

UNIT-5 HIGH TEMPERATURE MATERIALS CHARACTERIZATION

Classification, production and characteristics – methods and testing – determination of mechanical and thermal properties of materials at elevated temperatures – application of these materials in thermal protection systems of aerospace vehicles – super alloys – high temperature material characterization.

HIGH TEMPERATURE MATERIALS

Materials operating in service at elevated temperatures are relevant to many processing and productive industries and hence provide an illuminating example of the desirability for materials research to be carried out with a broad view of the ultimate applications of the product, rather than in concentrating on the satisfaction of a single requirement. Nevertheless in the final stages of development of a material the detailed requirements of each potential application must be considered. Close cooperation is therefore demanded between, on the one hand a research organisation with a wide understanding of the basic sciences involved and the production and application problems arising in materials technology, and on the other hand the designers and development engineering engaged in individual industries.

The extent of interest in high-temperature materials can be appreciated by considering the main fields in which they are used.

High temperature materials application in various industries as follows

High-temperature steam turbines

Oil- or coal-fired steam turbines provide the majority of power generation in the world, using maximum steam temperatures close to 600°C. In the steam-raising plant certain components reach higher temperatures and may be subject to severe erosive and corrosive attack; critical components are super heater tubes and tube supports. Piping and valves conveying steam from boilers to turbines are highly stressed and may also suffer steam erosion. In the turbines the casings and casing bolts are highly stressed due to the steam pressure, while the rotors, blades and nozzles have imposed stresses due to centrifugal forces, gas pressure and thermal changes.

Nuclear reactors

In all types of nuclear reactor high-temperature material problems arise with the fuel cans due to stressing by fuel expansion and to corrosion by the coolant. The majority of nuclear reactors at present operating, whether water cooled or gas cooled with carbon dioxide, generate steam at relatively modest temperatures in the range 300-400°C

Aircraft and Space Vehicles

The aircraft gas turbine provide the main stimulus for the development of modern superalloys, the term used to describe materials resistant to creep and fracture at temperatures in the range 700-1100°C. The alloys were originally required specifically for stator and rotor blades to resist the high centrifugal or thermal stresses imposed on the blades, but with progressive increase in the severity of operating conditions similar alloys are now used for other gas-turbine components including discs, combustion chambers, casings and tail pipes. The aircraft gas turbine is likely to remain the primary application of the most advanced superalloys or competitive high-temperature materials.

The rocket motor for space travel has led to severe problems in high-temperature materials technology. The high temperature and velocity of the exhaust gas generates high thermal stresses and erosive action; refractory metals, particularly tungsten, and special forms of graphite have been used to resist these satisfactorily, even though the required life may be restricted to a few minutes. Similar problems arise with re-entry vehicles on account of aerodynamic heating, and these have led to the development of special refractory ablative tiles or coatings.

Marine

Merchant shipping mainly relies on the diesel engine in which a number of critical components are subjected to severe mechanical or thermal stresses and corrosive attack at high temperatures. The highest temperature (about 800°C) is reached in pre-combustion chambers, but closely similar temperatures may be reached in exhaust valves, associated with high mechanical stress.

Chemical Industry

A wide range of chemical for the conversion of feedstock, from the oil industry or elsewhere, into required products, involve treatment at elevated temperatures and often at high pressures. The systems consist of the reactor tubes, which typically are 12-15 m long and 100 mm bore with a wall thickness about 20 mm, which are connected by smaller bore "pigtail" pipes to a header and hence to transfer piping. Welding is an essential operation in the construction of such plant. The operating temperatures of the equipment may rise to 950-1050°C.

TYPES OF HIGH-TEMPERATURE ALLOYS

The metallic materials used for high-temperature purposes range from the simplest plain carbon steels to the scarce and expensive metals of the platinum group, but they can be categorized into a few distinctive groups based on composition and structure. Typical compositions of representative alloys of the main groups are given in Table I and the principal characteristics of the structure and properties are indicated in the following sections.

