International Journal of Engineering Science 59 (2012) 108–139

Contents lists available at SciVerse ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

# Lifetime assessment of engineering thermoplastics

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ARTICLE INFO

*Article history:*
Received 2 May 2011
Received in revised form 7 December 2011
Accepted 7 January 2012
Available online 24 April 2012

*Keywords:*
Accelerated testing
Slow crack growth
Ductile–brittle transition
Crack layer
Thermoplastics

ABSTRACT

The life expectancy of thermoplastics in durable applications varies from about 10 years to 50 and even 100 years in certain cases. It calls for an accelerated testing of material and structures. The challenges of accelerated testing for lifetime are (a) to reproduce the mechanisms of field failures and (b) to develop a reliable procedure for extrapolation of a relatively short test data into long-term service conditions. Acceleration of fracture by high stress level turns to be inadequate, since the fracture mechanisms change with stress level. Acceleration of testing for lifetime by elevated temperature is the most widely used technique at the present. This paradigm, however, faces a problem associated with the changes in the mechanism and kinetics of slow crack growth (SCG). At a certain combination of load and temperature, a transition from a continuous SCG to discontinuous, stepwise crack propagation has been recorded. Optical and scanning electron microscopy observations suggest that the change of SCG mechanisms is closely related to the material ability to form in front of the growing crack a stable process zone that consists of single or multiple crazes and/or shear bands. The crack acceleration in the continuous growth mode is observed to be significantly higher than that in stepwise propagation. Such changes in the mechanism and kinetics of SCG are associated with a transition from a ductile to brittle behavior of microfibers within the process zone. It is referred to as ductile–brittle transition of the second kind (DBT2) based on a resemblance with well-known ductile–brittle transition in dynamic impact resistance. DBT2 is presented in form of SCG mechanisms map in temperature–stress intensity factor coordinates. SCG mechanism map implies certain limitations for extrapolation of conventional temperature accelerated test data to the service conditions of plastic components. An alternative to conventional accelerated testing approach to evaluate lifetime of plastics structures is proposed in this paper. It consists of three steps. The first is a characterization of the defects population that may be responsible for fracture initiation. Formulation of constitutive equations of fracture process based on specially designed tests is the second step. Numerical simulation of fracture process using constitutive equations developed within the second step and evaluation of the lifetime of plastic structure is the third step. A validation testing of the proposed program is required.



## 1. Introduction

There is a well-recognized quest for an accelerated testing of polymers, since the life expectancy of engineering structures made of polymers varies from about 10 years for automotive applications to 50 and even 100 years for water distribution and natural gas transmission pipelines. Commonly considered failure accelerating factors are stress level, frequency of

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http://dx.doi.org/10.1016/j.ijengsci.2012.03.016

loading (fatigue), temperature, and aggressive environment. There are two main challenges in development of an accelerated testing for lifetime:

(a) To reproduce in an accelerated test the failure mechanism (s) observed under much more moderate service conditions, since different mechanisms of failure make questionable the relevance of the accelerated testing to field failures.
(b) To establish a correspondence between the time to failure in an accelerated testing and the failure time under service conditions.

This paper examines the validity of failure accelerating techniques for lifetime assessment, potential limitations of their applicability and an alternative approach to plastic structures lifetime prediction based on the adequate modeling of fracture process.

The paper starts with analysis of failure acceleration by high stress level and then considers temperature as accelerating factors for time to failure.

### 1.1. Stress level dependency of failure time

High stress level indeed leads to an early failure; however, it commonly results in a ductile failure associated with large irreversible deformation. Example of ductile failure in polyethylene (PE) gas transmission pipe is shown in Fig. 1.

Ductile failure of pressure pipes externally appears as a ballooning depicted in Fig. 1(a) and (c). The ballooning results from highly localized large deformation. It is a direct manifestation of cold drawing of PE, often called "necking". In cold drawing the original isotropic material is transformed into highly oriented one with corresponding thinning and elongation up to a few hundred percent. Thus, necking leads to formation of a thin membrane pushed outward by internal pressure. The necking is well visible on the cross section through the center of the bulge shown in Fig. 1(b). Notice a sharp boundary that separates thick part of the pipe wall from drawn (thin and oriented) portion of the wall constituting the bulge. The cold drawing (necking) in polymers is discussed in details below, since it turns to be important for understanding various modes of fracture.

At an intermediate stress level, the failure occurs in a brittle manner, i.e., results from cracking. Thus, one cannot extrapolate high stress and short duration test results into long service life under intermediate stresses due to the change of the failure mechanism from ductile to brittle. Premature failure of plastic components widely reported in forensic literature is mainly attributed to brittle cracking driven by either mechanical stress or a combination of stresses and chemically aggressive environment. At a low stress level and very long service time, material aging such as chemical degradation rather than mechanical stress becomes the main cause of degradation driven brittle mode of failure.

Such changes of the leading mechanisms of failure with variation of stress level are depicted in Fig. 2. The solid lines indicate the $\log \sigma \sim \log t$ relations for ductile, stress driven brittle and degradation driven brittle modes of failure. The sketches and photos next to the lines depict the characteristic appearances of the corresponding failure mode.

This type of diagrams has been widely used for plastic components in various applications. To illustrate it, we schematically present in Fig. 3 the data reported in the international standard ISO 9080. It presents the hoop stress vs. failure time

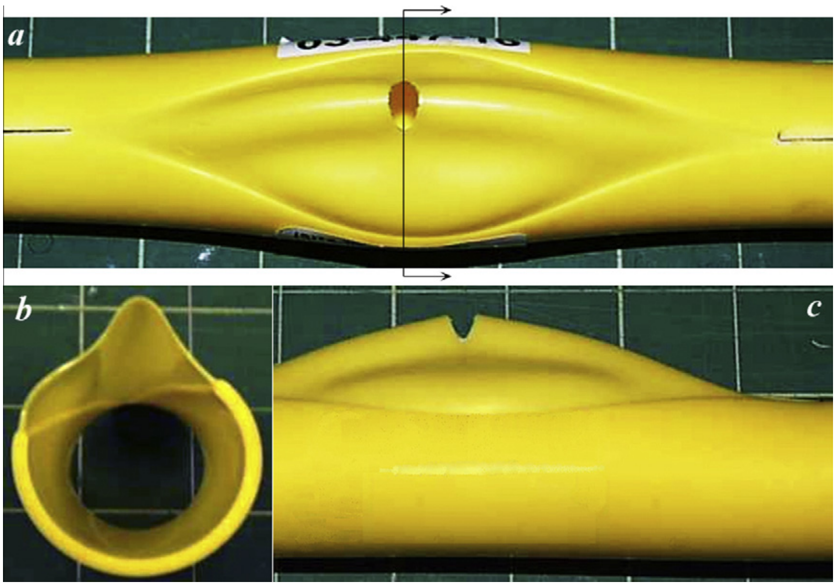


**Fig. 1.** External appearance of ductile failure as a ballooning (localized necking).