RATE DEPENDENT FRACTURE OF POLYMERS - APPLICABILITY AND LIMITATIONS OF FORCE BASED FRACTURE MECHANICS APPROACHES

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ABSTRACT

The overall objectives of this paper (1) are to describe the rate dependent fracture behavior of polymers in terms of material specific fracture property functions, and (2) to determine the applicability range of force based fracture mechanics concepts as characterization tool for the generation of fracture parameters for various failure modes and regimes. To cope with the problem of large-scale and cross-sectional yielding in the ductile failure regime, the limit load analysis (LLA) approaches are followed. For quasi-brittle fracture, under small scale yielding, linear elastic fracture mechanics (LEFM) approach based on the concept of a critical stress intensity factor (K_c and K_{Ic}) is used to determine rate dependent fracture toughness values.

1 INTRODUCTION

For many structural engineering applications of polymeric materials, fracture behavior under monotonic and impact loading conditions is of prime practical importance. Due to the viscoelastic nature of polymers, fracture properties are significantly affected by the loading rate, the test temperature and the local (if notches or cracks are present) and global stress state. As a result of the complex combination of the influence of these parameters, fracture values determined by conventional test methods (e.g., monotonic tensile test, standardized bending and penetration type impact tests, etc.) are only of limited use for advanced engineering design purposes based on finite element methods and numerical simulations as well as for a detailed and reliable material characterization to aid material ranking and selection for a given application. This is especially true for situations where parts or component are exposed to high loading rates.

Due to the wide range of fracture behavior generally observed in plastics from brittle (i.e., quasi-brittle failure) to highly ductile failure, numerous fracture mechanics concepts have been proposed and applied to characterize the failure behavior of plastics in terms of specific fracture parameters (Williams [1]). The different concepts reflecting the various degrees of crack tip yielding generally were applied to specific engineering polymers at pre-defined single testing rates or in a rather limited testing rate regime, so that hardly any investigations were reported using various fracture mechanics methods for a given polymer type over a wide loading rate range.

Considering the above, the overall objectives of this paper is to describe and discuss the rate dependent fracture behavior of polymers in terms of material specific property functions and to determine the applicability range of various force based fracture mechanics concepts as characterization tool for the generation of fracture parameters for various failure modes and regimes. The paper will be primarily concerned with the ductile and the brittle regimes (i.e., quasi-brittle) of rate dependent fracture along with the definition of limitations for the applicability of the associated fracture mechanics concepts. Furthermore, based on experimental results proposals will be made to define characteristic values for the lower and upper end of the rate dependent ductile-brittle transition. Having thus quantitatively established the upper and lower plateau curves along with the relevant transition points, rate dependent fracture behavior of polymers may then be characterized over a wide loading rate range using material specific, specimen configuration independent fracture concepts.

2 BACKGROUND AND SCOPE

There are two main categories of fracture mechanics analysis. The force based analysis (FBA) requires only critical loads to determine a particular fracture parameter, while the energy based analysis (EBA) requires either the entire load-displacement record of a fracture experiment or directly measured critical energy values.

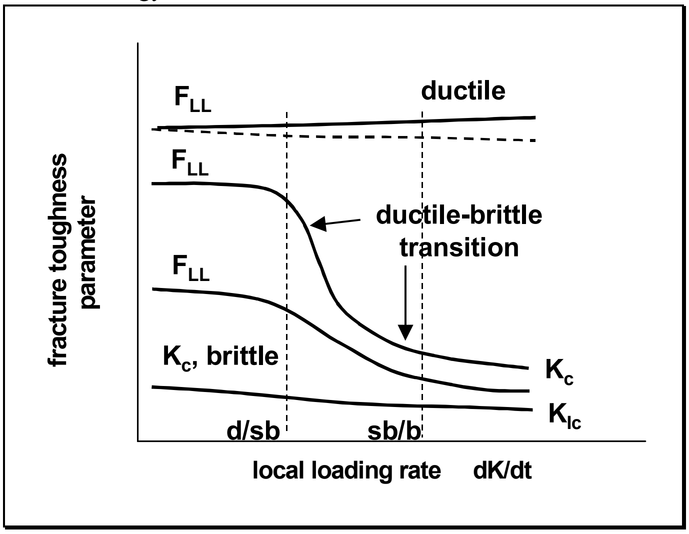


Fig. 1. Schematic illustration of rate dependent fracture property functions of polymers for various types of fracture behavior also indicating the appropriate fracture parameters and the lower (d/sb) and upper (sb/b) embrittlement transition points; FBA fracture mechanics concepts.

