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MECHANICAL AND TRIBOLOGICAL PROPERTIES OF POLYMERS AND POLYMER-BASED COMPOSITES

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Abstract. A definition of rigidity of polymers and polymer-based composites (PBCs) by an equation is formulated. We also discuss tribological properties of polymers and PBCs including frictions (static, sliding and rolling) and wear. We discuss connections between viscoelastic recovery in scratch resistance testing with brittleness B, as well as Charpy and Izod impact strengths relations with B. Flexibility Y is related to a dynamic friction. A thermophysical property, namely linear thermal expansivity, is also related to the brittleness B. A discussion of equipment needed to measure a variety of properties is included.

Keywords: polymer brittleness, polymer flexibility, polymer rigidity, polymer friction, polymer wear, polymer-based composites, polymer testing.

1. Introduction

This is a review paper, summarizing mechanical and tribological properties of polymers and polymer-based composites (PBCs) and also describing experimental methods of their determination. Equations for brittleness and flexibility are noted. Rigidity of polymers and PBCs is defined by a simple equation.

People known in the history for creating foundations of contemporary science have worked in this area. They include Leonardo da Vinci, Guillaume Amontons, Charles Augustin Coulomb, Leonhard Euler, Robert Hooke and Sir Isaac Newton. It is a complex area since one has to use a multi-scale approach.

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2. Tensile, Compression and Bending (Flexure) Testing

Tensile testing is the most often applied form of mechanical testing of polymers and PBMs. A so-called universal mechanical testing machine is shown in Fig. 1.

In a tensile testing the specimen is held aligned vertically between the two grips. The rate of extension is predefined. The machine can be placed in a large thermostat to assure a constant temperature. A force transducer or other means for measuring the load is needed.

A typical stress *vs*. strain diagram for a polymer is shown in Fig. 2.

The pertinent parameters involved are [2]:

$$\text{Engineering stress} = \sigma = F/A \quad (1)$$

where F is the applied force; A is the cross-sectional area.

We have

$$\text{Engineering strain} = \varepsilon = (l - l_0)/l_0 = \Delta l/l_0 \quad (2)$$

where l is the length produced by the applied force; l_0 is the original length.

We note that Fig. 2 is unusual since typically one plots the effect *vs*. the cause while in this case we have the coordinates inverted. However, this is the universal practice, hence we do not propose to change it. Possibly the reason for the inversion is the fact that in a certain range of stress values we have two values of strain for each stress value.

There are several parameters obtainable from Fig. 2. In the first linear part of the curve, that is for low values of strain, we have a linear proportionality between the two depicted quantities. Their ratio is the tensile modulus:

$$E = \sigma/\varepsilon \quad (3)$$

Ceramic materials have *only* this part of the diagram, so that fracture occurs at the end of the linear region.

Yield strength is the highest strength of the material such that after the removal of the stress the specimen will return to the original size and shape. It is not possible to locate this point! Therefore, one practically defines the yield stress as the point where there is 0.2 % deviation from the original straight line.

Fig. 1. Typical mechanical testing machine [1]

