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Derek Hull
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Chapter 1 Introduction to the concepts used in the observation, measurement and interpretation of fracture surface topography

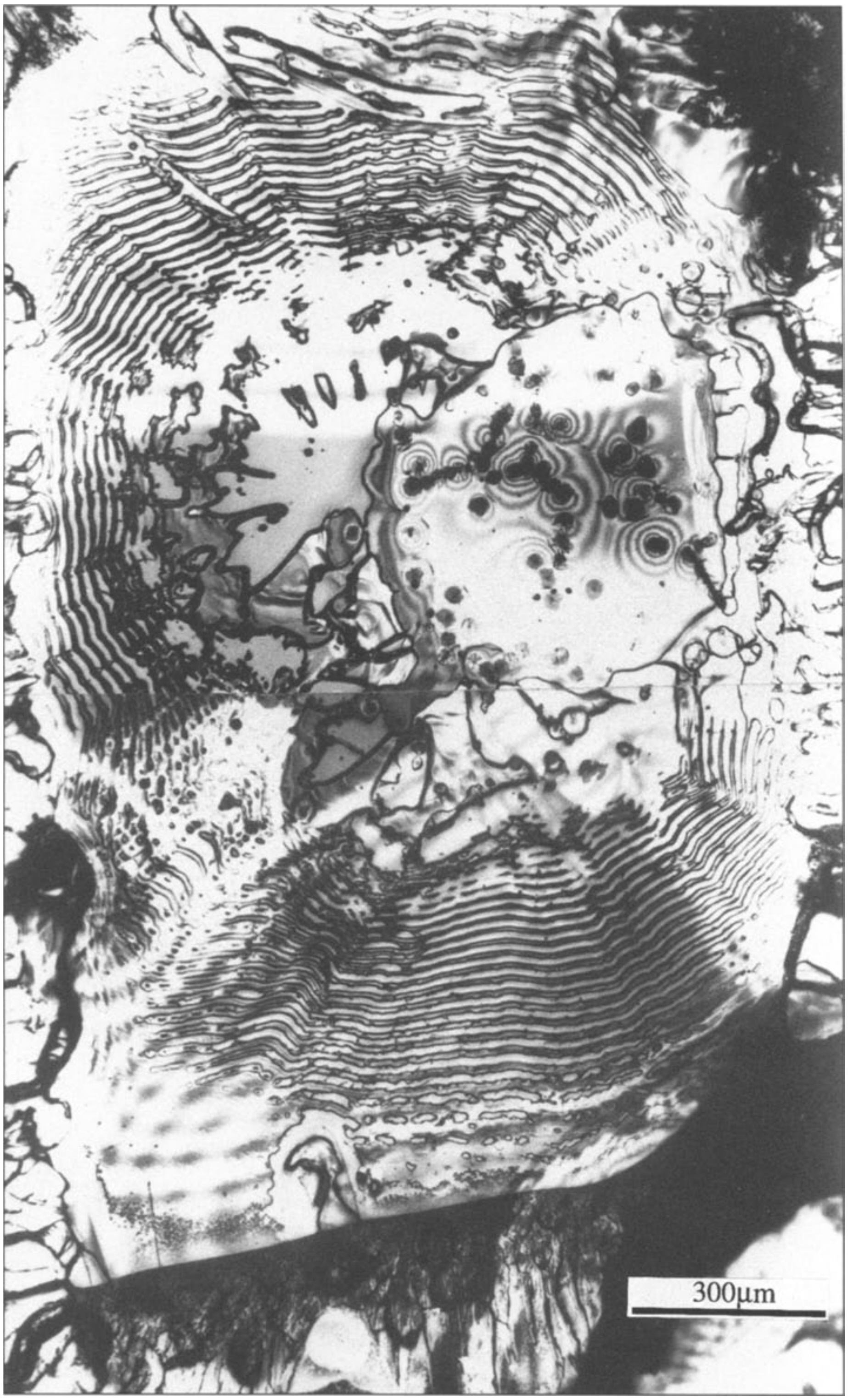
> *Whoever has once seen a dissection of the human body will understand and remember the relative positions of its parts with far greater certainty than if he had read the most exhausting treatises on anatomy, but had never actually seen a dissection performed.*
>
> (Comenius, *The Great Didactic*, 1641)