For an FBA approach, based on the experimental findings (Major [2]), rate dependent fracture property functions in terms of an arbitrary FBA fracture toughness parameter may be expected as depicted in Fig. 1. The relevant fracture parameters in a force based analysis (FBA) are the limit load, F_{LL}, for highly ductile fracture behavior in the sense of cross-sectional yielding (PYFM concept) (Anderson [3]), and the critical stress intensity factor, K_c, or K_{Ic}, for brittle fracture behavior (LEFM concept).

In terms of test procedure and measurement technique, the essential pre-requisites of an FBA approach is to determine material specific fracture toughness values, which requires a sufficient good quality of the load signal and the correspondence of the true specimen load with the experimentally determined external load. The relevant loading rate parameter controlling the failure mode is the local crack tip loading rate, *dK/dt* (Beguelin [4]). Also indicated in Fig. 1 are the limitations of the applicability of the various concepts on the loading rate scale in terms of relevant embrittlement transition points (ductile/semi-brittle transition point (d/sb) for the lower end of the embrittlement transition on the loading rate scale; semi-brittle/brittle transition point (sb/b) for the upper end of the embrittlement transition on the loading rate scale).

3 EXPERIMENTAL

To examine the applicability of various fracture mechanics concepts to rate dependent fracture of polymers, monotonic fracture experiments were performed with various polymers over a loading rate range of up to 7 orders of magnitude from 10^{-5} to 8 m/s (corresponding to 10^{-3} to 10^{4} $MPam^{1/2}s^{-1}$). The polymers selected for the investigations were the amorphous thermoplastics poly(carbonate) (PC) and poly(vynilchloride) (PVC), and the semi-crystalline thermoplastics poly(ethylene) (PE), poly(oxymethylene) (POM) and various grades of poly(propylene) (PP).

4 RESULTS AND DISCUSSION

The applicability limits of force based fracture mechanics concepts on the loading rate scale along with a definition of the lower and upper embrittlement transition points are shown in Fig. 2 for β^{+}-PP(H) as an example. First it must be noted that the FBA methods for ductile and brittle failure do not allow for a continuous function of fracture parameters over a wide loading rate scale due to the different mechanical concepts both fracture parameters are based upon. Hence, the diagram in Fig. 2 exhibits two ordinate descriptions, one being related to the LLA approach which is based on overall specimen loads (peak loads and limit loads), the other corresponding to the stress intensity factor concept which describes the local crack tip stress field.

