Viscoelastic Mechanical Analysis for High Temperature Process of a Soda-Lime Glass Using COMSOL Multiphysics

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Abstract: Glasses are widely used in the modern industry. For high temperature the glass behaves very much like a Newtonian liquid with temperature-dependent viscosity**.** The goal of this study is to set a numerical procedure in order to study the glass forming process of soda-lime glasses used in the automotive field by means numerical simulations.

Keywords: Nonlinear material, viscoelastic behavior, thermal stress.

1. Introduction

Glasses are widely used in the modern industry. In the basic formulation, the glass is made by fusing of silica with a basic oxide [1]. Usually, for the glass basic formulation, soda lime oxide are used. By use of a wide number of additive, it is possible to obtain glass product with specific property, like chemical resistance, hardness, transparency, thermal resistance, etc.

Among all definitions used to describe the glass state, there is the one which defines the glass like an undercooled liquid (metastable state). As stated in [2], the follow explanation is given to describe the glass formation: “*when a liquid is cooled below their freezing point crystallize readily. The high viscosity in a glass-forming liquid inhibits crystallization, and its liquid structure is retained well below the freezing point*”. The glass, therefore, is an amorphous solid.

This condition affects the physic behaviour of the glass. It behaves as an thermoelastic solid for low temperature, the structure can be considered frozen in a fixed configuration called glassy state [2]. For high temperature the glass behaves very much like a Newtonian liquid with temperature-dependent viscosity [3]. The temperature range between the liquid and the glassy state is called transition range [2], and the glass is mechanically viscoelastic.

The aim of this paper is to set a numerical procedure in order to study the glass forming process of soda lime glasses in the automotive field. In this work, using FEM analysis, the computed stresses in a tensile simulated tests are compared with the ones predict by analytic relationship. This step is repeated for several temperature near the glass transition temperature, T_g, of the analyzed glass that is the typical temperature range for sheet forming process. It will be highlighted the difference of the two predictive models.

2. The constitutive relationships

In this paper, the material behaviour of the soda lime glass is studied in a range of temperature close the T_g. In such range the glass behaves as viscoelastic material [4].

From [5], the viscoelasticity is the property of material to exhibit both viscous and elastic characteristic under deformation. For viscoelastic materials, the relationship between stress and strain depends on time. These materials posses the following properties: stress relaxation, creep and hysteresys.

In addition to the viscoelasticity, the mechanical behaviour of the analyzed glass can be assumed linear when deformation and load are small [6].

In the following we analyze the stress relaxation properties, where a strain is produced “instantaneously” and it is maintained at the initial value while stress is “measured” as a function of time [7].

In order to study the stress relaxation of linear viscoelasticity material, several models can be used to link the mechanical behavior to a linear combination of springs and dashpots elements. The spring elements account for the elastic component. The dashpot elements account for the viscous component [5].

The figure 1, summarizes the base elements and viscoelastic models in order of complexity.

For spring element, linear relation is assumed for stress σ, and strain ε:

