DETECTION OF DEFECTS AND ASSESSMENT OF SERVICEABILITY

H. Harper

Harper Consulting Limited, Harrogate, UK

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Contents

Summary

Solid materials contain defects that affect their properties and behavior. Some defects have useful effects but larger, structural defects adversely affect the serviceability of manufactured products and structures. They can cause structural failures. Defects arise from many causes in raw materials and manufacturing processes. Other defects, particularly cracks, occur in service by mechanisms that lead to failure. When materials are selected for practical purposes, preference is given to materials that are not prone to

contain defects and those that can tolerate them without failing prematurely.

Extensive tests are carried out on raw materials, manufactured products and structures to verify that they have the required properties. Most tests are carried out on representative samples of material, not on the product itself. Nondestructive testing (or nondestructive evaluation) is carried out to detect defects in the actual materials that are used in products and structures, without affecting the serviceability of the material or product to which it is applied. A variety of nondestructive testing methods exists to distinguish between defective and non-defective material. Some methods are capable of measuring defect sizes and other parameters. Studies have been made of the performance and reliability of nondestructive testing.

Empirical and scientific methods exist to predict the serviceability of products and structures that contain defects. These methods take into account the existence of defects, their characteristics such as size, the loadings applied to structures, the properties of materials and the effects of the environment in which they operate. One particularly important method is known as fracture mechanics. Nondestructive testing and fracture mechanics are complementary disciplines, offering a scientific basis for the detection of defects and the assessment of their significance.

1. Introduction

All solid materials contain defects or imperfections that are departures from perfect purity, regularity and order. These defects have profound effects on the properties and behavior of solids. Many microscopic and sub-microscopic defects have useful effects but larger, structural defects, such as cracks and pores, weaken materials and cause unpredictable variations in their properties. They adversely affect the serviceability of manufactured goods. Cracks are particularly harmful because they are the result of processes that will cause structures to fail if they are allowed to continue (Figure 1). Failures in structures such as bridges, aircraft and chemical plant can have catastrophic consequences and must be prevented if possible.

Figure 1. A crack in the shroud of a low pressure steam turbine.
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When materials are selected for practical purposes and structures are built from them, the possibility of defects occurring is taken into account. Preference is given to materials that are not prone to contain large numbers of defects and to those that can tolerate defects without failing prematurely. Manufacturing processes and service conditions are carefully controlled to ensure that the number of defects and their adverse effects are minimized. Manufacturers carry out extensive tests to verify that production processes are correctly applied and that batches of material have their intended properties. Most of these tests are carried out on representative samples of material, not on the product itself, and the possibility remains that the actual materials used in structures may contain defects that would not be revealed by the tests. Additional tests are therefore carried out to detect defects in the actual materials that are used. The procedure for doing this is known as nondestructive testing or nondestructive evaluation. The distinguishing characteristic of this discipline is that it does not affect the serviceability of the material or product to which it is applied.

The basic requirement for a method of nondestructive testing is that it should clearly distinguish between defective and non-defective material. A variety of methods exists, of which the most important use electromagnetic radiation (X-rays, gamma rays, visible light or infrared radiation), sound waves, electrical or magnetic effects. Some methods have the advantage of measuring defect sizes and other parameters.

Methods exist to predict the serviceability of products and structures that contain defects. Empirical methods are based on experience and take into account the quality of work that would be achieved by a conscientious manufacturer applying appropriate techniques in good conditions. In the later stages of manufacture and during the service life of a product or structure, there is a great incentive to distinguish between harmless defects and those that could cause structural failure. Great strides have been made in the assessment of serviceability since the middle of the twentieth century. Methods are available that take into account the existence of defects, their characteristics such as size, the deliberate and inadvertent loading applied to structures, the properties of materials and the effects of the environment in which they operate. One particularly important method is known as fracture mechanics. This aims to establish whether specific defects in real structures are likely to cause structural failure or collapse. Nondestructive testing and fracture mechanics are complementary disciplines for this purpose.

This article briefly introduces defects in solids, distinguishing between crystal defects and structural defects. A review is given of the origins, growth and development of structural defects as they occur in raw material production, manufacturing and service. Nondestructive testing and nondestructive evaluation are introduced and the methods of nondestructive testing are described. Methods of measuring the performance and reliability of nondestructive testing are outlined. The scientific background of fracture mechanics as a method of assessing the serviceability of structures that contain defects is presented, followed by an account of the way it is applied in practice to structures. Finally, mention is made of the actions that can be taken when defects are detected and assessed.