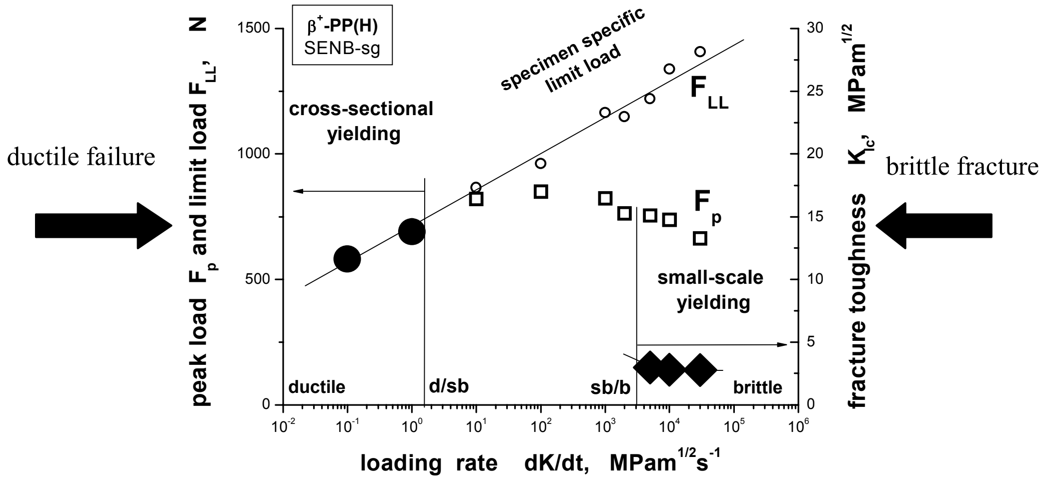
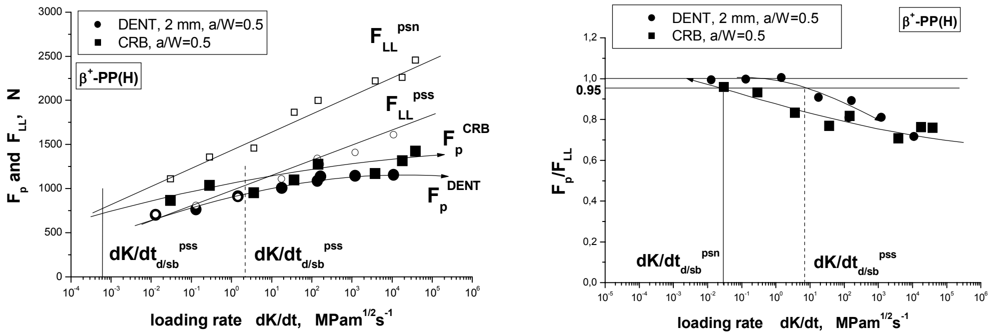


Fig. 2. Illustration of the loading rate dependence of the applicability of force based fracture mechanical concepts.

The lower transition point on the loading rate scale, termed ductile/semi-brittle transition (d/sb) point, is defined as the loading rate where significant deviations occur between the peak loads and the calculated, specimen specific limit loads using rate dependent yield stress values. In other words, the lower transition point refers to a loading rate above which crack growth commences prior to achieving full cross-sectional yielding of the remaining ligament. The upper transition point, termed semi-brittle/brittle (sb/b) transition is defined as the loading rate above which specimen configuration and geometry independent fracture toughness values K_c (plane stress) and K_{Ic} (plane strain) are obtained. Both of these transition points simultaneously define the limits of applicability of the respective fracture mechanics concepts.

4.1 Limit Load Analysis Concept

In the following, first effects of stress state - plane stress (pss) vs. plane strain (psn) - on the ductile/semi-brittle transition rates (i.e., $dK/dt_{d/sb}^{pss}$ and $dK/dt_{d/sb}^{psn}$) will be discussed. Subsequently, various polymeric materials will be compared with regard to their ductile/semi-brittle transition rates.



(a) (b)

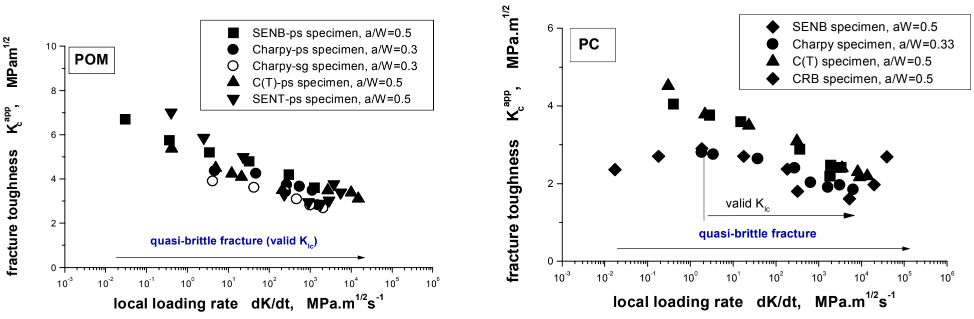
Fig. 3. (a) Influence of plane stress (pss) vs. plane strain (psn) conditions on the d/sb-transition over a wide loading rate for β^{+}-PP(H); 2 mm thick DENT (near plane stress; $dK/dt_{d/sb}^{pss}$) and CRB specimens (near plane strain; $dK/dt_{d/sb}^{psn}$ (b) Comparison of the constraint dependence of the ductile/semi-brittle transition for 2 mm thick DENT (near plane stress; $dK/dt_{d/sb}^{pss}$) and CRB specimens (near plane strain; $dK/dt_{d/sb}^{psn}$) for β^{+}-PP(H).

