Analysis of fatigue crack growth in polymers using the two-parametric approach

K. Sadananda[1], Nagaraja Iyyer[1], A.K. Vasudevan[1], M. Nani Babu[2], Nam Phan[3], and A. Rahman[3]

[1]Technical Data Analysis Inc
[2]Indira Gandhi Centre for Atomic Research
[3]Naval Air Systems Command

May 20, 2022

Abstract

Considering that the correct quantification of fatigue damage involves two load parameters, the available load ratio data on polymeric materials are analyzed. It is shown that crack growth can be characterized by two parameters, ΔK and K $_{max}$, without the need for any crack closure concept. The crack growth rates, starting from the threshold can be represented by the L-shaped curves in the ΔK-K $_{max}$ plane defining two limiting variables, ΔK* and K $_{max}$*. Crack growth trajectory maps for various materials are developed by plotting ΔK* versus K $_{max}$*, as a function of crack growth rate. The trajectory defines the crack growth resistance curve providing a measure of material resistance to increasing crack tip driving forces.

Analysis of fatigue crack growth in polymers using the two-parametric approach

K. Sadananda*[1], N. Iyyer[1], A.K. Vasudevan[1], M. Nani Babu[2], N. Phan[3], A. Rahman[3]

[1]Technical Data Analysis, Inc. Falls Church, Va

[2]Metallurgy and Material Group, Indira Gandhi Center for Atomic Energy,

HBNI, Kalpakkam, India

[3]NAVAIR, Patuxent River, Md

* Corresponding author – Kuntimaddisada@yahoo.com

Abstract

Considering that the correct quantification of fatigue damage involves two load parameters, the available load ratio data on polymeric materials are analyzed. It is shown that crack growth can be characterized by two parameters, ΔK and K_{max}, without the need for any crack closure concept. The crack growth rates, starting from the threshold can be represented by the L-shaped curves in the ΔK-K_{max} plane defining two limiting variables, ΔK* and K_{max}*. Crack growth trajectory maps for various materials are developed by plotting ΔK* versus K_{max}*, as a function of crack growth rate. The trajectory defines the crack growth resistance curve providing a measure of material resistance to increasing crack tip driving forces.

Keywords: Fatigue Crack Growth, Polymeric materials, Viscoelastic deformation, Crack growth by Crazing.

1. Introduction :

Fatigue requires two load parameters for quantification, as Gerber [1] and Goodman [2] recognized more than a hundred years ago. For S-N fatigue, stress amplitude and mean stress have been used. Fatigue S-N data are conveniently presented in the form of Haigh Diagrams in handbooks [3]. Of the five parameters, stress range ($\Delta\sigma$), maximum stress (σ_{max}), mean stress (σ_{mean}), minimum stress (σ_{min}), and load ratio (R), only two are independent. The rest of the parameters can be expressed in terms of the two. More importantly, at least two parameters are needed to quantify the fatigue damage correctly.

Two-load parameter requirement is also essential for the analysis of the fatigue crack growth (FCG). Still, this aspect has been ignored since Elber proposed the plasticity-induced crack closure concept in 1970 [4]. Subsequently, other forms of crack closure, such as oxide-induced, roughness-induced, etc., have been introduced to analyze the FCG data in different materials [5].

Note, however, that the crack closure is an extrinsic parameter and is not a substitute for the intrinsic two parametric requirements to quantify fatigue damage. If crack closure is present, it forms a third parameter that should be considered for FCG. Plasticity-induced crack closure was originally proposed for plane stress conditions by Budiansky and Hutchinson [6]. However, it was later extended to analyze the FCG data under plane strain conditions with some adjustable parameters, Newman et al. [7,8]. There are thousands of papers in the literature correlating the R-ratio effects of FCG using the crack closure concept. Using the dislocation theory [9], we have shown that plasticity under plane stain conditions does not contribute to crack closure, or its contribution is very minimal to account for the R-ratio effects. There was a follow-up discussion on this subject with Prof. Pippan's group [10-13]. The fact remains, however, that crack closure was originally proposed for plane stress conditions [6]. In addition, we have shown that for S-N fatigue, fatigue can be represented better in terms of σ_{max} and $\Delta\sigma$ for a given number of cycles to failure, N_F [14]. This representation is a modification of the familiar Haigh diagram for fatigue, where the data is generally expressed in terms of σ_{mean} and $\Delta\sigma$. Similarly, we have shown that the corresponding two parameters for FCG are K_{max} and ΔK [16]. These concepts were applied to analyze FCG in metals, alloys, and their composites. In this paper, we extend the analysis to FCG in polymers to show the applicability of the two-parametric nature of fatigue even though they deform differently from metals and alloys [17].

2. Deformation behavior of Polymers:

Unlike metals and alloys, polymers consist of long organic chains that undergo viscoelastic deformation depending on their composition, molecular structure, and external variables such as frequency of cycling and test temperature [18]. Hence yielding in polymers is controlled by their chain mobility. Polymer deformation can still be differentiated broadly into three types depending on the molecular structure. First is the shear-band-like deformation at stress concentrations due to low mobility of the chain segments. The bands can be 38^{o}to 45^o to the tensile axis. The second is the crazing, which is somewhat inhomogeneous deformation depending on the relative mobility of the molecular chains. It can lead to cavitation in the deformed region. Crazes typically form in planes perpendicular to the maximum applied stress and vary depending on the polymer's molecular structure. At low stains, polymers can undergo viscoelastic deformations that are time and temperature-dependent, similar to power-law creep in metals. Hence test frequency and temperature become important. At high strains, some viscoelastic deformation can still occur in competition with the crazing, depending on the structure of polymers. Some polymers are also somewhat brittle at room or low temperatures. Hence fatigue behavior of polymers can differ from material to material and vary with test conditions. Nevertheless, we show here that the two-parametric analysis for FCG is applicable to all cases considered.

Under cyclic load, we can still expect monotonic and cyclic plastic zones as in metals. The extent of each depends on the strength of the polymers and the applied stresses. Hence the characteristic cyclic, $\Delta\sigma$ (or ΔK) and monotonic σ_{max} (or K_{max}) stresses determine their fatigue damage. Therefore, the load ratio effects on fatigue damage can be significant since it changes with the relative ratio of ΔK and K_{max}. There is little work on the R-ratio effects in S-N fatigue of polymers. Hence, this study will be concentrated on the FCG behavior using the available R-ratio data in the literature.

