MULTISCALING ASSOCIATED WITH STRUCTURAL AND MATERIAL INTEGRITY UNDER ELEVATED TEMPERATURE

Fracture Mechanics and Applications

Editors: G.C. Sih, S.T. Tu and Z.D. Wang





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Fracture Mechanics 2006

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Multiscaling Associated with Structural and Material Integrity under Elevated Temperature

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Preface

This book contains the joint meeting of the annual conference of Fracture Mechanics (FM2006) and the triennial conference of High Temperature Strength of Material and Structure (HTSMS). The joint meeting is held at the International Conference Hotel in Nanjing, Jiangsu Province, China, November 17-20, 2006.

The annual conference of Fracture Mechanics (FM2006) is a sequel to the successful meetings of FM2003 held in Shanghai, China, 2003, FM2004 held in Huangshan, Anhui Province, China, 2004, and FM2005 held in Zhengzhou, Henan Province, China, 2005. The 9th National Conference of High Temperature Strength of Material and Structure (HTSMS) was initiated triennially by the High Temperature Strength of Materials Committee, Chinese Mechanical Engineering Society (CMES), which is intended to promote academic and technical exchange between Chinese scientists and engineers in the field of high temperature strength of materials.

The collaboration of the two groups is prompted by the advent of multiscaling in recent years where more and more attention is being focused on relating failure initiation from the small scale to the larger scale in order to increase the time interval for detecting possible sites of irregularity. Such a safety measure is particularly needed in the presence of aggressive environment such as elevated temperature. While the added influence of the environment can be tested under controlled laboratory conditions, the transfer of specimen data to the design of full size structural components is not always straightforward. Many of the conventional material constants and methodologies have limitation on the size scale within which they were determined and developed. This meeting will serve as the forum for exchanging ideas and discussing new findings.

The joint meeting is co-organized by Nanjing University of Technology, MOE Key Laboratory of Safety Science of Pressurized System of East China University of Science and Technology, National Technical Research Center on Safety Engineering of Pressure Vessels and Pipelines, Zhejiang University, Zhengzhou University, Zhejiang University of Technology and Institute of Metal Research of Chinese Academy of Sciences. It is co-sponsored by the Chinese Pressure Vessel Institution (CMES), the High Temperature Strength of Materials Committee of Chinese Materials Institution (CMES), Natural Science Foundation of China and General Administration of Quality Supervision, Inspection and Quarantine of China.

We would like to take this opportunity to thank the above organizations for making this joint meeting possible. We also wish to thank the other members of the program committee for their advice and for their reviewing the papers. For inspiration, special thanks go to the support of Professor George C Sih who suggested the Fracture Mechanics Group (FMG) and made the symposium series successful.

Jian-Ming Gong
Executive Chairman
Nanjing University of Technology

Shan-Tung Tu
Symposium Series Chairman
East China University of Science & Technology

November, 2006

From the Editors

This is the fourth annual meeting of the Fracture Mechanics series since 2003. Selected each year is a field where new findings from modern science and technology may be implemented to further advance the state-of-the-art in practice. The 2006 theme will probe deeper into the physical mechanism(s) of why the material and structure integrity are more vulnerable under high temperature. To this end, an effort has been made by the Nanjing University of Technology to hold a joint meeting of FM2006 and the 9th National Conference of High Temperature Strength of Materials and Structure (HTSMS). It will take place at the International Conference Hotel of Nanjing, November 17-20, 2006.The collaboration of the two groups has been prompted by the advent of multiscaling and mesomechanics in recent years where more and more attention is being focused on relating failure initiation from the small scale to the larger scale in order to increase the accuracy of predication for detecting small defects. The added safety measure is needed for structural components operating over a long time period at elevated temperature. Such conditions are the rule for petrochemical, power station and nuclear power plants rather than the exception. The effects of hostile environment further aggravate the deterioration of materials and structures.

