DEFORMATION AND FRACTURE OF POLYMERS: RELATIVISTIC APPROACH

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The ideas of the theory of complex systems are applied to the consideration of the anomalous behaviour of poly(vinyl alcohol) fibers during the fracture at high temperatures. The increase of the time-to-fracture with increasing of applied load occurs in the bifurcation region under the influence of arising critical fluctuations. Relativistic phenomena can play important role in the processes of fracture of solids, especially when velocity of kinetic units on microscopic or mesoscopic level approaches some limiting velocity. The role of the value of limiting velocity in manifestation of relativistic effects and its relation to the points of instability and to the processes of self-organisation is discussed.

INTRODUCTION

Fracture is a complex process which proceeds simultaneously at several levels (micro-, meso- and macrolevels) and interaction between these levels is of great importance.In some cases, the behaviour of materials during the process of fracture could seem anomalous from the viewpoint of the theories which currently dominate in science (Kausch(1)) or even from the viewpoint of common sense. Many phenomena, especially those related to instabilities, are still not well understood and one may assume the possibility that new physical processes are coming into play.

The purpose of the work reported here was to contribute to the investigation of new aspects of fracture mechanics by combining ideas of theory of complex systems with numerous attempts to use relativistic formula in consideration of mechanical behaviour of solids which have been undertaken before.

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RESULTS AND DISCUSSION

An anomalous behaviour of the time-to-fracture of poly(vinyl alcohol) fibers at various applied loads and temperatures is demonstrated in Table 1.(Kerch and Karlsone(2))

TABLE 1 - Lifetimes (in seconds) of poly(vinyl alcohol) fibers at various loads and temperatures.

	Temperature, ^{0} C		
Load,g	215	220	230
0.5	480	124	39
1.0	>10	5	20
5.0	$>10^{5}$	<1	<1
10.0	$>10^{5}$	<1 or $>10^{5}$	< 1 or $>10^{5}$
50.0	$>10^{5}$	<1 or $>10^{5}$	<1 or $>10^{5}$
100.0	$>10^{5}$	<1 or $>10^{5}$	<1 or $>10^{5}$
200.0	$>10^{5}$	<1 or $>10^{5}$	<1
300.0	$>10^{5}$	<1 or $>10^{5}$	<1
310.0	$>10^{5}$	160	<1
320.0	$>10^{5}$	<1	< 1
325.0	800	<1	<1
360.0	428	<1	<1
400.0	<1	<1	<1

The sharp increase of the time-to-fracture with increasing of applied load has been observed for poly(vinyl alcohol) fibers in the temperature interval 215 - 230 C. In the ranges of applied loads 10 - 300g at 220 C and 10 - 200g at 230 C two possibilities exist:

fracture occurs either immidiately or fracture did not occur at all during the time of experiment. Such a behaviour can be described by the theory of complex systems (Nicolis and Prigogine(3)). As a matter of fact we deal with dynamical dissipative system far from equilibrium which in the course of evolution reaches the region of instability, begins to oscillate and arising critical fluctuations lead to self-organisation and formation of new more stable structure

In the points of bifurcation the systems have the opportunity to make a choice between different ways of further development. In the case of poly(vinyl alcohol) fibers the chemical reactions of intramolecular and intermolecular crosslinking occur on microscopic level. The competition between these reactions determines structural rearrangements on mesoscopic level and growth or healing of cracks.

Figure 1 shows the schematic dependence of the time-to-fracture on load which resembles bifurcation diagrams (Prigogine and Stengers(4)).

Evidently, that when we deal with complex systems the value of the rate of exchange of signals among the parts of the system, the value of the limiting velocity of the propagation of interaction must be of great importance.