Table I. Typical Compositions of Selected High-Temperature Alloys

Alloy Type	Commercial Name	Cast or Wrought	Composition												
			Fe	Ni	Co	Cr	W	Mo	Nb	Ti	Al	C	Others		
Austenitic Cast Iron	Ni-Resist	C	Bal.	20	-	5	-	-	-	-	-	-	3	2 Si	
Ferritic Steel	FV 448	W	Bal.	1	-	11	-	0.7	0.4	-	-	-	0.1	0.05 N	
Austenitic Steel	AISI 321	W	Bal.	10	-	18	-	-	-	0.4	-	-	0.05	-	
	HK40	C	Bal.	21	-	25	-	-	-	-	-	-	0.4	0.05 N	
Nickel-chromium Alloys	Alloy 800	W	46	32	-	20	-	-	-	0.3	0.3	0.04	0.04	0.3 Cu	
	Nichrome V	W	-	78	-	20	-	-	-	-	-	-	0.04	2 Si	
Iron-based Superalloy	N 155	W	Bal.	20	20	21	2.5	3	1	-	-	-	0.15	0.15 N	
Nickel-based Superalloy	Nimonic 90	N	-	Bal.	18	20	-	-	-	2.5	1.5	0.1	0.1	B, Zr	
	IN 100	C	-	Bal.	15	10	-	3	-	5	5	0.2	0.2	B, Zr	
Cobalt-based Superalloy	HA 188	W	1.5	22	40	22	14	-	-	-	-	0.1	0.08 La	-	
Cobalt-based Wear-resistant Alloy	UmCo 50	C	22	-	50	28	-	-	-	-	-	-	0.1	-	
Refractory Metal	TZM	W	-	-	-	-	-	-	Bal.	-	0.5	-	-	0.08 Zr	
Platinum-Rhodium	-	W	-	-	-	-	-	-	-	-	-	-	-	80Pt,20Rh	

Irons and Steels

Cast irons

Conventional cast iron has been used for many years for grates and burners of combustion stoves, but progressive internal oxidation following the path of the graphite flakes leads to growth and distortion. This can be overcome by the use of austenitic cast irons containing nickel at levels up to 20 or even 25 per cent together with chromium and silicon, and these materials find application in combustion and heat-treatment equipment where stresses are not high but corrosive and erosive conditions are severe. They are serviceable at temperatures up to about 750°C.

Ferrite steels

Plain carbon and low-alloy steels are serviceable at moderate stresses at temperatures up to about 500°C but scaling due to oxidation limits their life at higher temperatures and the strength, in terms of creep resistance, falls steeply at temperatures above 400°C. The scaling resistance is improved by additions of chromium, usually in the order of 12 per cent, and strength by carefully balanced additions of molybdenum, niobium, vanadium, etc., so that there are many proprietary steels offering high strength and serviceability at temperatures up to about 600°C. Such steels are used for critical components, such as blades, in steam turbines.

Austenitic steels

These steels contain levels of nickel and chromium which are sufficient to stabilise the face-centred-cubic or austenitic structure at normal temperatures and to confer high corrosion resistance and, in general, good ductility. They range in basic composition from the simple 18 chromium, 8 nickel alloy normally used in the wrought form for a variety of corrosion-resistant applications, to 20 chromium, 35 nickel alloys used for moderately-stressed components in power plant. Many varieties of this broad class of alloy are commercially available with additions of molybdenum, manganese, titanium, niobium, etc. and with carbon up to about 0.5 per cent, to confer particular characteristics of strength or corrosion resistance. Most are used as wrought products but certain compositions are particularly chosen for use as castings.

Nickel-chromium Alloys

There is no structural difference between the basic austenitic steels referred to above and the high nickel alloys containing up to 80 per cent nickel with smaller contents of iron. Such alloys, typified by 60Ni, 24Fe, 16Cr; 76Ni, 8Fe, 16Cr and 80Ni, 20Cr, are widely in use, for their oxidation resistance at high temperatures, as electric heating elements and furnace parts and depending on the details of composition may be serviceable up to 1150°C.

Superalloys

This term has been adopted for alloys specifications developed to have high strength at temperatures in the range 700-1100°C. The alloys may be based on iron, nickel or cobalt, and normally require 15-20 percent chromium to ensure satisfactory oxidation or corrosion resistance. The high strength is developed by the precipitation or dispersion of fine particles throughout the matrix, usually by additions of titanium, aluminium or carbide-forming elements.

Iron-based superalloys

These alloys are developments of austenitic steels with nickel contents in the range 20-40 per cent, chromium contents usually 15-20 percent and sometimes with additions of cobalt. The strengthening precipitate is mainly the intermetallic compound γ' formed from additions of titanium and aluminium, but strength may also be conferred by carbides or nitrides of niobium or vanadium.