When the temperature is sufficiently high, permanent damage can occur over a period of time even at low stress levels well below the yield strength of the material. This time-dependent behavior is known as creep; it becomes a concern when the operating temperature is about 40% or more of the melting temperature. Creep can be a potentially lethal process that starts with void nucleation, develops into micro-cavities and leads to failure of pipe network, pressure vessels and a host of other structural systems. Current research trend has emphasized the establishment of a common ground for different disciplines even though they may appear to be diversified at the macroscopic scale. Linking results at the nano, micro and macro scale falls beyond the capability of the conventional approaches where analyses are subject to scale range restrictions.

Failure under long-term aging and aggressive environments has been the subject of many past discussions. Not enough emphases are placed on the extended scale of size and time effects that come under the discipline of "Multiscaling". Material failure models concentrate mostly on computational capacity of the numerical work in contrast to implementing the relevant underlying physics of the material damage mechanism(s). Atomistic simulations tend to be overwhelmed with numerical data, the interpretations of which are selective at best and are unavoidably limited to situations with limited or no available experimental results. While diffusion, corrosion and oxidation effects can all influence long- and short-time-scale processes, their dominance should be identified with the specific scale and related to that at which inspection and/or pre-warning signals are being monitored. More specifically, the use of bulk and/or local material properties and their definitions should be made known. Keep in mind that global homogeneity may entail local inhomogeneities. Their distinction and change with the operating temperature is an area that has received little or no attention. This can be evidenced from the open literature. On going research activities have not taken notice of these effects in relation to temperature changes.

The transfer of specimen data under controlled laboratory conditions to the design of full size structural components is another area that calls for concern. Many of the conventional material constants and methodologies have been case specific. This means the same or similar tests must be repeated over and over again as conditions are altered, however small. This is because material tests do not accommodate an interpolation scheme to account for the combined effects of loading, geometry and material. These details are not spelled out at present and have not been adequately treated by the professional societies such as ASTM, ASME, etc. Up-dating the design aspects of standards and regulations are in order. Some of the topics that need attention are

- Testing of metallic and non-metallic materials ranging from room to high temperature, say 500°C or higher;
- Determination of thermal-mechanical coupling effects qualified in terms of the constitutive constants;
- Methods for transferring uniaxial data to multiaxial stress states needed in design;
- Dilatational and distortional effects in regions away and near defects;
- Numerical and analytical methods for determining stress and strain states;
- Failure criteria identified with physical damage of the material and/or structure: local and global view points;
- Change of material inhomogeneity on ductile-brittle transient temperature;
- Interaction of system homogeneity with temperature and/or temperature gradient;
- Trade off between mechanical and thermal instability for high temperature resistance materials;
- Design of materials for high temperature applications;
- Failure assessment methodology.

What has been said should be reminded as a continuing dialogue from meetings to meetings and conferences to conferences as the problem of material/structure damage, and failure will always be faced with new challenges to resolve. The objectives of the FM series are to identify the critical areas and to bring together potential contributors to minimize failure. The editors are therefore indebted to the authors of this volume and those reviewed papers.

The editors wish to take this opportunity to express their gratitude to the representatives of the organizing institutions. Their collaborative efforts and ideas have contributed to the success of this conference. Thanks are due to Shen Shufang, Wang Zhenbang, Liu Xiao, Kong Shuai, Yang Bo and Mao Leyuan who assisted in typing, examining and editing manuscripts. In particular, thanks are also due to those who have assisted in taking care of meeting rooms, projectors, accommodations, local transportation and numerous tasks behind the scene that are often overlooked by the organizers.

