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Review of high temperature materials

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Abstract
High-temperature materials play a significant role in sustainable engineering across various industries and applications. Sustainable engineering aims to design, develop, and implement solutions that minimize environmental impact, enhance resource efficiency, and promote long-term sustainability. The availability of substances that can be used efficiently at high temperatures allows pushing the limits of possible measurable demands. These substances include ceramics, polymers and metals. It is used in elevated temperature materials, aircraft and space structures, and space exploration. In this study, high temperature metals are classified including superalloys, platinum and refractory metals, refractory metals such as W, Nb, Mo, Ta. Also, ceramic materials are high temperature materials. Ceramics are criticized to use in elevated temperature due to their high hardness, extraordinary strength in compression, excellent thermal stability, short-term thermal extension and tremendously great melting temperature. Ceramics that encounter these standards are carbides and borides of Zr, Nb, Ta, Ti and Hf. In addition, steel, nickel and copper alloys used in aircraft engines, space shuttles and turbine blades from aerospace materials were investigated. In addition, powder metallurgy and sintering techniques, which are the most widely used production methods of high temperature materials, are emphasized. In this study, important characterization techniques for analyzing some sample surface and subsurface properties are reviewed. Again, in this study, the use of AES, XPS, SSIMS and LEED methods for the chemical examination of surfaces is discussed. Optical, electron, and scanning probe microscopy is used for pictorial inspection of inspection specimens and structures, obtaining data on surface, shape, colors, and numerous additional physical properties. Here, AFM, SEM, TEM, EDX, FIB and EMP methods are discussed. Among the material analysis devices, XRD, x-ray fluorescence spectrometry, low energy electron diffraction, neutron diffraction and electron microprobe devices were examined.

Keywords: High temperature material, Sustainable engineering, Applications, Characterization

1. Introduction

From the moment people started to work with fire and heat, they utilized substances that can withstand high temperatures. Primarily, primitive peoples utilized rocks they collected from their neighborhoods. Nowadays, the assortment of high-temperature materials has been expanded to include metal alloys such as superalloys, stainless steels, titanium alloys, and refractory metals. Uses of elevated-temperature substances comprise airplane jet engines, nuclear reactors, gas turbines, furnaces, and lighting expedients.

For use at high temperatures, both the type of material and heat treatment [1] and coating [2] are important factors. In a previous study, the effect of heat treatment in an oxygen-containing environment on the fatigue properties of zirconium alloy specimens was demonstrated [1]. In this study, it was observed that the applied oxygen gas treatment improved the fatigue life in bending and tensile tests. The increase in fatigue life was explained by the formation of a layer near the hardened surface. In the second study [2], strain localization in heat resistant nanocoated steel at crack nucleation, coalescence, and fragmentation stage of nanocoating was investigated experimentally. The obtained results prove that the plastic deformation of the material leads to the formation of multiple cracking and micro-fragmentation processes in the nanocoating.

Usually, in materials science, the term elevated temperature is demarcated as the temperature greater than or identical to approximately two-thirds of the melting point of a solid [3]. Nevertheless, there are additional descriptions, as defined by Meetham and Voorde [4], which are based on application and indicate materials used for heat resistance above 500°C. Since the increase in temperature reduces the substance strength, they must have high strength with a safety margin at the required operating temperatures to be operational and inexpensive. Elevated-temperature substances should be sturdy to associated reasons of destruction, for example corrosion and oxidation, which are enhanced by temperature rise. As the temperature upsurges, numerous effects occur, counting deterioration of the material structure.

Incorporating high-temperature materials into sustainable engineering practices helps improve resource efficiency, reduce emissions, and enhance the overall sustainability of processes, systems, and products across a wide range of industries. High-temperature materials are essential for sustainable energy generation technologies such as gas turbines, steam turbines, and nuclear reactors as well as aircraft engines and propulsion systems. These materials can withstand extreme temperatures and harsh conditions, enabling more efficient and reliable energy production. Improved efficiency reduces resource consumption and emissions per unit of energy generated, contributing to sustainability.

In this study, high temperature materials were classified and examined, their application areas were reviewed, and aerospace materials were emphasized. In addition, the production methods of these materials were investigated and the characterization methods were examined, and the issues related to the future were examined in general.

2. Classification and applications

High temperatures are essential for numerous requests. Substances for a particular high temperature request are selected according to the application temperature, the surroundings in which they will charge, and the duration at the temperature. The description of what establishes an elevated temperature is comparative; because it depends upon the situation or request and is dissimilar for disparate supplies. For instance, 550°C is an identical elevated working temperature for Al, which thaws at 660°C, while it is a stumpy temperature for W, which does not thaw till 3400°C.

2.1 Sorts of elevated-temperature substances

2.1.1 Elevated-temperature metals

Generally, metals have higher density and ductility than ceramic or non-metal matrix composites. Another words, they are not conditional on brittle degradation. By its nature, it has greater thermal and electrical conductivity than most metals, ceramics, or non-metal matrix composites. Superalloys, platinum and refractory metals are three different types of high-temperature metallics. Superalloys are generally founded on group VIIIA rudiments such as Ni, Fe and Co. These alloys have outstanding mechanical strength, resistance to creep and phase stability. These alloys are used in the hot segments and turbine blades of gas turbines, turbocharged turbines and jet engines (Fig. 1). Pt, Rh and Ir, whose melting points vary between 1770°C and 2450°C, know their alloys as thermocouples and are used in places that require resistance to high temperature and chemical attacks.