Nickel - based superalloys

The addition of small proportions of titanium and aluminium to the 80Ni-20Cr oxidation-resistant alloy produced the first of the now large family of nickel - base superalloys. The strengthening precipitate is the intermetallic compound $\text{Ni}_3(\text{Ti},\text{Al})$ termed γ' , while the fracture resistance is promoted by grain-boundary precipitates of carbides. In the many alloys now in this group additions of cobalt, molybdenum or tungsten may be made to the matrix, while smaller additions of niobium, zirconium, boron and other elements control and modify the character of the precipitates. Such alloys provide the most advanced superalloys required for the rotor blades of gas turbines, while other alloys of the family are adopted for other gas - turbine components and for highly stressed applications in many engineering fields. Most may be used as wrought components but the most highly developed are used in the vacuum -- cast form.

Cobalt-based superalloys

Hardening by γ' precipitation has not been applied successfully to cobalt-base alloys, but carbide precipitations using stable carbide formers such as niobium, tantalum and vanadium can give attractive high-temperature strength, and this, combined with their ready castability, has caused the alloys to be used in many applications in gas-turbine technology. Cobalt-base alloys are also prominent in the field of corrosion- and wear-resistant high-temperature materials. In these the corrosion resistance is conferred by chromium contents in the range 20-30 per cent and wear resistance is developed by large proportions of carbides formed from additions of molybdenum, tungsten or niobium with carbon contents up to about 2 per cent. These alloys are mostly used in the cast form, either as shaped castings or as weld-deposited coatings on other materials, and find applications as furnace parts in the metallurgical industry and as protective coatings on valve seats in internal combustion engines and various parts of steam turbines subject to steam erosion.

Refractory Metals

The metals with melting points above 1800°C have, as would be expected, high strength at elevated temperatures, but the commoner refractory metals, viz. molybdenum, tungsten, niobium, tantalum and vanadium all form volatile oxides, so that they cannot be used for long-time service in oxidising atmospheres without a protective coating. No alloying elements have been found to form a self-protective scale so that high-temperature applications of these metals have been restricted to short-time (e.g. rocket nozzles) or non-oxidising atmospheres (e.g. lamp filaments, vacuum furnace elements, etc.). Alloys based on these metals have mainly involved the addition of small proportions of reactive elements or dispersed oxides to act as grain-growth restrictions or to maintain ductility.

Other Metals

The metals of the platinum group and alloys formed from them, in spite of their scarcity and high cost, are important high-temperature materials used for thermocouple wires, glass-melting and working equipment, crystal-growing crucibles, aircraft spark plugs etc. Other metals with high melting points, e.g. chromium, titanium, are important alloying constituents, but their high reactivity inhibits their use as a matrix for useful high-temperature alloys.

METAL AND ALLOY PRODUCTION AND USAGE

The problems arising in the use of metallic materials in high-temperature engineering range throughout the full range of the science and technology of metallurgy, from the mining and extraction of the virgin metals from their ores to the study and investigation of components in service and the analysis of failures. In all these areas there is scope for research and development action aimed at improving the serviceability or economics of the products.

Mining, Extraction and Refining

The provision of adequate supplies of the constituent elements of an alloy in a suitable form and of satisfactory purity is an essential first step. Since the natural occurrence of the element in the ore deposits is often at a low level (less than 1 per cent) and at regions of difficult access in politically unstable or antagonistic countries, problems of transport, energy availability, manpower and economic balance arise, and may play an essential role in the selection of the most suitable procedure.

The major steps in the recovery process are:

(a) Mining: the deposits may be near the earth's surface and recoverable by open quarrying, or in deep mines; they may be soft, so that they can be dealt with by mechanical shovels or drags, or hard, needing explosives to break up the rock.

(b) Beneficiation: to separate the desired ore from the unwanted gangue or waste rock, methods vary from hand-picking to sophisticated magnetic or grind the ore to a fine particle size, and for flotation methods, to treat with surface active agents to select the ore from the gangue.

(c) Roasting and reduction: depending on the composition of the ore it may need roasting to convert to oxide, for example by expulsion of sulphur dioxide. The oxide is then reduced to crude metal by thermal treatment using carbon or hydrogen as the reducing agent.

Alternative processes now being more widely used are hydrometallurgical in character and involve the solution of the ore in chemical reagents and the reprecipitation of selected compounds of the required metal, which then provide the feed material for subsequent reduction.

