POLYMER VISCOELASTICITY AND FATIGUE ENDURANCE

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MIL-A-83444 specification requirements on damage tolerance design limits flaw sizes at any feature considered as critical. Local conditions of importance include stress, fretting, surface condition and environmental conditions such as heat and chemical ones. The development of polymeric simple and composite materials has enhanced the local endurance. Correlations between fatigue endurance and polymer viscoelasticity become of primary importance. Some grounds for a broader project are here outlined.

1. INTRODUCTION

Lord Rutherford is credited with the statement that all science is either stamp-collecting or physics.

A considerable work on fatigue and failure seems to fall into the above referred first category. The collection having been particularly extensive in certain domains, some people have yielded to the temptation of embedding it into a statistical distribution.

Correlation of elastic, viscous and plastic material features with body life behaviour remains the main physical scope and so looks to belong to the second category.

2. AGEING, FATIGUE AND RELIABILITY

Polymeric materials are specially prone to ageing, i.e. to a slow, irreversible process, characterized by the decay of the values of certain physical responses.

Chemical action like oxydation, physical degradati-

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on like radiation effects, mechanical inputs like abrasion, flexure, torsion are common, recognizable causes of ageing of polymeric bodies.

Ageing and failure have a similar connection as fatigue and failure and so ageing and fatigue are often identified. Nevertheless, ageing is more specifically assigned to stochastic, not constrained stresses or inputs. Fatigue, on the other hand, is specifically assigned to designed inputs, namely artificial, accelerated ageing. The most popular fatigue is mechanical fatigue, but chemical fatigue appears often associated to it and careful isolation or control must be made.

Reliability is often evaluated through fatigue such as mechanical, thermal, environmental.

3. STATIC AND DYNAMIC FATIGUE

Accelerated artificial ageing i.e. fatigue can be induced either by stationary or by varying applied inputs. The most popular stationary fatigue is static fatigue, the most common varying one is harmonic fatigue.

Static fatigue, in the broad sense, includes the quasi-static tensile behaviour. Static fatigue times depend on the size of the applied stress. There is a maximum stress value, fatigue limit, that a body may sustain without the appearance of rupture or of appreciable development of flaws, i.e. without catastrophic failure on a practical infinite time.

Above the fatigue limit, stresses may induce creep and failure on a finite time. Following Griffith's hypothesis [6] , we admit that all engineering components contain microdefects that eventually evolve to cracks and crazes. In polymers, we have in general observed pores of about 1 nm size with the scanning electron microscope.

It may be asserted that every polymeric material contains flaws as weakness points, due to heterogeneities on composition and stereostucture. Because of the presence of sharp corners, nicks, cuts, scratches and embedded particles or other inclusions, applied stresses become magnified or concentrated in certain regions of the polymeric material, so greatly exceeding the main applied stress.

Fracture will begin at such stress concentrators where the local stress exceeds a critical level and the flaw starts then to grow as a crack. The exact nature of these failure sites is very difficult to ascertain. They may even consist of accidental damage in molded or cut surfaces. Great care must so be taken in preparing the test pieces, by molding against polished glass surfaces.

If a way could be found to eliminate the referred stress raisers, substantial increases in strength and in fatigue life might be achieved. At present, those stress concentrators appear to be a inevitable consequence of the manufacturing processes employed for obtaining polymeric compounds and components.

Dynamic fatigue favours the development of macrofailures and can be facilitated by notching, that is often used in polymers to facilitate heat dissipation due to viscosity effects [9] . According to Mark [7] , irreversible gliding precedes cracking and crazing, the gliding corresponding to the rupture of secondary bonds, like Van der Waals and hydrogen bonds.

Besides the rupture of secondary bonds, we have observed, on the scanning electron microscope, that textile and composite materials fibrillation can easily induce the development of cavities through covalent bond, primary bond rupture.

4. AMORPHOUS AND CRYSTALLINE POLYMERIC RESPONSE

For amorphous, typically viscoelastic polymers, crack propagates with a rate depending on two principal factors. the strain energy release and the temperature. The strain energy release, G represents the rate at which strain energy is converted into fracture energy as the crack advances. It may be defined in terms of the total strain energy, W and the evolving surface, A, by

$$G = -2 \, \partial W / \partial A \qquad (4.1)$$

For a tensile strip with an edge cut of depth l,

$$G = 2 \, l \, W' \qquad (4.2)$$

W' being the stored strain energy.

