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Nanostructured materials, structures and mechanical properties, processing and applications

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A B S T R A C T

Nanomaterials are becoming an integral part of high-performance products and services. As technology advances, the possibilities for engineering components with nanomaterials are more numerous, taking advantage of the benefits that these materials have the potential to provide. Nanostructured materials have bulk dimensions with a structure that includes nanoscale features, and have been around for quite some time, hidden in everyday items. More recently, they have been made possible to be analysed and manipulated with increasingly sophisticated instruments and processes. This ability has made them more accessible, however, challenges still remain in the more widespread adoption of these materials for exploiting their advantages. The present paper outlines the position and emergence of nanostructured materials in the broader context of nanomaterials, examining their mechanical properties, production methods and applications.

Keywords: nanostructures, strength of nanostructures, nanostructured material production techniques, nanostructured material use cases.

1. Introduction

The terms Nanomaterials and Nanotechnologies are widely used in a number of materials and technologies relating to structures with features of sizes below 100 nm (Figure 1). These encompass individual nanoparticles, nanofibers, nanoparticle-modified materials, or composites of nanosized materials with bulk materials and bulk materials with internal or surface nanostructured features (Jeevanandam et al. 2018). Such materials exhibit different and superior mechanical and functional performance over their bulk counterparts. These include improved and unique optical, electrical, thermal, magnetic, or other features, such as possibilities of surface functionalization (Harish et al. 2022; Barhoum et al. 2022). The research and development of nanotechnologies aim to generate novel nanomaterials for advanced engineering applications. These activities fundamentally include understanding the methods for production and designing nanomaterials, characterising their structure, determining their mechanical and functional properties, understanding the mechanisms for their properties, modelling their behaviour, and predicting their performance in practical applications.

The applications of nanomaterials are very broad, with use cases for improving the properties of coatings, adhesives, fibre composites, manufacturing components, combining different types of nanoparticles to produce synergistic effects, or exploiting their unique functional properties. The performance benefits that nanomaterials provide are useful in a number of fields, from automobile, aerospace and electronics industries, construction, cosmetics, healthcare, energy, environment, textile, food, and others (Talebian et al. 2021).

2. A short history on nanostructured materials

The use of nanoparticles and nanostructures dates back to Roman times, as evidenced by the inclusion of Au nanoparticles in the renowned Lycurgus cup from the 4th century AD (Freestone et al. 2008). Later, similar nanoparticles were used to provide decorative aesthetics in stained glass church windows, Ag or Cu nanoparticles were used for glittering ceramic glazes and pottery up to around the 17th century (Bayda et al. 2019). Despite the intentional use of nanoparticles' decorative features in essentially nanostructured materials, medieval artisans were unable to observe, study, or manipulate these nanoparticles' effects, as we are nowadays able to do with modern analytical instruments.

This inability to control nanomaterials caused some production methods to be forgotten and abandoned as it was difficult to consistently reproduce the desired results. An example is the production of Damascus blades, which were known for a sharp cutting edge, exceptional mechanical properties, and a distinctive banding pattern. With

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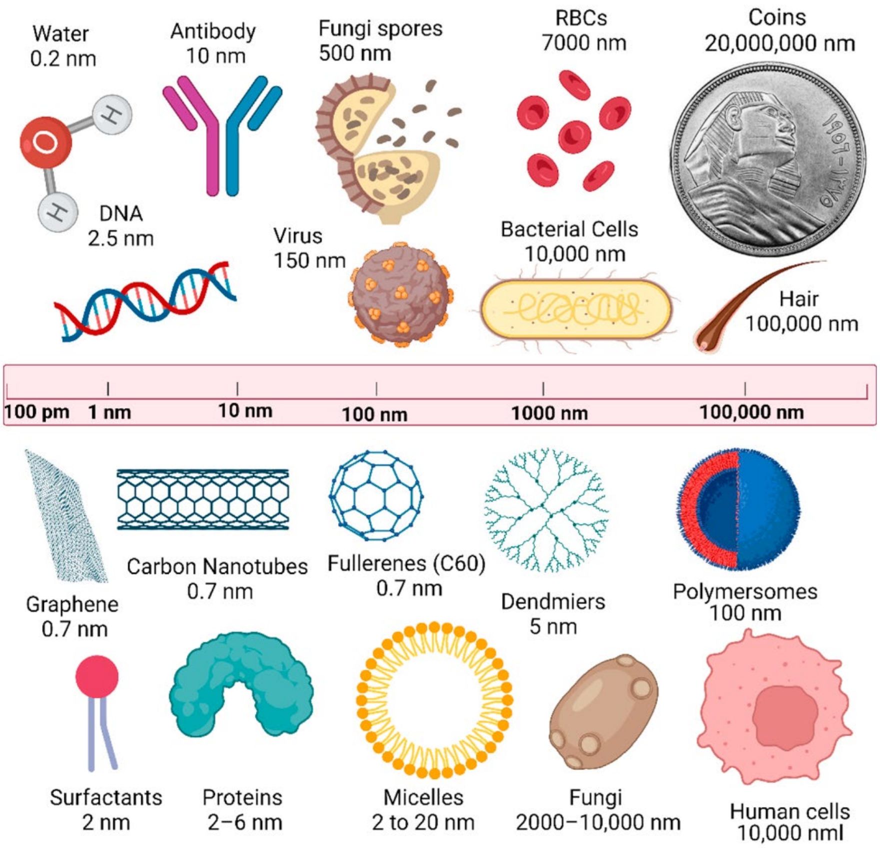