(d) Refining: the crude metal will normally contain appreciable quantities of other elements and, particularly for the manufacture of high-temperature alloys, these may be deleterious to the properties of the final alloys. Refining is therefore necessary and may be carried out by processes such as chemical solution and reprecipitation, electrolytic deposition, vaporization, etc. While the processes may be generalised in character the details must be specifically developed for the metal in question.

In addition to the supply of primary metal by the processes outlined above, significant contributions to the current industrial demands are made by recycling used materials - so-called secondary metal. For most materials secondary metal is used for lower-grade products in which some contamination can be tolerated, but with the possible future reduction or exhaustion of primary supplies and the consequent increasing costs, the need for improved recycling procedures is apparent. The system currently used for the precious metals provides a basis for extension to other metals as the economic or supply situations justify it.

The process of recovery of metals from their ores and the provision of them at the site of application is highly energy intensive and consequently very careful study of the energy consumption at all stages, including transport, is necessary to ensure the most economical process.

Development of Alloy Composition

Most current high-temperature alloys have been developed by essentially empirical methods over a period of years, but parallel studies of a basic scientific nature have provided guidance as to the effects of composition and structure on mechanical properties. Studies of the mechanisms of creep and fatigue in pure metals and single- and multi-phase alloys, have all contributed to an understanding of the way in which composition affects properties, and have enabled the alloy developers to improve their products by the adjustment of contents of the major constituents, by the elimination of injurious contaminants, and by the addition of trace elements having a beneficial effect on structure (e.g. boron and zirconium in the effects on grain-boundary

structures and of yttrium on protective scale formation). Continuing research of this nature is therefore essential to support and stimulate metallurgical developments of all types.

Alloying and Consolidation

The primary metals may be supplied in a variety of forms ranging from cast pigs to powder and either as nominally pure metals or as intermediate alloys (e.g. ferro-alloys for the production of alloy steels or iron-based alloys). The conversion of these to the required alloy composition usually involves remelting under carefully controlled conditions to minimize contamination by unwanted elements. High-temperature alloys are conventionally, and still to a large extent, melted in electric arc or induction furnaces open to the atmosphere but under a cover of a protective slag. The slag is chosen to minimize atmospheric pick-up (both oxygen and nitrogen) and also aids in the removal from the melt of unwanted low-melting-point elements. For the more advanced superalloys, however, air melting is inadequate, and improved techniques have been adopted. First, electro-slag refining, in which an air-melted alloy is cast in the form of suitable ingot electrodes and then remelted by electric arc under a complete cover of reactive slag; further refining takes place in the molten pool and progressive solidification gives an improved structure to the ingot, aiding subsequent hot working. Second, vacuum refining or complete vacuum remelting, usually by induction methods, enables atmospheric contamination to be eliminated and reduces the content of unwanted volatile constituents. It has been established that even very low contents of some elements (e.g. lead, silver, bismuth) measured in a few parts per million are detrimental to high-temperature properties of advanced superalloys.

The molten alloy, adjusted to the required composition, may be cast into ingots for subsequent hot working or into bars for remelting for castings, but, particularly for larger components such as rotor discs for gas turbines, the ingot structure may be too segregated and coarse grained for satisfactory forging or to give uniform properties. The alloy may therefore be blown by inert gas to produce an alloy powder for subsequent consolidation. The powder may be pressed to form in shaped dies as in conventional powder metallurgical techniques, but for critical components in advanced high-temperature alloys is more likely to be hot isostatically pressed. This involves enclosing the powder in an evacuated metal container and hot pressing using an inert gas as the pressure medium. A very uniform fine-grained compact is thereby obtained, suitable for further hot working. An additional advantage of the powder route to consolidated materials is that dispersion-strengthened alloys are readily produced. In such materials finely dispersed stable non-metallic compounds, usually oxides, are incorporated to the extent of a few per cent by volume, and provide additional strength at temperature higher than those at which intermetallic compounds are effective.

Working with material

The consolidated material in the form of cast ingot or pressed powder compact is now required to be shaped to be an intermediate form from which the final component is to be machined. Hot-

working processes are normally used and these serve to break down the coarse grain size and segregated structure of the ingot, thus improving the uniformity of properties of the material. Hot working may be by hammer or press forging, extrusion or hot-rolling, and the conditions of temperature, deformation rate, lubrication, etc., need to be separately developed for each particular material and for the form of product required. Some products such as sheet, tube and wire require further stages of cold working which again require careful development to ensure that a satisfactory and consistent material is obtained.