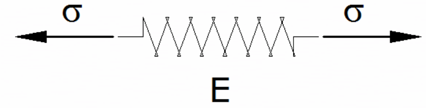
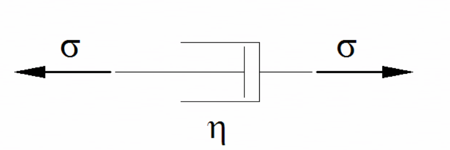
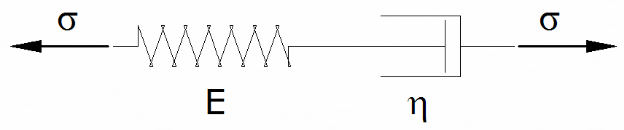
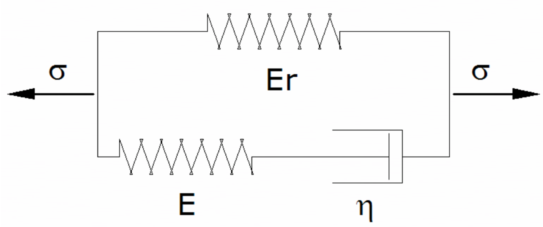
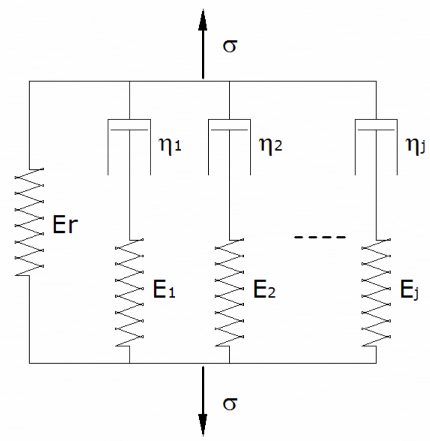
ELEMENTS/MODELS	VISCOELASTIC CONSTITUTIVE RELATIONSHIPS
	Spring element $\sigma = E\varepsilon$
	Dashpot element $\sigma = \eta \dfrac{d\varepsilon}{dt}$
	Maxwell model $\sigma(t) = E \exp\left[-\dfrac{E}{\eta}(t - t_0)\right]\varepsilon(t)$
	Standard Linear Solid $\sigma(t) = \left\{E_r + E \exp\left[-\dfrac{E}{\eta}(t - t_0)\right]\right\}\varepsilon(t)$
	Generalized Maxwell model $\sigma(t) = E_r\varepsilon(t) + \sum_{j=1}^{n} E_j\varepsilon_j(t)$ $\dfrac{d\varepsilon_j(t)}{dt} + \dfrac{E_j}{\eta_j}\varepsilon_j(t) = \dfrac{d\varepsilon(t)}{dt}$ $\varepsilon_j(0) = 0, \;\; j = 1,2,\ldots,n$

Figure 1 Base elements and viscoelastic models.

$$\sigma = E\varepsilon \quad (1)$$

For dashpot element, linear relation is assumed between stress σ and strain rate *dε/dt*:

$$\sigma = \eta \frac{d\varepsilon}{dt} \quad (2)$$

3. Use of COMSOL Multiphysics

In the present study the generalized Maxwell model (or Wiechert model) was implemented in Comsol Multiphysics 3.5a by use a coupled analysis. A 3D Structural Mechanical Module is coupled with a number of PDE Modules in a general form to perform a multiphysics analysis.

The PDE Modules allowed to consider the relaxation terms in the Prony series of the shear relaxation modulus, G(t) [8].

3.1 Material properties

The relaxation test results of a four point bending in [9] were here adapted in order to extract the mechanical parameters for the equation of Prony shear relaxation modulus. The relaxation time, the weight coefficients and the long term shear modulus were evaluated for a soda lime glass at 550°C.

In this study the thermorheological simplicity assumption is done [2]. For a material model containing multiple relaxation times, thermorheological simplicity demands that all the relaxation times have the same shift factor when the temperature is varied [10]. The shift factor a_T, for a secondary polymer transition, can be expressed by an Arrhenius relation [10]:

$$\log a_T = \frac{\Delta H}{2.303R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \quad (3)$$

Where ΔH is the activation energy for the considered glass, R the ideal gas constant, T_{ref} is the temperature for which the measurements are done and 2.303 is the conversion factor between natural and base 10 logarithms [10].

3.2 Analyzed geometry

Figure 2 shows the shape and dimensions of the analyzed numerical specimen, some of the relevant dimensions were taken from [11]. Figure 3 shows the analyzed subdomain, where the geometrical symmetries were used to reduce the DOF's of the models and so reduce the computation time.

