contact areas and the progress of a surface damage. Each test, at a given load, was repeated two times. A third test was conducted if the two previous tests produced significantly different results. Polymer elements of the assembly tested were machined from a solid PEEK rod and had, on average, initial surface roughness R_a = 1.57 μm and R_a = 0.79 μm for polymer ring and polymer disc respectively.

A typical test started with polymer elements of the assembly being cleaned in distilled water with a small addition of soap. Ceramic balls were cleaned with a general purpose solvent. After assembling them in the testing apparatus, a rotation speed of 200 rpm for the spindle was set. Afterward, the load was applied and testing was carried out for the interval of 5 hours. When the set test time was reached, polymer elements and ceramic balls were removed from the apparatus for microscope examinations.

3.2 Presentation of results

3.2.1 Polymer cone

Figure 9 contains optical microscope images showing typical forms of damage inflicted on the polymer cone.



(a) (b)

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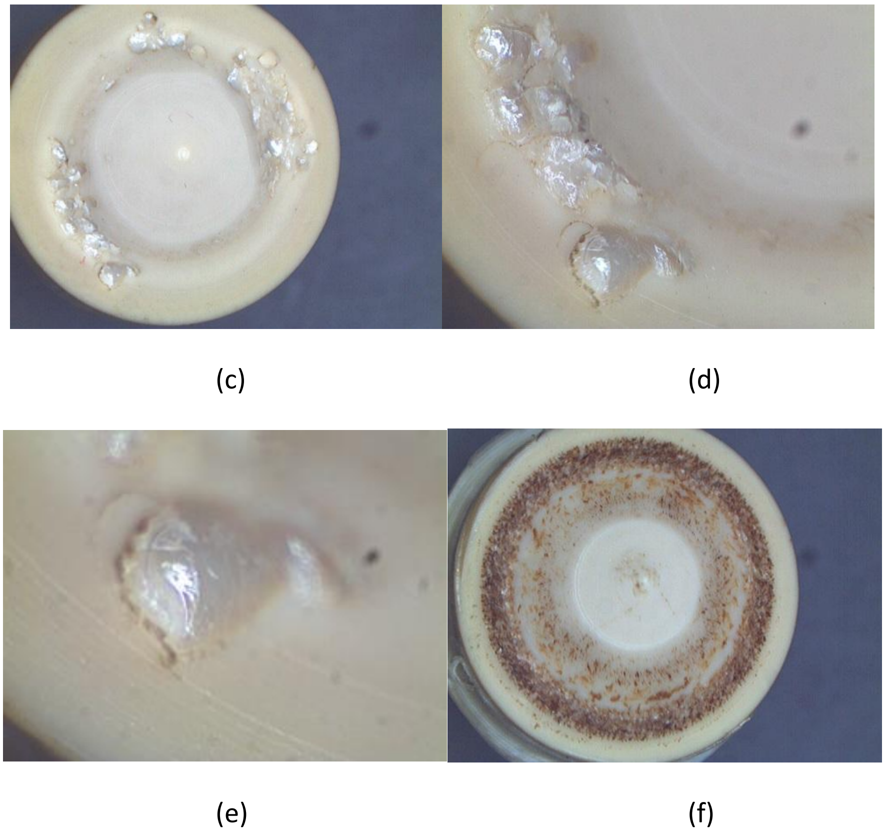

Figure 9. Optical microscope micrographs of PEEK cone in contact with silicon nitride balls.

(a) cone's surface after 12 hours of testing under 10 N (mag. x5); (b) the same as (a) but at mag. x10; (c) cone's surface after 43 hours of testing under 10 N (mag. x5); (d) the same as (c) but at mag. x10; (e) the same as (c) but at mag. x20; (f) cone's surface after 23 hours of testing under 30 N (mag. x5).