Shanghai, China
October, 2006

G. C. Sih
S. T. Tu
Z. D. Wang

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Exploration of multiscaling related to crack velocity behavior with temperature change under fatigue and creep

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Abstract

Mesomechanics and multiscaling have called attention to many fields of discipline. This applies equally well to the study of crack growth in fatigue and/or creep which by nature are coupled although the influence of each can vary for each application and material type. Although there are different ways to arrive at a general understanding of the underlying physical mechanism(s) for fatigue and creep, this work will focus on the similarities and disparities of fatigue and creep models, both from the view point of their formal appearance and the underlying physics. To this end, a dual scale micro/macro line crack model is used. It can accommodate as many of the geometry/material/load influencing parameters as needed. The model is designed such that the microscopic effects can be absorbed into the macroscopic empirical parameters under pre-specified conditions. Therefore, the analysis can be case-specific without being overwhelmed with details that may be necessary for other situations. Such a capability will be demonstrated by analyzing available data for the fatigue and creep velocity d*a*/d*t* behavior of PVC at different temperatures. Comparison of data from different sources are not always compatible, particularly when material type is altered. Metal fatigue studies for instance prefer to use the crack growth rate d*a*/d*N* with N being the number of load cycles. The distinction between d*a*/d*N* and d*a*/d*t* is obvious although its implication to data representation is not.

The possibility to establish a common ground for fatigue/creep damage by crack growth is explored using the PVC polymer since previous experience on using the dual scale crack model has been limited to metal alloys. Encouraging similarities seem to prevail between the contraction/extension behavior of the fibrils in the craze zone in contrast to the closing/opening of the adjoining crack front surface in metal fatigue. Both phenomena can be formally represented by the dual scale model. It is also demonstrated that the craze zone behavior is sensitive to temperature changes. On the other hand, scale shift in crack growth also prevails in the polymer where two different regions I and II for crack velocities can be established for the PVC at different temperatures. The distinction decreases with increasing temperature. These regions in terms of d*a*/d*N* are also referred to as regions I and II in metal fatigue and identified with the threshold where micro-cracking occurs and stable macrocrack growth, respectively. These partitions of data disappear when the transitory behavior of micro/macro damage is accounted for in the model. Linearization of the data would permit interpolation such that micro and macro results can be connected. The scheme of dual scaling also applies to nano/micro and can be extended to develop triple or multiple scale models.

Keywords: Multiscaling; Mesomechanics; Fatigue and creep; Crack growth; Velocity and load cycle; Polymer and metal; Temperature; Frequency; Stress intensification; Volume energy density; Crazing and fracture; Size and time; Scale shift.

1. Introduction

The extend of damage in a material depends not only on its atomic structure but also on the rate at which energy is being transmitted which can be referred to as loading rate. Different type of loadings are necessitated by practice. Empirical approaches based on data collection may not always be adequate. That is damage models in fatigue and/or creep are material as well as application specific. Within the frame work of fracture mechanics alone, the subject of crack growth rate (d*a*/d*N*) and velocity (d*a*/d*t*) modeling can involve many subtle issues. The distinction of using d*a*/d*N* in contrast to d*a*/d*t* remains not understood, the difference will be observed in this work.

By tradition, loading and specimen types are standardized and recommended by the professional societies in order to preserve consistencies in engineering application. By in large, the procedure has managed to get by except for a few

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instances when standards and/or certifications had to be recalled for reasons that are not purely technical. The 1954 Comet jet disaster is a case in point but it will not be the last. To begin with, it is important to recognize that consistency takes precedent in engineering application. Even the incorrect model can make things work. However, it is difficult to be consistently incorrect. Being correct some of the times causes trouble. Material and structure failure by fatigue and/or creep can often be traced to the lack of consistency in practice. A workable methodology therefore should appeal to the physical mechanism(s) of damage so as to minimize rules, regulations, standards and exceptions.

Starting with static loads, ASTM recommends that the strain rate should be in the neighborhood of 10^{-3}/s while dynamic loading prevails when the time period of natural frequency of the body is comparable to the time interval of loading that reaches from its initial to final level. The addition of the defect size comes into consideration in fracture mechanics. The line crack being adopted as the physical model for ranking the resistance of the material to fail by macro-fracture. The extension of this concept to microscopic failure, however, has not been met with equal success. This explains why the understanding of crack growth behavior associated with fatigue and/or creep has not advanced as far as it should have, even for phenomenological and empirical studies. The missing link can be attributed to the transition of micro to macro effects that arise in "crack growth". Predictive models have been limited to single-scale.

