Mechanical study of polymers in scratch test

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ABSTRACT: The numerical study of the scratch test on glassy polymers needs a well adapted mechanical behaviour law both viscoelastic and viscoplastic. To test different models, an algorithm which allows to assembly in series two models has been developped. In our cas, it is used to associate a viscoelastic model with viscoplastic one. The simulations carried out lead to some phenomenological results showing the importance to account for the time dependency of the stiffness modulus.

KEYWORDS: Viscoelasticity, viscoplasticity, polymers, scratch test, modelling.

1 INTRODUCTION

Polymeric materials are nowaday widely employed as much for the manufacturing of a lot of daily objects as in the high-tech sector. The amorphous glassy polymer is particularly used as thin coating films deposited on surfaces to protect them against the scratch.

These materials are well known for the extremely complex behaviour strongly depending on the time and the temperature. They are tough and brittle at low temperature and/or high strain rate and rather soft and ductile at higher temperature and/or low strain rate [10, 11]. Previous experiemental work carried out by Briscoe [4, 5] and later Gauthier [9] has characterized the behaviour of the amorphous glassy polymers during scratch tests. Through the infuence of the scratching velocity, at fixed temperature, they have shown a behaviour both viscoelastic and viscoplastic.

Our currently work aims at improving the understanding of the local phenomena occuring in scratch tests on solid polymers. An helpful numerical tool allowing to assembly in series two different behaviour models has been developped. Thanks to this algorithm, complex models by the association of two well knwon behaviour laws are built up. It is here briefly presented in the first part of this paper. It is then used to work out a viscoelastic viscoplastic model which improves numerical simulation of scratch test on PMMA. Hence the second part deals with the analysis of the results of several simulations, at different scratching velocities.

2 BEHAVIOUR MODELLING

2.1 Series model

Our case study needs a viscoelastic viscoplastic model and the ones, coming from the literature (ex:[6, 7, 8, 3]), are not really well adapted. We prefer to associate two more simple models, one viscoelastic and one viscoplastic. In this context, we have developed, in the finite element code Systus®, an algorithm to assembly in series two rheological models. Named series model, it associates two random models while their constitutive equations are already available in the code and in the same framework (updated lagrangian, total lagrangian, ...). It was implemented in the general case of the high deformation by the decomposition of the deformation gradient ($F = F^1 F^2$). More precisely, it is assumed that the deformation gradient in one of the two models is and remains much higher than in the other ($F^1 << F^2$). Hence it is possible to additively split the strain rate tensor [1]. However, to simplify the explanation, the presented reasoning follows the small strain assumption.

The governing equation, in each integration point of each element of the mesh and at each time step, are written :

$$\overline{\overline{\varepsilon}} = \overline{\overline{\varepsilon}}_1 + \overline{\overline{\varepsilon}}_2 \qquad and \qquad \overline{\overline{\sigma}}_1 = \overline{\overline{\sigma}}_2 = \overline{\overline{\sigma}} \quad (1)$$

where $\overline{\overline{\varepsilon}}$, $\overline{\overline{\varepsilon}}_1$ and $\overline{\overline{\varepsilon}}_2$ are respectively the total strain tensor, the strain in the model 1 and the strain in the model 2. Likewise, $\overline{\overline{\sigma}}_1$, $\overline{\overline{\sigma}}_2$ and $\overline{\overline{\sigma}}$ are the total stress tensor, the stress in the model 1 and the stress in the model 2. The quantities at the instant t are known. Moreover, $\overline{\overline{\varepsilon}}(t+\Delta t)$ is given by the code and the unknwon values of the problem are :

$$\overline{\overline{\sigma}}(t+\Delta t)\ ,\ \overline{\overline{\varepsilon}}_1(t+\Delta t)\ ,\ \overline{\overline{\varepsilon}}_2(t+\Delta t) \quad (2)$$

To relieve the notation, the value at $t+\Delta t$ noted $A(t+\Delta t)$ are for the rest of this section written A.

The algorithm has to solve the problem satisfying the equation 1, that is to say it has to compute the total stress at $t+\Delta t$ with the total strain tensor at $t+\Delta t$ and the quantities at the t. It uses an iterative approach in which the dispatching of the strain between the two models is corrected in function of the stress provided in each models.