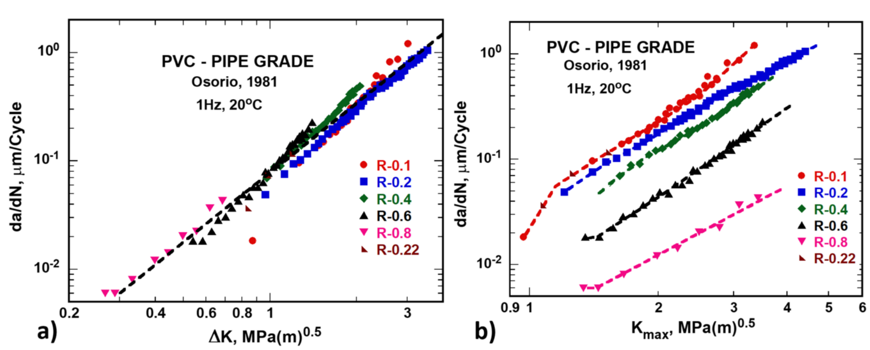
3. Fatigue crack growth in polymeric materials:

In this connection, there is an interesting paper by Hertzberg et al. on the fatigue failure of a polymer used in the lavatories [19]. Hertzberg was a student of Paul Paris and has done a significant amount of work on the fatigue crack growth at Lehigh University. A more exhaustive analysis of the behavior of polymers under fatigue is presented in the book by Hertzberg and Manson [20].

Osorio [21] has done significant work on the R-ratio effects on FCG in several polymeric materials. He has selected two modified polyvinyl-chloride (PVC) polymers. One is called PVC-PIPE grade, and the other is called DARVIC-110 grade materials. Both are amorphous materials. The modification involves small additions that make them more ductile and tough for applications. In addition, they have studied FCG in Epoxy, which is a somewhat brittle material. The crazing may be restricted to the crack tip plane at low R-ratios or mean stresses. At high ratios or high K_{max} values, the craze can spread around the crack tip in the plastic zone, thereby increasing the crack growth resistance of the material by energy dissipation. Craze formation is governed more by tensile stress than cyclic stress. For viscoelastic materials, deformation can also change with temperature and time. Hence frequency effects become important. FCG behavior in the brittle Epoxy will be different, where the fracture occurs by brittle crack extension, which is also K_{max} dependent.

Fig. 1 shows the crack growth behavior of PVC-PIPE grade polymer at 1Hz at different R-ratios. Fig. 1a shows the data in terms of ΔK and Fig. 1b in terms of K_{max} parameters. The spread in the data in terms of ΔK appears to be small except at low crack growth rates. In terms of K_{max}, the spread is more significant. Fig. 1c shows ΔK-R curves at low crack growth rates, and Fig. 1d shows the typical L-shaped ΔK-K_{max} curves defining the limiting values, ΔK^* and $K_{max}{}^*$ at each selected crack growth rate. These L-shaped curves define the relative variation of the two parameters to enforce the selected crack growth rates. The limiting values indicate that both minima must be met for a crack to grow at the selected growth rate while one or the other will be controlling. In addition, each L-shaped curve defies a particular mechanism of crack growth. If the mechanism changes the corresponding L-curve also changes along with its new limiting values. Plotting of the limiting values ΔK^* vs. $K_{max}{}^*$ defines the crack growth trajectory map for the material. Each point in the trajectory defines a crack growth rate, starting from the threshold. The 45^o line with $\Delta K^* = K_{max}{}^*$ defines the pure fatigue line. The data representing the material performance can deviate to the left of the pure fatigue line depending on the extent of the superimposed K_{max}-dependent process present during crack growth. For example, a viscoelastic deformation or deformation by crazing can shift the curve to the left depending on their contribution. Fig. 1e shows the crack growth trajectory map for the polymer. The trajectory initially seems to move towards the pure-fatigue line as the crack growth rate increases. With a further increase in crack growth rates, it diverges from the pure fatigue line. Thus, the contribution from the K_{max}-dependent process appears to change with increasing crack growth rate. The detailed fractographic analysis will be helpful to identify the crack growth mechanisms involved.

Fig. 2 shows the behavior of the same material but at a higher frequency, 10Hz. Interestingly, the author plotted the original data for both frequencies in terms of K_{max} and not ΔK, as indicated in



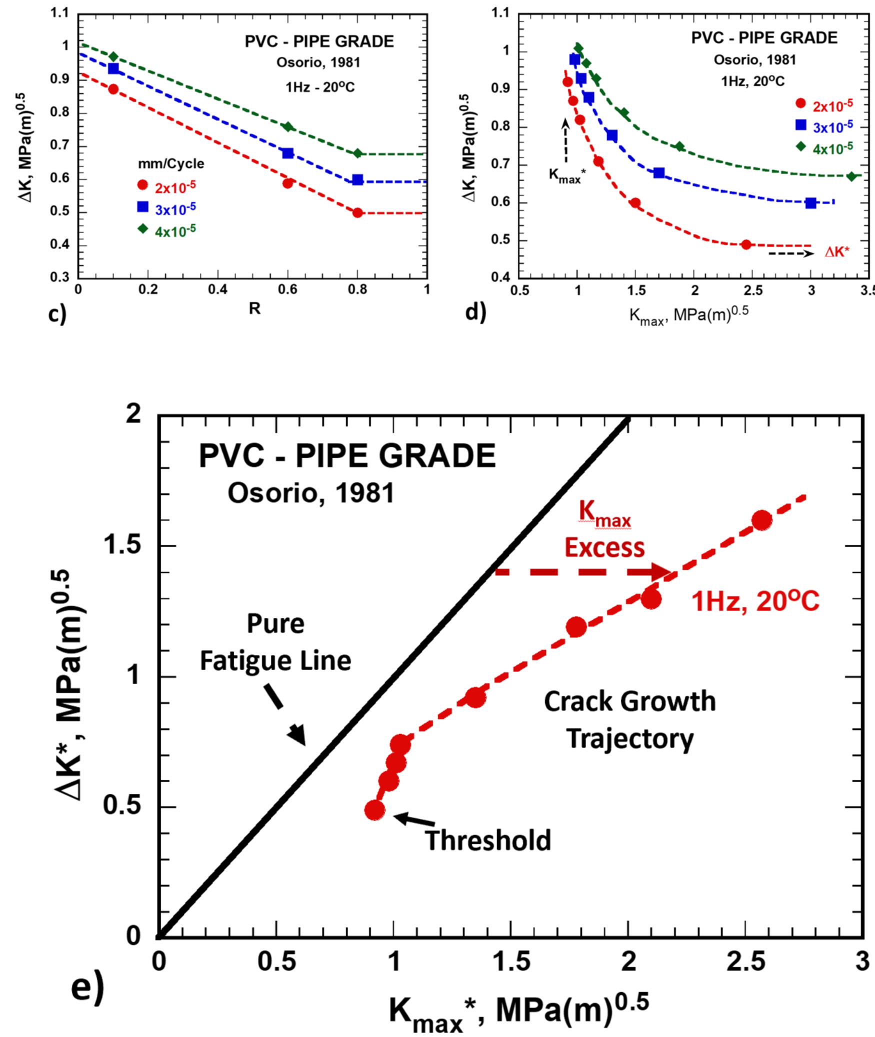


Fig. 1 FCG in PVC pipe grade material tested at 1Hz at 20°C. a) rates as a function of ΔK and b) K_{max}. c) ΔK-R plots for selected crack growth rates and d) ΔK-K_{max} plots showing an L-shaped type of behavior with limiting values of ΔK^* and K_{max}^*. e). The crack growth trajectory map in terms of ΔK^* and K_{max}^*.