Fig. 1. Size comparison of various objects in the nanoscale regime (Barhoum et al. 2022).

contemporary investigation techniques, it was discovered that these blades had cementite nanowires encapsulated by carbon nanotubes in their microstructure, which gave them their unparalleled mechanical properties (Figure 2). The supply of ores with the required alloying elements from very specific mines was dwindling, and the used blade treatment procedure alone was not sufficient to obtain a microstructure with the same features, causing the inability to reproduce such blades sometime in the 18th century (Reibold et al. 2006).

The development of analytical instruments for investigating materials, such as Scanning Tunneling Microscopy (STM), Transmission and Scanning Electron Microscopy (TEM and SEM), Atomic Force Microscopy (AFM) dynamic light scattering (DLS), Auger Electron Spectroscopy (AES), Secondary Ion Mass Spectroscopy (SIMS), Energy Dispersive X-ray Spectroscopy (EDS), X-ray Photoelectron Spectroscopy and other physical and chemical analytics, has accelerated the progress of nanotechnology and the use of nanomaterials, as it provided a means to observe, assemble, manipulate, and produce materials on the nanometer scale (Bayda et al. 2019). Since the discovery of carbon nanomaterials (graphene, nanotubes, fullerenes or buckyballs) in the second half of the 20th century, nanomaterials of all types and their commercial applications have been growing in the 21st century, with advances in a wide number of fields, discussed in the introduction (Talebian et al. 2021).

As the use of nanomaterials becomes more widespread, an increasingly interdisciplinary combination of methodologies and sophisticated analysis techniques will be required for characterization. In order to obtain relevant information about a material in a given field, various sample preparation techniques are also required. Non-destructive and direct measuring methods are preferred for many advanced nanoscale structures and their applications, for instance in the biomedical industry, where in-situ observations are usually the most relevant and challenging. Various interdisciplinary characterization processes thus require additional protocol design or are still in need of development to overcome current issues. Additionally, characterization data processing is mostly statistical due to physical and chemical testing method limitations (Jagadeesh, Rangappa, and Siengchin 2024). Establishing highly scalable and low-cost transdisciplinary characterization approaches is required for future research on

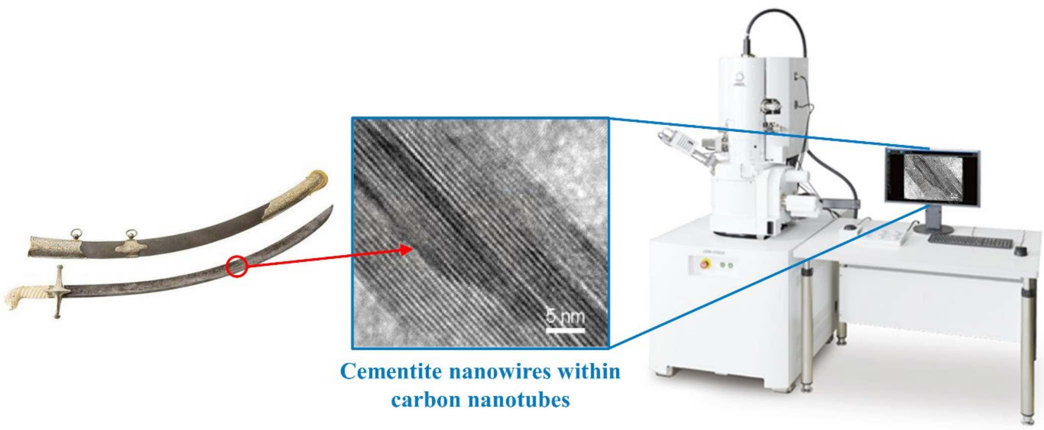

Fig. 2. Representation of a modern analysis of a 17th century Damascus blade, adapted from (Levin et al. 2005).

nanomaterials.