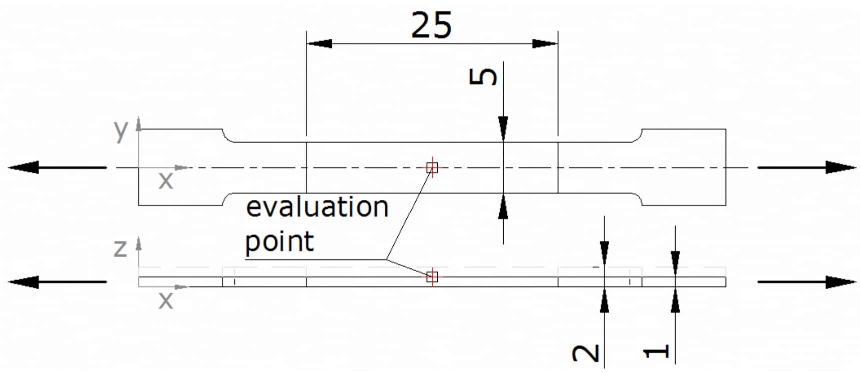


Figure 2 Tensile numerical specimen - main dimensions in millimetres.

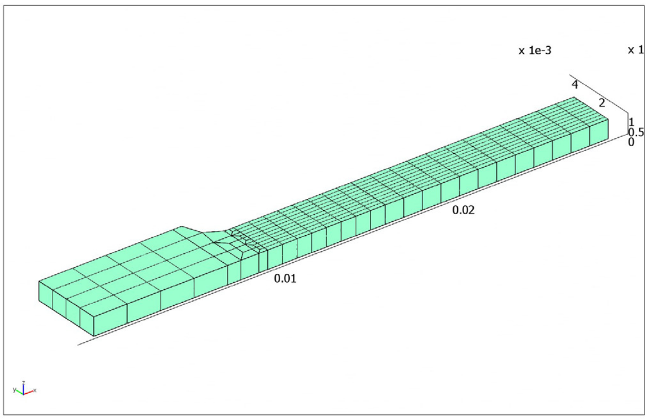


Figure 3 Analyzed subdomain, 1/4 of the original geometry.

4. Analytical formulation

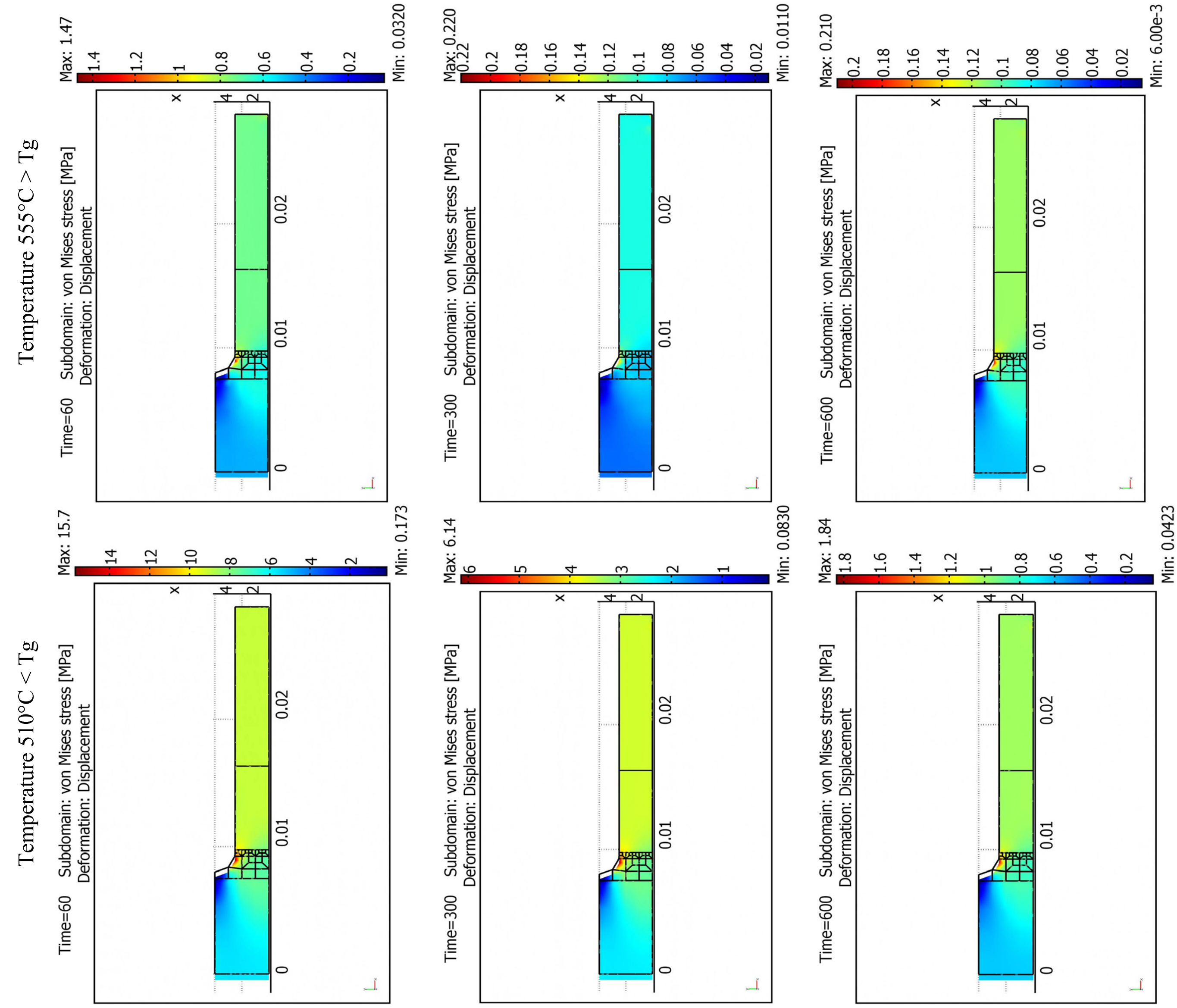
From [10], the stress-time analytical formulation was extrapolated. It presents the following expression:

$$\sigma(t) = \left[2(1+\nu)\cdot\left(G_{\infty} + \widetilde{G}(t)\right)\right]\cdot \varepsilon(t) \quad (4)$$

ν is the Poisson rate, G_{∞} is the long term shear modulus, $\widetilde{G}(t)$ is the time dependent part of the shear modulus. $\varepsilon(t)$ is the same strain value used in the numerical model.

5. Results and discussion

In the following, numerical and analytical results are presented. Figure 4 shows a comparison of the von Mises stress distributions obtained for a strain of 0.02% and for two temperature levels. In figure 5 the computed stress components along the "load" direction are plotted against the time, in a same point



Elapsed time 60 s | Elapsed time 300 s | Elapsed time 600 s

Figure 4 von Mises stress distributions.

(evaluation point in figure 2). In this plot, the relaxation phenomena can be observed.

It can be seen as the material response is time dependent. As expected, the stress magnitudes decrease with a slope depending from the material thermal state.

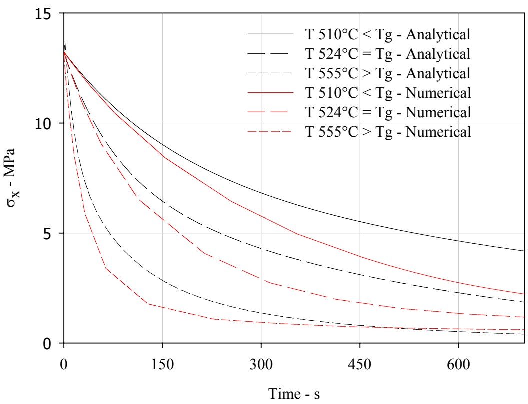


Figure 5 Stress component along the "load" direction.

At the beginning, agreement is found between the shape of numerical and the analytical stress curves. The gaps between the two models could be imputed to the different evaluation methods. For the numerical model the stress component is referred to the evaluation point, while the analytical results have to be considered as mean value on the specimen cross section.

6. Conclusions

The analysis conducted, allowed to test the capability of COMSOL Multiphysics to study the mechanical behaviour of the viscoelastic material such as the soda lime glasses. The mechanical and rheological characterization of non-linear material is the main critical step in a FEM modelling.

The physical/mechanical tests on the material and the analysis of the results are very ticklish activity. For new characterization is essential verify the computed results with the physical ones.

This study was employed as preliminary step to analyze the forming process of viscoelastic material in the manufacture of windshield in automotive field

7. References

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