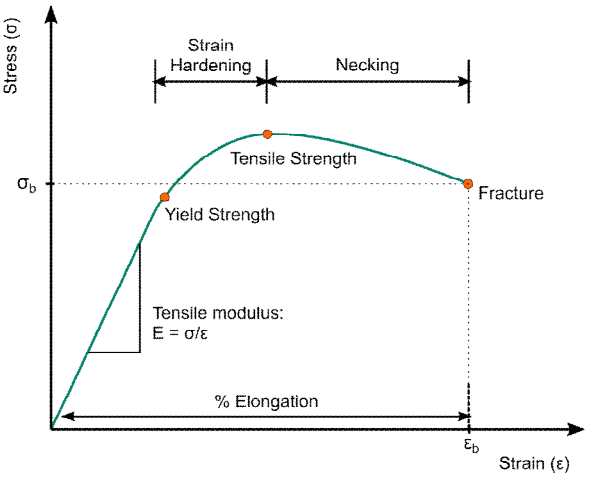

Fig. 2. Stress *vs*. strain diagram for an engineering polymer

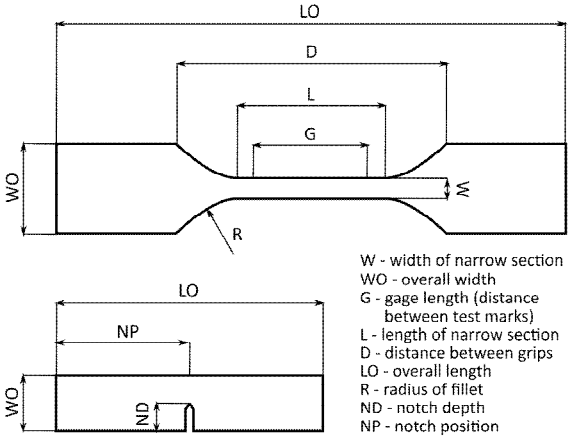

Fig. 3. Specimens for tensile testing, both of uniform thickness in the third (unseen) direction

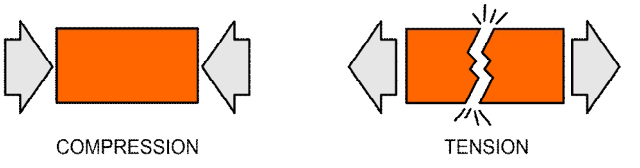

Fig. 4. Comparison of compression and tension testing

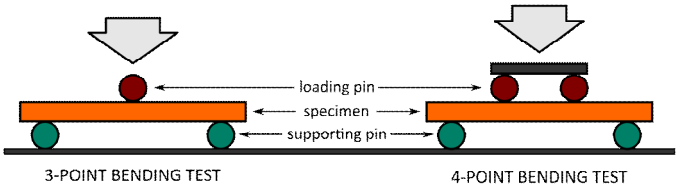

Fig. 5. Two kinds of bending (flexural) tests

The tensile strength seen in Fig. 2 is the maximum stress that a material can withstand while being stretched or pulled before failing.

Fig. 2 shows as well the stress at fracture, also called the stress at break σ_b. There is also strain at break ε_b which will be discussed more in detail below.

There are two kinds of specimens subjected to tensile testing. Both are shown in Fig. 3.

The top specimen in Fig. 3 (dumbbell-shaped) is popularly called a dogbone, data are obtained from the central narrow part. The bottom specimen is a rectangle, typically with a notch. Depending on the type and properties of tested material, specimen can have a round or rectangular cross-section and different values of the parameters defined in Fig. 3 [3, 4].

We shall only briefly consider compression testing, compared with the tension in Fig. 4. There is an analog of Eq. (3), that is the compression modulus is the ratio of stress and negative value of strain; since the strain in negative, one thus gets that modulus as a positive quantity.

Two kinds of bending or flexural testing are usually performed, shown in Fig. 5.

3. Impact Testing

Here we have two popular tests, Charpy and Izod, compared in Fig. 6.

As shown in Fig. 6, there are basic differences between the two kinds of impact testing. The Charpy test

is symmetric with respect to the center of the specimen. The Izod test is not, the bottom half of the specimen is made immobile in the vise. Moreover, in the Charpy test one applies the force on the opposite side of the notch (a man-made crack with predefined geometry) while in the Izod test the notch is on the same side as the force application. The amount of energy needed for the specimen to undergo fracture is the Charpy or Izod impact strength.