Fig.2a. The data spread is more extensive in terms of K_{max} than in terms of ΔK. The ΔK-R plots at low crack growth rates, Fig. 2c, seem to indicate two mechanisms governing the behavior, one at low R and the other at high R. The corresponding ΔK-K_{max} plots, Fig. 2d, indicate the possible two L-shaped curves corresponding to the two mechanisms involved. Fig. 2e shows the crack growth trajectories at both test frequencies. The two mechanisms operating at a higher frequency are shown, one following the pure fatigue behavior with ΔK=K_{max}, and the other deviating from

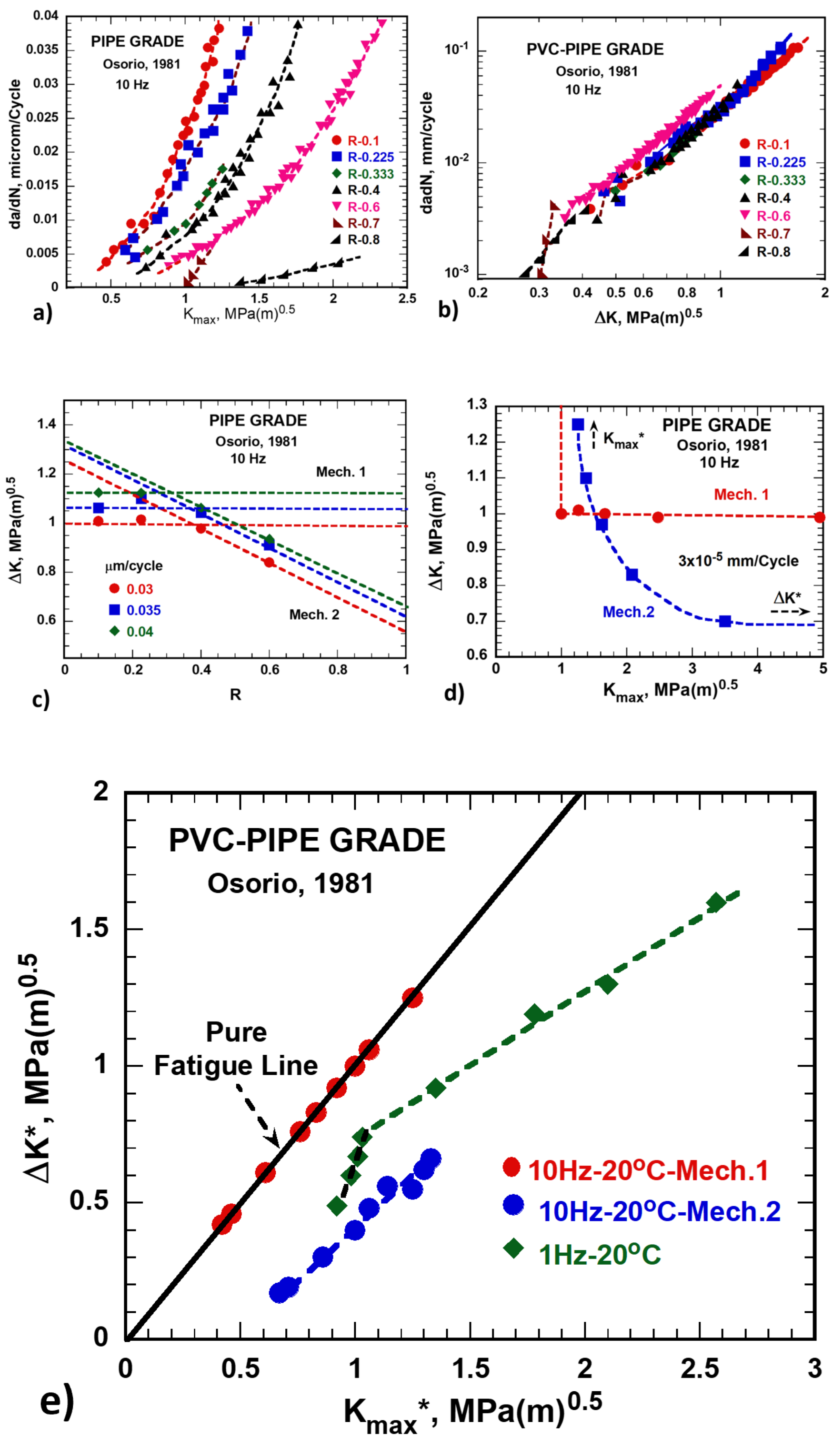
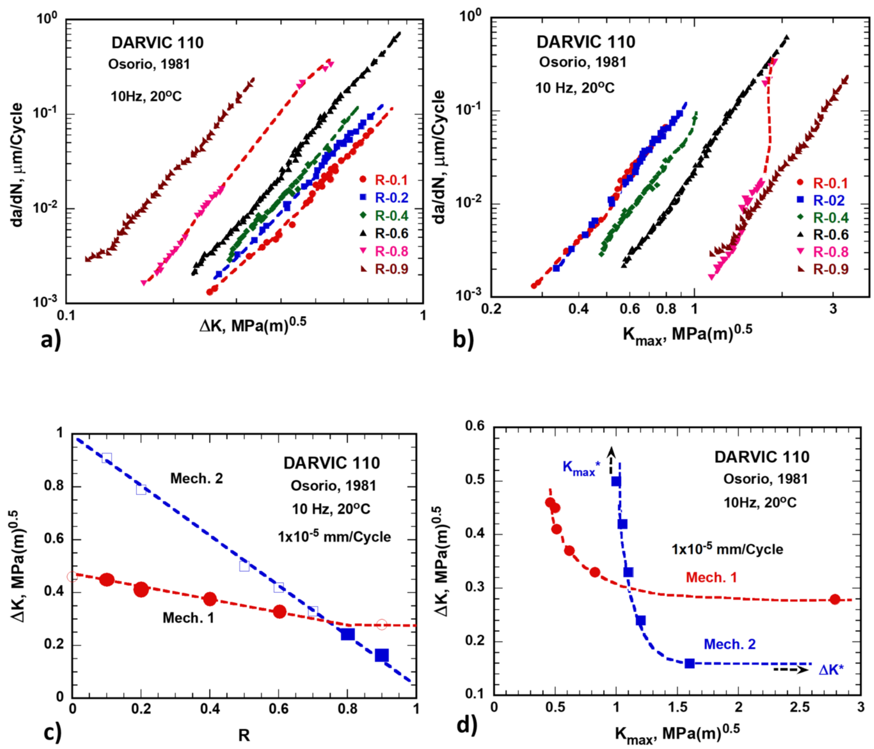