It can be seen that surface damage, in the form of pits and small areas of removed material, is progressing with the time. At higher magnification, morphology of damage is consistent with that typical for surface fatigue. Figure 9 (f) shows a different damage morphology which suggests that the contact track produced on the cone is covered with debris embedded into its surface. These wear particles are transferred material from ceramic balls produced by their direct contact. This phenomenon will be elaborated on later.

3.2.2 Polymer ring

Figure 10 contains optical microscope images showing typical forms of damage inflicted on the polymer ring. As in the case of the cone, damage develops with the time and its morphology points to the fatigue. Similar to that of the cone, the damage takes form of pits and small areas from which the material was plucked out. Some of that material was deposited within the contact track or pushed out of it.

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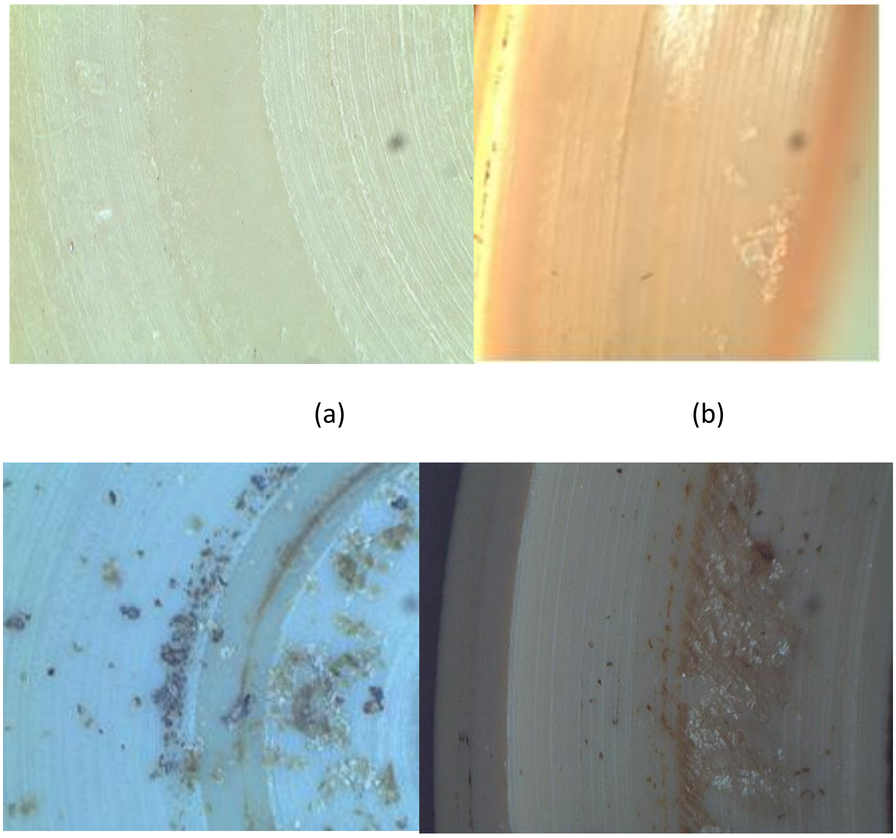

(a) (b)

(c) (d)

Figure 10. Optical microscope micrographs of PEEK ring in contact with silicon nitride balls.

(a) ring's surface after 12 hours of testing under 10 N (mag. x5); (b) ring's surface after 23 hours of testing under 10 N (mag. x5); (c) ring's surface after 34 hours of testing under 10 N (mag. x5); (d) ring's surface after 43 hours of testing under 10 N (mag. x5).

3.2.3 Polymer disc

Figure 11 contains optical microscope images showing typical forms of damage inflicted on the polymer disc.

