Predicting product performance limits for polymers

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Introduction

An important question in polymer engineering practice is what are the limits to the yield stress for safe usage. The lower limit follows from the time a product must bear a given load, whereas the upper limit from the mode of failure: ductile or brittle. Here we present an engineering approach, based on constitutive considerations and sound knowledge of the materials intrinsic behavior, to answer this question.

Relation between aging and embrittlement

From literature it is known that ductile polycarbonate becomes brittle after prolonged exposure to high temperatures [1]. The transition from ductile to brittle failure is considered to be the result of exceeding a critical hydrostatic stress [2].

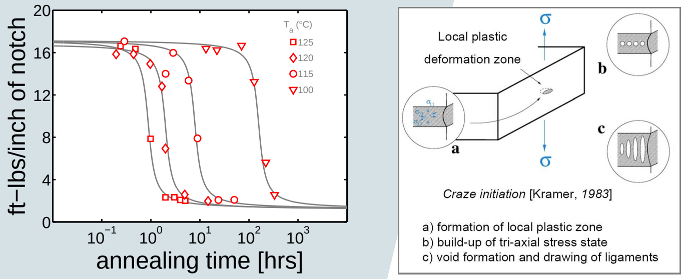

Figure 1 *Izod impact data on PC, taken from [1] (left); triaxial stress state leading to void formation (right)*

It is also known that exposing amorphous polymers to high temperatures (below T_g) lead to an increase in the yield stress. Therefore it can be hypothesized that the maximum hydrostatic stress occuring in a notched sample during impact testing increases with yield stress.

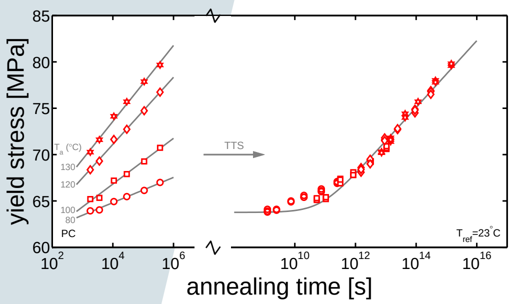

Figure 2 *Annealing data and mastercurve constructed thereof.*

The increase in yield stress with time was captured in previous work [3] by the following set of equations:

$$
\begin{aligned}
\sigma_y(t) &= \sigma_{y,0} + c \cdot \log(t_{eff} + t_a) \\
t_{eff} &= \int_0^t a_T^{-1}(T(\xi))d\xi \\
a_T(T) &= \exp\left(\frac{\Delta U_a}{R} \cdot \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)
\end{aligned}
$$

which were obtained from Time-Temperature-Superposition (TTS) of yield stresses measured at various annealing times and temperatures [3], as can be seen in Figure 2.

Defining a critical yield stress

Qualitative FEM analysis of 3D notched tensile bars showed that the maximum hydrostatic stress found in a sample is linear proportional to the yield stress of the material.

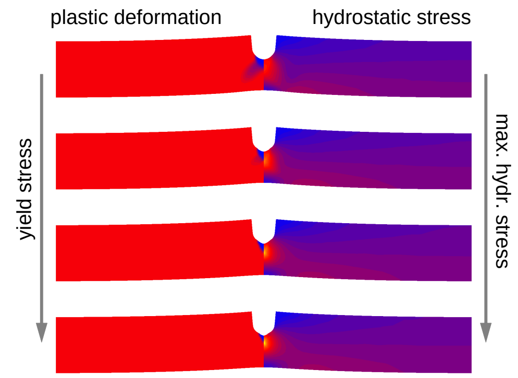

Figure 3 *proportionality between yield stress and maximum hydrostatic stress.*

This proportionality suggests that the critical hydrostatic stress exceeded upon passing the ductile-to-brittle transition corresponds to a critical yield stress. Translation of the experimentally observed ductile-to-brittle transition times (fig 1) to yield stresses indeed lead to a constant critical yield stress, σ_{DB}. This critical yield stress can be used as an upper limit to an application window. A lower limit can be derived from the minimum time-to-failure a product must have under a certain static- or dynamic loading condition, σ_{ttf} [4].

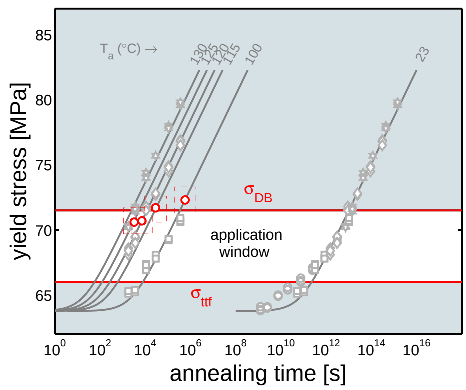

Figure 4 *translated critical yield stresses (markers) and the application window.*

Conclusions

We have shown that knowledge gained by constitutive modelling in combination with good insight into the intrinsic behavior can lead to the definition of an application window for glassy polymers.

References:

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