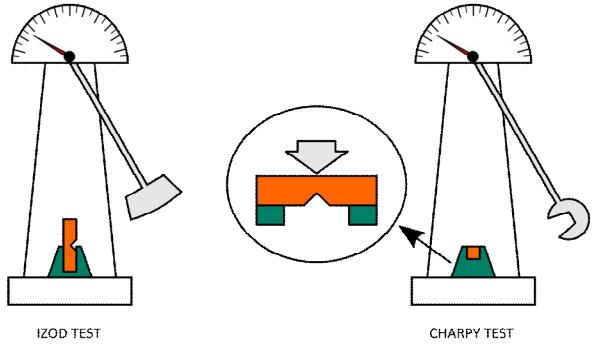

Fig. 6. Comparison of Izod and Charpy impact strength testing methods

4. Hardness and Dynamic Mechanical Analysis (DMA)

In general, hardness is a measure of material resistance to deformation caused either by mechanical forces or by abrasion. A highly respected source talks about "plastic deformation" – ignoring all polymers and PBCs in which the deformation is *viscoelastic* [2]. There are several ways of defining hardness. The oldest measure of hardness has been created by Friedrich Mohs, in terms of the capability of a material to scratch other materials. Thus, diamond has the highest value of 10 on the Mohs scale while talc has the lowest value of 1; for a discussion see for instance [2]. The most commonly applied methods for polymer and PBCs hardness testing are Shore hardness measured with durometers, Rockwell hardness test and Barcol hardness test. In Shore hardness test durometers there are slightly different A (for softer materials) and D (for harder ones) scales. Likewise, the Rockwell hardness test have 5 scales for different kinds of plastics (E, K, L, M and R) and 15 other ones for metal testing [5, 6]. Barcol test involves Barcol Impressor, a portable apparatus for hardness testing [7]. Important is the Vickers hardness testing – in which calculations are independent of the size of the indenter and one indenter can be used for materials of all kinds; it is represented schematically in Fig. 7.

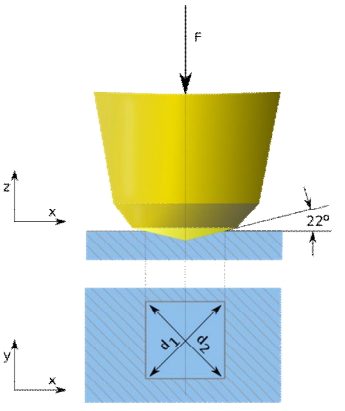

Fig. 7. A schematic of the Vickers hardness test

In dynamic mechanical analysis (DMA) one applies a sinusoidal load at a fixed frequency and a constant temperature or else manages temperature linearly increasing with time. This technique is particularly useful for polymers and PBMs since the material response can be divided into the storage (solid-like, elastic) quantity called the storage modulus *E*' and the loss (liquid-like, viscous flow) quantity called the loss modulus *E*". The DMA technique and the results it produces are discussed in some detail in [2].

5. Friction and Wear Determination

There are at least three kinds of friction: static (related to starting a movement), dynamic or sliding (related to maintaining a movement at constant speed) and rolling. Any kind of friction is a function of the speed of the movement. Three kinds are shown in Fig. 8.

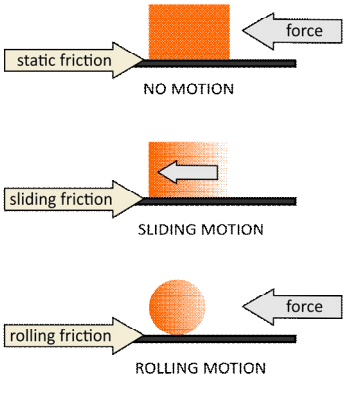

Fig. 8. Three kinds of friction

Very long ago Lord Kelvin wrote that the use of the word "coefficient" is "vicious" and "a mystery of circumlocution" [8]. His words had a limited effect since one still reads in the technical literature about "coefficient of friction" – while often the kind of friction is undefined.

In many circumstances one wishes *low* friction – since this is usually accompanied by a low wear. For this reason for instance Stembalski and his colleagues [9] studied friction on two kinds of steel. In some cases, such as driving a car on an ice-covered road, one wishes the *high* friction.

