Introduction

One contribution of 19 to a theme issue ‘Fracturing across the multi-scales of diverse materials’.

Subject Areas:
materials science, mechanical engineering, mechanics

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Fracturing across the multi-scales of diverse materials

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Everyone has to deal with fracturing of materials at one level or another, beginning from normal household chores and extending to the largest scale of observations reported for catastrophic events occurring on a geological level or even expanded to events in outer space. Such wide perspective is introduced in the current introduction of this theme issue. The follow-on organization of technical articles provides a flavour of the range in size scales at which fracturing occurs in a wide diversity of materials—from ‘fracking’ oil extraction and earth moving to laboratory testing of rock material and extending to the cracking of tooth enamel. Of important scientific interest are observations made and analysed at the smallest dimensions corresponding to the mechanisms by which fracture is either enhanced or hindered by permanent deformation or other processes. Such events are irrevocably linked to the atomic structure in all engineering materials, a sampling of which is presented, including results for crystalline and amorphous materials. Hooray for the broad subject description that is hoped to be appealing to the interested reader.

The root of the word ‘fracture’ comes from the Latin verb ‘frango’—‘I break’; following the sequence ‘frango, frangere, fregi, fractum’ we have the words ‘frangible’, ‘fragile’ and, of course, ‘fracture’. Fracture processes in a wide range of materials play a much larger role in everyday life than is commonly appreciated. In the home, we encounter fracture, not just when we drop glasses or crockery onto hard floors, or when a misdirected cricket
ball smashes a window, but every time we tear off a sheet of aluminium foil or ‘cling-film’; every

time we chop meat, peel vegetables, crack nuts, open sealed envelopes or packages, have our

hair cut, shave or trim our nails. Fractures in the wider world outside can be life-enhancing or

events that cause great consternation. Aesthetic examples of the former are associated with the

sculptures or wood-carvings that adorn our public places, civic and ecclesiastical buildings. Take,

for example, Michelangelo’s ‘David’ (Florence 1501–1504). The production of this masterpiece

involved fractures at two scales. First, a large slab of (Carrara) marble had to be quarried; second,

Michelangelo had to produce a myriad of small brittle fractures in the marble slab to sculpt the

finished form.

The quarrying of stone or the felling of trees is an essential pre-cursor to the craftsman

producing final shapes by means of many small fractures. The craftsman also has to have

confidence in the starting material: the stone must not contain internal cracks or pores that cause

ugly cavities to be revealed, or lumps to break off, during the sculpting process; the wood must

not contain knot-holes or the like that disfigure the final carving. A jeweller must take especial care

when cleaving a raw diamond en route to producing a gemstone. In more utilitarian applications,

the sawing of timber represents another common set of fractures and, in more general mechanical

engineering applications, the machining of screw-threads into nuts, bolts and screws represents

millions upon millions of ductile fractures. One of the most dramatic examples concerns the

fracture of eggshells. We all know that ‘You can’t make an omelet without breaking eggs’, and,

whether as omelets, boiled, fried, scrambled or in a cake mix, something of the order of a billion

eggs are fractured and eaten every day. But the real purpose of an eggshell is to provide nurture

and protection for bird chicks and for the young of some other species, such as turtles, alligators

and the duck-billed platypus. All have to begin independent life by fracturing the eggshell from

within. We ourselves begin independent life by the fracture (‘severing’) of the umbilical cord.

Fracture is ubiquitous and essential to life. Yet the downside of fracture is that a number of

the structures and machines upon which we rely so heavily for our well-being and comfortable

lifestyles have, from time to time, fractured unexpectedly, causing great upheaval and, often, loss

of life.

Among the more widely known historical fracturing events have been wire cable breakages in

mine shafts; failure of Liberty ships and Comet airplanes; collapse of the Johnstown, PA, dam

and other assorted highway and rail bridges; and, most recently, the 9–11 skyscraper impact

failures and the tsunami-induced catastrophe at Fukushima. And these civilian examples are

overwhelmed in number by those caused as a result of military actions. Individual curiosities

about why things should break have come a long way in the scientific and engineering

communities. In the same way that the craftsman has to be aware of possible defects in a slab

of marble or piece of wood, the engineer has to be aware that a fabricated structure may contain

defects. A marked advance over the last 50–60 years has been the development of quantitative

means of treating these defects: the engineering science of fracture mechanics. In turn, the

properties of the materials depend on their microstructures and deformation mechanisms at the

microscopic scale, and, for any fracture to occur, there must be mechanisms by which atomic

bonds break. Events occur at different scales.

An early example of the probabilistic nature of fracture is found in Leonardo Da Vinci’s work

on the strength of iron wire (ca 1487) in which he found that the strength depended upon the

length of the wire. These results have been interpreted as being due to the increased probability

of finding a critical defect the longer the wire. The method of making wire in the Middle Ages was

particularly prone to defects as were methods for obtaining the basic materials. Da Vinci’s results

may be regarded as the forerunner of probabilistic fracture mechanics. Materials, test methods

and analytical approaches have greatly improved. However, the so-called ‘size effect’ in fatigue

of nickel-base superalloys used in jet engine discs is a well-known phenomenon linking back to

Da Vinci’s experiments. The reduction in fatigue life is explained as being due to larger specimens

having a higher probability of containing a defect which causes early crack nucleation.