The energy G is high at high rates of stressing and at low temperatures, due to the freezing viscous components of the amorphous, viscoelastic polymeric material. It is approximately identical for all unfilled amorphous elastomers under conditions of equal segmental mobility, what means that G is strongly correlated with the viscoelastic behaviour, not so with the chemical particulars.

Crystalline and semicrystalline polymers such as fibres present a greater tearing and fatigue resistance, compared to amorphous polymers. The conclusion is easily experimentally verified for e.g. polydienic elastomers like natural rubber, that crystallize through stretching on a reversible way due to entropic elasticity. This crystalline organization needs a certain relaxation time and can eventually be concealed by low temperature or high rates of stressing.

The fatigue enhancement can be attained also by reinforcing amorphous elastomers with fine particles like carbon black and the response is also conditioned by appropriate relaxation times of applied stress inputs.

Amorphous elastomers fatigue is controlled by the available strain energy for fracture G. Strain-crystallizing elastomers do not tear continuously under small values of G, no cut growth occurring below a certain boundary G_o, except by chemical, oxygen and ozone attack, combined with the environmental temperature. It has been found that the cut growth, Δl is proportional to G^2,

$$\Delta l \quad \propto \quad G^2 \qquad (4.3)$$

5. COMPOSITE MATERIALS

Composites are inhomogeneous and anisotropic, accumulating damage in a general rather than localised form. Textiles and e.g. aircraft structural composites as well can be unidirectional and their loading may result in the fracture of the weaker fibres, followed by later fracture of the stronger ones.

In a composite with strong, stiff fibres in a soft, ductile matrix, fatigue will be fibre controlled because fibres will probably not be broken, whereas in a composite with a strong work-hardening matrix, crack-tip stress concentrations can easily exceed fibre strength and fatigue cracking is then matrix controlled.

The response of a composite is an important example of mechanical accomodation, Frias [4]. Plasticity yield boundaries are amplified through polymeric components and work-hardening effects are strongly favoured also.

In randomly distributed fibre composites, fibre-matrix interfaces are randomly affected, more or less uniformly throughout the material. In glass/polyester laminates, for instance, the bond response manifests macroscopically by a uniform whitening due to the development of randomly distributed light scattering interfaces.

Under cyclic loading, most composites sustain damage through the above referred plastic distributed response, so that eventual strength and stiffness reductions may be offset by local increases of strength and stiffness due to the fibre rearrangement induced by viscoelastic creep response of the material matrices.

Graphite/epoxy composites are one example of successful improvement in fatigue life of critical structures like aircraft ones [8]. The apparent superiority of composite components in comparision to mettalic ones is nevertheless strongly dependent on temperature and relative humidity and so extensive environmental research is needed.

6. A LABORATORY EXAMPLE

As a simple example, we have applied to two elastomeric tensile test strips, representing x and y batches of supply, respectively, a static tensile strength of 1000 newtons, the strips having been carefully prepared in order to avoid any surface scratches, as previously stressed.

We have further on observed the stress decay and obtained, respectively, for times in minutes up to 1000 minutes, the following values

minutes	newtons x	newtons y
0	1000	1000
1	920	960
10	785	950
100	675	920
1000	585	920

x behaved appreciably viscoelastically and y practically not. Correlation with abrasion and fatigue revealed as expected a superiority of the x batch over the y batch. Further investigation has shown that y batch had suffered a mechanical decay in properties due to bad temperature control during the production process.

7. CONCLUSIONS

A few years ago, American Chemical Society Polymer Preprints, 12,52,1971 published a paper signed by R.P. Kambour in which it was stated that fatigue in polymers is one unsolved problem of science. This picture has meanwhile changed, but a lot remain to be done to clarify many aspects.

The incomplete approach of polymeric science by the chemists, on one side, and a perhaps too quick extension of doctrine of metal fatigue to polymeric materials, on the other side, are responsible for the state of art on polymers and fatigue.

The fatigue crack propagation being an important subject in itself, reliability and safety problems have directed us more to fatigue endurance, i.e. to the approach to pre-yielding boundary surfaces, on which a fundamental research program has to be developed.

SYMBOLS

A = surface area
G = strain energy release
l = cut depth
T = temperature
W = total strain energy
W' = stored strain energy

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