Consider the sliding friction on a flat surface. As discussed in detail by Rabinowicz [10], we write

$$F = \mu L \tag{4}$$

where μ is the friction value for a given pair of interacting surfaces; L is the normal force.

An apparatus for one-time friction and also sliding friction determination (multiple passages of the indenter along the same groove) is shown schematically in Fig. 9, a photograph of the equipment in Fig. 10.

Let us have a closer look at the results of sliding wear determination; see Fig. 11. We see in Fig. 11 little particles separated from the base by the movements. Their total volume V_{loss} can be used as a measure of wear. The wear rate can be calculated from V_{loss} taking into account the force applied and the total area (sometimes distance) covered in the movement.

A different situation exists for sliding down on a slope; see Fig. 12. Looking at Fig. 12, it is worthwhile to consider the angle between a horizontal line and the slope. The larger that angle is, the larger is the gravitational pushing force shown in the figure. However, that angle is only one of the factors. Fig. 13 displays a variety of factors affecting friction and wear – since these two properties are closely connected.

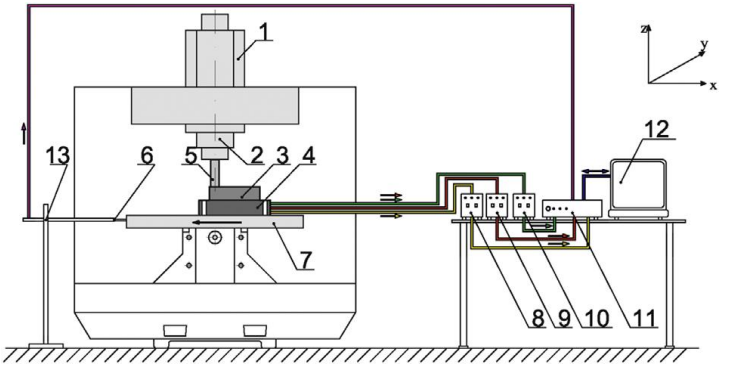

Fig. 9. Friction determination apparatus: 1 – milling machine; 2 – milling machine spindle; 3 – flat-surface test specimen; 4 – three-axis piezoelectric force gauge; 5 – cylindrical rubbing pin; 6 – displacement sensor; 7 – milling table; 8, 9 and 10 – charge amplifiers along the three Cartesian axes; 11 – measuring system; 12 – laptop; 13 – displacement sensor stand [9]

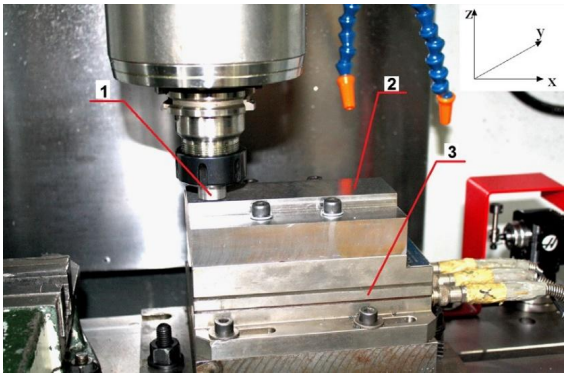

Fig. 10. A photograph of the friction determination equipment: 1 – cylindrical rubbing pin; 2 – flat rubbing surface of the sample; 3 – triaxial piezoelectric force gauge [9]