Fig. 2. FCG rates in Pipe grade PVC at 10 Hz at 20°C. a) in terms of K_{max} and b) in terms of ΔK. c) ΔK-R plots at low crack growth rates showing possible two mechanisms one at low R and the other at high R. d)

ΔK-K_{max} plots showing two L-shaped curves. e) Comparison of crack growth trajectories for PVC-PIPE GRADE material.

the pure fatigue line. At a lower frequency, the mechanism falls between the two. Osorio has also tested another PVC material, DARVIC110 at several R-ratios. Fig. 3a shows the da/dN curves in terms of ΔK and Fig. 3b in terms of K_{max}. The data for this PVC material seem to spread out in terms of both parameters, indicating that the response of this material differs from that of the Pipe grade material. The ΔK-R cures at low crack growth rates are shown in Fig.3c. Again, there seem to be two governing mechanisms operating, one at low R and the other at high R. The



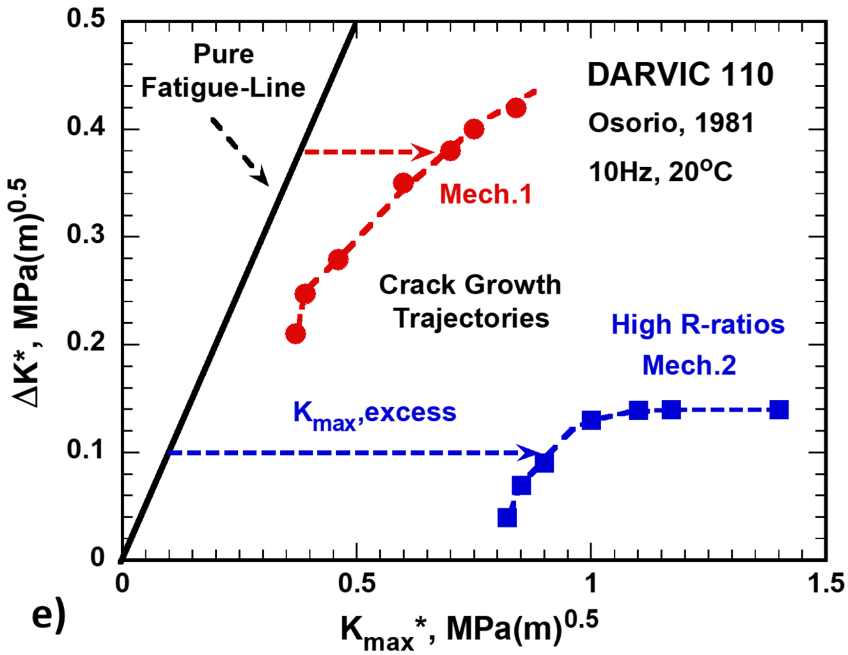
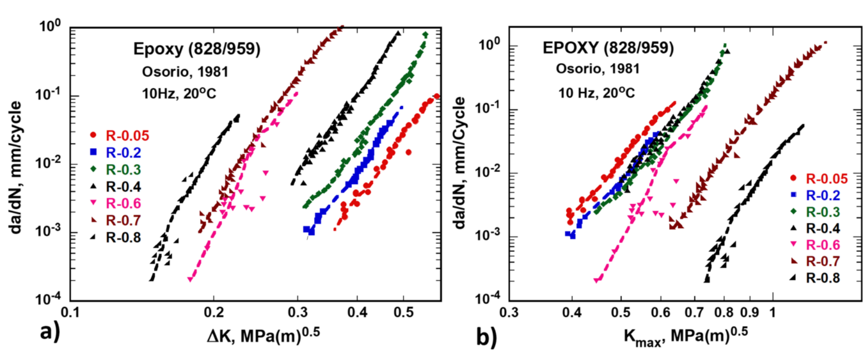


Fig. 3 FCG in DARVIC 110 material plotted in terms of a) ΔK and b) $K_{max.}$ c) ΔK-R curves for crack growth rate near thresholds showing two possible mechanisms. d) The corresponding two L-shaped ΔK-K_{max} curves with limiting values. e)FCG trajectory for the two mechanisms.

corresponding two L-shaped ΔK-K_{max} curves are shown in Fig.3d, with limiting values at each crack growth rate. The FCG trajectories for the material are shown in Fig.3e. Both mechanisms deviate from the pure fatigue line, with mechanism two operating at high R-ratios, deviating more towards the K_{max}-axis.

Osorio has determined FCG for somewhat brittle Epoxy(828/959) material also at many R-ratios. Fig. 4a shows the crack growth rates in terms of ΔK and Fig. 4b in terms of K_{max}. In contrast to PVC material, the data for Epoxy seem to spread out in terms of both parameters. Fig. 4c shows the plot of ΔK-R curves at low crack growth rates, which follows a typical trend. Fig. 4