2. Defects in Solids

Crystalline solids have regular, ordered arrangements of atoms, but some atoms are missing (vacancies), extra atoms occupy sites between the main structural atoms (self-interstitials) and some rows of atoms are arranged anomalously (dislocations). These departures from crystalline perfection are known as crystal defects (see Materials Science and Engineering). Impurities exist as foreign atoms (substitutional atoms) that replace some of those that make up the solid or occupy interstices between them (interstitial atoms).

Most of the solid materials used in practical applications consist of small, crystalline grains that vary in composition and orientation. Their size, shape, chemical composition and arrangement constitute the microstructure of the material. Individual grains contain crystal defects and the boundaries between grains are common sites for impurities, which may coalesce to form defects known as "precipitates".

Vacancies and interstitials exist on an atomic scale. They are observed indirectly - by spectroscopy or their effects on the properties of the material. Dislocations, precipitates and other microstructural defects are observed either directly, by optical and electron microscopy, or indirectly. Variations in the microstructure are studied by optical microscopy, electron microscopy and microanalysis, which reveals microscopic variations in chemical composition.

Defects greatly affect the properties of solid materials, particularly their optical, electrical and mechanical behavior. Vacancies give colour to many crystalline solids and impurities give colour to gemstones like rubies and sapphires. Controlled impurities are added to germanium and silicon to modify their semiconducting properties and create useful devices like transistors. Dislocations are responsible for many of the properties of metals, such as plasticity and hardness.

A class of defects that includes cavities, pores, cracks and inclusions exists on a larger scale. These "structural defects" consist of the absence of material (e.g. cavities and pores), the separation of material (cracks), the removal of surface material or the inclusion of foreign bodies. Structural defects cannot be avoided or eliminated entirely and they are of great practical significance. They weaken materials, cause them to fail and affect the quality and serviceability of manufactured goods. (See Defects Introduced in Metals during Fabrication and Service).

The detection and assessment of structural defects is the subject of this article.

3. Structural Defects

3.1. The Characteristics of Structural Defects

Structural defects are described as being volumetric, linear or planar, according to their shapes. Volumetric defects extend in three dimensions and consist of cavities or groups of pores. Some are empty; others contain gas or solid material. Linear defects are long in relation to their width and breadth; they usually consist of inclusions of foreign matter. Planar defects extend in two dimensions but very little in the third dimension. They may be buckled, rather than being flat, and may have complex, branching shapes. Cracks are planar defects, which is the class of defects most likely to cause materials and structures to fail.

The positions, orientations and dimensions of defects are important for detecting and evaluating them. Some occur at surfaces; others are embedded inside solid material. They are often associated with features such as crevices or welds. The distances of embedded defects from external surfaces are important. The orientation of a defect is defined by reference to external surfaces or other features. The dimensions of defects and their orientations in relation to important directions of stress may determine whether structural failure is likely to occur. Roughness of the defect surface affects the ease with which they may be detected. The crack opening displacement (COD), defined as the separation between the planar faces of a crack, is important for both detection and assessment.

Structural defects are caused by physical changes on solidification and cooling, chemical contamination, mechanical deformation, and the effects of heat, chemical attack or a combination of these factors. The specific causes are many and various. For example, external loads, acceleration, pressure, electrical and magnetic forces, corrosion and changes in crystal structure can all cause mechanical deformation that leads to the formation of defects. The following treatment gives a broad, but not exhaustive survey

of the origins of structural defects.

3.2. The Origins of Structural Defects in Solid Materials and Manufactured Products

The solidification of solids from molten liquids involves changes in temperature and large changes in volume. Gas may be evolved, setting up internal pressure, which leads to the formation of porosity and cracks. When casting metals by pouring liquid into moulds, gas-filled defects occur; these are known as "worm holes" and "blow holes" from their characteristic shapes. Air locks form if air is trapped in the moulds.

During solidification, the surface of a cast ingot is covered in slag, oxide and low-density particles, which flow to the top. In alloys, relatively pure metal solidifies first, leaving a liquid that is richer in alloying elements and impurities. This liquid solidifies later in a segregated area. When the ingot is converted into a useable product, the impurities become inclusions. Inclusions occur at the center of rolled steel plate, causing poor ductility across the section of the material. The stress of welding can open the inclusions, causing planar defects known as "lamellar tears", which have a characteristic step-like appearance, the steps being parallel to the surface of the plate.