1.1 Aspects of seeing

It is unlikely that more than a handful of people in the world will recognise or will be able to explain and interpret the image in Fig. 1.1. It is a photograph of a fracture surface taken with a light microscope. By careful examination it is possible to recognise a number of patterns and well-defined features in the image. The appearance of these patterns is dependent on many factors including: the chemical constitution of the material, the microstructure and deformation behaviour of the material, the method of testing, the conditions of the test (temperature, strain rate, environment, etc.), and the sequence of micro-deformation processes that resulted in the nucleation and propagation of the crack. It follows that the patterns, and the image as a whole, contain information about these variables. The study of fracture surface topography and its relationship to crack propagation, or, for short, fractography, is concerned with unravelling or decoding this information. This type of analysis provides a powerful scientific tool in many areas, such as microstructural analysis, materials development, diagnostic failure analysis and process control.

There are three basic steps in fracture surface analysis, as there are in all experimentally based scientific studies: (i) observing, (ii) describing and measuring, (iii) interpreting. These steps are not independent and cannot be treated as separate processes in an investigation, for 'what one sees or observes depends on what one knows and understands'. The processes of observing, describing and interpreting weave a complex web. This is particularly so for experimental work involving microscopy in all its forms. There are strong subjective factors in the observation process that are closely allied to more esoteric topics such as the appreciation of art. Although these issues cannot be explored in any depth, the reader who doesn't appreciate them is well advised to read Gombrich's *Art*

Figure 1.1 Light microscope photograph of fracture surface of polystyrene tested in uniaxial tension at 293 K showing many different topographical features associated with nucleation and propagation of a crack. Photograph taken in reflected monochromatic light (wavelength 590 nm). From J. Murray and D. Hull, Fracture surface of polystyrene, *J. Poly. Sci. A-2*, 1970, **8**, 583–94.



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and Illusion.[1.1] The approach used in Chapter 2 of this book was chosen to give some insights into the way that the images from microscopy, in all their forms, are translated into three-dimensional concepts so that they can be interpreted and communicated with a minimum of confusion. It is based on a relatively simple fracture surface topography that is reasonably well understood without recourse to complex descriptions. Difficulties arise when these ideas have to be extended to the description and understanding of topographic detail where there are no preconceived models on which to develop a description.

The ability to visualise three-dimensional objects and represent them in a two-dimensional sketch or drawing is both a gift and a skill that can be acquired by experience and practice. The shapes of fracture surfaces are often so complex that there is little scope for seeking mathematical descriptions.[1.2] There is no escape from the demanding task of finding methods to represent shapes in some form of diagram or sketch. This is one of the keys to successful fractography.

In everyday life the awareness of the shape of an object is strongly influenced by binocular vision. In binocular vision two slightly different retinal images are obtained and the brain interprets the disparity between the two images to produce a perception of depth. Without binocular vision every object appears flat until additional cues are identified through knowledge, experience and deduction. The same argument applies to the monocular view presented by a television screen, a photograph or a drawing. These give a flat image and the awareness of depth arises from secondary effects that the brain instinctively interprets as a 3-D view. Artists, photographers and creators of virtual reality images use many different techniques to trigger a response, which then produces an appreciation, by the observer, of 3-D shape. The subjective nature of the response, or, in other terms, the perception of the observer, means that everyone 'sees' different features in an image. Very strong cues about shape are needed to minimise confusion and it must be recognised, particularly for unfamiliar shapes, that 'knowledge, experience and deduction' play a major role.

The main cues in a 2-D image, that are used to produce an awareness of shape and depth, can be summarised as follows:

Interposition. One feature in an image partly hides another indicating that one is in front of the other.