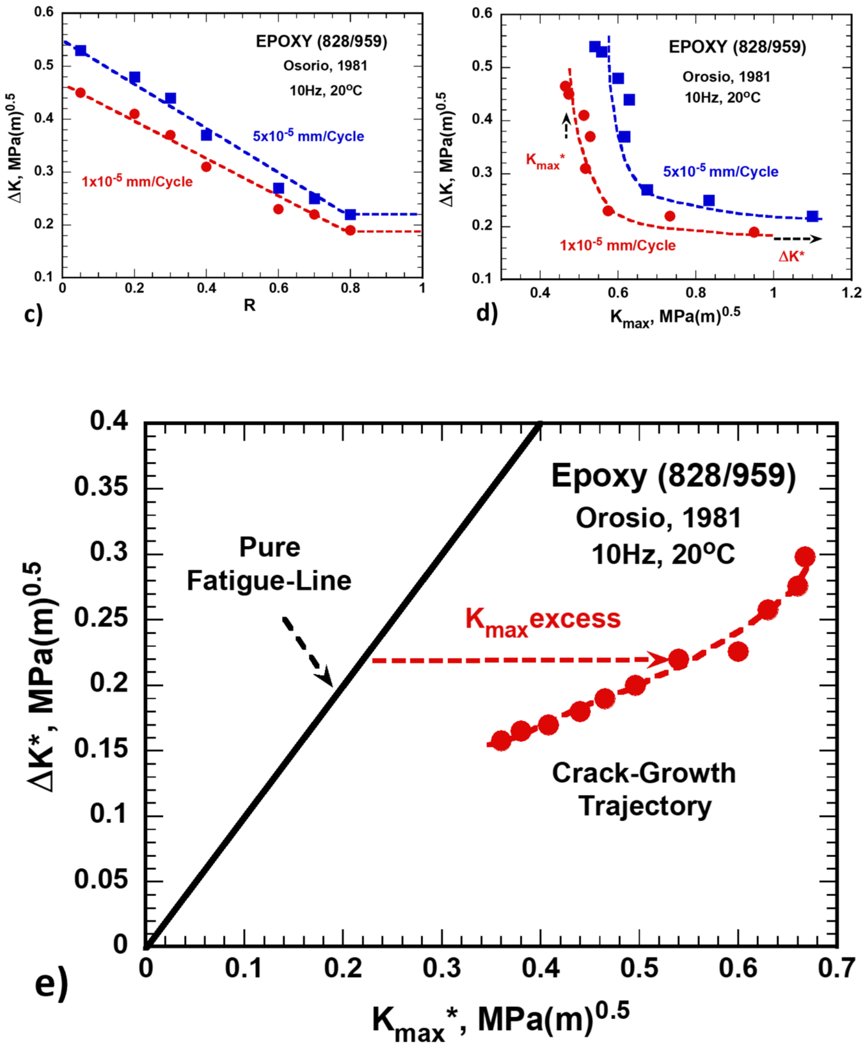


Fig. 4 FCG for Epoxy at different R-ratios. a) in terms of ΔK and b) in terms of K_{max}. c) ΔK-R plots at low crack growth rates. d) corresponding ΔK-K_{max} plots with limiting ΔK and K_{max}values. e) The trajectory showing deviation from the pure fatigue line.

shows the corresponding ΔK-K_{max} plots with characteristic L-shaped behavior. For this material, only one mechanism seems to operate for all R-values. Fig. 4e shows the FCG trajectory. Each point again corresponds to a crack growth rate starting from the threshold. The trajectory deviates from the pure fatigue line due to the superimposed K_{max}-dependent process. Here the mechanism could be the superimposed monotonic fracture which depends on K_{max}.

Fig.5 compares the crack growth trajectories of the three polymer materials tested by Osorio. Only Epoxy shows one crack growth mechanism governing FCG for all R values, while the other

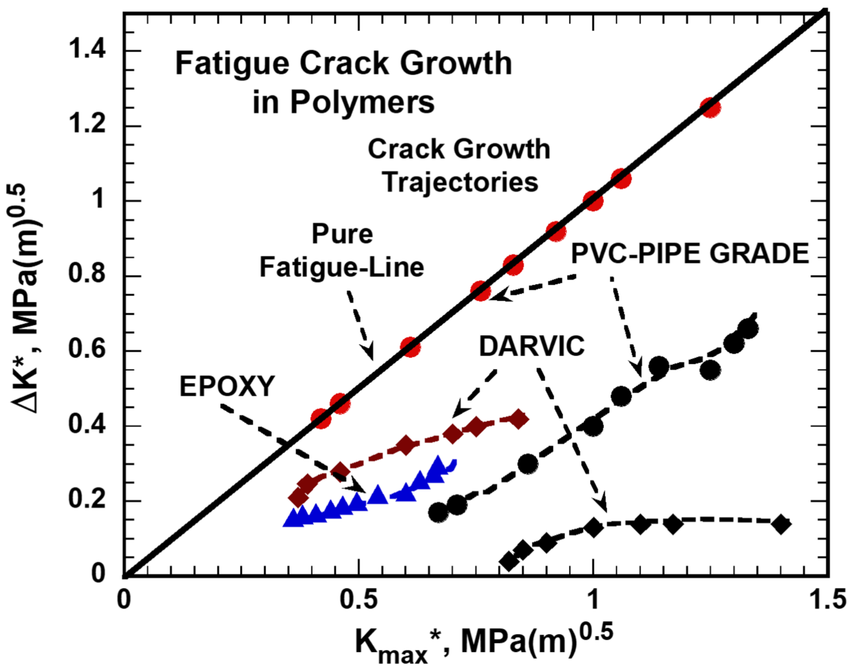


Fig. 5 Comparison of crack growth trajectories of three polymer materials tested by Osorio, 1981. PVC and DARVIC show two mechanisms while Epoxy shows one.

two show two mechanisms governing FCG, one at low Rs and the other at high Rs. PVC-Pipe grade material shows a pure fatigue mechanism at low Rs as the trajectory falls on the pure-fatigue line. For all other cases, the trajectories deviate toward the K_{max}-axis depending on the extent of the superposition of the K_{max}-dependent mechanism.

We next analyze another polymer called PMMA, a polymethyl methacrylate, known as acrylic or acrylic glass, with different trade names. It is a transparent thermoplastic used as an alternative to glass. The FCG studies were made on a commercial PMMA material at three different R-ratios, one K_{mean} = constant test and one K_{max} = constant test by Clark et al. [22]. The crack growth rates are plotted in terms of ΔK, Fig. 6a, and K_{max}, Fig. 6b. The growth rates in terms of ΔK run all over the plot while the same data in terms of K_{max} get compacted into a narrow band. The ΔK-R plot at crack growth rates close to the threshold is shown in Fig. 6c. All the crack growth data is falling on a straight line indicating of fully K_{max}-controlled mechanism governing the crack growth. As before, in these figures, we chose to draw a horizontal line at R = 0.8 to define the minimum ΔK needed for crack growth. Based on this, a corresponding ΔK-K_{max} plot is shown in Fig. 6d. All the experimental data is falling on the vertical line with a constant K_{max} value. Interpolated points and assumed constant ΔK value provide the horizontal line defining the selected ΔK constant minimum required for crack growth. Even here, the data from the constant K_{mean} test and constant K_{max} test also fall on the same L-shaped curve indicating the intrinsic