The ductile/semi-brittle transition point. The influence of plane stress (pss) vs. plane strain (psn) conditions on the d/sb-transition on the loading rate scale is shown in Fig. 3 for β^{+}-PP(H). For near plane stress conditions a 2 mm thick double edge notched tensile (DENT) specimen and for near plane strain conditions a cracked round bar (CRB) specimen was used. As expected, for near plane strain conditions peak loads and limit loads are higher, and the d/sb-transition occurs at a lower loading rate. To be able to define the d/sb-transition region more precisely, the data of Fig. 3 are replotted in Fig. 4 in terms of the F_p/F_{LL}-ratio (relative limit load), and the d/sb-transition is now defined as the loading rate at which the F_p/F_{LL}-ratio is reduced by 5% and thus intersects with an F_p/F_{LL} value of 0.95. This definition of the d/sb-transition yields values of 10^{-3} MPam$^{1/2}$s^{-1} for plane strain conditions and of $7*10^{0}$ MPam$^{1/2}$s^{-1} for plane stress conditions.

4.2 Stress Intensity Factor Concept

Analogous to the limit load analysis concept above, in the following first some examples and aspects related to the definition of the sb/b-transition point will be discussed. Furthermore, various polymeric materials will be compared with regard to their sb/b-transition rates and the loading rate sensitivity of crack tip stress field based fracture toughness values.

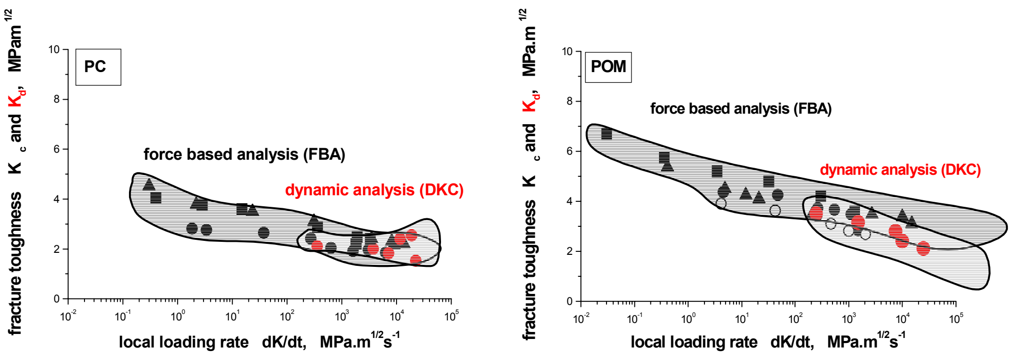
The semi-brittle/brittle transition point. As to the stress intensity factor concept, the upper transition point, termed semi-brittle/brittle transition rate ($dK/dt_{sb/b}$) is defined as the loading rate above which specimen configuration and geometry independent fracture toughness values, K_{Ic} are obtained. Examples of results of fracture tests over a wide loading rate range in terms of K_c^{app} vs. dK/dt and for various specimen configurations and geometries are shown in Figs. 4a and 4b for POM, PC. These examples were selected because they illustrate specimen configuration independent K_{Ic} values over the entire loading rate range investigated (i.e., POM in Fig. 4a), specimen configuration independent K_{Ic} values only above 2*10^0 MPam$^{1/2}$s^{-1} (i.e., PC in Fig. 4b). Further examples of the influence of specimen configuration and loading rates on fracture toughness values are presented elsewhere (Major, [2]).Values for $dK/dt_{b/sb}$ may be defined as local loading rates for which the scatter of K_c^{app} values for various specimen configurations is less than ±20 % relative to the respective mean value. Above the so defined semi-brittle/brittle transition rate, K_c^{app} values may be interpreted as true K_{Ic} values.



(a) (b)

Fig. 4: Effect of local loading rate on fracture toughness for β$^+$-PP(H) using various specimen configurations and data reduction schemes; (a) POM and (b) PC.