[1.1] E. H. Gombrich, *Art and Illusion: a study in the psychology of pictorial representation*, 5th Edition, 1977, Phaidon Press Ltd, London. Section 3, 'The Beholder's Share', is particularly relevant and well worth reading. Gombrich indicates that difficulties are not only because of an inability to copy nature but also to an inability to see it, and that the mind is the real instrument of sight and observation. Ian Hacking, *Representing and Intervening*, 1983, Cambridge University Press, Cambridge, provides a more scientifically oriented commentary on the same theme, in the context of the philosophy of natural science. The book includes a chapter on 'microscopy' that is used as a case study for issues developed elsewhere in the book.

[1.2] Many aspects of appreciating and describing shapes, including the development of mathematical descriptions are given by J. J. Koenderink, *Solid Shape*, 1990, M.I.T. Press, Cambridge, Mass.

Relative position. Features near the top of an image are usually interpreted or perceived as being further away.

Relative size. Large features in the image are considered to be closer, particularly if the relative sizes of the features are known.

Linear perspective. Progressive change in size of details in the image with distance. This is the most common feature of photographic images and is widely used in art.

Texture gradients. Changes in the apparent surface texture with position under conditions where the brain anticipates that there is no actual change.

Light and shade. Changes in the contrast or density of the image arising from the way that the surface is illuminated.

Shadows. Creation of a relief effect by the shadows produced by the lighting conditions.

All these factors are involved in 'seeing' in 3-D. Equally, they must be borne in mind in representing and communicating the 3-D shape of fracture surfaces. The photograph in Fig. 1.1 gives little indication of the shape of the surface, even to a knowledgeable observer. The complex patterns result primarily from differences in surface topography that influence the way that light is scattered at the surface. Although the surface may appear smooth and flat, it has, in reality, a complex 3-D shape. Incidentally, none of the features in Fig. 1.1 can be attributed to local variations in the microstructure of the material because this particular material is homogeneous to dimensions well below 1 μm. Additional detail of the fracture surface, shown in Fig. 1.1, is obtained by examination and photography at higher magnifications, as well as the use of other observation techniques and quantitative measurements of specific features, as outlined in Appendix 1. Even with a large amount of photographic, and other, information the observer has to interpret and describe the images in words and diagrams. This theme is developed in Chapter 2. Illustrative sketches are very important. They are a powerful tool for understanding and communicating the main features of the shapes of surface.

A less subjective approach to communicating shape, which introduces the possibility of quantitative descriptions, is the use of contour diagrams and sections; techniques widely used in geography. The example in Fig. 1.2(a) is a contour map of a mountain ridge. The lines map out locations at a constant height above sea-level in 100 m intervals. Section A–B in Fig. 1.2(b) is taken normal to the plane of the map and illustrates the shape of the hills and valleys. The shape is exaggerated because the scale in the vertical direction is different from the scale in the horizontal direction. A more accurate impression of the shape of the mountains is shown in Fig. 1.2(c) where the scale is the same in both directions. A set of equally spaced sections parallel to A–B would provide yet another impression of the shape. For geographical contours the reference surface is sea-level. In representing fracture surface topography in this way there