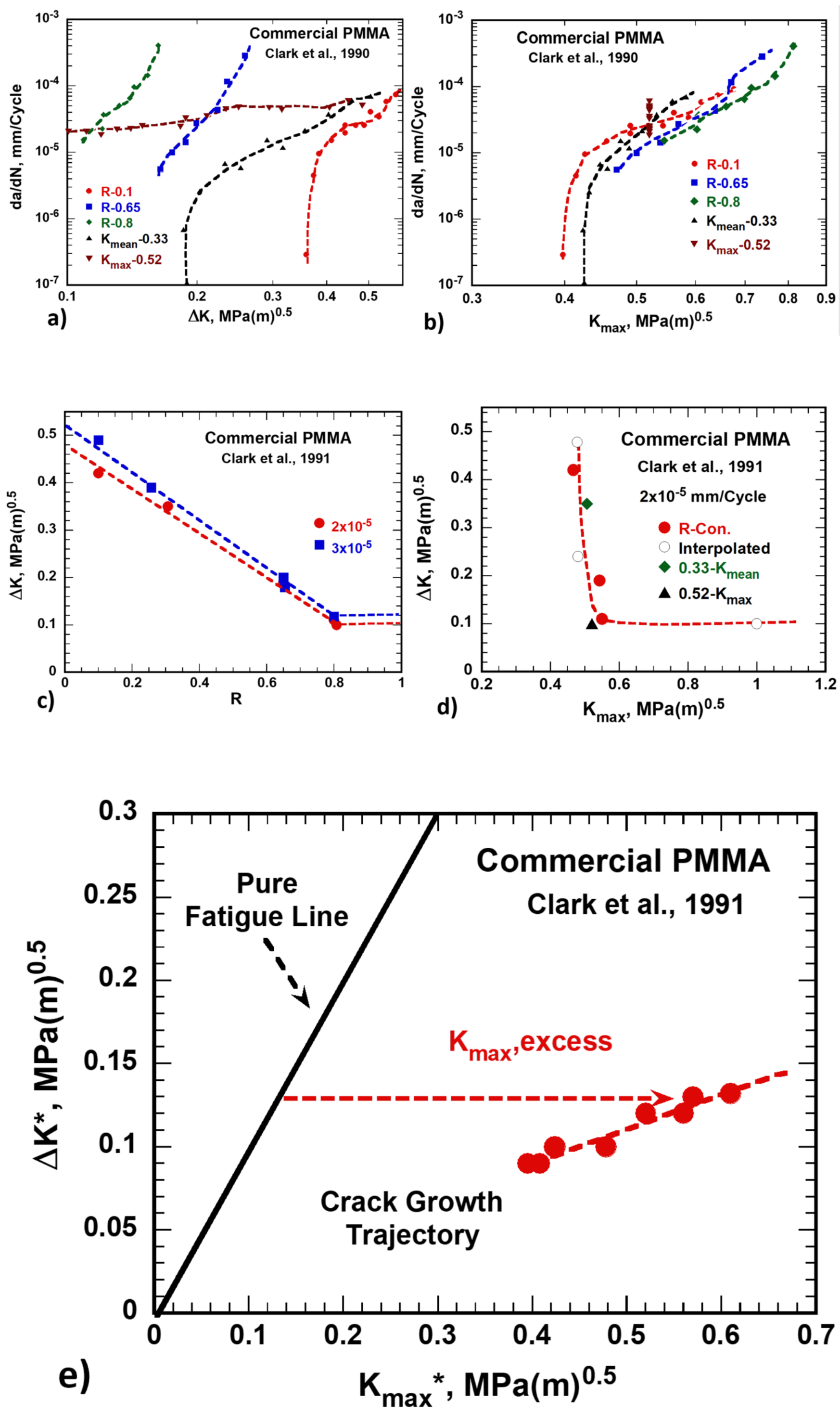


Fig. 6. FCG behavior of commercial PMMA plastics a) as a function of ΔK with three R-ratios and one K_{mean} and one K_{max} constant tests. b) The data in terms of K_{max}. c) ΔK-R plots at selected crack growth rates close to the threshold value. d) The ΔK-K_{max} plot showing L-shaped curves. e) The FCG trajectory showing its deviation from the pure-fatigue line.

behavior of the material under fatigue. Fig. 6e provides the crack growth trajectory map for this material. Naturally, the data deviate from the pure fatigue line toward the K_{max}-axis.

Fig.7 shows crack growth rate data of Epoxy resin but toughened by rubber, studied by Hamda et al.[23]. Fig. 7a shows crack growth rates in terms of ΔK. Two values for some Rs imply that two tests were done at those R-values. The crack growth data is represented in terms of K_{max} in Fig.