3. Classifying nanostructured materials

Nanomaterials are usually classified by their dimensionality, while other classifications are also possible, according to their origin, composition, porosity, phases, and dispersion (Barhoum et al. 2022). Classification according to dimensionality arranges nanomaterials in classes by constraining one or several of their dimensional features in the nanoscale range up to 100 nm, while the rest of their dimensions are not constricted on the nanometre scale (Figure 3). In this way, nanomaterials can be categorised by the number of dimensions that are not on the nanoscale: as zero-dimensional (0D – nanoparticles), one-dimensional (1D – nanotubes, nanorods, nanofibers), two-dimensional (2D – thin layers, nanoplates, graphene), and three-dimensional (3D – nanocrystalline materials, nanocomposites).

Nanostructured materials are a part of 3D nanomaterials, wherein the material bulk dimensions are not on the nanometre scale, while the internal or surface features and structures are. As composites, such nanomaterials can contain dispersions of nanoparticles, nanowires, nanotubes or nanolayers bonded to a matrix core. They can be metals, ceramics or polymers, with crystalline or amorphous structure, or even be entirely composed of multinanolayers (Ashby, Ferreira, and Schodek 2009). More complicated structures are also possible, such as metal-organic frameworks and combinations of carbon-based, metal-based, or organic-based nanomaterials with any form of metal, ceramic, or polymer bulk materials (Jeevanandam et al. 2018). Coatings and thin films applied to structural bulk materials, for improving wear resistance, friction, or corrosion resistance are also classified as nanostructured materials, even though the bulk properties of the underlying material are unchanged.

4. Mechanical properties of nanostructures

Using nanostructures to increase the mechanical strength of materials has been known for decades (Tian 2017). Precipitation hardening of metal alloys with dispersed nanoscale particles provides barriers for dislocation motion, greatly increasing the overall alloy strength. Most contemporary alloys obtain their strength by dispersion hardening at the nanoscale, work hardening or alloying, and increasing strength at the atomic level. High-strength steels, aluminium, magnesium, and titanium alloys are strengthened by 10-100 nm carbides and precipitates, obtained by heat treatment. The alloy matrix is not nanocrystalline, while the dispersion particles represent about 1-5% of the overall material volume (Ashby, Ferreira, and Schodek 2009). Further increasing the mechanical properties of these materials entails reducing the size of the bulk material crystals into nanocrystals.

Most materials have a polycrystalline internal structure, made up of crystals with ordered atomic lattices, with exact distances between atom bonds. At the boundaries of these crystals, the atoms are disordered and the atom bonds are stretched or squeezed, similar to amorphous material structures. In regular polycrystalline structure size scales, the crystal sizes are typically around 0.1 to 1 mm. The boundaries of such a material compose a small part of the total bulk material volume, even less than one part in a million (Ashby, Ferreira, and Schodek 2009). As the crystal sizes become smaller, the volume fraction of the boundaries increases, and the disordered material structure now becomes influential on the mechanical and other properties of the bulk material. In nanocrystalline materials, the crystal sizes are in the nanomaterial range, from a few nm to 100 nm. The volume fractions of intercrystal regions of such materials can be 30% for 10 nm grains, or up to 50% for 5 nm grains (Tian 2017). Below the nanometre dimensions of the crystals, the atoms are completely disordered and form an amorphous or glassy structure (Figure 4).

The driving force for nanocrystalline grain growth amplifies as the volume fraction of grain boundaries increases. Preventing grain growth and maintaining the beneficial properties of such nanostructured materials is very difficult. With such small grain sizes and a high fraction of grain boundaries, grain growth is possible even at room temperature. In order to reduce the grain boundary energy and the grain growth driving force, solute segregation or kinetic mechanisms that reduce grain boundary mobility may be used, such as reduced diffusivity or chemical ordering (Cavaliere 2021).

The mechanical properties of nanocrystalline materials are of great interest, as these exhibit very high hardness and strength, up to 2 or 10 times higher than materials with conventional grain sizes. The effect is known as Hall-Petch strengthening or grain boundary strengthening. In smaller grains, a smaller number of dislocations are able to accumulate at the grain boundary, building up stress in the neighbouring grain where new dislocations form and deformation occurs. Limiting the available number of dislocations by changing the grain size increases the yield strength and deformation resistance of the material up to a certain point, where grain sliding begins to occur (Schuh and Nieh 2002). With grain sizes below about 10 nm, the grain sliding mechanism is responsible for increased ductility and superplastic behaviour of these materials at low homologous temperatures (Horita et al. 2000).

