INSTABILITIES IN FRACTURE AND DEFORMATION OF POLYMER MATERIALS.

G.M.KERCH

Centre of Science and Engineering EKOTRA,
Nicgales str.4-235, Riga,LV-1035, Latvia

ABSTRACT

Relativistic phenomena can play the important role in 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 was considered and the relationship between structure, value and sign of the thermal expansion coefficient on the one hand and weight changes of polymers during the process of fracture on the other hand was discussed. Instabilities and anomalous mechanical behaviour in the vicinity of limiting velocity have been considered. The use of relativistic approach on microscopic level to model material behaviour was illustrated.

INTRODUCTION

It has been shown previously that motion of crystal dislocations during plastic deformation and propagation of cracks during the process of fracture demonstrate a number of particularities which cannot be understood from the viewpoint of classic theories of fracture and deformation. Equations of motion of crystal dislocations can be brought into a form analogous to those of a particle in special relativity [1-3]. 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 [4] found that the velocity of a crack in solids should asymptotically approach a terminal velocity. This velocity is governed by the supply of kinetic energy to the crack field. It has been shown recently [5] that comparatively large weight changes of viscose fibers as a result of fracture can be observed due to relativistic reasons.
The purpose of this paper is to demonstrate the role of finite limiting velocity in the processes of deformation and fracture of polymers.

RESULTS AND DISCUSSION

Relativistic approach

Derivations of Lorentz transformations that dispense with postulate of the invariance of speed of the light are known for a long time [6-9] and underline a general character of special relativity as a universal theory describing the structure of space-time [10]. The apparently ad hoc and privileged selection of a specific physical process of the light-signal propagation as a fundamental phenomenon underpinning 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 relativity principle and some specific experimental observation such as the law of light propagation.
Consequently the acceptance of the relativity principle must necessarily lead to the manifestation of relativistic effects in solids and velocity of elastic waves should be considered as the limiting velocity for mechanical displacements. So the analysis of the motion of kinetic units on microscopic and mesoscopic levels in such systems as solids could give the key to understanding of a number of anomalous from the current point of view phenomena during the processes of deformation and fracture.
The important result discovered by modern physics is that any motion proceeds in Minkowski space-time and it is evident that for mechanical displacements of the elements of solids and fluids (dislocations,segments of macromolecules…) the limiting velocity differs considerably from velocity of electromagnetic waves in vacuum. As a consequence, if one takes into consideration that motion proceeds in Minkowski space-time, where limiting velocity is not as high as velocity of light, the drastic change of mechanical characteristics in the vicinity of critical velocity becomes predictable phenomenon.

Experimental evidence

Kobayashi et al [11] experimentally demonstrated that cracks in amorphous brittle materials always travel at velocities smaller than the Rayleigh wave speed. Relativistic effects have been observed in a number of works [5,12-21] dealing with dynamical fracture. Yoffe [12] 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[13] and Marder and Fineberg [14]. The energy needed to form a new crack surface increases drastically [15] , the velocity of cracks begins to oscillate [16] and the fracture surface shows periodic structure as the velocity of a crack approaches some characteristic limiting velocity. It has been observed that effective surface energy [17], stress intensity factor [18,19] , dynamic fracture toughness [20,21] also increase sharply as the limiting speed is approached.

Weight changes

If an amount of energy ΔU be given to a body, the inertial mass of the body increases by an amount $\Delta U / c^2$.
It was found that inertia is not a fundamental property of matter but a property of energy. In the case if ΔU is internal energy changes of a solid the c should be equal to velocity of sound. So comparatively large changes of the weight of polymers are expected to be observed under the comparatively small changes of internal energy.
Experimentally measured weight changes after fracture of polyethylene and poly(vinyl chloride) samples vary from $1x10^{-6}$ kg to $4x10^{-6}$ kg [10]. The value of weight changes is too high to be attributed to the absorption or desorption of gases or to other experimental errors. One can calculate from the internal energy changes $\Delta U = \Delta mc^2$,which vary between -0.5 and 2.0 Joules. These values are consistent with experimental data reported by Godovsky.[22] if c is velocity of elastic waves.
It has been shown [23] that negative linear thermal expansion coefficient and evolution of heat under stretching of an oriented polyethylene may be associated with crystalline structure characterized by c-axis orientation of crystallites and positive linear thermal expansion coefficient and absorption of heat under stretching of an oriented polyethylene may be associated with crystalline structure characterized by a-axis orientation of crystallites.
So one can expect positive weight changes as a result of fracture for oriented polymers with negative linear thermal expansion coefficient and weight losses for polymers with positive linear thermal expansion coefficient.