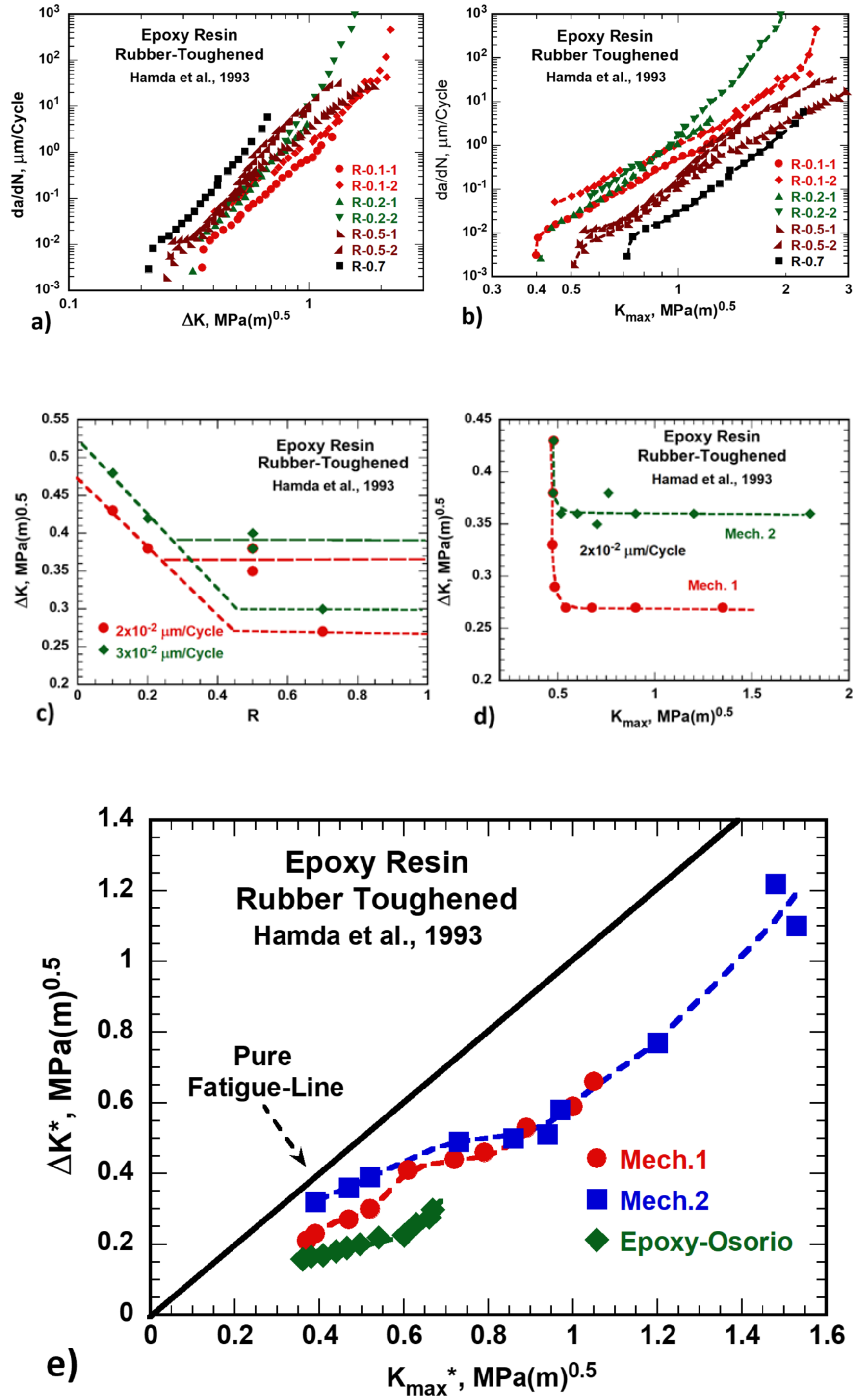


Fig. 7 Crack growth rates in rubber toughened epoxy resin. a) in terms of ΔK and b) in terms of K_{max}. c) ΔK –R plots for selected crack growth rates showing two mechanisms. d) ΔK-K_{max} plots showing two L-shaped curves. e) Crack growth trajectory maps for the two mechanisms. The results are compared with the trajectory of Epoxy material tested by Osorio.

7b. From the data, ΔK-R plots are made as shown in Fig. 7c. Only one line can be drawn through the data at low crack growth rates. On the other hand, at high Rs, the data diverges into two levels indicating two possible mechanisms operating at high R values. Thus, both mechanisms seem to have the same K_{max} limiting value but different ΔK limiting values. It is the first time we are observing this type of behavior. Fig. 7e shows the crack growth trajectories for

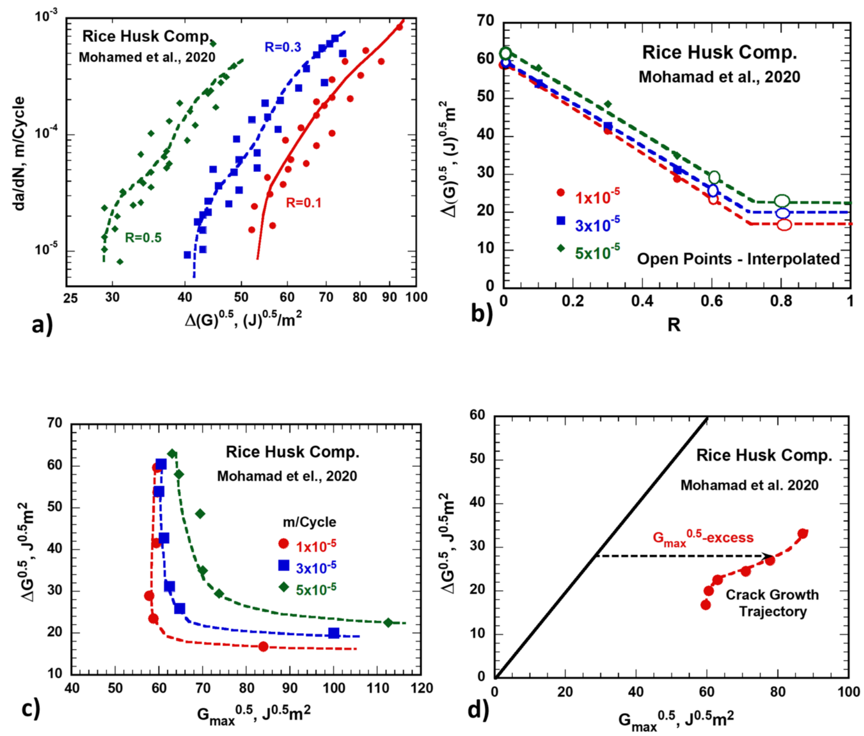


Fig 8. The FCG rates in Rice Husk composite. a) in terms of amplitude, [?]ΔG. b) the [?]ΔG versus R plots for selected crack growth rates. c) [?]ΔG vs [?]G_{max} plots at selected crack growth rates showing the L-shaped curve with limiting [?]ΔG and [?]G_{max} values. d) shows the cack growth trajectory deviating from the pure fatigue line.

the two mechanisms involved. It also compares the Epoxy trajectory data of Osorio discussed earlier.

Fig. 8 shows the FCG behavior of a polymer composite with rice husk fibers as a strengthening phase [24]. The crack growth rates were determined at three R ratios, 0.1, 0.3, and 0.5. Interestingly the authors have used ΔG instead of ΔK, where G corresponds to the crack tip driving force. From our analysis point, it would not make any difference in terms of the two-parametric requirement. In this case, the corresponding two parameters will be [?]ΔG and [?]G_{max} as the stress intensity factor K is proportional to [?]G.

Fig. 8a shows the crack growth rates in terms of [?]ΔG. The [?]ΔG – R plots for crack growth rates near the threshold are shown in 8b. The linear portion is extended up to R = 0.7, and a horizontal line is drawn with a possible constant [?]ΔG value at high R-ratios. The corresponding [?]ΔG - [?]G_{max} plot, Fig. 8c resembles the typical L-shaped plot of ΔK-K_{max} defining the limiting values of the parameters for each crack growth rate. The crack growth trajectory of this rice-husk composite is shown in Fig. 8d. The trajectory as expected deviates from the pure fatigue line indicating the [?]G_{max}-controlled mechanism governing the crack growth. The behavior of this composite follows that of other polymer materials. This data further proves that the two parametric nature involving amplitude and peak stress is fundamental to FCG.

4. Summary and Conclusions:

It was well established that fatigue requires two load parameters for proper analysis. For fatigue crack growth these parameters correspond to the amplitude ΔK and the peak stress intensity factor, K_{max}. Crack closure is not required to account for the load ratio effects. This two-parametric approach is shown to be applicable to account for the crack growth behavior in several polymeric materials. In contrast to metals and alloys, polymers deform either by crazing, viscoelastic deformation, localized brittle fracture, or their combination. The analysis establishes that the two-parametric nature of fatigue crack growth remains the same and is relevant for all materials.

5. Acknowledgements: The authors acknowledge the funding support from TDA's ONR contract # N68335-16-C-0135. Special acknowledgments are due to Mr. Bill Nickerson, Program Officer of ONR, who encouraged this research and provided valuable insights and guidance.

References

1. Gerber, W. Z. Bestimmung der zulässigen Spannungen in Eisen-Constructionen (calculation of the allowable stresses in iron structures). Z. Bayer. Arch. Ing. Ver., 1874, 6(6), 101–110.