The effects of grain boundary fractions in nanostructured materials have been a subject of research for decades (Dangwal et al. 2023). Characterization advances for investigating grain refinement hardening and softening have given substantial information on the relationship

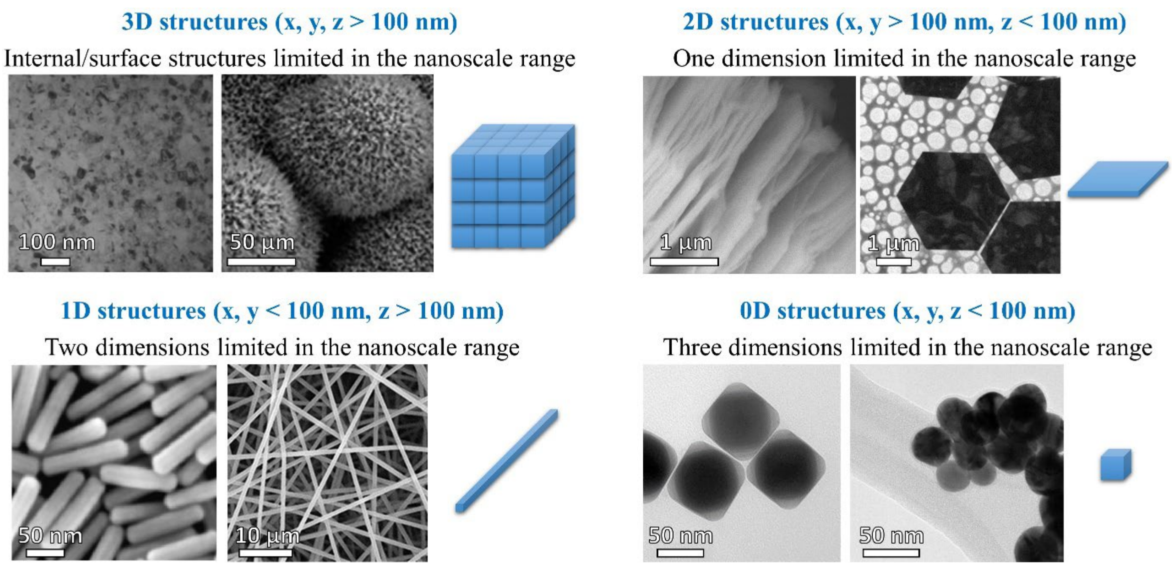

Fig. 3. Classification of nanomaterials by dimensionality

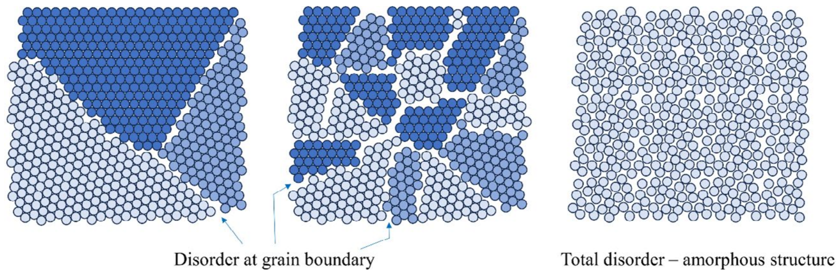

Fig. 4. Comparison of the volume fractions of intercrystal grain boundary regions in a coarse and fine grained material, with a representation of an amorphous structure.

between grain size and mechanical properties in nanostructured materials. Models for tailoring the properties of these materials are now available, predicting general trends under multiple conditions, also with computer molecular dynamics simulations (Roberto B. Figueiredo, Kawasaki, and Langdon 2023). The inverse Hall-Petch behaviour of nanostructured metals and high entropy alloys is of special interest for materials research (Dangwal et al. 2023; Naik and Walley 2020; Quek et al. 2016; Jones et al. 2020), discovering the limits of dislocation pile-up and transition between hardening and softening due to grain sliding.

Nanostructuring allows for the production of high strength and ductile materials, a combination that is generally mutually exclusive (Wu et al. 2015). Such a combination of properties is also not possible using nanoscale grains everywhere in the material. However, nanoscale grains spread out over a matrix of a finegrained material can act similarly to precipitates in precipitation hardening alloys. The difference is that only a single phase material is used. These nanoscale domains are numerous, but constitute only a small volume % in the material matrix. Such a microstructure was produced with a pulsed electrodeposition procedure for Ni to provide simultaneous high strength and ductility of the metal, approaching 1.3 GPa and an elongation of ≈ 30%. The results were compared to coarse-grained and nanostructured Ni, obtained with various production methods (Figure 5) (Wu et al. 2015).

Superplastic forming is well-established in producing high quality, curved complex parts from sheet metal, since being discovered in a Bi–Sn and Pb-Sn alloy with elongations of ≈1950% and ≈1505% as early as 1934 (Wongsa-Ngam and Langdon 2022). Typically, slow forming rates are needed to achieve high elongations, for example, about 20–30 min per part when using the standard superplastic Al-2004 and Al-5083 alloys (Horita et al. 2000). As a result, superplastic forming was used mainly in the aerospace and automotive industry or building design, for low-volume, higher priced components (Wongsa-Ngam and Langdon 2022; Horita et al. 2000). Using nanocrystalline materials can improve the forming times below 60 seconds. With very small grains, the Hall-Petch strengthening mechanism begins to break down, and the bulk material strength is no longer increased as the grain sizes are reduced. The grain sliding mechanism is then the dominant deformation mechanism, allowing for elongations up to several 100% (Figure 6) (Cavaliere 2021).