For the current theme issue, we draw inspiration from one of the early Fellows of the Royal

Society: Robert Hooke. Hooke had many interests, but in the field of structural engineering,
these ranged from the very large scale to the microscopic scale [1]. In his collaboration with Christopher Wren on the re-building of St Paul’s Cathedral, he made a major contribution at the macroscopic scale, by suggesting that the dome should take the form of a ‘cubico-parabolical conoid’. In Hooke’s words (translated from his cipher) ‘ut pendet continuum flexile sic stabit grund Rigidum’ [2] (see also Lisa Jardine’s biography of Wren ‘On a Grander Scale’). Hooke was also aware of the fracture of brittle building materials and he made painstaking observations of the fracture surfaces of the oolitic limestone to be used for St Paul’s, using a microscope, but taking sequential focus positions, so that he was able to produce ‘three-dimensional’ representations in his seventeenth century Micrographia publication as shown on the theme issue cover page. From ‘The Grander Scale’ to the microscopic scale!

Hull has researched Hooke’s work on this topic and obtained interesting information at the time on use of the material for building construction in Cambridge and on wider interest in fracturing [3]. Only one century later, Reaumur was to comment from observation of fracture surfaces that excellent steels were distinguished from mediocre steels according to the fineness of their grains [4]. This was some 130 years before the Bessemer steelmaking process came into being: Reaumur had his own process for making steel (for which he was awarded a prize by the French Government). Hull mentions even later nineteenth century interest of Sorby in geological materials [5]. Sorby became so absorbed in founding the microscopic examination of sectioned metal microstructures that he made the following comment [6]: ‘Compared with what can be learned from good sections, the study of mere fractures teaches very little respecting the ultimate structure because a fracture occurs along a line of weakness between the constituent grains, whilst a section shows the true relation and ultimate constitution of the constituent crystals’. In one sense, the difference is determined by what defect-free material condition should control the fracturing property when compared with what local defect condition did control the observed condition of failure. And for an example of modern fractographic analysis, one can quote James [7]: ‘The fracture surface contains a complete record of the events experienced by the component during fracture and the skill in fractography comes in understanding and interpreting those features in a clear description of causes and mechanisms involved in the cracking process’. Lynch & Moutsos [8] have given an important review of fractographic images dating back to observations made in the eighteenth century by Reaumur.

Armstrong has previously established modern connection with Reaumur’s observations relating to the influence of polycrystal grain size in initially defect-free material on determining the brittle fracturing behaviour of steels [9]. More recently, Knott produced a quantifying description of steel quality in his 2008 Hatfield Memorial Lecture [10]. Otherwise, the internal structural relationship of the mechanical properties of (mostly ionic) mineral versus those of metallic crystals had continued to be described in a common manner, for example, as contained in the seminal book produced in the first third of the twentieth century by Schmid & Boas [11]. Each subject then became so large and diversified that information on the two types of material behaviour have proceeded to develop essentially on their own. As mentioned earlier, one purpose of this theme issue is to contribute to ‘bridging the gap’.

Another purpose of this theme issue is to deal with the dimensional scale at which fracture-controlling events occur and are observable with modern atomic resolution capabilities. A recent review of observations made of hardness indentations put into various crystal, polycrystal, polyphase and amorphous material surfaces, often with associated cracking, has covered a smallest dimensional scale from 0.06–0.07 nm to approximately 1.0 mm [12]. The range in dimensional scale coincides with that observed for the internal organization of (crystal) grains in material structures, although cast heavy steel plate material is known to exhibit dendritic solidification heterogeneity on a scale of centimetres, comparable with the dimensions applicable to reinforced concrete and other larger scale engineering structures. But even for the further scaling up of real macro-engineering structures, it should be remembered that the same understanding of fracturing behaviour applies for the lower specified dimensional scale. A recent report [13] providing a thermal cycling explanation of cracking origin for the regolith covering the 54 km length of the chondritic asteroid Ida relied on the ‘Paris law’ whose development...
was motivated by the need to predict the fatigue crack growth rate in airframes \[14\].\(^1\) Even more recently, an account has been given of the widely witnessed explosive fracturing of the half-megaton asteroid at 45–40 km over Chelyabinsk \[15\], and deduced to have occurred at a dynamic (air) pressure in the range of 0.7–1.0 MPa. For contrast at opposite material and dimensional scales, the mechanisms determining resistance to fracturing of bone materials have been described recently at length scales ranging from the nano- to mesoscale in the hierarchical structure \[16\].

The theme issue begins with the physics and mechanics of fracturing at the largest dimensional scale. Great progress was made by Inglis \[17\] and Griffith \[18\] in the beginning of the twentieth century in taking account of the effect of pre-existing cracks on determining the fracture strength of steel and glass materials. Irwin and colleagues carried the work forward in the mid-twentieth century with the development of the subject of fracture mechanics \[19\]. Cherepanov \[20\], Rice \[21\], Atkinson & Eshelby \[22\] and colleagues have put fracture mechanics on a firm mathematical foundation. The dynamics of crack growth given by Mott \[23\] have been extended by Rabinovitch \[24\] employing the condition of crack length being larger than determined by the Griffith criterion. Frank & Lawn \[25\] provided a Griffith-based analysis of cone-cracking at indentations in glass materials and which analysis was rapidly extended to other indentation crack geometries \[12\].