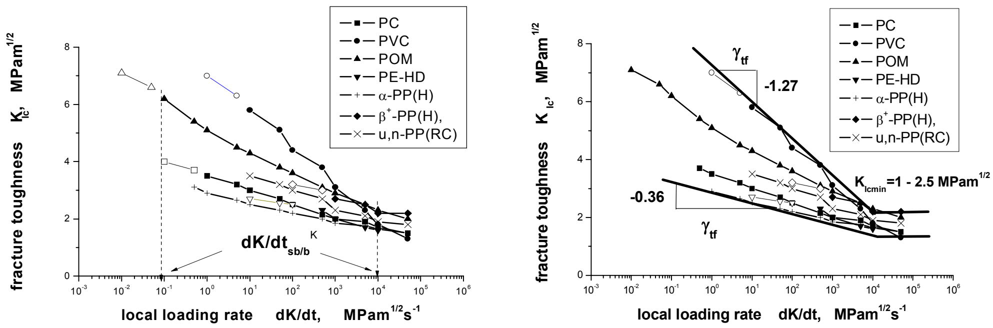
The good agreement of force based analysis K_{Ic} values and K_{Id} values obtained from dynamic key curve (DKC) experiments in the high loading rate regime is shown in Fig. 5a and b for PC and POM. While in the DKC experiments only bending type specimens were used, tensile and bending type specimens were used in the FBA experiments.



(a) (b)

Fig. 5. Comparison of loading rate dependence of fracture toughness values (FBA method) and dynamic fracture toughness values (DKC method) for, (a) PC and (b) POM.

Material comparison. Fracture toughness values, in terms of true K_{Ic} values according to the above definition are plotted vs. loading rate in Fig. 6 comparing various materials. Each of the data points for a given material represents a mean value of all tests performed with different specimen configurations and geometries, including data of both the FBA and the DKC experiments (the latter of course only at high loading rates). Also indicated in Fig. 6a by large full circles are the semi-brittle/brittle-transition points for each of the materials. With a value of about $5*10^{-2}$ $MPam^{1/2}s^{-1}$, POM exhibits the lowest sb/b-transition point, whereas β^{+}-PP(H) reveals the highest sb/b-transition point with approximately 10^4 $MPam^{1/2}s^{-1}$. In other words, the sb/b-transition rates of the materials investigated differ by more than 5 orders of magnitude.



(a) (b)

Fig. 6: Fracture toughness, K_{Ic}, as a function of local loading rate on for all engineering polymers investigated in this study (average curves of all specimen configurations for a specific material type); (a) indication of sb/b-transition rates ($dK/dt_{sb/b}^{K}$), and (b) indication of slopes and lower bound K_{Ic} values (K_{Icmin}) values.

Moreover, the rate dependence of the K_{Ic} values in the brittle failure regime of the various materials investigated also varies to a significant degree. As is shown in Fig. 6b, with values of -1.27 and -0.36 for PVC and PC, respectively, these materials exhibit the highest and lowest slopes in the semi-logarithmic diagram. Finally, also worthwhile noting is that rate dependent K_{Ic} values of all materials investigeted converge at about 10^4 $MPam^{1/2}s^{-1}$, reaching a lower bound fracture toughness (K_{Icmin}) in the range of 1.0 to 2.5 $MPam^{1/2}$.

5 CONCLUSIONS

To examine the applicability of various fracture mechanics concepts to rate dependent fracture of polymers, monotonic fracture experiments were performed with various polymers over a loading rate range of up to 7 orders of magnitude from 10^{-5} to 8 m/s (corresponding to 10^{-3} to 10^4 $MPam^{1/2}s^{-1}$). In the brittle failure regime at high loading rates the critical stress intensity factor concept of linear elastic fracture mechanics (LEFM) may be applied. Depending again on the stress state, the relevant fracture parameters are the plane stress fracture toughness, K_c, and the plane strain fracture toughness, K_{Ic}, respectively. In contrast to the rate dependence of the limit loads in the ductile failure regime, the fracture toughness values decrease with loading rate before reaching a lower bound level.

6 REFERENCES

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