Fatigue damage has been recognized as a process of energy accumulation due to distortion or shape change, normally known as yielding and plastic deformation. ASTM recommends that the amplitude of the repetitive load should be about 50% of the yield strength for a line crack specimen such that the state of the local stress would be above and beyond the yield point for metal alloys. For chain molecule polymers, the mechanism may involve local crazing which is different from polycrystals. Similar differences also occur for metals and polymers under creep loading where a constant stress or strain may be sustained on the material over a long period of time. The physical mechanism(s) of crazing in polymers in contrast to void creation in metals may require different model representations. For the same material, fatigue and creep damage by crack growth can entail different physical mechanism(s) even though the formalism of the analytical models using da/dN or da/dt can be similar.

The state-of-the-art concerning material integrity under creep can be found in ASTM [1]. Analysis has followed the concept of the path independent integral C^* [2, 3] together with the commercialized ABAQUS [4] computer program. Much of the specimen and loading specifications for a given material type are left to the discretion of the investigator. This makes data comparison nearly impossible. The recent work in [5] for zircaloy cladding has related the steady state C^* integral in creep to the volume energy density criterion [6, 7] that can be applied to unsteady creep crack growth. When the material type is changed, application of specific programs such as [4] has to be modified accordingly.

This work calls attention to the need to distinguish microcrack and macrocrack growth in creep as it was done in fatigue [8, 9] for metals by using a dual scale line crack model [10,11]. To make use of the experience gained in [8, 9], possible similarities in modeling creep crack growth are explored for the PVC polymer on account of the available data based on da/dt. The physical mechanism of metal fatigue [8, 9] may be similar to that of crazing in PVC. More specifically, the closing and opening of the metal crack surfaces may be similar to the extension and contraction of the fibrils in the craze zone. Whether the open ended metal microcrack tip segment of aluminum [14] is equivalent to yielding ahead of the craze zone for polyethylene [15] remains to be investigated. Any possible similarity or disparity is worthwhile exploring in order to better understand the different crack growth behavior between polymers and metals, particularly with reference to micro/macro effects. The same applies to the difference between fatigue and creep of the same material. Creep effects after all cannot be avoided in fatigue even though they may be small. This depends on relative magnitude of the stress amplitude $\Delta\sigma$ in contrast to the mean stress σ_m. The states ($\Delta\sigma$>>, σ_m<<) and ($\Delta\sigma$<<, σ_m>>) correspond, respectively, to fatigue dominant and creep dominant situations. Mesoscopic effect results when $\Delta\sigma$ and σ_m are comparable. Frequency

ω and temperature T will further complicate the crack growth behavior. Mesomechanics and multiscaling will be the major concerned. Hence, reference will be made to [12, 13] where the rigor of equilibrium classical continuum mechanics will be relaxed in order to extend the time and size scale range of application by segmentation of the non-equilibrium and non-homogeneous process. This is because the physical model of microcracks differs fundamentally from that of macrocracks. A study of this difference has been made for the aluminum alloy [8, 14] and will be further examined in this work for the PVC (polyvinyl chloride) polymer [16] with reference to crack growth in fatigue and creep.

2. Fatigue crack growth velocity

Successful application of the line crack model was made in the early 1960's in linear elastic fracture mechanics and it took the next two decades to understand why it can work equally well for non-linear inelastic fracture mechanics with little or no substantial modifications. The model, however, can be stymied when the physical mechanisms of cracking are not reflected in the model even though the basic line crack configuration can still be maintained. In retrospect, crack growth in fatigue and creep falls into this category where the two-dimensional line crack remains applicable in many instances even at nano-scale. Admittedly, the behavior of nanocracks, microcracks and macrocracks can be drastically different. But the effort to model their behavior has lacked consistency, especially when the time and size effects at the different scale levels have introduced scattered to the data. The belief that practical application could be somehow carried out by empirical means has proven to be far from the reality and can be detrimental to the pocket book.