Instabilities in deformation and fracture

It has been shown by Mott that the balance of energy should contain not only the terms relating to available elastic energy and surface tension (with or without the addition due to the plastic work factor) but also that due to the kinetic energy of the material disturbed by the progressing crack. The influence of stress waves

appears to be to limit the volume of material to which kinetic energy must be supplied, rather than to modify the stress distribution from the static values about the crack.
As a matter of fact the question in dynamic fracture mechanics why energy consumption should rise abruptly past a critical threshold or why when energy flux to the crack tip exceeded a threshold, the velocity stopped increasing, is formulated inaccurately.
When velocity of kinetic unit V approaches limiting velocity c the changes of energy E in localised region of material are described by equation

$$E = E_0 / (1 - V^2/c^2)^{1/2}$$

The inability during the short periods of time in localised regions to convert kinetic energy into heat or into internal energy of material causes sudden transitions from one state to another and instabilities in processes of deformation and fracture are observed due to redistribution of energy in the whole volume of material.
All above consideration is qualitative: we have not made attemts to predict precisely the shapes of experimental curves and to calculate exactly the numerical coefficients involved. Our aim is only to draw attention to the possibility that new effects may show up in some measurements in the vicinity of critical velocities.
Localised necking in elastic-plastic bodies under tensile loading is a failure mechanism that is frequently observed in various metal forming processes. Necking of polymers is another example of instability during the process of deformation. Localisation of strain is accompanied by abrupt transition from unoriented to oriented state of macromolecules in crystalline and amorphous regions of polymers. Under the idealized loading conditions instability of the primary mode of deformation is usually associated with bifurcation from the fundamental equilibrium path to a secondary equilibrium path. Evidently that in this case the limiting velocity is determined by the values of relaxation times and characteristic dimensions of the regions where strain is localised. Sharp transition is observed when velocity of deformation approaches the limiting velocity. Local jumps of temperature are the consequences of energy fluctuations in the vicinity of limiting velocity. The value of limiting velocity in this case is very low as compared with velocity of elastic waves. It is very important to ephasize that localisation of plastic deformation takes place not after the maximum load has been passed but when velocities of kinetic units on microscopic level of structure approach some limiting value.
Experimental data on the fracture of highly oriented poly(vinyl alcohol) (PVA) fibres during heat treatment show the anomalous behaviour of the values of the time-to-fracture of PVA fibres in the temperature range 210 – 230 ^{0}C [24]. For example, the increase of the mechanical load from 0.5 g/fiber up to 20 g/fiber leads to deacrease of the value of time-to-fracture from 39 seconds to less than 1 second. But further increase of mechanical load till 25 g/fiber drastically increases the time-to-fracture till more than 10^4 seconds. So the unusual phenomenon of sharp increase of the time-to- fracture with the increasing of mechanical load was observed. The bifurcation in values of the time-to-fracture can be attributed to the joint impact of mechanical load and chemical reactions of intermolecular and intramolecular crosslinking on the microstructure of PVA fibres.

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 neighborhood of the limiting velocity gives the opportunity to develop a new approach to consideration of mechanical deformation and fracture of solids. Manifestation of relativistic effects is more pronounced in polymers which are characterized by the great value of thermal expansion coefficient and comparatively low value of the velocity of elastic waves. The anomalous behaviour of PVA fibres during the process of fracture can be attributed to instabilities arising in the transition region when velocities of physical transformations approach their limiting velocity. Instabilities during deformation arise not after the maximum stress or strain has been passed but rather when velocity of mechanical displacements of kinetic units on microscopic level approaches some critical value.

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