The more advanced high-temperature materials are not workable even at temperatures close to their melting points, and hence must be cast to form. Precision casting by developments of the lost-wax technique are used, and to avoid atmospheric contamination may be carried out entirely in vacuum. Improvements in pattern production, moulding, melting and pouring techniques all contribute to advancement of this art in high-temperature materials technologies and may be expected to be applicable to other metallic materials.

Machining

The conversion of intermediate forms to the required final shape of component involves machining of the material. The hardness, and in general rapid work-hardening characteristics of high-temperature alloys, make this often a difficult process and although conventional high-speed steels and sintered carbide tools are widely used, alternative methods are being sought and brought into use. Spark machining and electrochemical methods are already established and other high-energy methods, such as the use of lasers, electron beams and ultrasonics are of interest. Continuing research on this topic can yield benefits to many fields of engineering production.

Heat Treatment

The properties of high-temperature alloys are critically dependent on the metallurgical structure developed by controlled heat treatments, which may be carried out before or after machining to final form. The treatments often need to be effected in controlled atmospheres or environments to avoid detrimental surface reactions, or to produce surface layers with improved mechanical or corrosion-resistant characteristics. Heat treatments may also be designed to minimise internal stresses or, in special component shapes to develop favorable stresses to combat the initiation of fatigue failures. The study of heat treatment and its association with controlled mechanical deformation is a fruitful field of investigation for all metallic materials.

Joining

Particularly for larger complex installations such as boilers and petrochemical plant, the individual components must be joined together either by dismantable mechanical joints or by permanent or semi-permanent methods. Welding is the most widely used permanent joining method and for the less ductile of the high-temperature materials difficulties arise due to cracking in the weld metal itself or in the heat-affected zone alongside the joint. The choice of

welding method and of the consumable materials -electrodes or filler wires- depends critically on the parent alloy and the dimensions of the parts to be joined, as well as on their location and mobility. Much research is in progress on the welding problems associated with high-temperature materials and should continue, particularly on the high-energy-input processes such as electron beam welding and laser welding. The higher strength high-temperature alloys are not weldable even in quite thin sections, and semi-permanent joints made by brazing, or perhaps diffusion bonding, are possible alternatives. Brazing alloys with melting points in the range 900-1200°C have been developed specifically for use with high-temperature alloys, the most familiar of which are the gold-nickel alloys or those based on palladium alloys. Improvement in these alloys and in the techniques of their use, as applied to the superalloys and the refractory metals, could lead to benefits in other engineering fields.

For all types of joint data are required relating the mechanical strength of the joint to that of the parent material at the temperatures and stress levels of interest.

Protection

The search for high strength at elevated temperatures has eventually led to alloys which have inadequate inherent resistance to environmental corrosion at the service temperature and hence to the need to develop protective coatings.

Specifications and Testing

In order to ensure the reliability and consistency of materials used for engineering purposes it is necessary that specifications should be established for the benefit of producer and user. These may be individually arranged between the two parties or established by industrial, national or international bodies. The specifications normally define the composition of the material and the type and limits of specific property tests required. The formulation of specifications should be in the hands of both engineers and material scientists, so that all factors of importance are taken into account.

Similar considerations apply to the preparation of design codes which define the way in which material property data are used in engineering design. Such codes are of especial relevance in high - temperature engineering where interpolation or extrapolation of property data in terms of time or temperature is often necessary. The various attempts being made to correlate creep and fatigue data by mechanistic or phenomenological methods are aimed at giving greater confidence in these procedures. The acceptance of materials in their part-processed form and as finished components rests on testing to specification requirements and to such proof testing and non-destructive testing as is feasible. The latter field, embracing radiography by X-rays or y-rays, ultrasonics inspection and various electrical and magnetic tests is a progressive field of research the results of which are generally applicable to all materials.

Failure Investigations

Inevitably from time to time failure occur in service and much can be learnt by careful scientific study of these. Material faults may be diagnosed or design faults identified, and steps then taken to remedy the shortcomings. In the same area of study are the attempts being made to assess the remaining life of high-temperature components after a period of service, for this would enable the safe life of plant to be extended without risk of early failure. Recovery treatments by thermo-mechanical processing are also possible, and indeed are already partly in use, particularly for aero-engine gas-turbine blades.