Fatigue and creep are in fact inseparable because the latter may be regarded as the mean stress level considering constant amplitude and frequency. At least two parameters are required to define repeated loading. They can be chosen from σ_{max}, σ_{min}, $R=\sigma_{min}/\sigma_{max}$, $\Delta\sigma=\sigma_{max}-\sigma_{min}$ or some combinations involving $\sigma_m=(\sigma_{max}+\sigma_{min})/2$. The problem is to determine the number of cycles and/or time for a specimen and material to cease operating in accordance with the specifications. The fact of the matter is that the problem has been open-ended because the specifications are speculative at best. The three criteria for the life of passenger aircrafts may be used as the guide line. They are 20 years, 20,000 take offs and 60,000 flight hours. These conditions must be set before the aircrafts are built. Hence, hindsight cannot be used. The open literature will testify that the majority of fatigue data have been made available by institutions or companies associated with the aircraft industry. Having made the above remarks, the existing technologies are not only material specific but also application specific. The specifications for structural and engine design are clearly not the same. There prevails a natural division between the objectives of the structural and material engineers although their interest do overlap more and more for advanced materials where the behavior of microcracks and macrocracks and their interaction may have to be addressed simultaneously.

2.1. Crack velocity representations

Recall that at least two parameters such as $(R,\Delta\sigma)$ or (σ_{max},σ_m) are needed to even specify the simplest fatigue loading. Hence, any fatigue crack growth rate relation that accounts only for the stress intensity factors

$$K_{max}=Y(\frac{a}{W})\sigma_{max}\sqrt{\pi a}$$

$$\text{or}\quad K_{min}=Y(\frac{a}{W})\sigma_{min}\sqrt{\pi a} \tag{1}$$

would be leaving out the mean stress effect. In Eqs. (1), the half crack length is a for a central crack or the full length for an edge specimen. The quantity Y is used to denote the correction for specimen width W. It follows that

$$\Delta K=K_{max}-K_{min}=Y(\frac{a}{W})\Delta\sigma\sqrt{\pi a}$$

$$\text{where}\quad \Delta\sigma=\sigma_{max}-\sigma_{min} \tag{2}$$

In what follows, the fatigue crack growth relation will be written in da/dt instead of da/dN. They are related with the knowledge of dN/dt, i.e., the number of cycle in a unit of time. The role with which dN/dt plays with reference to the physical mechanism(s) of crack growth in creep and fatigue will not be known until further studies are made. The preference for using the crack velocity da/dt is based on the availability of the PVC data in [16]. In what follows, both creep and fatigue can be modeled as

$$\frac{da}{dt} = A(\Delta K)^n \quad \text{for fatigue} \tag{3}$$

and

$$\frac{da}{dt} = B^*(K_{max})^{m^*} \quad \text{for creep} \tag{4}$$

Note that Eq. (3) can also be expressed in terms of $\Delta K = K_{max}(1-R)$ in view of Eqs. (2) and the factor $(1-R)^n$ can be absorbed by A to become A^* such that Eq. (3) would have the same form as Eq. (4):

$$\frac{da}{dt} = A^*(K_{max})^{n^*} \quad \text{in fatigue} \tag{5}$$

Hence, the use of Eq (3) or (5) would be equivalent except for the interpretation of the same fatigue data. The parameters A, n, A^* and n^* are accounted for automatically. The difference will be understood and no further elaboration will be made. Eq.(3) for fatigue and Eq. (4) for creep apply to macrocracks only because ΔK and K_{max} are derived with no consideration given to microcracking. The distinction between microcracking and macrocracking will be emphasized subsequently. It should be remarked that although the equivalence of the formal appearance of Eqs.(3) or (5) and (4) have been pointed out, the underlying physical mechanism(s) for creep and fatigue of polymers and metals can be quite different. That is the same ΔK and K_{max} can have different expressions containing different micro/macro parameters and variables for expressing material microstructure behavior.