As it cools, solidifying liquid contracts and shrinkage defects occur near the center of cast sections or, on a small scale, between growing crystals. If a casting is restrained while it is hot and weak, cracks known as "hot tears" occur. These have ragged, irregular shapes. In castings of complicated shape at lower temperatures, contraction stresses cause "cold cracks" or "stress cracks". Similar effects occur in solidifying weld metal. As weld metal solidifies, a thin film of liquid is left between solidified grains. Stress caused by differential thermal expansion ruptures the weak film and causes "solidification cracks". The worst solidification cracks occur as continuous defects at the center-lines of welds, parallel to the welding direction. In other cases, the cracks are intermittent and may be transverse to the welding direction.

If a welding process fails to fuse metal correctly, "lack of fusion" defects occur. "Lack of side-wall fusion" occurs between the weld and the parent metal. "Incomplete fusion" occurs at the root of the weld. Between layers ("runs") of weld metal, it is "lack of inter-run fusion". All these defects are caused by poor welding methods, particularly attempting to lay down weld metal that is sluggish because it is too cool.

Joints between components may be imperfectly shaped. In welds, "undercut" results from the melting of parent metal and its removal by the force of the welding process. Undercut is more prevalent in welding processes that use high energy density, such as plasma arc welding, electron beam welding and deep-penetration manual metallic arc welding. Excessive penetration is the protrusion of weld metal through the root of the weld, leaving it with an irregular profile. In extreme cases, the weld metal collapses, resulting in holes in or at the side of the weld. This is known as "burn through". Other imperfect shape defects include linear and angular misalignment, excess weld metal overlapping the parent metal, incompletely filled grooves and irregular surfaces.

Miscellaneous welding defects arise from grinding, chipping and hammer marks. The

forcible removal of temporary attachments causes torn surfaces. A welder may inadvertently strike an arc outside the weld region, resulting in surface damage and cracks. Weld metal may spatter on adjacent surfaces, though it is generally harmless and is easily removed.

For a solid with a given chemical composition, different crystal phases are stable at different temperatures. As it cools, phase changes occur, with changes of volume and crystal structure. In sintered ceramic materials, these changes can rupture the material, especially if one or more of the constituents is brittle. When this process occurs in a metal casting, it is known as a "clink". Clinks can open into large cavities when cast material is subsequently worked.

Rapid temperature changes cause temperature gradients and "thermal stress" as the material accommodates varying amounts of thermal expansion. Thermal stress occurs, for example, in containers subjected to rapid changes of temperature by contact with hot or cold fluids. Thermal stress that is retained in a solid is self-equilibrated. That is, a tensile stress in one region is balanced by a compressive stress in another region. This is an example of "self-stress", also known as "residual stress" or "internal stress". It causes distortion in welded structures and it can cause cracks, which grow until the tensile stress is relieved. Welds are heat-treated to reduce residual stress and improve their microstructure and properties. If the material passes through a temperature range at which it is brittle before the welding stress is relieved, cracking known as "reheat cracking" or "stress relief cracking" can occur.

Mechanical deformation is introduced by manufacturing processes that involve the working of material (see Materials Processing and Manufacture). Forging improves the properties of metals by closing or flattening pre-existing defects and by breaking down and refining the grain structure. It relies on the material having sufficient ductility to deform without damage. If the forging temperature is too low or if too great a reduction is attempted in one operation, the ductility is insufficient and gross cavities are formed inside the forging. These are known as "bursts". Material may be folded at the surface to form "laps".

Hydrogen diffuses through metals and collects around segregates. Pressure builds up and causes cracks in susceptible material. The diffusion of gas takes time and the defects may appear long after the process that caused them. Hydrogen cracks in forgings ("flakes") are extremely fine and often occur in groups, aligned with the flow direction of the forged material. They are very harmful and usually lead to the rejection of the forging. Vacuum degassing of steel eliminates hydrogen cracking and it is rare in modern forgings. In welds, hydrogen originates from consumable materials, producing "hydrogen-induced cold cracks".