Refractory metals such as W, Nb, Mo, Ta, Re all have melting points in surplus of 2400°C (2477–3400°C), are exceptionally sturdy to heat, abrasion and flow, and are relatively chemically inert. These metals are similarly utilized, for instance, in the forging of rocket nozzles, jet engines, and incandescent lamp filaments.

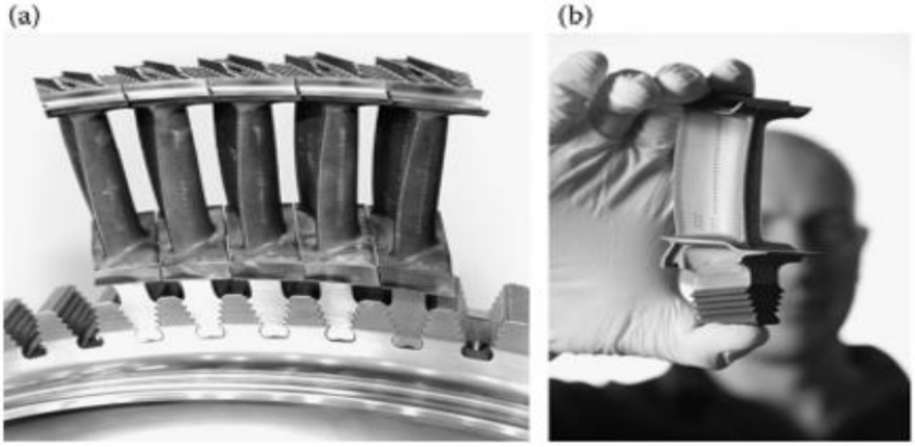

Figure 1. Schematic view of a jet engine turbine a) blades b) cooling channel

2.1.2 Ceramic materials

Ceramic supplies are elevated-temperature materials, and some are UHT supplies. Ceramic resources are inorganic, non-metallic substances prepared from combinations of a metal and a nonmetal. Ceramic resources can be crystalline or amorphous, and the mainstream are detained overall by covalent or ionic links. Unlike metals, the robust bond in ceramics reasons these materials to breakage before plastically deforming if the temperature is underneath the brittle-ductile transition (DBT) temperature.

Ceramics are used in applications such as high hardness, elevated strength in compression, excellent thermal constancy, stumpy thermal extension and tremendously elevated melting temperature. Requests comprise heater rudiments and lining, catalytic converters (Fig. 2), thermal barriers, ball bearings, and fuel cells. It is utilized in surroundings that involve durability in addition to conservation resistance to erosion and wear at tremendously elevated temperatures. Ceramics that encounter these principles are mainly carbides and borides of Zr, Nb, TaTi and Hf.

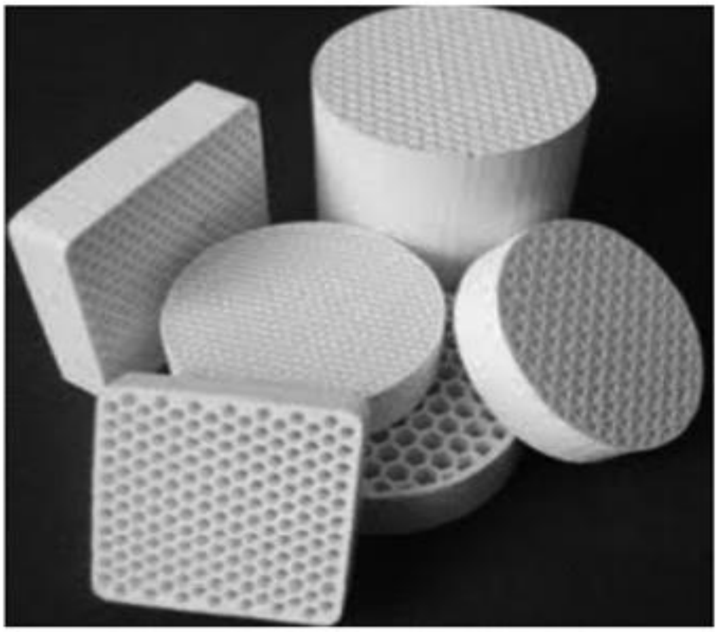

Figure 2. Ceramic catalytic converter

2.1.3 Elevated-temperature composites

Composites include a huge group of substances [5], wherein the strengthening phase is embedded in an incessant matrix phase, subsequent in possessions that are not likely to achieve by a solitary substance. The strengthening may be in the arrangement of particulate, whisker, incessant or intermittent fibers, nanotubes or nano-phase particles. In elevated-temperature composites, the strengthening and matrix substance is restricted to ceramic, metal, and carbon.

It should be noted that the improved properties of the compounds are due to the function of their components. Matrix and strengthening play complementary functions. For instance, in a fiber-supported composite, the fibers are the main load-bearing constituent. The matrix impasses the fibers completely, keeping them allied to convey the load, and transferring the load smeared to the composite to the fibers via the fiber-matrix tie, enabling the composite to endure compression, bending and shear forces and tensile loads.

When pairing a matrix material with a fiber, it is important to have chemical and thermal compatibility. Usage temperatures can cause the matrix to crack during cooling at what time thermal extension disparity is existent. Chemical compatibility also averts deprivation of the fiber-matrix interface at high machining, heat treatment and usage temperatures. Deterioration can be produced by chemical responses amid substances or by phase variations in both components. Coatings are smeared to defend the fibers from chemical bout, for example when carbon fibers are used in a SiC matrix. Fiber coatings are also used to adapt the strength of the bond between fiber and matrix. This bond strength, when too strong, causes a decrease in the toughness of the composite.