Let us demonstrate that mechanical behaviour of polymer materials in critical region could be governed by relativistic effects provided that the value of limiting velocity is equal to velocity of elastic waves. As far back as 1910 (Umov(5),Berzi and Gorini(6)) it is known that Lorentz equations in special relativity can be obtained without imposing from the onset the principle of the constancy of light velocity. Derivations of Lorentz transformations that dispense with the postulate of the invariance of velocity of light are considered in the works of Terletskii(7), Rindler(8), Levy-Leblond(9). Shepanski and Simon(10), Kaiser(11) criticized the overemphasized role of the speed of the light in the foundations of special relativity as well. The apparently ad hoc and privileged selection of a specific physical process of the light-signal propagation as a fundamental phenomenon underpining the basis of special relativity obviously restricts the area of application of the theory. It has been noted(9) that special relativity rules all classes of natural phenomena, not only electromagnetic interactions, which have no privilege other than a historical one.So, it is a more general approach if the bases of Einsteinian relativity are taken as the special relativity principle and the existence of limiting speed, instead of the relativitv principle and some specific experimental observation such as the law of light propagation.Moreover, Gonzalez Gascon(12) has introduced transformation formulas for the relativistic equations that contain a dicsrete spectrum of singularities.

On the other hand, it has been shown (Frenkel(13),Frank (14),Eshelby(15)) that equations of motion of crystal dislocations can be brought into a form analogous to those of a particle in special relativity.Dislocations suffer Lorentz contraction in the direction of motion and the total energy is also given by the relativistic equation.But in all equations velocity of light is replaced by velocity of sound. Velocity of elastic waves is the limiting velocity for mechanical displacements in solids. Mott (16) found that the velocity of a crack in solids should asymtotically approach a terminal velocity. Kobayashi et al (17) eksperimentally demonstrated that cracks in amorphous brittle materials always travel at velocities smaller than the Rayleigh wave speed. Yoffe (18) showed that stresses in the neighborhood of the crack adopt a universal form near the tip, and this universal singularity contracts in the direction of motion as the cracks approach the speed of sound and that at around 60% of the Rayleigh wave speed a crack should become unstable, since the maximum tensile stress would no longer be directly ahead of the crack, but would instead be off at an angle. Crack tip instabilities have been discussed recently by Marder and Gross (19) and Marder and Fineberg (20).The energy needed to form a new crack surface increases drastically (Green and Pratt (21)), the velocity of cracks begins to oscillate (Fineberg et al (22)) and the fracture surface shows periodic structure as the velocity of a crack approaches some characteristic limiting velocity. It has been also observed that effective surface energy (Rose(23)), stress intensity factor (Dally et al (24),Knauss and Ravi-Chandar (25)), dynamic fracture toughness (Kanazawa et al (26),Rosakis and Zehnder (27)) also increase sharply as the limiting speed is approached.

All the above mentioned as well as the experimental evidence on the increase of the weight of oriented polymers as a result of fracture (Kerch (28)) underpines the conception that the ideas and the results of special relativity should be applied to describe the mechanical displacements in solids taking into account that the value of the limiting velocity is equal to the velocity of elastic waves or to the velocity of fracture wavefront propagation. One can consider the velocity of sound, as well as velocity of light or any other characteristic velocity, as a limiting velocity.Energy and inertia of kinetic elements of any system increase in the neighbourhood of the limiting velocity irrespective of its value and coefficient of proportionality between energy and inertia must be equal to squared limiting velocity. We can suggest that instabilities occur when velocity of kinetic elements on microscopic or mesoscopic level of the system approaches its limiting value and that systems may run through a hierarchy of instabilities and accompanying structures characterized by different limiting velocities. In other words, instabilities on macroscopic level can be explained by relativistic phenomena on mesoscopic or microscopic level.

CONCLUSIONS

The realization of the significance of the limiting velocity and relativistic ideas about interrelation between energy and inertia of the processes and their sharp increase in the neighbourhood of the limiting velocity gives the opportunity to develop a new approach to the consideration of mechanical deformation and fracture of solids. Combination of the relativistic ideas with the theory of complex systems opens new ways to the investigations of instabilities.

REFERENCES

(1) Kausch,H-H., "Polymer Fracture", Springer-Verlag, Berlin, 1987.

(2) Kerch,G. and Karlsone,G., Dokl. Akad. Nauk SSSR, Vol.252, 1980, pp.1115-1116.

(3) Nicolis,G. and Prigogine, I., "Exploring Complexity.An Introduction",W.H.Freeman and Co, New York, 1989.