Plastics contract on solidification from the melt. Sink marks, or surface depressions, occur above sections where there is local thickening; the core of hot material reduces the cooling rate of the surface and draws the surface inward. Voids are formed when the external surface of the material cools rapidly and becomes rigid enough to resist sinking. Contraction of the core then produces internal cavities. Voids assume particular importance in thick sections of transparent materials. Sinks and voids occur mainly in injection molding and extrusion. They tend to be less of a problem in blow molding and

rotational molding.

Amorphous materials such as glass do not have regular, periodic structures and cannot contain crystal defects. Nevertheless, their mechanical properties are very similar to those of crystalline solids and, like them, they contain structural defects. Ceramics and glass are not capable of plastic deformation like metals. They are brittle and less tolerant of imperfections and defects. Failure occurs from cracks too small to be seen with the naked eye.

Grinding and mechanically polishing the surfaces of ceramics help to eliminate serious defects. Surface glazing keeps out moisture and mitigates the effects of surface defects. Glass-ceramics, which are polycrystalline materials produced by the controlled crystallization of special glass, have fine grain sizes and are relatively free from the defects and inhomogeneities that occur in conventional ceramics. Therefore, they have higher mechanical strength than glasses and some have good resistance to thermal shock.

The size of defects is limited in fibrous materials, which are therefore stronger, weight for weight, than bulk materials.

Composite materials consist of two or more components combined to use the most favorable characteristics of each. Each of the components contains defects and additional ones occur at the boundaries between them. Many composite materials use components that are brittle solids in the bulk form. They are converted into fibers to eliminate the defects normally present in brittle solids, thus producing strong, rigid materials. The strong fibers are incorporated into a matrix of metal, plastic or ceramic. The matrix protects the fibers from abrasion and chemical attack from the environment and it separates the fibers so that a crack cannot propagate from one to another. Porosity and voids may occur in the matrix. The matrix may crack if it is brittle or flow if it is plastic. Fibers may be misaligned, distorted or broken. Foreign bodies may be inadvertently introduced into layers of fiber. "Debonding" can occur between the fibers and the matrix. Composite materials are weak perpendicular to the fibers because the fibers are easily debonded or the matrix fails. Composite materials such as glass-reinforced plastics therefore contain layers in which the fibers are laid in different directions to confer uniform strength in all directions. The layers of material may separate, causing a defect known as "delamination". Sandwich structures are created from outer layers of strong laminates and inner layers that consist of foam or honeycomb material. The skin of sandwich structures may be poorly bonded to the core.

Concrete and other aggregate materials have complex compositions and structures. Defects in the individual components are of little concern but large-scale structural defects have serious effects. The materials may suffer from large cracks because of poor control during mixing, pouring or setting. Reinforcing bars and pre- and post-stressing tendons may suffer from corrosion and cracking.

Many of the processes used in manufacturing produce structural defects. Large-scale processes and those that involve large changes are more prone to produce them than precision processes and those involving small changes. Processes such as grinding,

drilling and machining remove material with considerable force, causing defects, especially cracks, by mechanical action. Thermal stress cracks form at external surfaces by local heating caused by grinding or machining. Pressing and extrusion cause defects by mechanical deformation. Joining methods such as bolting, riveting, soldering and brazing cause defects in the joints and fasteners.

Coatings are applied to protect the surfaces of materials from environmental attack or heat. They may be thinner than intended and they may be disbonded from the surface. They may be penetrated by pores or cracks, thus providing incomplete protection.

The mechanisms by which defects occur in service are closely related to those by which they develop and, eventually, cause failure. These topics are therefore dealt with together in the next section.

3.3. The Growth and Development of Structural Defects in Service

Defects initiate and develop in service by overload, creep, fatigue, impact, wear, oxidation, corrosion, environmental attack and the effects of radiation.

Structures are overloaded by being subjected to stress greater than their strength. They can fail suddenly by brittle fracture or plastic collapse. Brittle fracture is the unstable propagation of cracks. In plastic collapse, the material deforms continuously and permanently until rupture occurs. Overloading causes damage, even if it does not cause failure; defects initiate, residual stress is introduced and distortion occurs.

Creep is a continuous deformation of materials under steady load. Three stages of creep are identified. In the early stages, the material increases in strength and hardness. In the second stage, there is a balance between work hardening and progressive softening of the material; hence, the rate of creep is constant. The third stage is a period of accelerated creep associated with the onset of necking, or narrowing of the cross-section, and metallurgical instability. In the third stage, voids and cavities appear in the material; they eventually coalesce and grow to form cracks. Thereafter, the material rapidly proceeds to failure.