2.2. Fatigue crack velocity of polyvinyl chloride (PVC)

Fatigue data for PVC at 23°C with ω=1 Hz, R=0.1 and K_{max}=0.96, 0.82 and 0.62 MPa·m$^{1/2}$. Three different cases are considered and are defined in Table 1. Refer to Figs. 1(a) and 1(b) for a versus t and da/dt versus ΔK, respectively, as given in [16]. These data are given in Tables A1 and A2 of Appendix 5.1. They will be re-analyzed because of the apparent scatter of Fig. A1 which is the equivalent of 1(b) in Fig. 1(b) of [16]. Instead of one straight line as represented in Fig. A2 or Fig. 1(b), the data in Table A2 for R = 0.1 can be separated into three curves that are displayed in Figs. 1, 2 and 3 corresponding to the three K_{max} values of 0.62, 0.82 and 0.92 MPa·m$^{1/2}$, respectively. These curves have a common feature. That is they can all be identified by two distinct regions I and II. The separation of these two regions will become clear when the data are identified with the crack length in conjunction with the tightness of the adjoining crack surfaces to be defined by the dual scale micro/macro line crack model [11]. Crack length alone is not sufficient for determining the size scale of cracking. Based on the information in Tables 3 and A2, Eq. (3) can be applied to find the crack length a. The numerical values can be found in in Table 2. Now, since

$$\frac{da}{dt} = f(a) \tag{6}$$

the data in Table 2 can be used to integrate Eq. (6). The variation of crack length a with time t can be obtained approximately as.

$$t = \int_0^a \frac{da}{f(a)} \approx \sum_{i=1}^{n} \frac{\Delta a_i}{f(a_i)} \tag{7}$$

Table 1. Classification of Cases I, II and III of fatigue data in [16] for PVC.

	Values of applied stress (MPa)		
	Case I K_{max}=0.62 MPa·m$^{1/2}$	Case II K_{max}=0.82 MPa·m$^{1/2}$	Case III K_{max}=0.96 MPa·m$^{1/2}$
σ_{max}	4.95	6.54	7.66
σ_{min}	0.495	0.654	0.766
σ	4.455	5.886	6.894

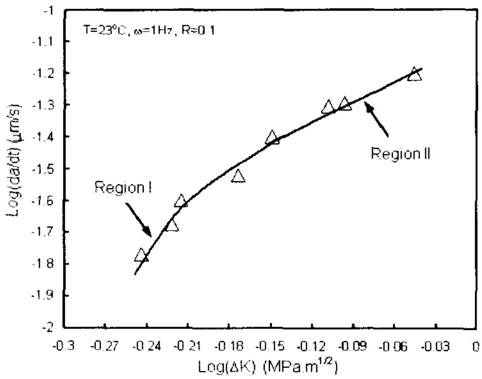

Fig. 1. Crack velocity da/dt versus ΔK at 23°C for K_{max}=0.62MPa·m$^{1/2}$.

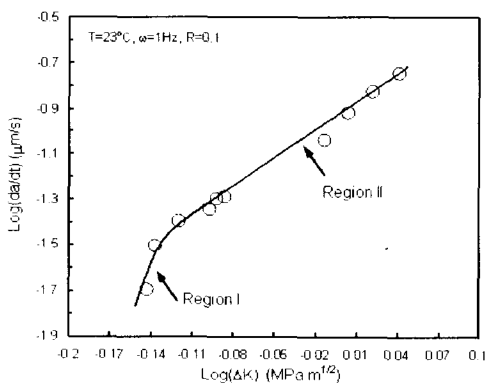

Fig. 2. Crack velocity da/dt versus ΔK at 23°C for K_{max}=0.82MPa·m$^{1/2}$.