REFRACTORIES AND CERAMICS FOR HIGH-TEMPERATURE SERVICE

Conventional Refractories

Non-metallic materials have a long history of usage in high-temperature technology, mainly as thermal insulating and containment materials for such purposes as metal-melting crucibles, hearths and linings for pottery kilns and for industrial furnaces of all types. For such applications strength is an important factor but is not the primary requirement, since failure usually results from thermal cracking due to temperature changes, or from reaction with the contained material. The high-tonnage refractory materials of this type are mainly mixed oxides or silicates and the commercial materials have been developed to balance performance against cost. For more critical applications pure single oxides are increasingly used, alumina, zirconia, magnesia and beryllia being the commonest, since these generally have higher melting points than the mixed oxides.

Advanced Ceramics

Non-metallic materials other than oxides have become of increasing importance in high-temperature technology in recent years. Silicon carbide, long known as an abrasive and also for many years as a high-temperature electrical furnace element, is finding increasing use in a variety of advanced refractory applications, particularly in the self-bonded or reaction-bonded form. The high strength and low density of this material make it a strong candidate for certain aero-space components. Similarly silicon nitride provides competitive levels of strength and hot-corrosion resistance. Both these materials are formed from cheap and abundant elements so that there are no problems of availability, and the cost of components made from them will depend on energy costs and the level of commercial demand. Many other non-metallic materials, elemental or compound, are being examined in the light of their possible merits as high-temperature materials, and these include oxides, carbides, nitrides, borides and silicides, predominantly of the higher-melting-point refractory metals, but also of the more reactive metals such as aluminium, magnesium and calcium which can form compounds of high thermal stability. In the same class of advanced non-metallic refractory materials must be included carbon. Although its oxidation resistance is generally poor, so that it can only be used at high temperatures in a protective atmosphere or vacuum, it can be obtained in a range of crystalline or vitreous

forms, depending on the production process adopted, so that its extremely high melting point can be exploited.

Production and Consolidation Processes

The constituent compounds of ceramic materials are derived either from naturally occurring deposits of suitable precursors, which may be purified by conventional chemical means and then thermally decomposed to yield the oxide, or by high-temperature exothermic reactions between the elements to be combined or between selected compounds of them, often gaseous, e.g. ammonia to produce nitrides. The required compounds are usually obtained in the form of powders or crystals, which may need milling to refine the grain size, and they must then be consolidated. This is the step that offers considerable scope for the development of special methods appropriate to individual materials. The common methods include slip casting, cold pressing or paste extrusion, all followed by sintering; hot pressing; hot isostatic pressing; activated or reaction sintering; fusion casting; and deposition by chemical vapours or by pyrolytic decomposition. In most all these processes the effect of particle size of the powders, and of the presence of small proportions of impurities or added compounds, may have critical effects on the properties of the resultant material.

The shaping of ceramic or refractory materials to the required form presents considerable difficulties since many of them, and certainly the more advanced fully-densified materials, can only be machined by the use of diamond tools. The tendency, therefore, is to employ the materials in relatively simple forms which can be produced directly by the consolidation process, or to machine in the "green" or partly-sintered condition, with allowance for shrinkage in final sintering to be within acceptable limits. Research on consolidation processes and their effects on shrinkage and resultant mechanical and physical properties are hence of major relevance in the application of these materials.

Mechanical, Physical and Chemical Properties

Ceramic materials are essentially brittle in character and their mechanical properties cannot be directly compared with those of ductile metal alloys, since different testing procedures are adopted. Bend tests normally take the place of tensile tests and the fracture stress is reported on a statistical basis since the results are more scattered due to the influence of minor flaws. Nevertheless measurements of bend strength against temperature and of time to fracture against bending stress provide a suitable basis for the comparison of different high-temperature ceramics and for the assessment of their temperatures of serviceability. These data need to be supplemented by determinations of impact strength and thermal shock resistance, which properties, in general, are much lower than those for metals. Application of recent developments in fracture mechanics should improve the confidence with which these brittle materials can be used.

The physical and chemical properties of ceramic materials are required for design guidance, with particular attention being paid to the influence of environmental attack on fracture characteristics. Surface changes may promote or inhibit crack propagation.

Testing

Procedures for inspection and testing, and analysis of service failures must be developed and applied in exactly the same manner already referred to for metallic materials.