2. Goodman J, Mechanics Applied to Engineering, 1stedition, 1989, Longmans Green, London.

3. ASM HandBook, Fatigue and Fracture, Vol. 19, 1996. https://doi.org/10.31399/asm.hb.v19.9781627081931

4. Elber W, 1970, Fatigue crack closure under cyclic tension, Engineering Fracture Mechanics, 1970; 2: 37–45.

5. Suresh, S. Fatigue of Materials, 2nd Edition, October 1998, Cambridge University Press, NY.

6. Budiansky B, Hitchinson JW, Analysis of Crack Closure in Fatigue Crack Growth, J. Appl. Mech., 1978; 45:267-276.

7. Newman, JC Jr, Finite-Element Analysis of Fatigue Crack Propagation-Including the Effects of Crack closure. Ph.D. Thesis, Virginia Polytechnic Institute, and State University, Blacksburg, VA, May 1974.

8. Newman JC Jr, Elver W, Mechanics of Fatigue Crack Closure, ASTM STP, 198: 892

9. Louat N, Sadananda K, Duesbery M, Vasudevan AK. A theoretical evaluation of crack closure. Metall Trans A 1993;24A:2225-32.

10. Riemelmoser FO, Pippan R., Discussion of error in the analysis of the wake dislocation problem, Metall. Materials Trans., A, 1998; 29:1357-1358

11. Sadananda K, Vasudevan AK, Discussion of error in the analysis of the wake dislocation problem, Metall. Materials Trans., A, 1998; 29: 1359-1360

12. Riemelmoser, F.O., Pippan, R., Discussion of 'reconsideration of error in the analysis of the wake dislocation problem'- Reply, Metall. Mater. Trans.A., 1999, 30: 1452-1457.

13. Sadananda, K., Vasudevan, A.K., Authors Response, Metall. Mater. Trans.A, 1999, 30: 1457-1459.

14. Sadananda K, Sarkar S, Kujawski D, Vasudevan AK, A two-parameter analysis of S–N fatigue life using $\Delta\sigma$ and σ_{max}, International Journal of Fatigue, 2009; 31:1648–1659.

16. Sadananda K, Nani Babu M, Vasudevan AK, The Unified Approach to subcritical crack growth and fracture, Eng. Frac. Mech., 2019; 212:238-257.

17. Strombro J, Micro-mechanical mechanisms for deformation in polymer-material structures, Ph.D. Thesis, 2008, KTH School of Engineering Sciences Department of Solid Mechanics Royal Institute of Technology SE-100 44 Stockholm, Sweden.

18. Sternstein S.S. in Properties of Solid Polymeric Materials, (ed. J.M. Schultz), Academic Press, New York, 1977; 541-598.

19. Hertzberg, RW, Hahn MT, Rimnac CM, A laboratory analysis of a lavatory failure. International Journal of Fracture. 1993, 23: R57–R60 https://doi.org/10.1007/BF00042819

20. Hertzberg RW, Manson JA, Fatigue of Engineering Plastics, Academic Press, New York, 1980.

21. Osorio, AMBA, Stress ratio effects on fatigue crack growth in polymers, Ph.D. Thesis, 1981, Department of Mechanical Engineering, Imperial College of Science & Technology, London SW7 2BX.

22. Clark TR, Hertzberg RW, Manson JA, "Influence of Test Methodology on Fatigue Crack Propagation in Engineering Plastics," Journal of Testing and Evaluation, 1990; 18: 319-327. https://doi.org/10.1520/JTE12493J

23. Hamda, MA, Mai YW, Wu SX, Cotterell, B., Analysis of fatigue crack growth in a rubber-toughened epoxy resin: effect of temperature and stress ratio, J. Polymer, 1993; 34: 4221-4229.

24. Mohamed SAN, Zainudin ES, Sapuan SM, Azaman MD, Arifin AMT, Effects of Different Stress Ratios on Fatigue Crack Growth of Rice Husk Fibre-reinforced Composite. BioResources, 2020;*15:* 6192-6205

Figure Captions

Fig. 1 FCG in PVC pipe grade material tested at 1Hz at 20°C. a) rates as a function of ΔK and b) K_{max}. c) ΔK-R plots for selected crack growth rates and d) ΔK-K_{max} plots showing an L-shaped type of behavior with limiting values of ΔK^* and K_{max}*. e). The crack growth trajectory map in terms of ΔK^* and K_{max}*.

Fig. 2. FCG rates in Pipe grade PVC at 10 Hz at 20°C. a) in terms of K_{max} and b) in terms of ΔK. c) ΔK-R plots at low crack growth rates showing possible two mechanisms one at low R and the other at high R. d) ΔK-K_{max} plots showing two L-shaped curves. e) Comparison of crack growth trajectories for PVC-PIPE GRADE material.

Fig. 3 FCG in DARVIC 110 material plotted in terms of a) ΔK and b) $K_{max.}$ c) ΔK-R curves for crack growth rate near thresholds showing two possible mechanisms. d) The corresponding two L-shaped ΔK-K_{max} curves with limiting values. e)FCG trajectory for the two mechanisms.

Fig. 4 FCG for Epoxy at different R-ratios. a) in terms of ΔK and b) in terms of K_{max}. c) ΔK-R plots at low crack growth rates. d) corresponding ΔK-K_{max} plots with limiting ΔK and K_{max} values. e) The trajectory showing deviation from the pure fatigue line.

Fig. 5 Comparison of crack growth trajectories of three polymer materials tested by Osorio, 1981. PVC and DARVIC show two mechanisms while Epoxy shows one.

Fig. 6. FCG behavior of commercial PMMA plastics a) as a function of ΔK with three R-ratios and one K_{mean} and one K_{max} constant tests. b) The data in terms of K_{max}. c) ΔK-R plots at selected crack growth rates close to the threshold value. d) The ΔK-K_{max} plot showing L-shaped curves. e) The FCG trajectory showing its deviation from the pure-fatigue line.

Fig. 7 Crack growth rates in rubber toughened epoxy resin. a) in terms of ΔK and b) in terms of K_{max}. c) ΔK –R plots for selected crack growth rates showing two mechanisms. d) ΔK-K_{max} plots showing two L-shaped curves. e) Crack growth trajectory maps for the two mechanisms. The results are compared with the trajectory of Epoxy material tested by Osorio.

Fig 8. The FCG rates in Rice Husk composite. a) in terms of amplitude, [?]ΔG. b) the [?]ΔG versus R plots for selected crack growth rates. c) [?]ΔG vs [?]G_{max} plots at selected crack growth rates showing the L-shaped curve with limiting [?]ΔG and [?]G_{max} values. d) shows the cack growth trajectory deviating from the pure fatigue line.

———————

Conflict of Interest:

The authors have no conflict of interest.

—————-

Contributions by the authors

K. Sadananda – contributed in terms of research and preparation of the manuscript

N. Iyyer – contributed towards research, review of the manuscript and getting grants for research.

A.K. Vasudevan – Contributed to research and review of the manuscript

N. Phan – Review of the manuscript and procuring funds for the research

A. Rahman – Review of the manuscript and procuring funds for the research