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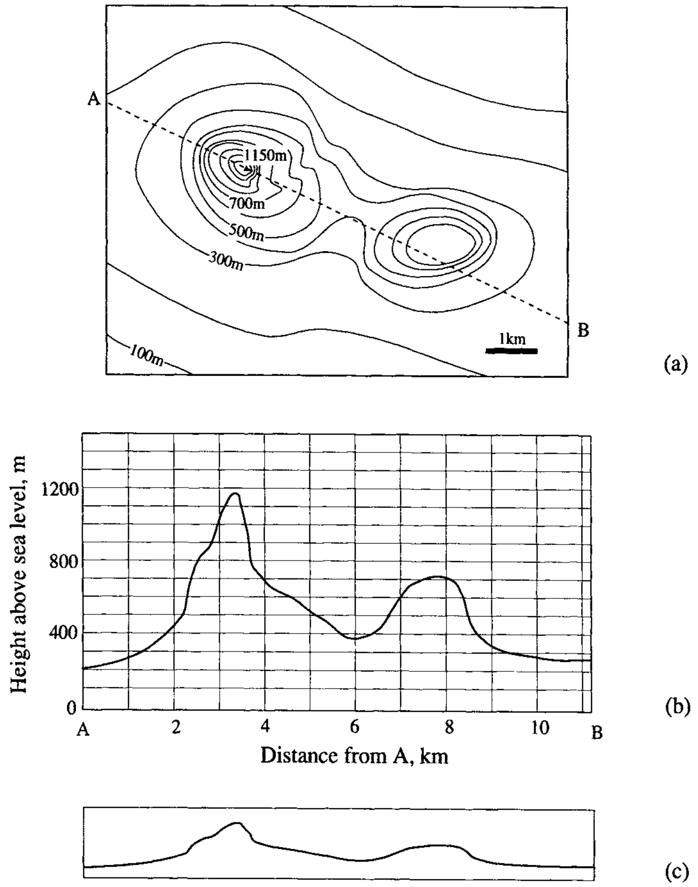

Figure 1.2 Use of contour maps to illustrate shape of a surface: (a) contour map of a mountain ridge showing contour lines at 100 m intervals, (b) vertical section along A–B with different scales for horizontal and vertical axes, (c) same section as (b) with identical scales for horizontal and vertical axes.

are a number of possible reference surfaces. These include the main axes of the testing system, the average plane of fracture, and the axes of the measurement system. This topic is developed in Chapter 2.

In principle, determinations of the contour lines in Fig. 1.2(a), and the shape of the section in Fig. 1.2(b), require a knowledge of the Cartesian co-ordinates of all points on the surface. In practice, this is impossible. The contours are produced by measuring the co-ordinates of a limited number of points and then interpolating between them to obtain the final contour. A fundamental question, that is discussed in more detail in the next section, is how closely spaced should the measurements be?

The approach outlined in the present section, with the emphasis on observing, describing and interpreting, provides a theme that is adopted throughout the book and so distinguishes it from many other books on fractography.[1.3] Most of

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[1.3] The main fractographic atlases are: ASM Handbook, Volume 12, *Fractography*, 1987, ASM International; L. Engel, H. Klingele, G. W. Ehrenstein and H. Schaper, *An Atlas of Polymer Damage*, 1978, Carl Hanser Verlag, Vienna; G. Henry and J. Plateau, *La Microfractographie*, 1967, Institute de Recherches de la Sidérurgie Français (IRSID): Editions Métaux, France: J. E. Welton, *SEM Petrology Atlas*, 1984, The American Association of Petroleum Engineers, Tulsa, Oklahoma.

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these books have a strong orientation towards a specific class of materials: metals and alloys, polymers, rocks, etc. Some books adopt the approach of a fractographic atlas in which large numbers of photographs are presented. These provide a basic resource that can be used to identify specific features on unknown surfaces. The ASM (American Society for Materials) Handbook on fractography is the most substantial book of this genre. Written by a host of experts, it includes introductory chapters on the history, techniques, interpretation and applications of fractography. These are followed by a collection of nearly 1500 images of fracture surfaces of a wide range of metals and their alloys. A small number of examples of fractures in non-metallic materials are included in later editions of the Handbook.

Although much of the published work is specific to one class of materials there are many ideas and principles that transfer from one material to another. These include features of fractographic detail, application of fracture mechanics and damage mechanics, and approaches to interpretation. One of the consequences of work being done in different disciplines in isolation, with different publishers and scientific journals, is that different words are used to describe what are essentially identical phenomena. One solution to this problem is to insist on describing fractographic detail in terms of the topographical features rather than by reference to some convenient morphological metaphor or simile. This approach has its attractions but it is not always easy and can lead to tortuous wording. In many cases, metaphors and similes have become closely associated with particular phenomena such as, for example, ‘mirror’, ‘mist’ and ‘hackle’, discussed in Section 5.1.