3. Aerospace materials

Elevated temperature procedures and uses need their related constituents to spread high temperatures with concerns on material possessions. Elevated temperature oxidation is one such result and outcomes from chemical responses with the nearby atmosphere. Contingent upon harshness, substance enactment may suffer due to surface stagnation or internal brittleness, which places confines on temperatures and periods of use. Coatings, chilling arrangements or gas alterations are frequently used to counter these belongings and deliver a harmless working cover.

The oxidation and corrosion of HTM is significant in an extensive variety of requests. Many industrial processes, for example, forging, rolling, heat treatment, chemical arraying, and the like, depend on the high temperatures of the processing apparatus in addition to the product material. Heat exchangers, boilers, and fuel cells are some particular instances. In the aerospace expertise arenas, these uses comprise the rocket engines and hot stages of airplane engines.

Understanding the oxidative and corrosive procedures in a request primarily involves identifying the surroundings to which the constituent is exposed. Airplane turbine engines characteristically blister an extraordinary clarity hydrocarbon fuel. A graph of the fuel-air ratio versus equilibrium combustion products at characteristic adiabatic lame temperatures of ~1000–2400 K. These are intended with NASA CEA code [6] and overall compression 1. rod. Real overall compressions in a gas turbine can be 10 bar or more. Aircraft turbine engine can reach extremely high temperatures with hot stages, re-entry surfaces, meaningfully inferior overall gas pressures and actual small exposure times.

3.1 Metals, alloys and intermetallics

Essential alloying elements for example Ni, Co, Fe, Ti, Cu, and the like, used to formulate structural alloys, are alloyed to varying degrees with numerous elements to achieve a steadiness between good mechanical possessions and oxidation resistance. Al, Cr and Si are the utmost beneficial in so long as oxidation resistance. As these numerous rudiments are included at low stages, the oxidation performance variations to interior oxidation of the more stable oxide. To evade mechanical property effects, a subordinate deoxidizer for example Cr or Si to Ni-Al alloys is used to support specific Al2O3 scale progress [7, 8]. Here, two effects occur on the passing oxidation order. The first is the aid of a subsequent steady oxide in the primary surface coating of the alloy. This inclines to "suffocate" additional advance of the rapidly rising non-protective NiO base metal oxide.

Ideally, if all components behave similarly, symmetric transitions to alternative outer scales can be expected to appear Case A in a triple-scale formation map. Nevertheless, the role of the subordinate acceptor produces an expanded defensive region of the strongest dopant (Case B), as predicted from its position in the thermos-kinetic diagram. These ideas affect the occurrence recognized as passing oxidation. This is just a transitional retro in which oxides of other rudiments appear before steady-state progress of the stable, curative, defensive layer. Upper oxidation degrees are associated with this retro. Though this occurrence can persist for an important period of time, the rather it vanishes, the more probable the alloy will be valuable as an oxidation-resistant substance.

3.1.1 Copper alloys

With a melting temperature of 1083°C, copper is not usually reflected an elevated temperature alloy, nonetheless merits singular attention since the space shuttle uses the copper alloy NARloy–Z (Cu–3Ag– 0.1Zr, wt.%). This request of Cu substances is due to the penetrating thermal load of hydrogen-oxygen rocket drain in excess of 3000°C, which will abolish most substances. Nonetheless the behind refrigeration with -250°C liquid H2 and the extraordinary thermal conductivity of Cu ensure the survival of this alloy. While classical oxidation is not observed with an integral surface scale, the substance damages in an occurrence recognized as "bleaching". At this point, transitions in the exhaust gas yield a cyclical oxidation-reduction procedure with substance ingesting and flagging of tinny pieces, perhaps from start-up and shutdown. There are numerous oxidation investigations on Cu alloys [9-12]. In one instance, 17% Cr (by weight) was found to reduce growth rates, nonetheless inadequate to form a curative Cr2O3 layer.

3.1.2 Steels

Steels denotes the most common usage of metals by mass, with important requests at (slightly) raised temperatures (500°C), characteristically utilizing Cr–V–Mo steels. Requests comprise boiler containers and exhaust and steam pipes, turbine chutes and initial turbine compressor blades. Cheap, low alloy carbon steels can be utilized underneath ~400°C anywhere oxidation is fewer of a problematic. For upper temperatures up to ~650°C, greater Ni and Cr substances are essential for strength and oxidation resistance, prominent to more expensive stainless steels. Partly due to poor oxidation resistance, load-bearing low-carbon steels have been reduced to comparatively stumpy temperature systems (~370°C). Great Cr, Ni austenitic stainless steel alloys display superior oxidation resistance and have valuable strength at 650°C. Also, numerous kinds of stainless steels can display an extensive distinction in oxidation behavior (Fig. 3) [13]. As shown in Figure 4, a delicate balance has been achieved amid alloying for strength (Nb, C, B) and alloying for oxidation resistance (Al, Cr, Si, Hf, Y) with excellent developments in oxidation performance. Likewise, significant, the cost of AFA alloy is about 2 fold that of 347, nonetheless meaningfully fewer than advanced-strength Chroma previous for example Haynes Alloy 230 or Incoloy 625. FeCrAlY heater alloys can also be reflected in this Fe-based grouping. These usually contain ~20–25% Cr, 5% Al and 0.1 Y.

