Creep and recovery of spherical contact on amorphous polymer: experimental results and numerical analysis

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Classical method used to determine the mechanical properties of a material from a load-displacement curve obtained in micro- or nano-indentation tests assume that the materials behave elastically-plastically during the loading phase and elastically during the unloading phase. At room temperature, contact on an amorphous polymers exhibits time and temperature dependency [1, 2]. When a constant normal load is applied to the surface, the creep occurs during the loading phase and increases the indentation depth and consequently the true contact area. After withdrawal of the indenter, on may observe the self healing of the material as shown on figure 1. The aim of this study was to analyse the creep and recovery of an amorphous polymer (PMMA) during a micro-indentation test. Creep and recovery were studied using a home made experimental device [3] which allows us to record the evolution of the contact area and the imprint created by an indentor tip during the loading and self healing phases. Micro-indentation tests were conducted with spherical tips of radius R = 400 µm under different conditions of temperature (-20 °C ≤ T ≤ 100 °C) and holding time (10 s ≤ t ≤ 105 s). The applied normal load was chosen so as to perform tests at different ratios a0/R ranging from 0.1 to 0.2 (a0 is the contact radius at t=0s) these limits being selected to prevent full yielding of the PMMA around and under the contact area. Classical definition of the mean contact strain will be used Tabor [4] \( \varepsilon = 0.2, a/R \) in the following discussion.

The contact strain during the recovery phase must be defined, whatever the geometry of the indentor. The true strain in a uniaxial compression test may be defined by:

\[
\varepsilon(t) = \ln\left(\frac{l(t)}{l_0}\right) = 1/3 \times \ln\left(\frac{l(t)}{l_0}\right)^3
\]  

where \( \varepsilon, l \) and \( l_0 \) are the true strain, the length of the sample under deformation and the initial length of the sample, respectively. Using the equation for the general definition of strain, we propose a strain representative of creep tests and the recovery of the imprint:

\[
\varepsilon_{rp}(t) = \frac{1}{3} \times \ln\left(\frac{V(t)}{V_0}\right)
\]  

where \( V \) is the volume of the imprint and \( V_0 \) is initial volume, respectively.

Figure 2 shows the evolution of \( \varepsilon_{rp}(t) \) as a function of time at different temperatures for an initial mean geometrical contact strain according \(< \varepsilon_{rp}>\) of 4%. The representative strain increases with time, while as the temperature rises, the rate of creep increases. We observe non-linear behavior for the curves corresponding to the two highest temperatures. Figure 3 describe the evolution of \( \varepsilon_{rp}(t) \) as a function of time normalized by creep duration \( t_0 \). The curves are not superimposed and the recovery becomes non-linear. The permanent deformation is more important when the creep duration is longer. The evolution of \(< \varepsilon >\) is not the only parameter reflecting the conditions producing a permanent deformation; the situation is more complex and therefore requires a numerical analysis to gain a better understanding of the phenomena occurring in the contact.

Finite element numerical simulations were used to analyse the experimental results and estimate the contact strain distribution. To estimate the viscoelastic properties of the materials under study, creep experiments in uniaxial compression measurements have been performed. Elastic modulus \( (E) \) can be described by deviatoric modulus \( (G) \) as:
The evolution of the deviatoric modulus as a function of time can be described by the following equations:

\[ G(t) = G_0 + \sum G_i \cdot e^{-t/\tau_i} \]  

(4)

\( G_0, G_i, \tau_i \) are the fitting parameters, \( i \) is the number of characteristic times used to describe correctly the experimental data. Experimental procedure of identification consists to describe the deviatoric modulus and the displacement of the sample under solicitation during the creep phase and the displacement during the recovery phase. A small stress \((\sigma_{app} = 2\% \cdot \sigma_{app})\) is applied for obtain the recovery of the sample after the first constant solicitation \( \sigma_{app} = 75\text{MPa} \). This value was identifying from a first study confronted to experimental result of indentation. Inverse method of identification has been performed with a numerical creep test simulation. Boundary conditions, load and displacement controls are the same that experimental conditions. The objective is to obtain a displacement from numerical simulation equal to experimental displacement for the uniaxial compression measurement. A new approach is purposed and consists to separate the identification for creep and recovery phases (see Figure 4). This assumption can be validated by the physic and kinetic considerations. Then comparison to experimental results from indentation will be presented.

References