1.2 Some scaling issues[1.4]

1.2.1 General

The story of the blind men and the elephant is a familiar one. Ten blind men are taken to the zoo to meet an elephant and are asked to describe it. One feels the trunk, another the tail, another the ears, and so on. Their descriptions of the

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Numerous examples of fracture surface images can be found in the scientific literature. Particular reference is made to the following books: D. Bahat, *Tectonofractography*, 1991, Springer–Verlag, Berlin; J. J. Mecholsky and S. R. Powell, Eds., *Fractography of Ceramic and Metal Failures*, STP 827, 1984, American Society for Testing and Materials (ASTM), Philadelphia; A. C. Roulin-Moloney, Ed., *Fractography and Failure Mechanisms of Polymers and Composites*, 1988, Elsevier, Barking, England; J. E. Masters and J. J. Au, Eds., *Fractography of Modern Engineering Materials: Composites and Metals*, STP 948, 1987, ASTM, Philadelphia; A. K. Bhowmick and S. K. De, Eds., *Fractography of Rubbery Materials*, 1991, Elsevier, London.

[1.4] There is a fascinating essay on scaling in relation to a wide range of physical and natural phenomena in Chapter 2 of the classical book by D. W. Thompson, *On Growth and Form*, (1942 Edition), Cambridge University Press, Cambridge, (First Edition published in 1917).

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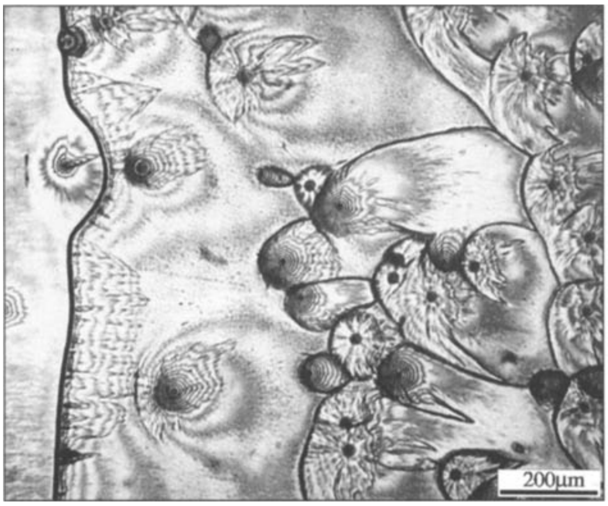


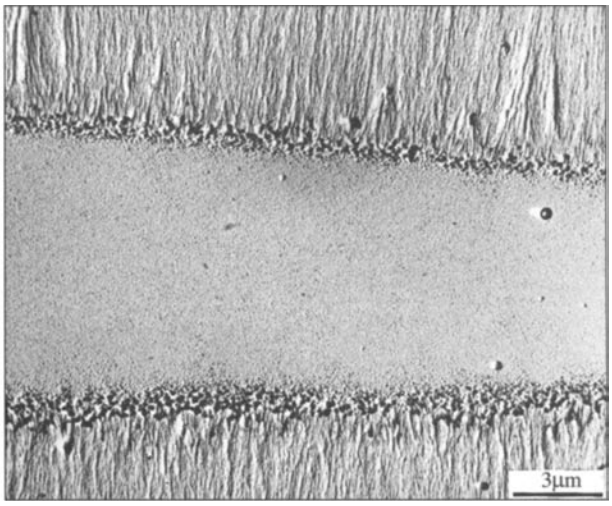


Figure 1.3 (*above, left*) Light microscope image of fracture surface of polystyrene taken from a region similar to central part of Fig. 1.1. From Murray and Hull, see caption Fig. 1.1.