The ideal strength a material could have is proportional to atomic bond strength. The bonds in most metals are strong, the bonds in ceramics, carbides or diamond are stronger, while the bonds that bind polymer molecules are much weaker (Ashby, Ferreira, and Schodek 2009). Crystal imperfections, dislocations and plasticity make the practical strength of a material much lower than the theoretical ideal strength. Flaw density in the crystals may be controlled by improving the crystal quality or reducing the crystal size. A number of studies have shown that almost theoretical material strength can be achieved in metal nanowhiskers, grown as a single monocrystal (Richter et al. 2009;

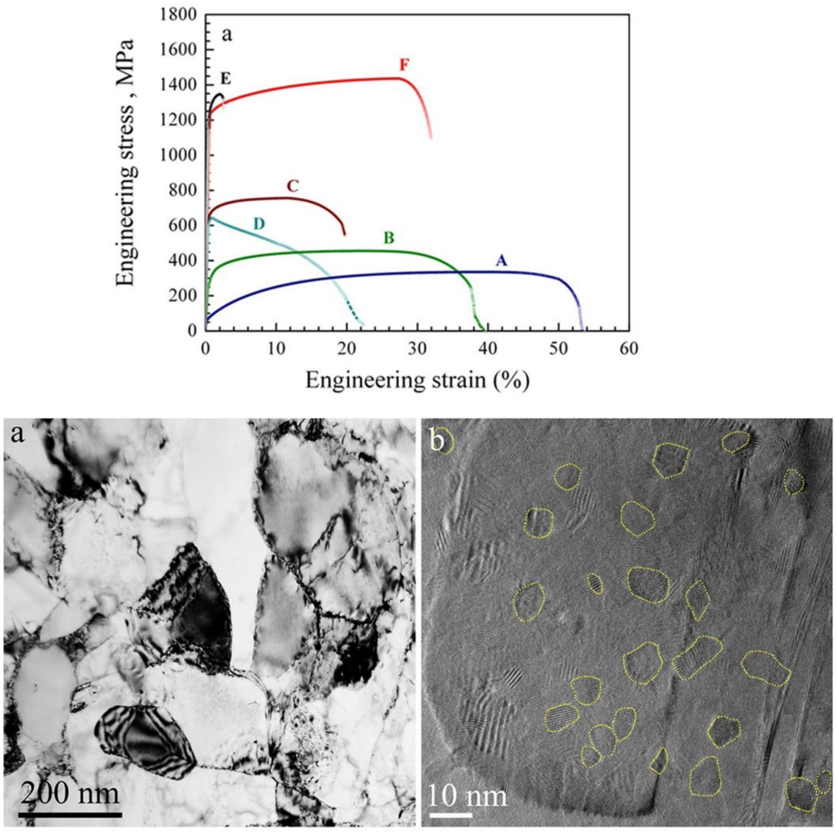

Fig. 5. Engineering stress-strain curves and microstructure images of Ni with different nanostructures obtained with various methods. Grain sizes: A-27 µm, $R_p0,2$ = 70 MPa; B-1 µm; C-200 nm, D-200 nm; E-18 nm; F-150 nm with 7 nm nanodomains, $R_p0,2$ = 1300 MPa. Adapted from (Wu et al. 2015).

Suzuki et al. 2010). Physical vapour deposition methods were used to produce metallic whiskers from Al, Ti, Cr, Mn, Fe, Co, Ni, Zn, Cu, Ag and Au (Suzuki et al. 2010). TEM investigations have shown no dislocations or structural contaminations in the monocrystal of the Cu whiskers for in situ tensile testing measurements of these whiskers inside a SEM/FIB instrument (Figure 7). Results have shown a 1000x increase in yield strength of Cu nanowhiskers as compared to bulk Cu metal (Richter et al. 2009). The measured strengths in these nanowhiskers were very close to the theoretical strengths of these materials. These investigations demonstrate the importance of crystal imperfections and dislocations on material strength, which may be a route to providing high-strength nanostructured materials by combining bundles of similar nanowhiskers or long nanowires into a bulk material.

