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Review

Observations on the role of fracture mechanics in biology and medicine

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ABSTRACT

Fracture mechanics has been of great benefit in the fields of biology and medicine. Biological materials have low fracture toughness and often fail by cracking, so the knowledge which has been developed for engineering materials can usefully be applied to study the failure of bone, cartilage and many other natural materials. Medical devices such as artificial joints and stents experience complex failure modes owing to their interactions with the human body: materials science and fracture mechanics experts have played an important role in the development and validation of new materials for these applications. It is also true that the fields of biology and medicine have been very good for fracture mechanics, presenting us with new and interesting challenges such as the inclusion of repair processes in theoretical models of fracture. This article describes some examples of work in this area, including the development of low modulus titanium alloys, the application of fracture concepts to study human bone and the wide range of biological materials which Nature has evolved for load-bearing applications.

1. Introduction

As Engineering Fracture Mechanics celebrates its 50th birthday, I myself have completed 40 years of research in this field. I started as a PhD student in John Knott's research group in 1977 and spent five years working on the fracture mechanics of fatigue in various metallic materials. It was an exciting time: John was already recognised as a world leader in a field which was advancing rapidly. At that time there were many issues in fracture mechanics which were of fundamental importance and which were hotly debated, issues such as the significance of crack closure in fatigue, the anomalous behaviour of short cracks and the use of the J integral to characterise toughness. Conferences in those days were exciting affairs, as different paradigms were proposed and discussed in a robust manner. Progress was rapid, with new results and theories coming out all the time.

During the 1980s, the rate of progress tended to cool off, at least in my opinion and that of many of my colleagues in the field. It seemed that some problems had been solved, whilst others seemed incapable of solution, at least with the tools we had available. This is very typical: all scientific fields experience periods of rapid development followed by periods of relative dormancy. A field such as ours, though it involves aspects of fundamental science, is essentially driven by the needs of industry, and by the end of the 1980s it seemed to me that the major industries were satisfied that they could predict fatigue and fracture in their components accurately enough, with the models we were giving them, so there was no great appetite for investment in further research.

Many colleagues left the field at that time to pursue research in other fields. Others, such as myself, continued to work on mainstream aspects of fracture mechanics (in my case notches in fatigue and brittle fracture) whilst also trying to diversify by looking for other areas in which an understanding of fracture mechanics could be useful. One such area, which for me turned out to be very fruitful, was biology and medicine. I began by working with medical companies, and surgeons in local hospitals, to identify durability

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problems with products such as prostheses, implants and surgical instruments. I was surprised to find that, despite the high level of technology involved, designers in these companies had relatively little understanding of fatigue and fracture issues and worked with very limited test data for their materials and products. Materials which had been chosen on rather arbitrary grounds, many being derived from the aerospace industry, were adopted with little attempt to optimise their performance or modify them for use in the human body. These issues remain to some extent even today, but great improvements have been made in the development of new materials, a subject which I will return to later in this article, taking the example of new titanium alloys for medical devices.

For me the journey continued farther. Having begun by working on devices designed to replace parts of the human body, such as hip joint implants, I became interested in the original human body materials themselves, such as bone, cartilage and other tissues. It took me some time to realise the obvious fact that these materials almost invariably fail by cracking. Low fracture toughness and the relatively easy propagation of fatigue cracks are crucial factors affecting the durability of the materials that make up our bodies. I found that my background in fatigue mechanisms, especially the behaviour of short cracks, was very useful in understanding the durability of bone. To some extent, the approaches we had developed for engineering materials could be usefully applied, but there were some important differences. Bone is a living material, capable of growing and changing in a dynamic way and able to respond to its mechanical environment. Understanding this, and devising ways to modify fracture mechanics approaches to take account of it, has been a challenge and an enduring fascination for me. I will discuss this in more detail later in this article.