Figure 1.4 (*above, right*) Transmission electron microscope shadowed carbon replica image of fracture surface of polystyrene taken from a region similar to central part of Fig. 1.1. From Murray and Hull, see caption Fig. 1.1.

elephant are completely different. The blind man who feels a leg says that an elephant is like a tree with deep circumferential furrows and a wide base. The man who feels the tail says that the elephant is like a thick hairy rope, and so on. Each description is accurate, but it doesn't describe the shape and form of the elephant as a whole. The message is clear; in making observations it is essential to see the object as a whole before attempting more detailed descriptions.

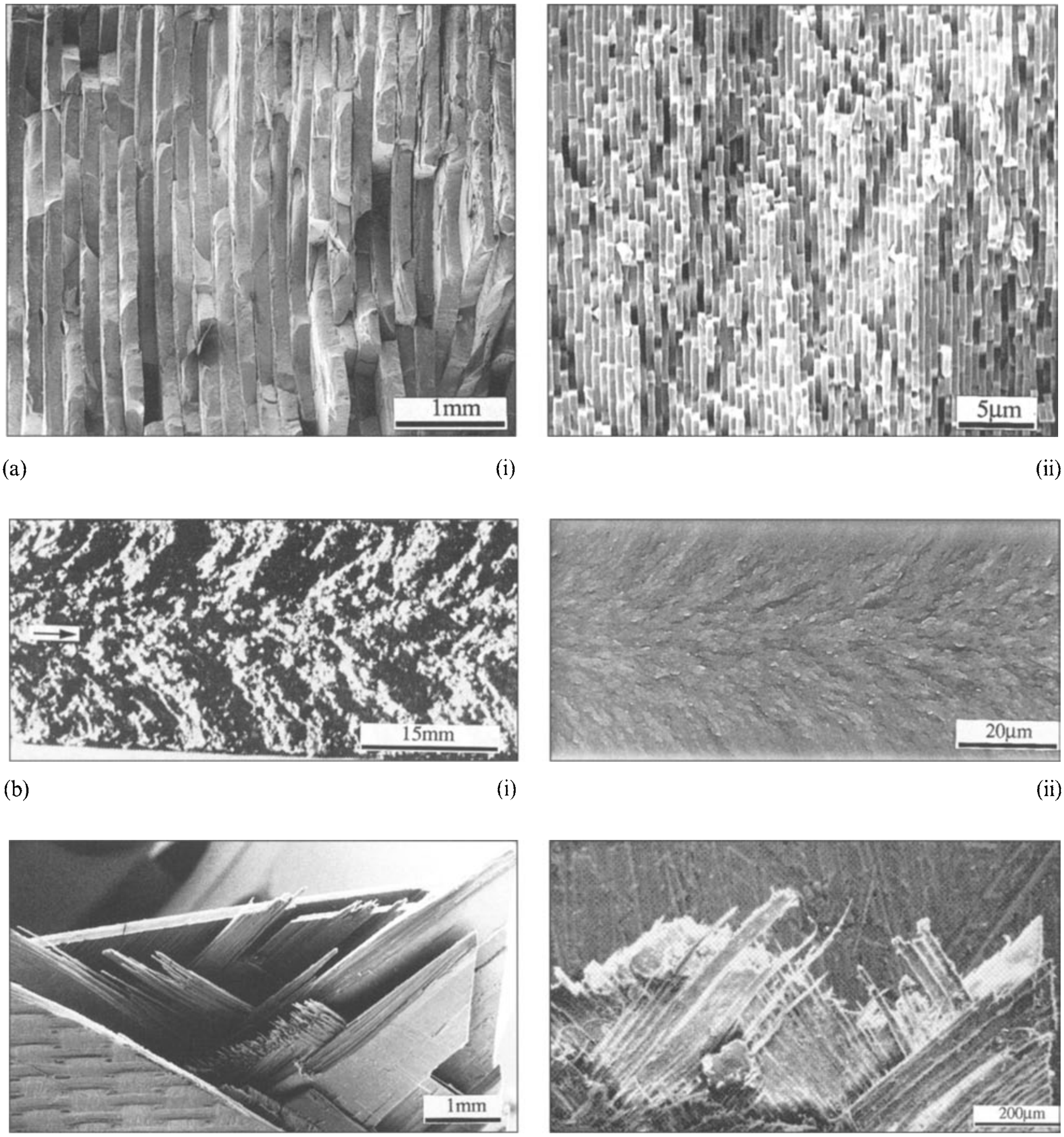
This idea can be extended to the examination of fracture surfaces. An essential first step is to examine the complete surface. This usually involves direct viewing by eye or at low magnifications, with a single lens or a light microscope. In parallel with the elephant story, one can envisage a whole series of different images as the magnification, and the place where the observations are made, change. These comments are particularly important in fractographic investigations because the overall shape and form of the surface is not nearly so obvious as that of an elephant. It is essential, in making and reporting fractographic detail, to specify the position of the observation and the magnification of the image.