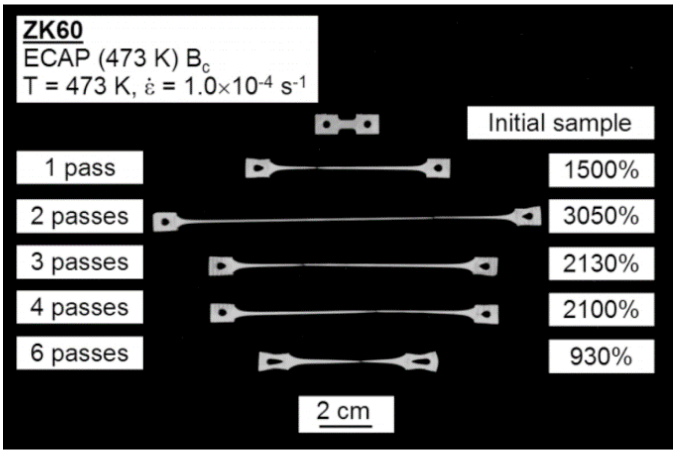

Fig. 6. Examples of tensile testing of superplastic metals, tested after processing by ECAP with different numbers of passes (R. B. Figueiredo and Langdon 2008).

Nanostructured materials exhibit excellent mechanical properties, with a strength within about a factor of 3 of the ideal material strength (Figure 8). Most high-strength materials we use for transport, aerospace and other demanding applications, such as high-strength steels, aluminium, titanium and other alloys, are strengthened with some form of nanoscale dispersed precipitates (Ashby, Ferreira, and Schodek 2009). However, obtaining very small grain sizes in the matrix is very difficult or even impossible by using standard thermomechanical processing procedures (Horita et al. 2000). A number of other production processes and their combinations are used to acquire nanostructured bulk materials.

5. Processing of nanostructured materials

Nanostructured materials can be made by top-down or bottom-up approaches and in between, intermediate approaches. In top-down approaches, the coarse grained material is broken down into nanocrystalline, while in bottom-up approaches, smaller constituents are consolidated into clusters and larger components (Figure 9). Some processing methods following these approaches are rapid solidification, inert gas condensation, electrodeposition, mechanical alloying, milling and compaction, and severe plastic deformation (Tian 2017; Ashby, Ferreira, and Schodek 2009).

Rapid solidification produces nanostructures by not allowing the atoms from a melt to solidify into large crystals, by rapidly cooling, and by not allowing for the time required for the atoms to assume the ordered crystal structure. Extremely high cooling rates are required, even up to 1,000,000°C/sec, limiting this technique to producing thin wires and ribbons from which heat can be conducted quickly. Additionally, the melt includes elements with atoms of different sizes that favour different atomic spacings and crystal structures, which additionally makes crystallisation difficult. Newer rapid solidification alloys achieve an amorphous state at relatively slow cooling rates of 10°C/sec, with the ability to cast thicker sections up to 20 mm with the melt spinning technique. Rapid solidification can also be achieved by melting a thin layer of a bulk material's surface with a focused laser beam. The heat is conducted into the material below, and the surface becomes nanocrystalline or amorphous (Ashby, Ferreira, and Schodek 2009).

Inert gas condensation and electrodeposition can be used for making nanostructured bulk materials or applying coatings and thin films to structural bulk materials in order to improve surface wear resistance, friction and corrosion resistance. Contemporary nanostructured coatings and thin films are used mainly for the wear protection of cutting tools and for the reduction of friction in sliding parts (Koch 2007). In inert gas condensation, metal atoms collide with inert gas atoms and

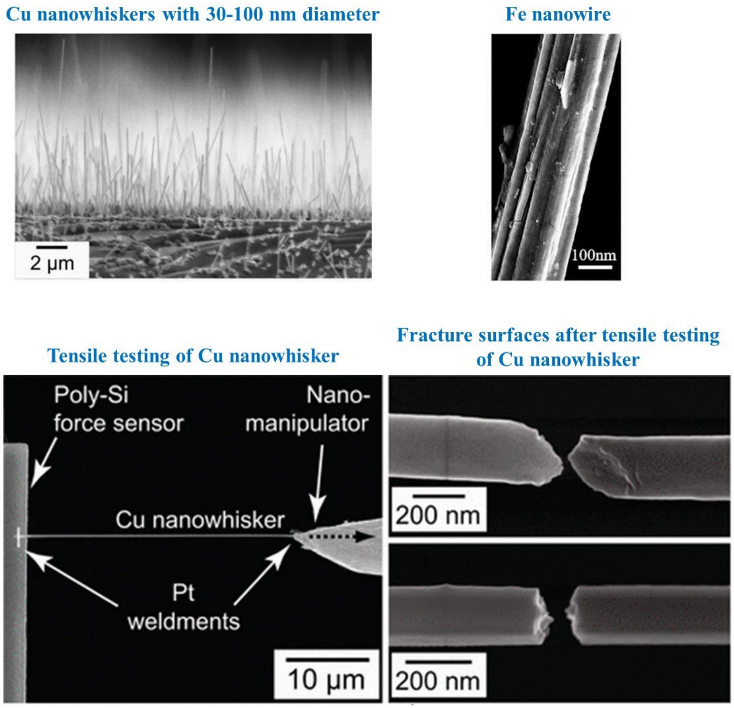

Fig. 7. Cu and Fe nanowhiskers, with a representation of tensile testing and fracture surfaces after tensile testing in the SEM. Reprinted (adapted) with permission from (Richter et al. 2009). Copyright 2009 American Chemical Society.