In recent years, my work has moved towards fundamental aspects of fracture and repair in a wide range of biological materials. Looking around, I realised that the issues faced by human body materials are also encountered by structural materials in many different organisms, such as insects, marine creatures and plants. Though my work addresses the basic science in this area, possible applications of the results are many, especially in the field of biomimetics. This area is wide open, in the sense that very few fracture mechanics experts are addressing it. Below I will give a flavour of some recent work and future directions in this field.

2. Novel titanium alloys for biomedical applications

Medical devices, especially structural components such as fracture plates and orthopaedic implants, are often heavily loaded, so the designer has little option but to use a metallic material, despite the potential incompatibilities involved in placing metals inside the human body. Initially, the alloys chosen for biomedical devices tended to be those developed for aerospace and related applications, such as cobalt/chromium alloys, stainless steels and titanium and its alloys. These had the obvious advantage of a relative inertness – though it has emerged that none of these metals is totally inert in the body – combined with good strength, toughness and fatigue resistance. But over the last two decades or so there has been a strong effort to create entirely new alloys specifically with biomedical applications in mind. The very unique challenges involved, along with the prevalence of funding for medical research in many countries, has attracted metallurgists and fracture mechanics specialists to this field.

Metals may react chemically with the body – for example they may be toxic or they may corrode in contact with body fluids. For example, the well-known titanium alloy Ti-6Al-4V is widely used for orthopaedic implants. In the past there was concern over the use of aluminium and vanadium, especially aluminium which had been linked to Alzheimer's disease [1], though the current consensus is that this link does not exist. This led, for example, to the development of Ti-Nb alloys which appear to be more biocompatible and can be realised in forms which have good mechanical properties (e.g. [2]). But metals can also be incompatible from a mechanical point of view. Niinomi has made a study of this effect, coining the phrase "mechanical biocompatibility" [3]. In particular, a problem arises owing to the relatively high Young's modulus values of metallic materials, compared to that of human bone, which lies in the range 15–20 GPa. When two materials of different moduli are fastened together and loaded, the stiffer material tends to experience more stress than the less stiff material. The result, for a bone replacement device such as artificial hip joint, is that the bone close to the implant experiences less stress than normal, an effect known as "stress shielding" [4,5]. Bone is very sensitive to stress and will remodel over time, tending to become thicker and stronger if the stress is increased, and conversely to resorb if the stress is too low, so significant bone loss may occur as a result of stress shielding near the implant (see Fig. 1), eventually leading to loosening and failure of the device. This effect tends to be greater in older people, whose bones dissolve away remarkably quickly if they are not sufficiently loaded.

One possible way to avoid this problem is to use materials with lower Young's moduli, closer to that of bone. Mechanically this is not the ideal solution that it might seem to be, because if the moduli are perfectly matched, high shear strains can arise at the interface between the metal and the bone, leading to micromotions and ultimately to loosening due to formation of a soft, fibrous tissue layer (Fig. 1). Also, materials with lower Young's modulus tend to have lower strength and lower toughness as well (though there are exceptions to this rule); however the stresses to which these components are subjected are relatively modest, compared to the stressing of aerospace or automotive components, for example. Ti-6Al-4V, when used in an orthopaedic implant, is probably operating with a safety factor of more than 10, so some loss of strength can be tolerated. Therefore the challenge for metallurgists has been to devise alloy combinations which have reduced modulus whilst retaining sufficient strength and durability. A wide range of solutions have emerged, including some very novel and complex combinations of alloying elements, as well as other options such as deliberately introducing porosity to reduce stiffness. Researchers have taken advantage of new approaches in the field of alloy development which allow systematic examination of a wide range of possible compositions, for example using the combinatorial approach, creating microscopic samples by laser deposition [6].

One particularly interesting approach has been to find alloy combinations which stabilise the β phase of titanium, because this body-centred-cubic phase has a significantly lower modulus than the normal room-temperature α phase. In theory, Young's modulus values lower than 40 GPa can be achieved in the β phase, at least in certain crystallographic directions. Values around 50–55 GPa have been achieved with some alloys, and further reduced by extensive cold rolling [3]. However most of the practical alloys have