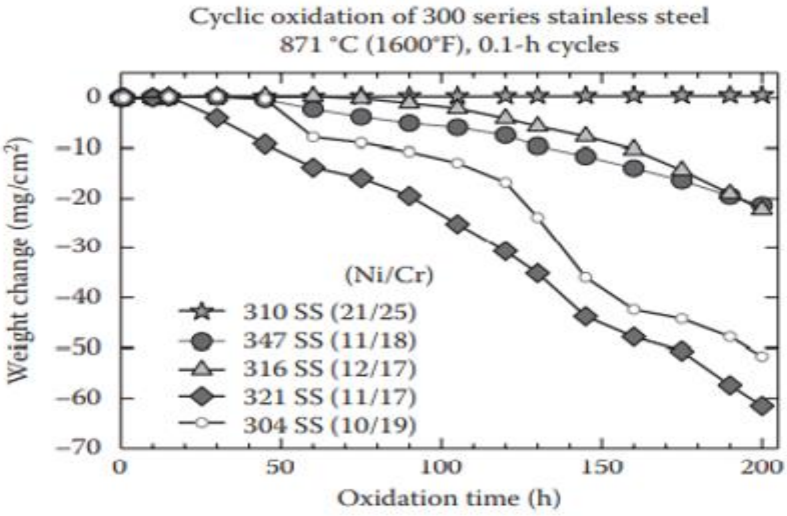

Figure 3. Oxidation behavior of numerous stainless steel [13]

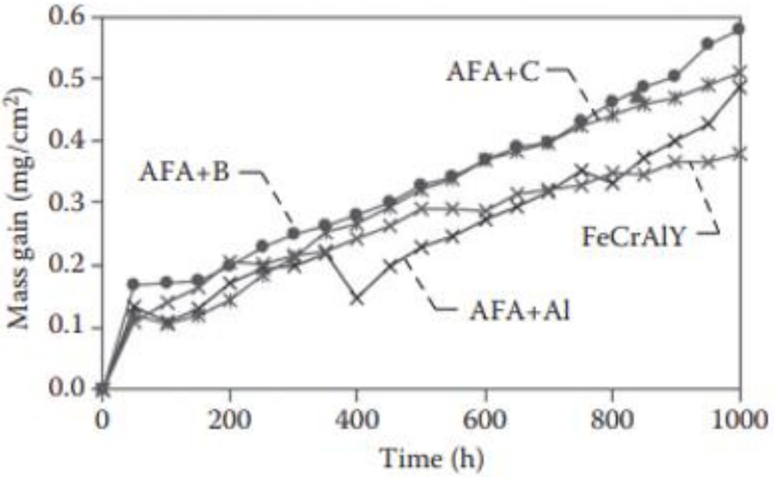

Figure 4. Oxidation behavior of aluminum oxide and stainless steel [13]

3.1.3 Nickel-based alloys

The origins of elevated-temperature Ni-based alloys can be traced back to initial Ni-Cr alloys, where accompaniments of Cr formed Cr2O3 flakes and delivered about oxidation resistance at middle temperatures. Additional multifaceted Fe–Ni–Cr alloys propose lucrative machined substances that evolve with additions of refractory elements such as Ta, Nb, W, Mo for reinforcement. Cast alloys usually have an addition of about 5% (by weight) aluminum.

Factually, a great body of oxidation investigation and alloy improvement has been resulting from the utilize of cast Ni-based super alloys in turbine appliances. Vital mechanisms comprise the combustion chamber liner, turbine blade and bladed air profiles, and the discs to which the blade profiles are devoted. The driving force of radical substance growth is higher turbine efficacy and abridged emissions formed by upper working temperatures. Characteristic single-crystal configurations are 5–10 Co, 5–10 Cr, 5–6 Al, 6–12 Ta and 4–6 wt% W, equilibrium Ni. They are developed from conservative cast or machined alloys, usually containing upper Cr and inferior Al, and sometimes upper W, Mo, Nb, Ti or V. Cr and Al provide oxidation resistance, while Ti, Nb and Ta separate into the γ'-Ni3Al cuboidal precipitate reinforcement phase and strengthen it. Great additions of Mo, W, and Re with high melting point and slow spreading deliver γ-Ni solid solution reinforcement and creep resistance.

The interaction amid Cr and Al monitors ample of what has been educated around fleeting oxidation and ternary oxide maps. Exactly, Cr supports Al in closing an uncovered metal surface with the concurrent creation of Cr2O3 and Al2O3, both mod energetically favored over fast-growing NiO [14]. Ultimately, a comprehensive Al2O3 layer develops and the oxidation rate stabilizes at a small equal. These instruments are reproduced in the oxide maps, which display the significantly abridged Al content (5%) essential to create custom Al2O3 scales by accumulation ~5% Cr, in contrast, corresponding to ~20% Al required deprived of Cr (Fig. 5).