Fatigue is the failure of materials under the repeated application of a cycle of stress. Small cracks are nucleated, usually on the surface of the material where the tensile stress is high. The cracks grow under repeated action of the stress cycle until they reach a size at which the material is overloaded and failure occurs. Fatigue cracks usually cross grains and grain boundaries; they are then described as "transgranular cracks".

Fatigue occurs due to the application of a small number of high stress cycles ("low cycle fatigue") or a large number of relatively small cycles ("high cycle fatigue"). The stress causing fatigue may be imposed by fluctuating applied loads, thermal effects and mechanical effects such as centrifugal force. Low cycle fatigue is encountered, for example, in the repeated pressurization of pressure vessels. High cycle fatigue is commonly caused by vibration. This is a particular problem in aircraft engine parts, which rotate at high velocity, buffeted by powerful flows of gas. Fluctuating thermal stress may be caused by repeatedly filling a vessel with hot or cold liquids.

At high temperatures, stress fluctuations and creep deformation may occur together. "Creep fatigue interaction" occurs, causing failure more rapidly than either creep or fatigue acting separately.

Corrosion is the progressive wearing away of materials, especially metals, by chemical attack from the environment. It involves the removal of electrons from metals and the formation of more stable compounds such as oxides. General corrosion leads to the relatively uniform removal of a surface, but grain boundaries, precipitates and the boundaries between metals and inclusions may be selectively attacked. By these mechanisms, corrosion causes pits and cracks. Corrosion compounds form on the surface of solid materials. If a hard and impenetrable compound adheres to the surface, it forms a protective film and the progress of corrosion is arrested. If the compound is loose and porous, however, corrosion proceeds unhindered.

Corrosion compounds may lodge inside open cracks and this has two undesirable effects. The corrosion products often have a volume greater than that of the parent material that produced them. They force apart the crack faces, imposing stress that accelerates crack growth; a specific example of this is known as "oxide jacking". Secondly, the corrosion products make cracks more difficult to detect.

Galvanic corrosion occurs when two different metals are placed together in a solution. One metal gives up ions to the solution more readily than the other; this difference in behavior brings about a difference in electrical voltage between the two metals. If the metals are in electrical contact with each other, electricity flows between them and they corrode. For example, if steel bolts are used in an aluminum framework subjected to rain or fog, multiple galvanic cells occur at the point of contact between the two metals, corroding the aluminum.

Many metals develop cracks when they are subjected to stress while in contact with a corrosive environment. This phenomenon is known as "stress corrosion". Stress corrosion also occurs in plastics. For example, Perspex cracks in the presence of water.

Corrosion fatigue occurs when chemical attack accelerates the weakening of a structure by fluctuating stress. The fatigue process exposes fresh, bare metal that is rapidly corroded. When the stress is reversed as part of the fatigue cycle, the corrosion products are displaced, interfering with the deformation process, aiding fatigue and shortening the time to failure.

In a system which contains a liquid, the environment at the tip of a crack, crevice or pit may be different from that occurring elsewhere at the surface. This may give rise to enhanced, localized corrosion (crevice corrosion or pitting corrosion). Crevice corrosion sharpens blunt crevices, creates new cracks and extends existing ones. These sharper defects concentrate stress, making crevice corrosion a very damaging mechanism.

Components and structures exposed to the flow of solids or to the flow of liquids or gases containing solid particles suffer impact damage. This may result in immediate failure but pits and cracks occur in less severe cases. Stone damage of automobile

windscreens is a good example. Damage to composite materials in service is most often caused by impacts (See Composite Defects and their Detection).

Wear is the removal of material from a solid surface by mechanical action exerted by another solid. Adhesive wear arises from strong adhesive forces at the interface of two solid materials. Abrasive wear occurs when a hard, rough surface slides over a softer one, producing grooves on the latter. It can also be caused by loose, abrasive particles rolling between two soft sliding surfaces or by particles embedded in one of the opposing surfaces. Corrosive wear occurs when a gas or liquid chemically attacks a surface left exposed by the sliding process. If continuous sliding takes place, the sliding action removes the surface deposits that would otherwise protect against further corrosion, which thus takes place more rapidly. Surface-fatigue wear is produced by repeated high stress due to rolling motion, such as that of metal wheels on tracks or a ball bearing rolling in a machine. The stress causes subsurface cracks to form in either the moving or the stationary component. As these cracks grow, particles separate from the surface and pitting ensues.