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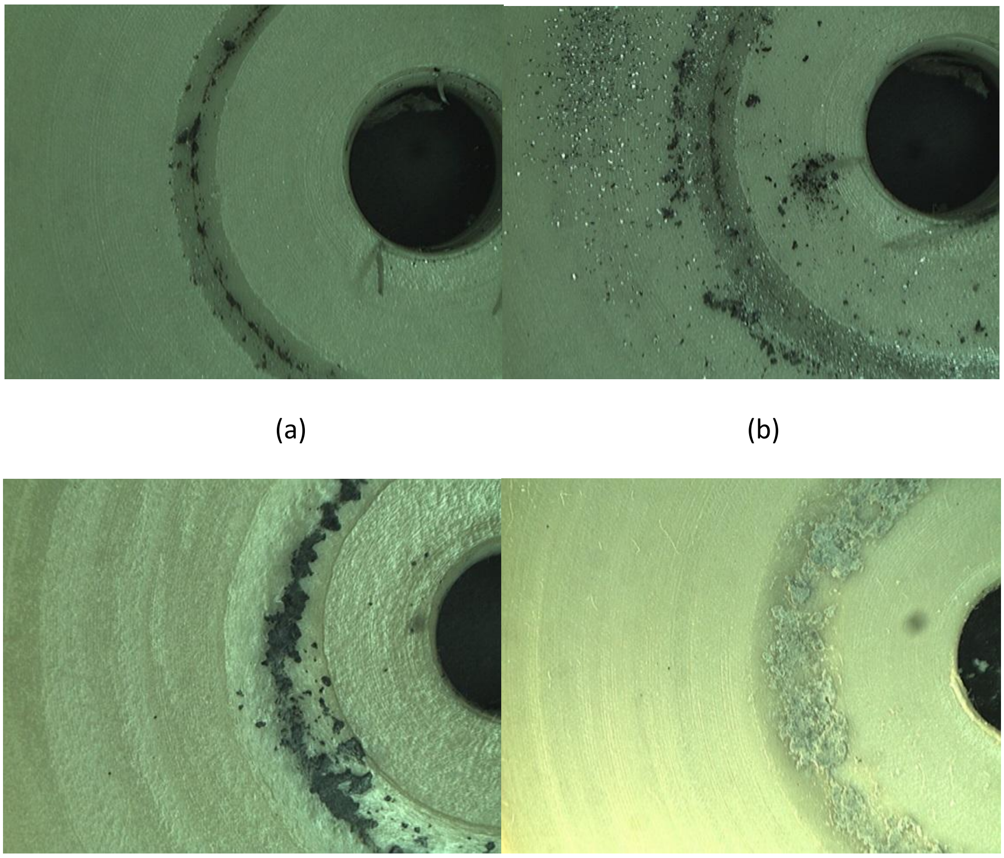

(a) (b) (c) (d)

Figure 11. Optical microscope micrographs of PEEK disc in contact with silicon nitride balls. (a) disc's surface after 12 hours of testing under 10 N (mag. x5); (b) disc's surface after 23 hours of testing under 10 N (mag. x5); (c) disc's surface after 34 hours of testing under 10 N (mag. x5); (d) disc's surface after 43 hours of testing under 10 N (mag. x5).

All images clearly show contact path formed on the surface of the disc by rolling ceramic balls. Again damage is in the form of pits and small areas from which the material was removed. Some of it was deposited outside the contact path or rolled in into the track. Figure 11(b) shows some shiny particles outside the contact track. These are, undoubtedly, ceramic wear debris resulting from the direct contact between ceramic balls.

3.2.4 Ceramic balls

Interesting and unexpected phenomenon took place during testing. The assembly used for testing is supposed to operate without allowing for the direct contact between three lower balls. External load applied on the assembly pushes the balls away from the central axis of rotation and forces them to make contact with the outer ring and the bottom disc (see Figures 2, 3, 4). Therefore, what was observed is really interesting and should be attributed to the nature and combination of materials tested.

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Figure 12 shows optical microscope images of ceramic balls after testing in rolling contact with components made of PEEK.