More precisely, at the iteration i of the process, a decomposition of the strain tensor is given by :

$$\overline{\overline{\varepsilon}}_1^i = \overline{\overline{\varepsilon}}_1(t) + \Delta\overline{\overline{\varepsilon}}_1^i \quad and \quad \overline{\overline{\varepsilon}}_2^i = \overline{\overline{\varepsilon}}_2(t) + (\Delta\overline{\overline{\varepsilon}} - \Delta\overline{\overline{\varepsilon}}_1^i) \quad (3)$$

Since the behaviour laws in each model are known, the stress tensors in each one can be computed. These latters have to satisfy the equation 1. The following criterion is thus used to compare these tensors : $\frac{\left(\overline{\overline{\sigma}}_1^i - \overline{\overline{\sigma}}_2^i\right)_{eq}}{\sigma_{eq1}^i + \sigma_{eq2}^i} < \alpha$, with α a small value to be defined by the user.

A Newton-Raphson algorithm is chosen to correct the decomposition of the strain tensor if the precision is not reached.

2.2 *Viscoelastic viscoplastic model*

The series model is used to work out a viscoelastic and viscoplastic model (figure 1). The model 1 refers to a classical linear Voigt model whereas the model 2 refers to an Arruda-Boyce model ([2]). This is an elastic viscoplastic law specifically dedicated to the glassy polymers, using a viscoplastic element type Argon associated to a strain hardening element type elastomeric hyperelasticity based on the Langevin function.

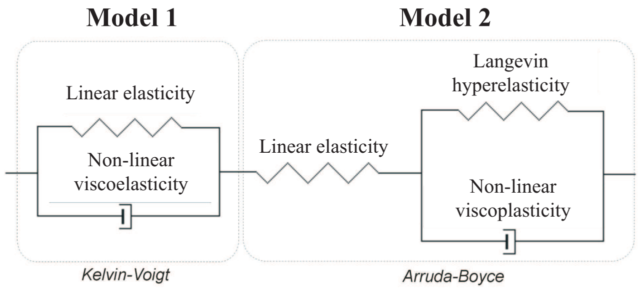

Figure 1: 1 D rheological model via the series model.

3 SCRATCH SIMULATIONS

3.1 *Numerical model*

The numerical model uses a spherical indenter of 50 μm radius which penetrates a solid at an imposed depth (10 μm). Since the scratching penetration depth is fixed, the strain remains constant during the steady state of the process. Several simulations are carried out for different tip velocities. The solid is represented by a parallelepiped with dimensions high enough to avoid boundary effects. It follows the behaviour model previously presented (figure 1).

3.2 *Results*

Since the behaviour of the PMMA is firstly phenomenologically studied, it is not harmful to use arbitrary material parameters. Actually, those for the model 2 (viscoplastic) come from the literature [2], whereas for the viscoelastic model, they have been fitted on the DMA test in the range of frequency corresponding to our simulations.

The main characteristic of the amorphous glassy polymers, which interests the industrial, concerns the healing feature. The healing C is defined here as the ratio of the depth of the residual groove h_e, left on the surface behind the indenter after relaxation process, on the penetration depth of the tip h. The variation of the healing versus the tip velocity is here analysed.

Two behaviour aspects are observed. First the viscoelastic characteristic shows its importance. Then the interest of accounting for the strain hardening is discussed.

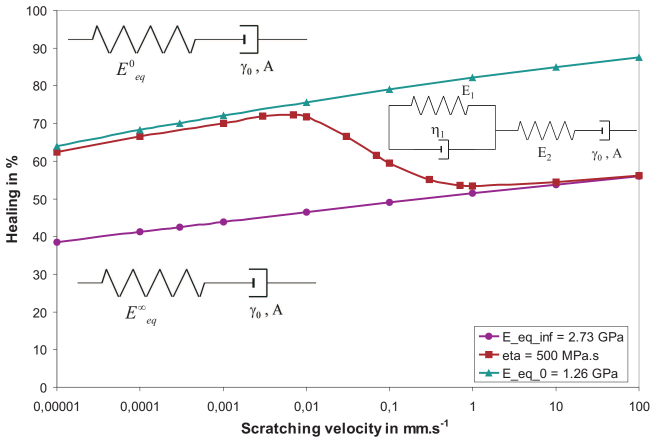

Figure 2: Healing with an elastic viscoplastic model and with a viscoelastic viscoplastic one.