A combination of wear and corrosion leads to erosion-corrosion. Erosion occurs by the impact of small particles and by cavitation - the collapse of vapor bubbles in a fluid flowing past a component. Erosion enhances corrosion by preventing the build up of a protective film, continuously exposing fresh material to the corrosive fluid.

Ultra-violet radiation is a serious problem for users of plastics in outdoor applications. Ultra-violet radiation disrupts the molecules and enhances the chemical reactivity of the polymer, especially in the presence of oxygen. Weakening, embrittlement and loss of transparency result from this.

4. Nondestructive Testing and Nondestructive Evaluation

Nondestructive testing (NDT) is a procedure for inspecting and testing any material, component or assembly by means that do not affect its quality or serviceability. The term "nondestructive evaluation" (NDE) is used synonymously with NDT, though strictly its use includes the evaluation of NDT results.

The purpose of NDT inspections is to detect defects and provide information for them to be evaluated. It determines whether defects are present and whether they break the surface or are embedded in the test-piece. The positions, dimensions and orientations of defects and their relationship to external surfaces, features of the test-piece and other defects are measured. The area affected by multiple defects such as porosity is measured and, in some cases, the number, density or spacing of the individual defects can be determined. If a test-piece is known to have defects, NDT may be repeated at intervals to check whether they are growing. Ideally, the type and cause of the defect would be determined but NDT methods do not provide this information directly; it must be inferred from the design, origin and history of the test-piece.

NDT is carried out at the earliest opportunity so that defects are detected as soon as possible after the process that caused them, thus avoiding wastage of materials and resources doing expensive work on defective material. NDT is carried out on raw

materials, basic products, between manufacturing operations, after manufacture, immediately before the product enters service (pre-service inspection) and in-service. Some of these inspections may be required by a contract. For example, a product manufacturer may require an inspection to verify the quality of raw materials. Similarly, the purchaser of a manufactured product may require an assurance that it is free of defects that could affect its service life. Other inspections are carried out to check the correct performance of manufacturing processes.

The requirement to carry out certain inspections is specified in published Codes and Standards. Some of these require NDT inspections to be carried out for safety reasons. This is the case for in-service inspection of nuclear reactor containment plant, for example. The Codes and Standards require NDT at specified intervals to confirm that there are no defects to cause failure during the service life of the plant. The Codes and Standards are given legal force by safety regulatory authorities.

Pre-service inspection is carried out as a final check on a product before it is accepted by a customer. It may be required as a condition of acceptance by the customer or it may be demanded by a regulator. Pre-service inspection also acts as a baseline to provide information with which the results of later in-service inspection may be compared. In-service NDT is carried out to verify that the assumptions and calculations made by the designers remain valid and to detect unexpected mechanisms of deterioration before they cause damage or failure. In-service inspection is usually carried out when plant is shut down. It is complementary to condition monitoring, which includes the assessment of a component or machine while it is operating.

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Biographical Sketch

Harold Harper obtained his B.Sc. (1964) and Ph.D. (1968) in physics at the University of Sheffield. After working on glass-ceramics and amorphous materials as a Research Fellow at the University of Warwick, he joined the Central Electricity Generating Board in 1971 to carry out research and development in its Non-Destructive Testing Applications Centre. His work included the development of a novel type of ultrasonic flaw detector, the scientific basis of magnetic particle flaw detection and a variety of nondestructive testing applications on power plant. He developed techniques for mechanized ultrasonic flaw detection and introduced them into fossil-fired, hydro-electric and nuclear power plant. He chaired the committee which drafted the British Standard on magnetic particle flaw detection. Subsequently, he held managerial appointments in the electricity industry, including responsibility for engineering applications on four of the UK's civil nuclear power stations and providing technical support to the power stations in the north of England and North Wales. Since 1994, he has worked as an independent consultant. His consultancy interests include policy studies in the power industry, structural integrity, the planning of research and development programs in nondestructive testing, independent endorsement of validation procedures for nuclear nondestructive testing, advice on contract disputes, the validation of undergraduate engineering programs and the evaluation of research proposals for international funding. Dr Harper is a Fellow of the Institute of Physics, a Chartered Physicist and a Fellow of the British Institute of Non-Destructive Testing. In 2000, he begins a two year term as President of the British Institute of Non-Destructive Testing.