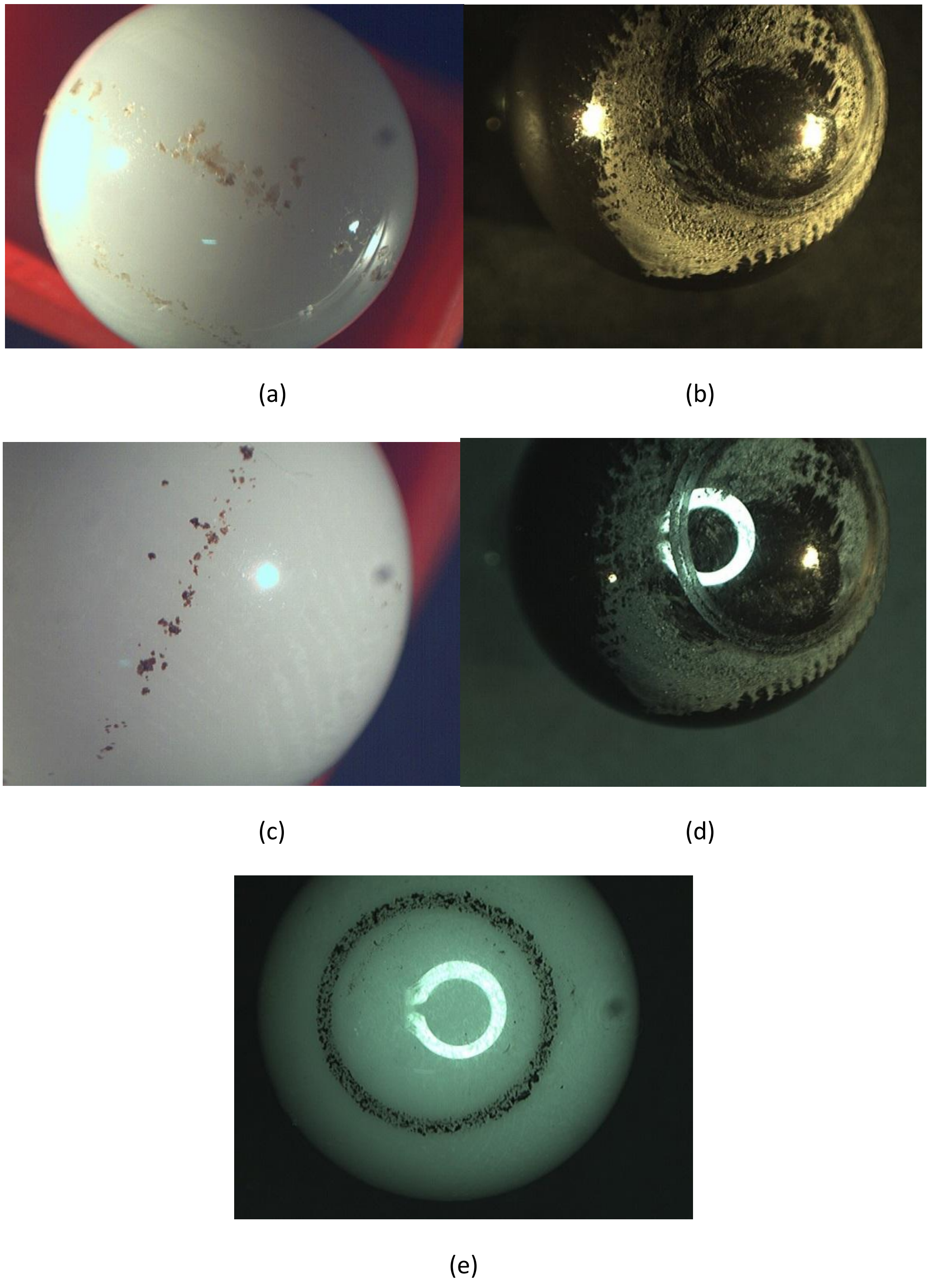

Figure 12. Optical microscope images of ceramic balls in rolling contact with elements made of PEEK.