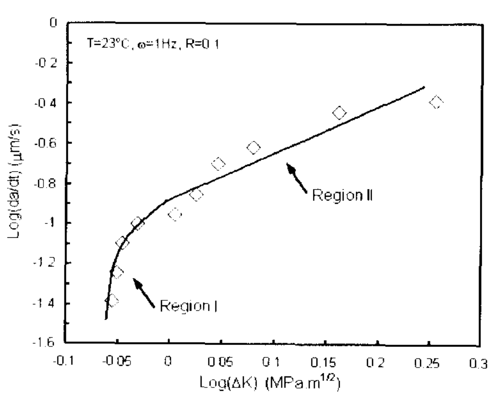

Fig. 3. Crack velocity da/dt versus ΔK at 23°C for K_{max}=0.96MPa·m$^{1/2}$.

The corresponding numerical results are listed in Table 3 and displayed graphically in Fig. 4. With crack length and time scale similar to those in [16], numerical calculations stopped short at a ≈5mm although smaller crack length can be obtained for σ_{max} = 7.66 and 6.54 MPa. Nevertheless, uncertainties increase as the origin is approached. It is not likely that the three curves would intersect. This is precisely the region near which micro/macro transition are likely to take place.

2.3. Multiscaling in fatigue fracture

Creep damage is concerned with long-term effects where the loads can be sustained over several months or years such that the damage is sensitive to the details of the material microstructure. More time is allowed for the load to seek out the minute details of irregularities. They can start as nanodefects and develop slowly to microcracks and then to macrocracks. The corresponding physical damage mechanism(s) for material with different internal structures would differ, especially if they are made of chain molecules such as polymers or polycrystals such as metals alloys. In general, they are material specific. Fatigue on the other hand involves relatively short time where the load is repeated many times by altering the stress amplitude such as tension-tension or tension-compression. The basic damage mechanism is one of energy accumulation.

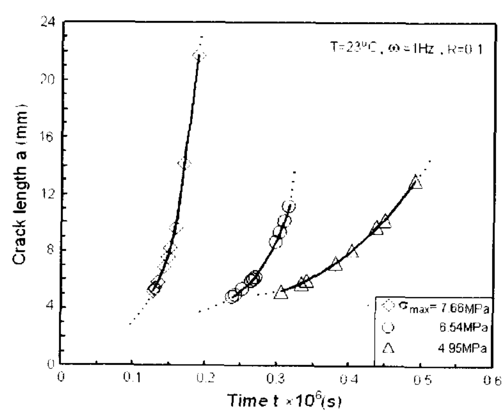

Fig. 4. Re-interpreted crack length versus time data of PVC in [16].

Table 2. Values of a, ΔK and da/dt for Cases I, II and III in Table 1.

σ_{max}=4.95MPa			σ_{max}=6.54MPa			σ_{max}=7.66MPa		
a (mm)	ΔK ($MPa{\cdot}m^{1/2}$)	da/dt (μm/s)	a (mm)	ΔK ($MPa{\cdot}m^{1/2}$)	da/dt (μm/s)	a (mm)	ΔK ($MPa{\cdot}m^{1/2}$)	da/dt (μm/s)
			4.76	0.72	0.020	5.19	0.88	0.041
5.21	0.57	0.017	4.90	0.73	0.031	5.31	0.89	0.057
5.77	0.60	0.021	5.31	0.76	0.040	5.42	0.90	0.080
5.97	0.61	0.025	5.88	0.80	0.045	5.79	0.93	0.10
7.20	0.67	0.030	6.03	0.81	0.050	6.83	1.01	0.11
8.08	0.71	0.040	6.18	0.82	0.051	7.53	1.06	0.14
9.76	0.78	0.050	8.64	0.97	0.091	8.25	1.11	0.20
10.26	0.80	0.051	9.37	1.01	0.12	9.64	1.20	0.24
12.99	0.90	0.063	10.13	1.05	0.15	14.08	1.45	0.36
			11.12	1.10	0.18	21.70	1.80	0.41

Table 3. Reinterpreted crack data for a, Δa and t of Cases I, II and III in Table 1.