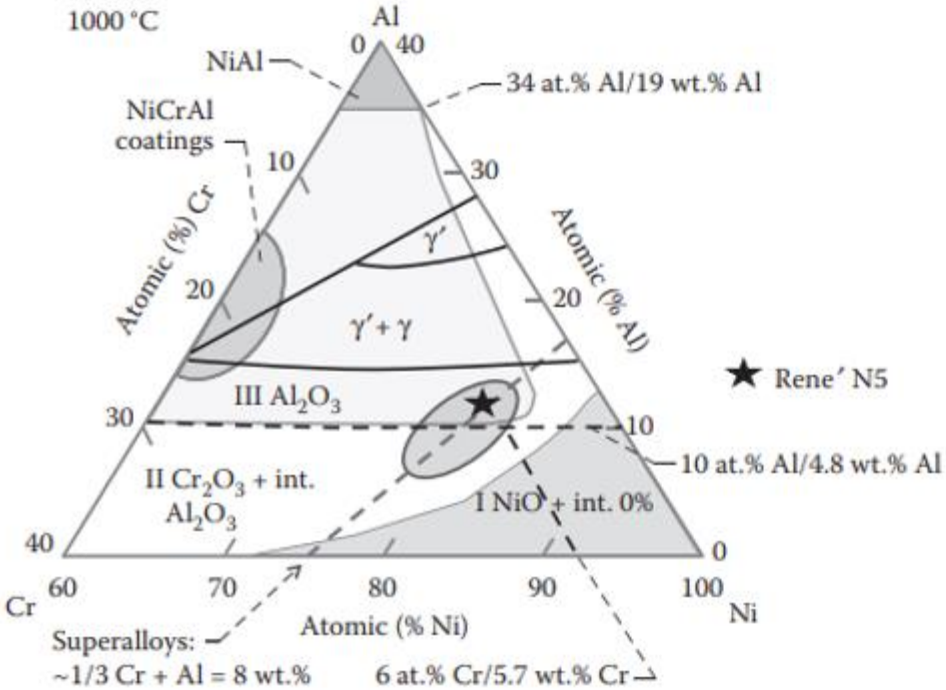

Figure 5. Ternary diagram of Al-Cr-Ni alloys examine at 1000 ºC [14]

4. Processing

Ultra-elevated-temperature ceramics (UHTCs) are a period of supplies applied in extreme temperature and pressure environments. Some researchers select to describe UHTCs by their melting temperatures, referring to temperatures reaching from 2500°C to 3000°C [15]. Further investigators think that UHTCs should be able to operate at working temperatures of 1800–2500°C [16]. But most substances categorized as UHTC cannot endure lengthy contact at these temperatures if the atmosphere is oxidizing.

We will select to arbitrarily describe UHTCs as nitrides, borides, silicides, and carbides with melting temperatures beyond 2000°C. For instance, SiC has an inferior melting temperature than zirconium and hafnium diborides, but is utilized as a preservative to recover the oxidation resistance of these substances at high temperatures [17]. A partial list of materials considered UHTC is provided in Table 1. It may be essential to remain to change the description of UHTCs as UHTC composites are intended to endure the punitive circumstances of numerous requests and varieties of circumstances.

The utmost shared UHTCs are non-IV-VI change metal oxides. Carbide and nitride combinations, both of which drop into this group, can be measured as intermediate combinations [18]. The electronegativity change amid the two rudiments (ie transition metal and carbon or nitrogen) is huge; therefore, the dimensions of the carbon and nitrogen atoms are minor adequate to fit into the gaps of the metal lattice. The bond in these substances is metallic, leading to extraordinary electrical and thermal conductivities, but is also partially covalent and ionic, foremost to the refractory and brittle nature of the compounds.

Additional UHTC substances, for example silicon and boron carbide, are categorized by low electronegativity, small element size changes, and bonding that is fundamentally covalent [18]. In Table 1 there are about 240 binary UHTC substances with a melting temperature beyond 2000°C and as a minimum 130 UHTC materials with a melting temperature beyond 2500°C [19]. The usage of oxides, sulphides and phosphides on their own has not been so well developed for UHTC applications.

Table 1. Several UHTC compounds and their melting temperatures [18]

Compound	T_m (ºC)	Compound	T_m (ºC)	Compound	T_m (ºC)
HfB_2	3370	HfC	3830	NbN	2630
LaB_6	2450	SiC	2550	NB2N	2630
MoB	2180	TaC	3830	TaN	2630

NbB_2	3000	TiC	2940	Ta2N	2950
TaB_2	3270	WC	2790	TiN	2950
TiB_2	3230	AlN	2200	VN	2350
ZrB_2	3000	BN	2970	ZrN	2960
B_4C	2450	HfN	3330	MoS2	2020

4.1 Powder synthesis

A particular problem with the fabrication of UHTC composites is that their high melting temperatures and instability in oxygen environments make them luxurious to procedure and meaningfully hamper their aptitude to be used in a diversity of requests. Creating very fine and well-dispersed powders has the possible to lower sintering temperatures and periods throughout merging, thus plummeting machining prices. From a financial point of view, this is highly anticipated.

Combination can be performed by a diversity of methods and can be divided into three groups: top-down, bottom-up, and transitional attitudes. In the top-down method, a large construction is wrecked down into lesser parts by means of physical or chemical approaches. In the bottom-up method, atomic or molecular types are combined into arrangements for example particles, wires, or rods. Transitional methods may include a combination of top-down and bottom-up combinations. The full extent of powder synthesis cannot be easily enclosed, and consequently only an outline will be made here, focusing on the significant thoughts that must be made through creation. There are many resources obtainable to the involved reader to obtain more details about the various synthesis methods [20]. A list of obtainable methods for top-down and bottom-up practices can be tabulated in Tables 2 and Table 3, correspondingly.

A perfect combination technique that will consequence in best association should produce fine powder crystallites with low stages of aggregation, high phase and high chemical cleanliness. It must be energy effectual, fast, ascendable and flexible for the construction of various material groups, also in terms of cost. All characteristic combination approaches meet some of these standards, but frequently lag behind a few crucial desirable properties.