(a) ball's surface after 23 hours of testing under 10 N (mag. x10); (b) ball's surface after 12 hours of testing under 30 N (mag. x10); (c) the same as (a) but at mag. x20; (d) ball's surface after 23 hours of testing under 30 N (mag. x10); (e) ball's surface after 43 hours of testing under 10 N (mag. x10).

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It can be clearly seen that under the load of 10 N (see Figure 12 (a), (c), and (e)) surface of the ball is covered with transferred polymer particles. Most of the ball's area is smooth and shiny. The image shown in Figure 12 (b) and (d) is completely different. It points to a substantial wear resulting from direct contact between balls. A further evidence for that supposition is provided by the image shown in Figure 13.

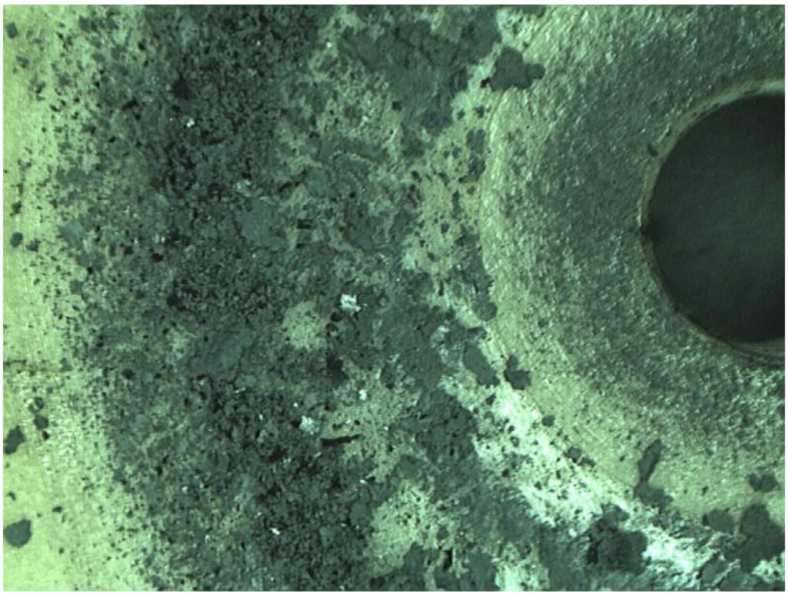

Figure 13. Optical microscope image of disc's surface (PEEK) after 23 hours of testing under 30 N showing transferred ceramic wear debris (mag. x20).

It is clearly seen that the contact path between the disc and ceramic balls is covered by wear debris resulting from the direct contact of the balls.

3.3. Discussion of experimental results

3.3.1 Damage morphology of PEEK components

The main aim of the study reported here was to find out the modes of failure to which elements made of PEEK are subjected in a rolling contact. In the test configuration used observed failure modes reflect the characteristic feature of polymeric materials. They, unlike metals, are inhomogeneous on a gross scale and anisotropic. They tend to accumulate damage in a general rather than a localized way. Moreover, failure does not usually occur by propagation of a single macroscopic crack. Also, it has to be remember, polymers are viscoelastic materials.

Optical microscope images for the cone (see Figure 9), which was the most heavily loaded element in the assembly, unequivocally point to the surface fatigue. Well-developed pits from which the material was plucked out are clearly visible. In most cases the removed material has been rolled into the contact track and some of it transferred onto the balls' surfaces due to adhesion. Thus, the results confirm that a mechanically strong polymer such as PEEK predominantly fails due to surface fatigue and so called "self-healing" process well known for other thermoplastics, such as Nylon 66 or polyethylene is not applicable here.