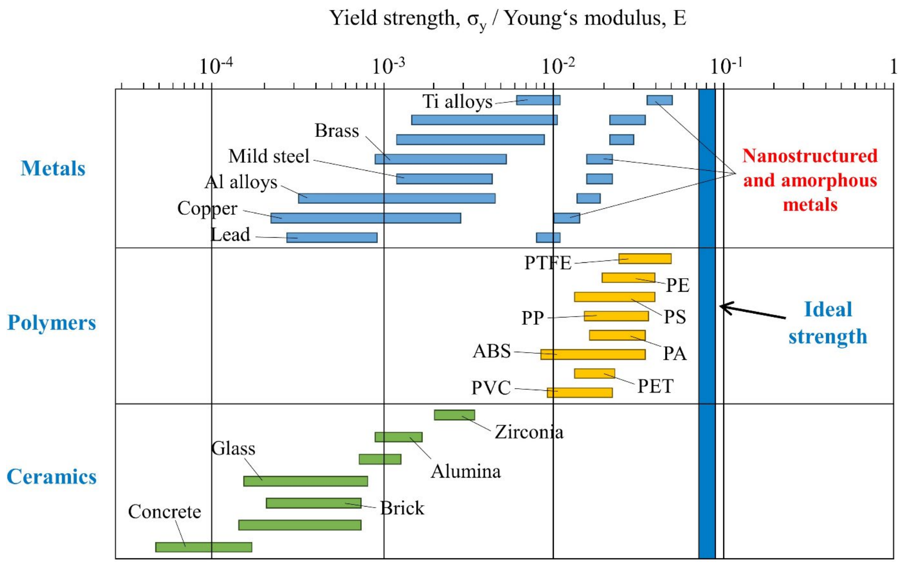

Fig. 8. Ideal strength diagram for various materials, excerpt from (Ashby, Ferreira, and Schodek 2009).

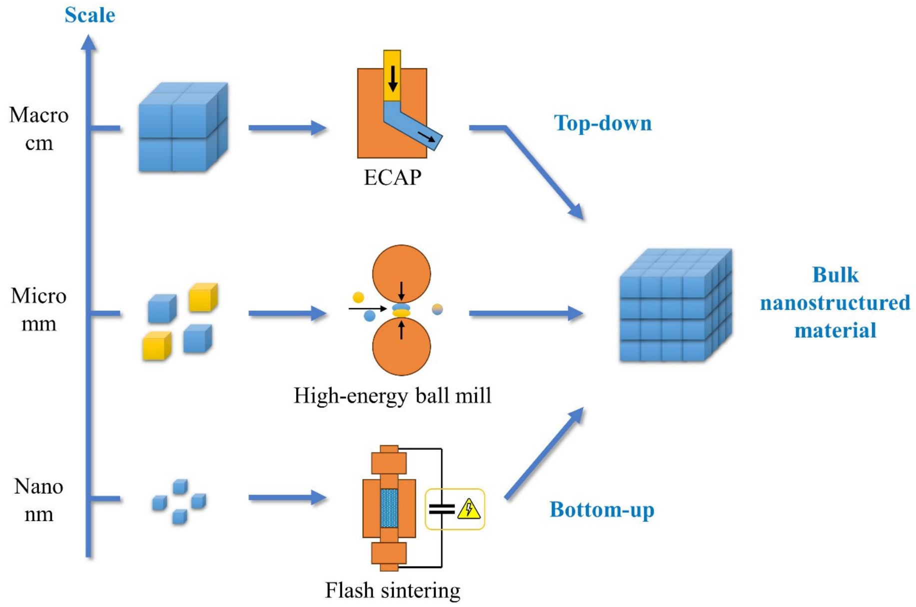

Fig. 9. Top-down, bottom-up and intermediate approaches for producing bulk nanostructured materials.

condense into small particles. This method suffers from porosity or the difficulties of maintaining a fine grain size. In electrodeposition methods, the atoms are deposited from solution on the cathode at such a rate, that they are not able to form large crystals. An advantage of this method is that there is no porosity and a high product output (Tian 2017).