σ_{max}=4.95MPa				σ_{max}=6.54MPa				σ_{max}=7.66MPa			
a (mm)	Δa (mm)	$\Delta a/\Delta t$ (μm/s)	t (10^6s)	a (mm)	Δa (mm)	$\Delta a/\Delta t$ (μm/s)	t (10^6s)	a (mm)	Δa (mm)	$\Delta a/\Delta t$ (μm/s)	t (10^6s)
				0				0			
0				4.76	4.76	0.020	0.238	5.19	5.19	0.041	0.127
5.21	5.21	0.017	0.306	4.90	0.14	0.031	0.243	5.31	0.12	0.057	0.129
5.77	0.56	0.021	0.333	5.31	0.41	0.040	0.253	5.42	0.11	0.080	0.130
5.97	0.20	0.025	0.341	5.88	0.57	0.045	0.265	5.79	0.37	0.10	0.134
7.20	1.23	0.030	0.382	6.03	0.15	0.050	0.268	6.83	1.04	0.11	0.143
8.08	0.88	0.040	0.404	6.18	0.15	0.051	0.271	7.53	0.70	0.14	0.148
9.76	1.68	0.050	0.438	8.64	2.46	0.091	0.298	8.25	0.72	0.20	0.152
10.26	0.50	0.051	0.448	9.37	0.73	0.12	0.304	9.64	1.39	0.24	0.158
12.99	2.73	0.063	0.491	10.13	0.76	0.15	0.310	14.08	4.44	0.36	0.170
				11.12	0.99	0.18	0.315	21.70	7.62	0.41	0.189

Based on the observation [14] that the microcrack tip remains open, a dual micro/macro line crack model was developed [8, 9] to account for the transition of microcraking to macrocracking, particularly suited for fatigue crack growth where the crack can close in compression and open in tension regardless of the crack length. A pertinent parameter in the model is σ^* that adjusts for the tightness of the adjoining crack surfaces. It consists of the ratio of the restraining internal stress of the material and the external applied stress. The opening segment of the microcrack tip relative to the crack or microstructure dimension is d^* while μ^* reflects the relative macro/micro properties of the material. The three quantities μ^*, d^* and σ^* are known as the essential parameters of the model that are contained in the intensification range ΔK^{macro}_{micro} for alternating stress such that a fatigue crack growth relation similar to Eq. (3) can be written as

$$\frac{da}{dt} = C^*\left(\Delta K^{macro}_{micro}\right)^{n^*} \tag{8}$$

with C^* and n^* being empirical parameters. Since

$$\Delta K^{macro}_{micro} = \left(K^{macro}_{micro}\right)_{max} - \left(K^{macro}_{micro}\right)_{min} \tag{9}$$

The relationship between ΔK^{macro}_{micro} and $\left(K^{macro}_{micro}\right)_{max}$ or $\left(K^{macro}_{micro}\right)_{min}$ is clear. Moreover, it is known from [8, 9] that

$$(K^{macro}_{micro})_{max} = \frac{6\sqrt{\pi}(1-\nu_{macro})\mu_{micro}\sqrt{c^2-a^2}}{5d^{0.25}\mu_{macro}} \cdot \left(1-\frac{2\sigma_o}{\pi\sigma_y}\sin^{-1}\frac{a}{c}\right)\sigma_{max} \tag{10}$$

and

$$(K^{macro}_{micro})_{min} = \frac{6\sqrt{\pi}(1-\nu_{macro})\mu_{micro}\sqrt{c^2-a^2}}{5d^{0.25}\mu_{macro}} \cdot \left(1-\frac{2\sigma_o}{\pi\sigma_y}\sin^{-1}\frac{a}{c}\right)\sigma_{min} \tag{11}$$

The use of Eqs. (9) to (11) yields