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The disc loading was the second in terms of the magnitude. Images of Figure 11 suggest that the predominant mode of damage suffered by the disc was also surface fatigue. Additionally, being at the bottom of the assembly, it was inevitably covered by wear particles produced by the direct contact of ceramic balls. This debris, being abrasive in nature, could have influenced the morphology of damage to a certain extent. One of the possible scenarios here is that ceramic wear particles were embedded into the contact path formed on the disc's surface. As a result that part of the disc could have been "reinforced" in some way thus altering the failure modes. Morphology of damage inflicted on the ring (least loaded component of the assembly) is given by images shown in Figure 10. The damage is less severe comparing to that of cone or the disc. However, the predominant feature in some of the images (see Figure 10 (c) and (d)) is the accumulation of loose particles with the passage of test the time. They were mainly identified as ceramic particles and, to a lesser extent, PEEK particles.

Appearance of ceramic balls, shown in Figure.12 (b) and (d), inevitably points to the direct contact between them, which has to be considered rather unusual to occur in the test configuration used. In order to explain why that happened in a configuration which, by design, excludes such a possibility it is necessary to consider mechanics of polymer rolling contact.

3.3.2. Surface damage of ceramic balls

The stress in polymeric materials subjected to rolling contact conditions is influenced by the rate of strain and, therefore, the contact stress and deformation depend upon the speed of rolling. The simplest way to account for time dependent characteristics of a polymeric material is to model it as a linear viscoelastic material. However, application of the linear theory of viscoelasticity to rolling contact is not simple since the situation is not one in which the viscoelastic solution can be obtained directly from the elastic solution. It is not difficult to appreciate the reason for that. During rolling, the material located in the front half of the contact is being compressed, while that at the rear is being relaxed. With perfectly elastic material the deformation is reversible, so that both the contact area and the stresses are symmetrical about the centre-line. Viscoelastic material such as PEEK, however, relaxes more slowly when it is compressed, so that the two bodies in contact (ceramic ball and PEEK component, for example cone) separate at a point closer to the centre-line than the point where they first make contact. This is illustrated in Figure 20, where $z_1 < z_2$ and recovery of the surface continues after contact has ceased. The geometry of rolling contact of a polymeric material is different from that of the perfectly elastic case, and therefore the viscoelastic solution cannot be obtained directly from the elastic solution. Moreover, the point at which separation occurs, that is $x = z_2$, cannot be defined in advance. Usually, it has to be located where the contact pressure drops to zero.

A one-dimensional model of the contact between polymeric material and a rigid ceramic ball of radius R is shown in Figure 14.

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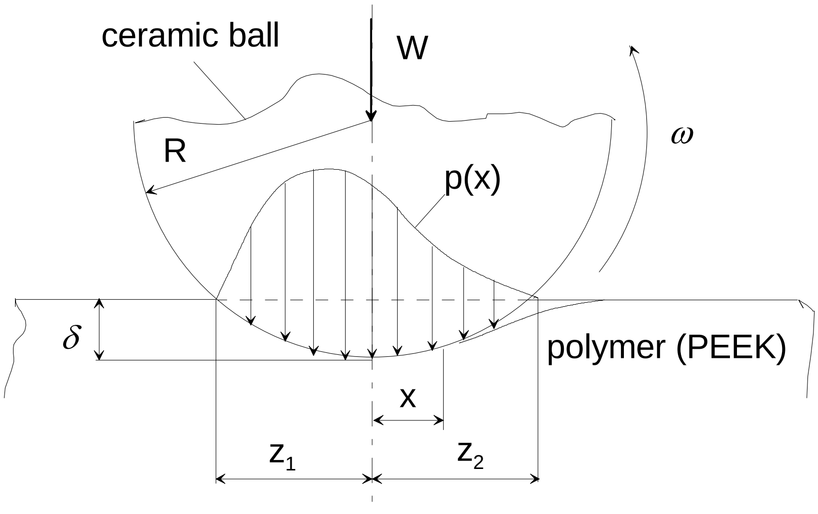

Figure 14. Contact between ceramic ball and viscoelastic material (PEEK)
p(x) – contact pressure; δ – depth of penetration