The figure 2 shows the variation of the healing versus the tip velocity for three particular cases. The difference between these cases concerns the behaviour law employed. Indeed, to observe the importance of the viscoelastic behaviour, different simulations with and without this feature have been carried out. More precisely, the stiffness modulus of such materials is known to change with the strain rate. The influence of its value is firstly observed thanks to two simulations performed by using an elastic viscoplastic model, with two toughness moduli. The values of this parameter are abitrary chosen equal to the limit states of the viscoelastic model for the very high strain rate (E^{∞}_{eq}) and for the very low strain rate (E^{0}_{eq}). These two curves show that the healing increases linearly with the tip velocity. That means the reversible part of the strain increases when the tip velocity decreases. Since the total strain is fixed by the numerical model, higher the reversible part of the strain, lower the irreversible part. Hence higher the tip velocity, lower the plastic strain and lower the depth of the residual groove. Moreover, these curves show another important result. Indeed, for a fixed value of the tip velocity, the value of the healing depends on the value of the stiffness modulus. Higher the stiffness, lower the healing. It means higher the stiffness, lower the reversible part of the strain and as previously, higher the irreversible part. Hence higher the stiffness modulus, higher the plastic strain and deeper the residual groove.

To better account for the influence of the time on the stiffness modulus, an simualtion using the whole behaviour model, presented above (figure 1), has been carried out. Here the viscoelasticity replaces the elasticity in the previous model. The viscoplastic part of the model does not change. The curve obtained ($eta = 500MPA.s$) presents the same values and the same trend at the extrem tip velocities. That is to say for the very low tip velocity, the healing observed for the viscoelastic viscoplastic simulation is the same as the one obtained with the elastic viscoplastic model (E^{0}_{eq}). Here the strain rate state corresponds to a limit state of the viscoelastic model and the equivalent modulus of this latter equals E^{0}_{eq}. In the same way, for the very high tip velocities, the viscoelastic viscoplastic healing is the same as the elastic viscoplastic one. Between these two limit states, the healing decreases with the tip velocity in a particular range. Indeed the range of scratching velocity corresponds to a range of strain rate where the viscoelastic transition takes place and thus where the equivalent modulus of it increases from E^{0}_{eq} to E^{∞}_{eq}. It is noticed that the transition range is very close whereas the polymers present a wide range.

The figure 3 aims at showing the influence of the particularly strong strain hardening of the amorphous polymers on their healing feature. To well catch that we have carried out four simulations : two elastic viscoplastic scratches without the strain hardening (E^{0}_{eq} and E^{∞}_{eq}), and the same with the strain hardening. We can observe that for each stiffness, the curves obtained accounting for the strain hardening present the same values and pretty the same trends as without it. That can be explained by the fact that the strain level met in our simulations is not high enough to trigger the typical the exponential increase of the strain due to the strain hardening.

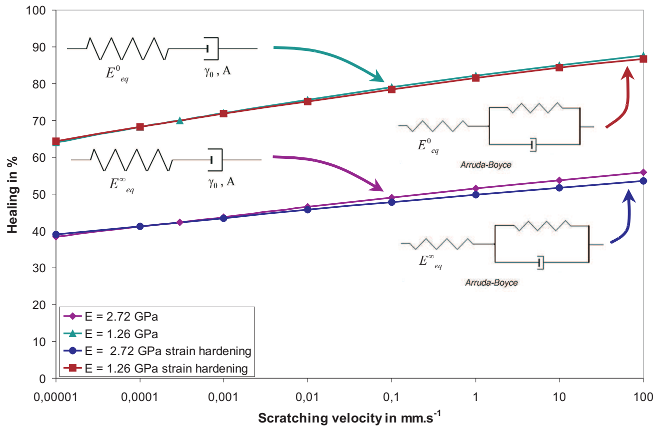

Figure 3: Healing with and without strain hardening

4 CONCLUSION

The study of the phenomena appearing during a scratch test on an amorphous glassy polymer needs a correct understanding of the mechanical behaviour. Being well known to present a complex behaviour both viscelastic and viscoplastic, this material has been focused by numbers of researches, leading to a lot of behaviour models. To assembly in series a viscoelastic model and a viscoplastic model among the latters, in finite element code Systus®, an algorithm has been developed. This one, named series model, has been used to assembly a linear Voigt model with an Arruda-Boyce one. Several simulations of scratch on PMMA have been carried out for different scratching velocities. The analysis of the healing curves has phenomenologically shown the importance to account for the viscoelastic characteristic of the polymer. On the contrary, the strain hardening of such a material is not necessary to be accounted in simulations. The incoming work will deal with the viscoelastic transition range to be widened and the influence of the temperature to be accounted for.

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