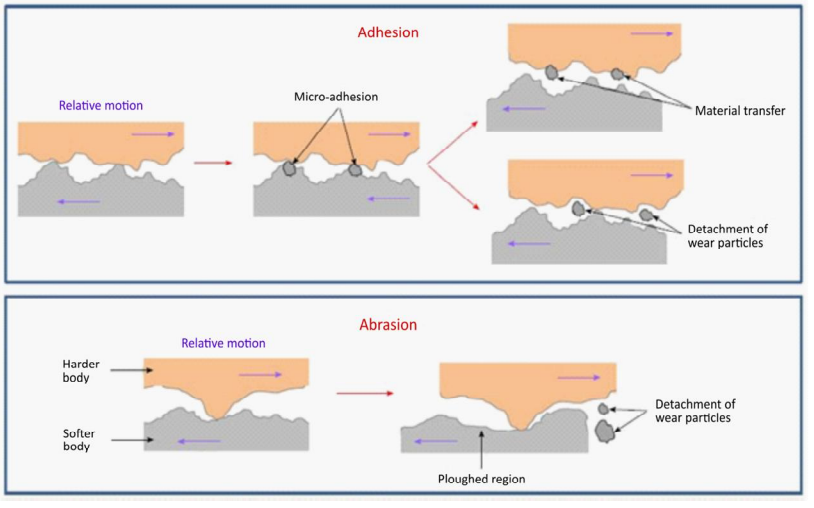

Fig. 11. Adhesive (top) and abrasive (bottom) wear [11]

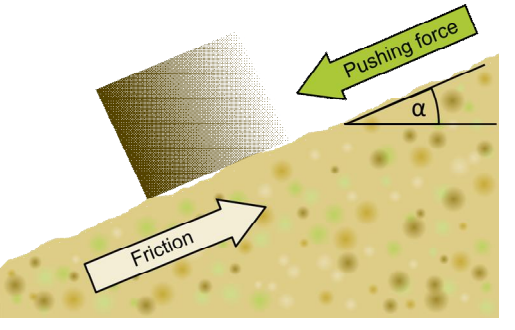

Fig. 12. Moving down on a slope

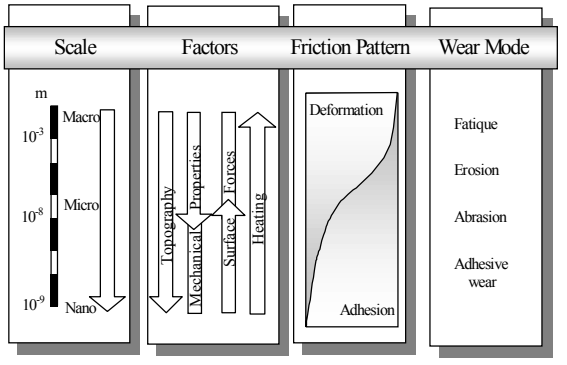

Fig. 13. Factors affecting friction and wear

The above figure explains in particular how factors depend on the scale considered. At the *macroscopic* scale the deformation is considered to be one of the main reasons for friction force generation. There is mechanical energy dissipation determined by friction conditions, material properties, environmental effects, and other factors. At the *microscale*, friction and wear are determined by asperities, that is small contact spots, hence surface forces and adhesion are very important. The growth and breakage of the contact joints are affected by surface phenomena and environment. Wear is also related to dominant components of friction. Thus fatigue wear is mostly affected by deformation, while adhesive wear and friction transfer are affected by adhesion. Erosion and abrasion are the wear modes dominated by a material removal by microcutting of solid particles or asperities – as we have seen in Fig. 11. This fact constitutes the basis of the so-called Bump Model [12]. Both deformation and adhesion factors are important.

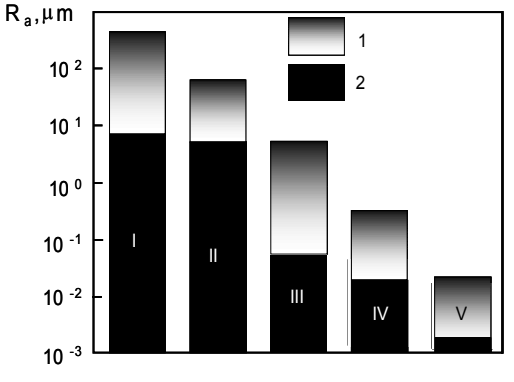

Fig. 14. The rectangle I is for two elastomers, II for metal + elastomer, III for two polymers, IV for polymer + metal and V for two metals. Relative contributions of deformation (1) and adhesion (2) to the total value of R_a are shown

Needless to say, the kinds of materials involved in the interacting pair are important. In Fig. 14 we show the surface roughness R_a for several such pairs. For each pair we show relative contributions of deformation and adhesion to R_a. The roughness is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form – such as horizontal completely flat. The Figure is based on the extensive work of the tribology team in Homel [13-18].