Table 2. Top-down methods [20]

Technique	Specific Examples
Mechanical energy methods	Ball milling Rolling and beating Extrusion and drawing Mechanical machining/polishing/grinding Mechanical cutting Compaction and consolidation Atomizing
Thermal fabrication methods	Annealing Electro polishing Liquid dynamic compaction Gas atomization Evaporation Template extrusion Sublimation Polymer carbonization
High-energy and particle methods	Arc-discharge Laser ablation Solar energy vaporization Ion milling Electron beam evaporation Pyrolysis Combustion

	High energy sonication
Lithographic methods	LIGA techniques Photolithography Immersion lithography Electron beam lithography Focused ion beam lithography Nanoimprint lithography Scanning atomic force microscopy nano-stencil Scanning probe nanolithography
Chemical methods	Chemical etching Chemical-mechanical polishing Electro polishing Anodizing

Table 3. Bottom-up methods [20]

Technique	Specific Examples
Gas-phase methods	Atomic layer deposition Thermolysis-pyrolysis Organometallic vapor phase epitaxy Molecular beam epitaxy Ion implantation Gas phase condensation
Liquid-phase methods	Molecular self-assembly Super molecular chemistry Nucleation and sol-gel processes Reduction of metal salts Single-crystal growth Electrodeposition / electroplating Molten salt solution electrolysis Template synthesis Combustion
Physical vapor deposition	Vacuum evaporation Sputtering Molecular beam epitaxy
Chemical vapor deposition	Atmospheric pressure chemical vapor deposition Low pressure chemical vapor deposition Plasma assisted chemical vapor deposition. Photochemical vapor deposition Laser chemical vapor deposition Metal organic chemical vapor deposition Chemical beam epitaxy Chemical vapor infiltration

In summary, there are many issues to be addressed, and with recent developments allowing rapid sintering procedures for example spark plasma sintering to attain nanoparticle structures, the field is poised for major breakthroughs. The encounter with UHTCs remains the extraordinary sintering temperatures required for full densification, and this temperature can be problematic to attain deprived of supporting overstated grain growth.

Furthermore, the usage of such substances in extremely oxidative surroundings is a problematic as they are extremely vulnerable to deprivation which can lead to worsening of possessions. Some UHTCs are restricted by the creation of defensive oxide flakes on their surface. The overall method to obtain an appropriate oxide measure is the design of composite substances.

There are two customs to project degradation-resistant materials: (1) the progress of a completely defensive oxide scale or (2) the improvement of a partly defensive oxide scale where ablation can be properly measured. For the former to be actual, the oxide scale must be shown to be protective under the atmospheric circumstances of the request and throughout the whole request period. Oxidation should slow down or remove scale additional oxidation will be measured defensive and will never lead to an enhanced and energetic oxidation state where residue and fundamental substance are quickly detached from the UHTC surface. Upholding a defensive oxide scale delivers the protection and reliability that would be required for a UHTC constituent.

A partly defensive oxide scale should be completely defensive at stumpy and medium temperatures. Nevertheless, in the utmost thrilling heating circumstances, measured ablation of the substance can donate to heat elimination courses by removing it along with the gases shaped through decomposition.

Reusability is another key consideration to decrease prices and additional encourage the usage of UHTCs for progressive thermal defense schemes. In this respect, a completely defensive oxide flake is additional helpful than a partly defensive oxide flake based on ablation.

5. Characterization

In general, image examination is extensively utilized to study physical construction. For the analysis of the surface of the material, the informal straight convenience to the surface permits the request of numerous logical utensils. Examination of constructions underneath the surface is completed with methods that allow the understanding and measurement of interior properties, including stress and strain, and chemical configuration.

There are numerous logical methods used to study high-temperature materials. Here, some important techniques are reviewed.

5.1 Material and process analysis

Substances advanced for high temperature requests need trying at numerous phases of their lifetime, from investigation and improvement to withdrawal from usage. These approaches can be utilized to aid in substances development, pre-service quality pledge, in-use characterization, or failure analysis. Visual inspection of materials may include photographic imaging and the usage of an optical microscope.

Challenging is characteristically achieved: (a) during manufacture, (b) before service, (c) through service, and (d) after a failure to control the foundation. Description of substances comprises chemical, mechanical, micro/macro, destructive and non-destructive analysis and testing. Testing may include elemental analysis, microstructure, phase analysis, and whether the material meets the required requirement(s). Trying may also comprise examination of fracture, creep, fatigue, wear, distortion, corrosion control, material assessment and improvement. Furthermore, examinations may comprise microstructure assessment, grain size purpose and examination of heat treatment, in addition to pore or law documentation and hardness testing.

Microscopic tests can be achieved to define microstructure, carburization and decarburization, coating width, intergranular corrosion, surface infection, number of nodules.

To decide the mechanical possessions of the test substances, coupons of numerous configurations are made (Fig. 6, right dog-bone coupon example) and mechanically tested (Fig. 6, left). Tests, heating, cooling, humidity, etc. and strain, plastic distortion, failure pattern, and several additional properties are inspected. Additional tests may comprise determination of residual stresses, toughness at high temperatures, and thermal tests to determine high temperature deformation. In addition, tribological capacities and tests are achieved to inspect friction, lubrication and wear properties.

Figure 6. Tensile test machine (a) and a standard specimen (b)

5.1.1 Chemical analysis methods for surface

Surface chemical examination is significant for the description of high temperature substances for the following causes:

a) The surface of a substance is the interaction interface in mechanical schemes, and its surface chemistry may differ from bulk chemistry. Surface action can result in meaningfully dissimilar surface conformation and physical possessions.
b) Surface infection frequently leads to failures in perilous aerospace applications. Analysis of the first 100 Å provides information on material performance adverse contamination, oxidation, corrosion and surface weathering.
c) For metals and additional conductive substances, grain boundary production is significant to develop harder materials. Surface analysis tools for example field emission Auger electron spectroscopy (FE-AES) can deliver data around grain boundaries.