The polymer will be modelled by a simple visco-elastic foundation of parallel compressive elements that do not interact with each other. The rolling velocity is V and the ball makes first contact with polymer substrate at x = $-z_1$. Since there is no interaction between the elements of the foundation, the surface does not depress ahead of the ball. Assuming that $z_1 << R$, the compressive strain in an element of the foundation at x is given by,

$$\epsilon = -\left(\frac{\delta - x^2}{2R}\right)\frac{1}{h}$$

where h is the thickness of the polymer foundation, $-z_1 \leq x \leq z_2$, and δ is the maximum depth of penetration of the ball.

In the case of a perfectly elastic foundation characterized by a modulus K, the contact would be symmetrical, that is $z_1 = z_2$, and the contact stress also be symmetrical. For viscoelastic material the elastic modulus, K, is replaced by a relaxation function $\Psi(t)$. Thus the stress in the viscoelastic element located at z is given by,

$$p(x,t) = -\int_0^t \Psi(t-t')\frac{\partial \varepsilon(t')}{\partial t'}dt'$$

At steady rolling the following is applicable:

$$\frac{\partial \varepsilon}{\partial t} = \frac{Vx}{Rh}$$

therefore, changing the variable from t to x, the stress in a viscoelastic element can be expressed as:

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$$p(x) = -\frac{1}{Rh}\int_{-x}^{x} x'\Psi(x - x')dx'$$

Further analysis requires specification of the relaxation function for the polymer used. However, one important thing to note is that the contact pressure is distributed asymmetrically causing uneven resistance to the rolling motion of the ceramic balls. This, however, depends of the rolling speed. At slow rolling speed the contact time between polymer components of the test assembly and ceramic balls is long by comparison with the relaxation time of the polymeric material, therefore the pressure distribution is quite close to that for a perfectly elastic material with modulus K and there is practically no uneven resistance to the rolling motion. However, at relatively high rolling speeds which were used during testing presented here, the pressure distribution is governed by the modulus of the viscoelastic foundation. Hence, it is obvious that the relaxation effects play an important role in the behavior of contact. This is especially true when the contact time between contacting elements in rolling motion is approximately equal to the relaxation time of the foundation material. Taking into account the above, it is possible to put forward a hypothetical mechanism responsible for direct contact between ceramic balls to occur. Due to asymmetric contact pressure distribution the resistance to the rolling motion of ceramic balls in contact with polymer (PEEK) components of the assembly is not uniform over the contact interface. This, in turn, could produce random acceleration of a ball as well as deceleration depending on the local contact conditions of individual balls. Remembering that ceramic balls are very close to each other (nominal separation equal to 0.2 mm as informed by the geometry of the assembly shown in Figure 4) it is quite possible they the touched one another and produced surface features shown in Figure 12. Thus, the viscoelastic nature of a polymer is believed to be responsible for experimentally observed surface markings, production of ceramic wear debris and premature degradation of components made of PEEK. It has to be emphasized that the direct contact between balls in the four-ball configuration is, quite probably, a unique feature for viscoelastic materials. To the best of our knowledge, direct contact between balls in the four-ball configuration does not normally occur when elastic materials are tested. This is confirmed by published results [11].

4. Conclusions

The most important conclusion resulting from the research presented in this paper concerns the direct contact between the three lower ceramic balls in the test configuration used when they are rolling under a load over components made of PEEK.

Direct contact between ceramic balls lead to their surface being damaged and the production of wear debris, which in turn accelerated degradation of PEEK components tested.

It is believed that the viscoelastic nature of the PEEK is responsible for experimentally observed direct contact between ceramic balls – a phenomenon

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normally not observed when nominally elastic materials are tested in the four-ball configuration.

Based on the results presented here it is postulated that the rolling contact fatigue of engineering polymers should be assessed in a different configuration than that of four-ball unless steps are taken to ensure that direct contact is effectively prevented.

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