While so much attention of engineers is directed at mechanical properties, industry in each country suffers *large financial losses* because of the need to replace worn and otherwise useful parts. Already in 1966 a Government of the United Kingdom created a panel of scientists and engineers for the purpose of defining future directions of the British industry. The panel has created what is now known as the Jost report from the name of its chairman [19]. The report underlined the size of financial losses caused by wear – and also coined the term "tribology" for science dealing with phenomena which occur on surfaces of moving parts. While there has been a significant progress in tribology, the issues noted in the Jost report have *not* disappeared [13-18, 20, 21].

Wear can be defined as a gradual loss of material at two surfaces in contact. Extensive work done in Homel [13-18] has led to the conclusion that there are three kinds of wear in polymers: abrasive wear, adhesion wear and fatigue wear.

We have noted above the role of asperities. They can be approximately classified in terms of their heights and spacings between them; see Fig. 15.

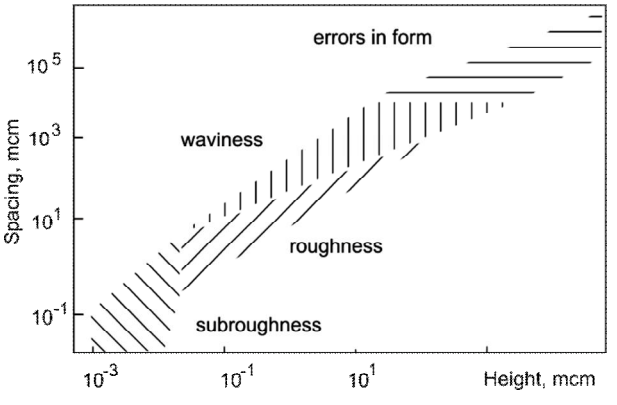

Fig. 15. Approximate classification of asperities

6. Some Useful Definitions of Mechanical Properties

Tensile testing is the most often applied kind of mechanical testing. The tensile modulus E defined in Eq. (3) seems the most often used mechanical parameter. In this section we shall consider some *less used but quite pertinent* parameters.

For a long time technical publications and reports talked about brittleness but only in a qualitative way. In 2006 brittleness B has been defined by an equation [22]:

$$B = 1/(\varepsilon_b \cdot E') \quad (5)$$

We recall that ε_b is the tensile elongation at break while E' is the storage modulus, both noted above. Some applications of definition (5) have been discussed earlier in this journal [23] and also in [2]. The number of those applications keeps on increasing.

Flexibility has been used as well for a long time as an important property characterizing polymers and PBCs – also in a qualitative way. In 2019 an equation defining flexibility Y has been formulated [24], namely

$$Y = \frac{V_{sp}}{\sum_{i}^{n} U_{bi}} \quad (6)$$

where V_{sp} is the polymer specific volume in cm^3/g at a given temperature while the summation extends over the strengths of all bonds in the monomer of a given polymer. Eq. (6) has been inspired by the work of Linus Pauling on chemical bonds [25].

Another property of polymers that used to be discussed in the literature in hand-waving arguments without a definition is rigidity. Given Eq. (6), our task is very easy. We herewith define rigidity of polymers and PBCs as

$$R_p = 1/Y \quad (7)$$

7. Some Relationships Between Properties Discussed Above

Definitions from the previous section would have been of little use if they could not be connected to other properties. Fortunately, both brittleness and flexibility appear in quantitative relationships.