Some surface analysis techniques used to investigate surface properties are given in Table 4.

Table 4. Methods for surface analysis [20]

Acronym	Name	Analysis/Information	Strengths	Challenges
AES	Auger electron spectroscopy	Elemental and some chemical bonding depth composition profiles	Small analysis area, profile capability, insulators are relatively fast	Solid samples, more difficult
XPS	X-ray photoelectron spectroscopy	Elemental and chemical bonding	Small analysis area, profile capability, on	Charge control, slower analysis

		information depth composition profiles	insulators, fast, semiquantitative than AES	
SSIMS	Secondary ion mass spectroscopy	Mass spectral identification, molecular ions	Can be very surface sensitive	Data analysis and interpretation
LEED	Low-energy Electron Diffraction	Surface structure and geometry	Precise atomic layer analysis	Surface must be clean, single phase.

5.2 Imaging and visualization analyzers

Pictorial examination of examination specimens and constructions is the humblest and wildest technique of gaining data about shape, colors, surface and numerous additional physical properties. Countless tools are utilized, counting enlarging glasses and numerous microscopes, to see substances beyond the usual volume of the human eye. In general, there are triple groups of microscopes including electron, and scanning probe and optical microcopy. Electron microscopes utilize the connections of electron beams with substance and gather data about in what way the sample reproduces, refracts, refracts and/or scatters radiation. The beam can be concentrated on the specimen in a wide-area irradiation or raster scan through a straight beam. Scanning probe microscopes utilize the contact of a probe tip and the surface of the substance under test, including tunneling current, magnetic fascination, and lateral force and adhesion. A swift of the methods is tabulated in Table 5.

Table 5. Methods for image analysis [20]

Acronym	Name	Analysis/Information	Strengths	Challenges
AFM	Atomic force microscopy	Contact and noncontact surface morphology	Straightforward analysis, digital data files	Solid samples, irregular surface difficult
SEM	Scanning electron microscopy	Secondary electron detectors (SED) Backscattered electron detectors (BSD)	Fast imaging of conductive materials	Insulators are more difficult. Cannot look at liquids
TEM	Transmission electron microscopy	High-energy electron transmission	Very high spatial resolution, some 3D information	Sample prep can be tedious/ expensive
EDX	Energy dispersive X-ray analysis	Elemental composition	Very fast, semiquantitative	Not sensitive to low-Z number elements
FIB	Focused ion Beam	Surface topography	Fast analysis of semiconductor defects / features	Technology is expensive than SEM
EMP	Electron microprobe	Elemental composition	Fast, sensitive, semiquantitative	

5.3 Material analyzers

5.3.1 X-ray diffraction (XRD) examination

XRD examination is utilized to examine the crystallography of materials, in addition to obtain data about the element composition and physical possessions of substances [21]. These possessions are derived from the sprinkling amount of an x-ray beam illuminating substance in film and powder arrangements as a purpose of event and dispersed angle, polarization and wavelength. Specified its aptitude to deliver a description of substances, a small XRD arrangement was comprised in the apparatuses set on the Curiosity Rover of the Mars Science Lab mission, which propertied on Mars in August 2012 (Table 6).

Table 6. XRD methods, applications and capabilities [21]

Method Provides	Capable to Analyze	Applications
Structural information, crystal lattice structure, identification of crystal and material phases	Metals, alloys, glasses and ceramics, particles, powders, polymers and biopolymers	Crystal structure and material phase determination, process
	development	

Since the crystal construction is a property of the substance under test, a sole decoration is shaped when illumined with an x-ray beam, and the occasioning diffraction pattern is utilized to describe the substance under test. Usually, the XRD examination gauge is utilized to quantity the diffraction intensity decoration (Fig. 7). The diffraction relationship is recognized as Bragg's rule and is in this way:

$$2d (\sin \theta) = \lambda o \tag{1}$$

d is the crystallographic lattice interplanetary space, θ is the angle of incidence of the x-ray beam (Bragg angle), and λ is the wavelength of the x-ray beam.