The variation of fracture appearance with position is illustrated by the image in Fig. 1.1. Even without being able to explain the details in the photograph, it is clear that, at this magnification, the image is completely different in different parts of the fracture surface. This is demonstrated further by the more detailed analysis of this surface given in the Appendix. The appearance of the surface also changes when a single region is observed at different magnifications as illustrated in Figs. 1.3 and 1.4. For this example, the observations were made with different microscopic techniques, which adds further to the problems of making accurate comparisons. The high-magnification image in Fig. 1.4, which covers less than 30 µm, is from a shadowed carbon replica of the surface examined by transmission electron microscopy (TEM), a technique described in more detail in Section 7.3. Note that the images in Figs. 1.3 and 1.4 are not merely scaled versions of each other. This is important in relation to the description of fracture surfaces in terms of fractals, discussed later in this section. It is relevant also to the use of fractographic atlases. Since there are significantly different images at different magnifications, and from different parts of the same fracture surface, great care is necessary is using the images in atlases, particularly when there is no information about the test conditions and the overall geometry of the fracture.

The examples in Fig. 1.5 illustrate another aspect of scaling. They show similar images from fundamentally different materials with large differences in the scale of observation. The images were obtained using a variety of techniques that are described in later chapters. This apparent scaling of the fracture features in Fig. 1.5 arises partly because of the close similarity between the micro- and meso-structures in these materials, the primary distinction being the scale of the structure. There are also similarities in the relationship between the properties of the constituents of the structure. Thus, for example, the plate-like composites in Fig. 1.5(a) both consist of rigid plates of hard, brittle materials (silicon carbide and calcium carbonate) bonded together with relatively weak materials (graphite and protein respectively) that allow the rigid plates to slide past each other. Fracture separation occurs almost entirely at the boundaries of the plates and so the shape and form of the plates dominates the appearance of the fracture surface topography. The curved chevron patterns in Fig. 1.5(b) are observed on a wide variety of materials at many different scales. They are a consequence of the similarity in the way that cracks extend, as described in Chapter 8.

The convention for representing scale and magnification on the image is illustrated in Fig. 1.1 and has been used on all the images in the book. The advantage of showing a bar line superimposed on the image, is that any change in magnification of the image, for example in reproduction at another magnification, applies equally to the bar line and the image, so that the ratio of scales is maintained. Note that the scales on images produced by scanning electron microscopy (SEM) are not necessarily the same in all directions (see Section 2.8).

It is a universal feature of fractography that there is detail at all magnifications, down to the atomic level. This raises the question as to the magnification at which the surface is to be examined. The answer depends on many different factors and, in particular, on the purposes of the examination and the type of information required. A key issue is the scale of the observation in relation to the scale of the microstructure. Fractographic observations are made over a very wide range, from 10^{-10} m to 1 m, and beyond. The individual techniques have a limited range of applicability and there may be problems in reconciling features observed with different techniques at the same magnification. The microstructural dimension is a characteristic of the material. In many materials there are several levels of structural organisation and a hierarchy of microstructural dimensions. The



(a) (i) (ii)

(b) (i) (ii)

(c) (i) (ii)