Plastic flow considerations enter into both the nucleation of cracks and the nature of crack extensions, in the latter situation, no matter how brittle the material may appear to be. Thus, the crystal dislocation based plasticity theory co-invented just earlier in the twentieth century by Taylor \[26\], Orowan \[27\] and Polanyi \[28\] has been carried forward with important relevance to fracture, for example, in the work of Orowan \[29\], Petch \[30\], Cottrell \[31,32\], Crussard and co-workers \[33,34\], Yokobori \emph{et al} \[35\], Nabarro \[36\], Kochendörfer \emph{et al} \[37\], Friedel \emph{et al}\[38\] and Hirsch \emph{et al}\[39\], among many other colleagues. Current developments include such computational ‘code’ calculations as mesoscale cracking simulations to elucidate material deformation and cracking behaviours \[40\]. A recent example of simulated atomic-scale plasticity initiated at nanoscale holes in tantalum crystals is given by Tramontina \emph{et al}\[41\] for which a comparison is made of molecular dynamics results obtained using two different empirical lattice potentials.

The ubiquitous aspect of fracturing events and accompanying processes first mentioned covers a broader range of interest than could be contained in the present theme issue, even for the range in dimensional scale and diversity of materials that have been reported on. The omissions are regretted. In the current project, overlapping contributions were sought in a number of subject areas beginning with the issue of macroscale fracturing as put forward in the article by Cherepanov \[42\]. Related references \[43–46\] are added here to provide examples of complementary analyses extending from a latest report on fracking through mining technology to geophysical aspects of snow avalanching and cracking within glaciers.

Towards the ‘opposite’ crystal/polycrystal/nanopolycrystal level of size scale, coverage is provided by Antolovich \[47\], Armstrong \[48\], Hohenwarter & Pippan \[49\], Ovid’ko \[50\] and Pineau \[51\]. Emphasis is given by these authors to the importance of crystal/grain boundaries. Useful information on engineering of grain boundary structures is in \[52,53\]. Lower limiting dimensional considerations are described for atomic-scale fracturing by Brenner & Shenderova in the case of diamond \[54\] and by Rouxel for glass materials \[55\]. The jeweller’s cleavage of a diamond is analysed at the atomic scale. Atkinson \emph{et al}\[56\] report on the perceived construction of diamond lenses for historical eye-glasses as compared with Lodes \emph{et al}\[57\] reporting on the fracturing of smaller crystals in diamond foil. There is interesting local atomic order/amorphous material consideration in \[58\] and corresponding extension to amorphous material aspects of fracturing in \[59,60\].

\(^1\)Paris’ major contribution was to recognize that, independent of geometry, \(\Delta K\) provides a practical engineering forcing function for fatigue crack propagation. Some form of \(\text{d}a/\text{d}N\) versus \(\Delta K\) is now widely used for life prediction; however Paris’ considerable difficulties in gaining publication resulted in an unusual publication outlet!
The dynamics of fracturing at highest crack speeds are theoretically modelled at the atomic scale by Behn & Marder [61] and experimentally described for projectile impacts on glass materials by Chaudhri [62]; rather more sophisticated than a cricket ball smashing a glass window. Related theoretical analyses in the former case are in [63,64] and, for glass material, to essentially static hardness testing by Rouxel [55] and applied to hierarchical structural aspects of tooth enamel by Yilmaz et al. [65]. Other benefits of structural considerations dealing with experimental fractographic analyses, building onto Hull’s attribution to Hooke [3], are provided in [66,67], relating also to an exposition of ductile versus brittle fracturing considerations in the articles by Tekoglu et al. [68], Armstrong [48], Knott [69] and Matic et al. [70].

Early promotion of fracture mechanics aspects of the topic [19,71], including microstructural aspects [72], was carried forward in many research articles, for example, in [73]. Quite a few years earlier, Orowan [29] had remarked in pioneering work that fracturing is a mechanism-sensitive process, hence such added descriptions as ‘fatigue fracturing’, ‘creep fracturing’, etc. Such consideration applies to any number of different type observations made in the already referenced articles [42,49,50,53,59] and relates to other variable stress aspects of controlled fracture testing as exemplified in the articles by Atkinson et al. [74], Matic et al. [70] and Mughrabi [75].

And lastly, we co-editors mention our pleasure to have organized the current compilation of reports on fracturing, including those sub-topics, contained in this theme issue.

Acknowledgements. Appreciation is expressed to the authors for their diligence in providing the articles commissioned for the present theme issue. Special thanks go to the approximately two-times greater number of reviewers that have provided guidance to the authors. A grateful note of appreciation is owed to Bailey Fallon, Commissioning Editor, for providing very helpful guidance and advice to us at all stages of the project.

References

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