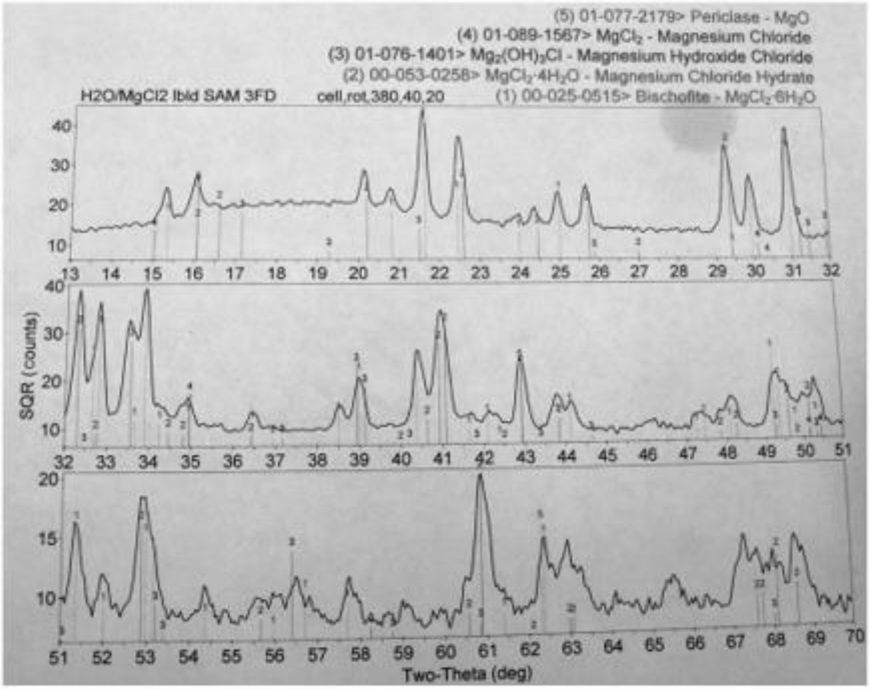

Figure 7. XRD peaks on the paper

5.3.2 X-Ray fluorescence spectrometry

Bombardment of substances with elevated-energy x-rays or γ-rays causes fluorescent emission of x-rays and this process is utilized to describe materials [22]. The attack reasons the emission of electrons with binding energies lesser than the energy of x-rays. Released radiation, which has the properties of atoms existent, is restrained by comparative pawns or numerous solid-state detectors. X-ray fluorescence (XRF) devices are extensively utilized for fundamental examination of metals, glass and ceramics. XRF and XRD devices were utilized on the Mars Curiosity instrument suite's CheMin analyzer, which propertied on Mars on August 5, 2012. A swift of XRF's competences and requests is provided in Table 7.

Table 7. XRF applications and capabilities [22]

Method Provides	Capable to Analyze	Applications
Elemental composition of inorganic elements in a variety of materials, thin films and solids. Qualitative and semiquantitative data with the use of standards	Solid materials and thin films, ceramics and glasses, powders, particles, plastics, and polymers	Trace element quantitation, alloy composition, thin film analysis, material validation, and QA / QC

5.3.3 Low-energy electron diffraction (LEED)

LEED is a method for decisive the surface structure of crystalline substances by blasting the surface with a collimated beam of low-energy electrons reaching from 20 to 200 eV and examining diffracted electrons as spots on a fluorescent screen [23]. The LEED method is utilized to inspect the diffraction pattern and deliver data around the evenness of the surface construction. Likewise, the concentration of the diffracted beams as a purpose of the energy of the occurrence electron beam is examined to attain precise data around the atomic locations on the surface of the verified substance.

5.3.4 Neutron diffraction

Neutron diffraction is utilized to determine the atomic structure of substances [24]. A cold or thermal neutron beam irradiates the material under test, and the resulting diffraction pattern is utilized to regulate data about the material's structure. Alike to the XRD technique, the diffraction of the scattered neutron beam monitors Bragg's rule and delivers balancing data. For some light atoms, the diffraction concentration is quite sturdy even in the attendance of rudiments with great atomic numbers.

The chief drawback of neutron diffraction is the restricted obtainability of the radiation basis. Test specimens are utilized with crystals much greater than those utilized in XRD. Because the neutrons transmit a spin, they interrelate with the magnetic moment of the electrons, permitting the microscopic magnetic arrangement of the materials verified to be examined.

5.3.5 Electron microprobe (EMP)

EMP is apparatuses of defining the element composition of solid supplies in trivial volumes (characteristically $\leq$10–30 μm^3). They are similarly recognized as electron microprobe analyzer (EMPA) [25]. Alike to SEMs, they bombard the verified substances by an electron beam and the strongminded wavelengths of the animated x-rays are utilized to achieve rudimentary examination. Developments in the capability of EMP apparatuses have directed to important precisions in gaging minute concentration of trace rudiments.

5.4 Summary

At high temperatures, rare compounds and metastable phases are shaped. The subsequent structures and properties of these compounds cannot be predicted from extrapolation of their low temperature possessions. Sympathetic and decisive material possessions require multidisciplinary information and knowledge in materials science in addition to chemical, electrical and mechanical engineering. Key properties to be considered comprise chemical purity particle size, crystallinity, and surface structure.

Uniting image, chemical and structural testing with physical property measurements enables us to develop better materials by understanding basic material structure and property associations. Especially, material description of surfaces can be valuable in sympathetic the movement of atoms in a matrix at high temperature. Information of chemistry, kinetic, phase and physical possessions variations assists materials engineers in material assortment. In addition, grain boundary engineering and description helps progress ceramics, composites and advanced-performance metal alloys that retain strength at elevated temperatures.

Structural examination by means of FESEM, TEM and XRD gives substances engineers insight into the atomic bonds of crystals, what structures and chemistries form phases, and how a material's physical and macrostructural possessions depend upon micro/nanostructured areas.

Physical property capacities are as significant as material description and upkeep the improvement of the enactment of elevated temperature substances Strength, elastic modulus, thermal expansion, thermal and electrical conductivity, optical possessions are determined in material laboratories and play a significant part in material assortment.

6. Deductions

The obtainability of substances that can be used efficiently at high temperatures permits pushing the bounds of possible requests that can be measured. Substances obtainable and appropriate for these requests comprise ceramics, polymers and metals in both monolithic and composite forms. High temperature materials, aircraft and space structures and space exploration are used. These materials are lightweight and heat-resistant, contributing to fuel efficiency, reduced emissions, and increased sustainability in aviation. As a result, high-temperature substances are progressively desired for an increasing number of requests, counting the aerospace and automotive productions, in addition to power generation and space investigation. As new materials are developed, including nanomaterials, the ability of mechanisms and structures to withstand and perform at high temperatures becomes easier to realize.

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