Figure 1.5 Similar fracture surface images from two completely different materials at two different magnifications (note the scale marks): (a) platelike composites (i) a layered SiC–graphite composite, (ii) a layered calcium carbonate–protein composite in mollusc shell *pinctada margaritifera* (from W. J. Clegg, The fabrication and failure of laminar ceramic composites, *Acta metall.*, 1992, **40**, 3085–93), (b) chevron-patterned surfaces (i) low-alloy steel, (ii) silica-based sol–gel, (c) fibre composite laminates (i) carbon fibre reinforced plastic with fibres oriented in layers at +45°/−45°, (i) chitin fibres in a proteinaceous matrix of a beetle shell *pachynoda sinuata*, with a similar fibre architecture (from H. R. Hepburn and A. Ball, On the structure and mechanical properties of beetle shells, *J. Mat. Sci.*, 1973, **8**, 618–23).

dimension relevant to a particular fractographic dimension depends on the nature of the problem being studied.

1.2.2 Fractal geometry

The roughness of fracture surfaces, apparent at all scales of observation, makes it particularly difficult to describe the topography of these surfaces either qualitatively or in mathematical terms. The problem is common to many phenomena, particularly in the complex patterns of nature. These patterns appear random and chaotic and yet they exhibit some evidence of internal consistency. Mandelbrot introduced a new mathematical approach to such problems and used the word 'fractal' to describe these irregular and fragmented features. The approach applies to a wide range of topics and has been adopted enthusiastically in many branches of science and engineering, and by some fractographers, particularly those involved in quantitative analysis.[1.5,1.6] The application of the fractal approach has been possible because of the development of powerful image analysis equipment and computer software. Although there are many limitations to the use of fractal geometry in fractography the underlying concepts provide a valuable tool for understanding some aspects of the subject. Attempts have been made to correlate the fractal parameters of fracture phenomena with the engineering performance of materials, such as the strength of damaged bone and the weathering of stone containing arrays of cracks. A few simple ideas are presented here as an introduction.

In the context of surface roughness the issues relate closely to the question, 'How closely spaced should the measurements be?', posed in Section 1.1 in connection with the mapping of the contours and sections shown in Fig. 1.2. A starting point is to consider another question, which was discussed by Richardson in 1961, 'How long is the coast-line of Britain?'.[1.7] At first this seems

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1.5 Mandelbrot has published widely on fractal geometry. His classical book is B. B. Mandelbrot, *The Fractal Geometry of Nature*, 1982, W. H. Freeman, New York. There is now a vast literature on fractals and chaos theory. Two sources for references are A. Bunde and S. Havlin, Eds., *Fractals and Disordered Systems*, 1991, Springer–Verlag, Berlin, and J. Feder, *Fractals*, 1988, Plenum, New York.

1.6 The first paper relating fracture and fractals was B. B. Mandelbrot, D. E. Passoja and A. J. Paullay, *Nature*, 1984, **309**, 721–2. They measured the fractal dimension of fractured steel, using slit island analysis, and correlated it with the toughness. Reviews of the subject include: E. E. Underwood and K. Banerji, Fractals in fractography, *Mat. Sci. & Eng.*, 1986, **80**, 1–14. V. Y. Milman, N. A. Stelashenko and R. Blumenfeld, Fracture surfaces: a critical review of fractal studies and a novel morphological analysis of scanning tunneling microscopy measurements, *Prog. Mat. Sci.*, 1994, **38**, 425–74. A well-informed review that recognises the importance of microstructure, is E. Hornbogen, Fractals in microstructure of metals, *Int. Materials Reviews*, 1989, **34**, 277–96.

1.7 Richardson's ideas had a major influence on the development of Mandelbrot's work on fractal geometry. The problem of measuring the length of an irregular line posed by the question 'How long is the coast-line of Britain?' was developed by L. F. Richardson, The problem of contiguity: an appendix of statistics of deadly quarrels, *General Systems Yearbook*, 1961, **6**, 139–87.