We have not discussed above thermophysical properties; we shall now define one called linear isobaric thermal expansivity:

$$\alpha_l = \frac{(\partial l / \partial T)_p}{l} \quad (8)$$

where l is length as before while the numerator is divided by l to obtain an intensive quantity independent of the size (height) of the material. A relationship has been obtained between α_l and B [26], namely

$$\alpha_\lambda = 104 B^{0.132} \quad (9)$$

We have discussed above the Charpy and Izod impact strengths. Equations have been derived relating each of them to brittleness [27] but we are not including these equations here for brevity.

We have seen above in Fig. 11 the sliding wear determination by repetitive scratching along the same groove [22]. In either single scratch testing or in any of the consecutive runs there is an instantaneous scratch depth R_p. It is also called the penetration depth. In viscoelastic materials inside of 2 min there is a recovery of the groove bottom to a shallower depth R_h. That depth is also called a healing depth (hence the subscript) or else recovery depth. Let us call the viscoelastic recovery f. It can be quantified in percents [22] as follows:

$$f = 100\% \frac{R_p - R_h}{R_p} \quad (10)$$

We have demonstrated a correspondence between B and viscoelastic recovery f [22] for a variety of polymers with different chemical structures as well as for PBCs. The relationship is:

$$f = 30.6 + 67.1 e^{-B/505} \quad (11)$$

Thus, the larger brittleness is, the smaller is the viscoelastic recovery in the sliding wear testing. As one would expect, high values of the parameter f correspond generally to the low wear. Since f is obtained from a tribological testing, Eq. (11) provides a connection between tribology and mechanics – the latter is represented here by B.

A relationship between the flexibility Y and dynamic friction μ has been demonstrated [24], namely

$$Y = 0.311 \mu^{-0.987} \quad (12)$$

We have already seen that the tensile elongation at break appears in the equation defining brittleness. A relationship between that elongation and Vickers hardness h_V has been demonstrated [28], namely

$$h_V = 17.61 - 0.0406 \varepsilon_b + 2.719 \cdot 10^{-5} \varepsilon_b^2 \quad (13)$$

8. Conclusions

Mechanical properties of polymers and polymer-based composites (PBCs) are discussed typically in a quantitative way on the basis of tensile, compressive or bending tests, and also on the basis of impact testing (Charpy or Izod). Other mechanical properties such as brittleness B and flexibility Y had been discussed for a long time qualitatively only – until quantitative definitions were provided and we discuss them here. A simple new definition of polymers and PBCs rigidity by an equation has been formulated. We also discuss tribological properties of polymers and PBCs including frictions (static, sliding and rolling) and wear. We discuss connections between viscoelastic recovery in scratch resistance testing with B and briefly Charpy and Izod impact strengths relations with B. Flexibility Y is related to a dynamic friction. A thermophysical property namely linear thermal expansivity is also related to the brittleness B. We include a discussion of equipment needed to measure a variety of properties.

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МЕХАНІЧНІ ТА ТРИБОЛОГІЧНІ ВЛАСТИВОСТІ ПОЛІМЕРІВ І КОМПОЗИТІВ НА ЇХ ОСНОВІ

Анотація. *За допомогою рівняння сформульовано визначення жорсткості полімерів та композитів на їх основі (РВС). Розглянуті трибологічні властивості полімерів та РВС, включаючи тертя (статичне, ковзання та кочення) та зношування. Описані взаємозв'язки між в'язкопружними властивостями і крихкості при випробуваннях на стійкість до подряпин та зв'язки крихкості з ударною в'язкістю за методами Шарпі та Ізода. Показано, що гнучкість пов'язана з динамічним тертям, а лінійне теплове розширення пов'язане з крихкістю. Проаналізовано обладнання, необхідне для визначення різноманітних властивостей.*

Ключові слова: *крихкість полімерів, гнучкість полімерів, жорсткість полімерів, тертя полімерів, зношування полімерів, композити на основі полімерів, випробування полімерів.*