(4) Prigogine,I. and Stengers,I.,"Order Out of Chaos",Heinemann,London,1984.

(5) Umov,N.,"Selected Works",Gosizdat,Moscow,1950.

(6) Berzi,V.and Gorini,V.,J.Math.Phys.,Vol.10,1969,pp.1518-1524.

(7) Terletskii,Y.,"Paradoxes in the Theory of Relativity",Plenum,New York,1968.

(8) Rindler,W.,"Essential Relativity",Springer-Verlag,New York,1979.

(9) Levy-Leblond,J-M.,Am.J.Phys.,Vol.44,1976,pp.271-277.

(10) Shepanski,J. and Simons,R.,Am.J.Phys.,Vol.40,1972,pp.486-487.

(11) Kaiser,A.,Am.J.Phys.,Vol.37,1969,pp.216-217.

(12) Gonzalez Gascon,F.,Il Nuovo Cimento,Vol.41B,1977,pp.317-326.

(13) Frenkel,J.,"Vvedenie v teoriju metalov",Nauka,Leningrad,1972.

(14) Frank,F.,Proc.Phys.Soc.,Vol.62A,1949,pp.131-134.

(15) Eshelby,J.,Proc.Phys.Soc.,Vol.62A,1949,pp.307-314.

(16) Mott,N.,Engineering,Vol.165,1947,pp.16-18.

(17) Kobayashi,A.,Ohtani,N. and Sato,T.,J.Appl.Pol.Sci.,Vol.18,1974,pp.1625-1638.

(18) Yoffe,E.,Phil.Mag.,Vol.42,1951,739-750.

(19) Marder,M. and Gross,S.,J.Mech.Phys.Solids,Vol.43,1995,pp.1-48.

(20) Marder,M. and Fineberg,J.,Physics Today,1996,N9,pp.24-29.

(21) Green,A. and Pratt,P.,Eng.Fracture Mech.,Vol.6,1974,pp.71-80.

(22) Fineberg,J.,Gross,S.,Marder,M. and Swinney,H.,Phys.Rev.,Vol.B45,1992, pp. 5146-5154

(23) Rose,L.,Int.J.Fracture,Vol.12,1976,pp.799-813.

(24) Dally,J.,Fourney,W. and Irwin G.,Int.J.Fracture,Vol.27,1985,pp.159-168.

(25) Knauss,W. and Ravi-Chandar,K.,Int.J.Fracture,Vol.27,1985,pp.127-143.

(26) Kanazawa,T.,Machida,S.,Teramoto,T. and Yochinari,H.,Exp.Mech.,Vol.21,1981, pp.76-88.

(27) Rosakis,A. and Zehnder,A.,Int.J.Fracture,Vol.27,1985,pp.169-186.

(28) Kerch,G.,Int.J.Fracture,Vol.83,1997, pp.L33-L34.

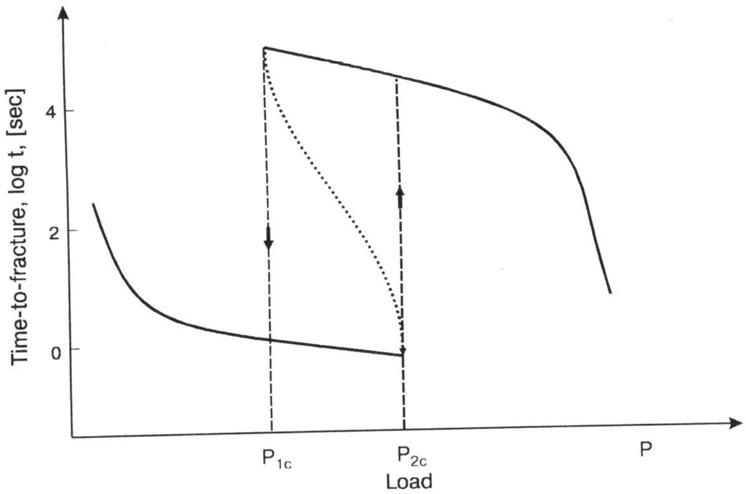

Figure 1 Bifurcation diagram of the fracture of poly(vinyl alcohol) fibers