Mechanical alloying and compaction uses a high-energy ball mill to repeatedly cold weld together two materials that do not mix. The high energy ball mill flattens, welds, and breaks up the metal particles within a protective atmosphere, creating mechanically alloyed nanostructured particles. The next step involves compacting and sintering these particles into a bulk component. With this method, it is difficult to control material purity and achieve full density (Tian 2017). Recently emerging materials utilising high-energy ball milling are high-entropy alloys, which mix relatively equal proportions of five or more elements. These alloys often have an amorphous structure, with high hardness, excellent strength and favourable resistances to wear, oxidation, and corrosion (Ji et al. 2015). Mechanical alloying has a high potential for widespread applications, as it is versatile and cost-effective for producing a variety of nanostructured steels, nanocomposites based on Al, Mg, and Ti, oxide dispersion strengthened superalloys, supercorroding alloys, hydrogen-storage materials, solders, paints, and other products in a number of various industries (Suryanarayana, Al-Joubori, and Wang 2022; Khan, Mirza, and Gupta 2018). With additional development, this is one of the techniques with the potential to overcome the issues of producing sufficient quantities of nanostructured products, while being economically viable.

Consolidating powders and particles into a nanostructured bulk component requires the sintering of powders pressed into a die. This is usually a process carried out at elevated temperatures for some time, allowing for diffusional bonding to occur between the powder particles. Using such a technique makes it difficult to retain the nanostructure features, as it coarsens the structure. In order to minimise coarsening, the sintering time should be kept to a minimum. A possible method to sinter such particles is by flash sintering, wherein the powder is compressed in a die through which an electrical capacitor is discharged. The thermal shock created by the resistance of the packed powder is enough to consolidate the particles without considerable coarsening (Ashby, Ferreira, and Schodek 2009). Additionally, spark plasma sintering is able to densify various nanostructured metallic and ceramic materials with optimum density. This method has a higher heating/cooling rate, a lower processing temperature, and a shorter holding time at the sintering temperature, as compared to conventional sintering processes (Sharma et al. 2018).

With severe plastic deformation, the material is subjected to a very high strain without changing the bulk overall dimensions of the component. Equal-channel angular pressing (ECAP) is the most important severe plastic deformation processing technique, where a rod or bar is pressed through a die constrained within a channel that is bent through a sharp angle within the die (Wongsa-Ngam and Langdon 2022). The shearing and extreme deformation of the rod, while suppressing fracture, form a refined structure of the rod. The rod may be passed through the die channel several times to obtain the desired structure with grain sizes of about 100-500 nm.

Other processes and routes are also available and being developed for producing nanostructured materials, following the top-down and bottom-up approaches, such as micromachining, or photolithography. There are numerous chemical, physical, and biological (green) methods for producing 0D, 1D and 2D nanomaterials, which are not mentioned here, but also give the possibility of consolidating the obtained smaller constituents into a bulk nanostructured, 3D nanomaterial.

With their superior properties, nanostructured materials may replace existing conventional grain size materials, if they are able to be processed cost effectively at scale. Most processing techniques do not produce sufficient quantities or sizes of nanostructured products without defects. As such, the development of these techniques is still underway, with many techniques showing good potential for overcoming these issues in a number of industries (Suryanarayana, Al-Joubori, and Wang 2022). Additionally, modern characterization techniques and their development are necessary tools for the development of these materials and production techniques (Fomin and Filippov 2021). Microstructural stability is another important feature for the long term successful operation of nanostructured materials. Multiple studies are focused on identifying the reason for grain growth and providing a means for resisting it. Grain growth in nanostructured materials is thermally or mechanically assisted through grain boundary diffusion, limited solute at grain boundaries, lower activation energy for grain growth than lattice diffusion, or grain boundary sliding/rotation (Hornbuckle, Solanki, and Darling 2021). Grain growth often hinders the potential advantages of nanostructured bulk products. Strategies for limiting grain growth include solute segregation, chemical ordering, porosity drag, second phase drag, solute drag, and grain size stabilisation (Koch 2007; Qin, Shivakumar, and Luo 2023). Even though there are numerous studies on nanostructured materials, the precise grain boundary mechanisms and maintaining stability remain inconclusive (Ye et al. 2021). Efforts to stabilize the nanosized grains of these materials are expected to facilitate the production of bulk nanostructured products for advanced applications (Kotan 2018).

6. Applications of nanostructured materials

Design and development activities in all economic sectors, from transportation, construction, sports, textiles, energy, medicine, household appliances, etc., depend heavily on materials. The broad driving forces for developing nanomaterials for these sectors include cost reductions, improved product performance, usability, reliability, and durability, as well as realising health, environment, energy, and safety objectives. The unique properties of nanostructured materials make them good candidates for the desired improvements in products and services, generating motivation for their further development.

The transportation, automotive, and aerospace industries are the world's largest users of nanomaterials (Ashby, Ferreira, and Schodek 2009). For instance, using high-strength materials can reduce weight, which leads to greater fuel efficiency, reduced emissions, improved appearances, and cost savings. New functionalities of components can be obtained by using nanocomposites, such as electrically conductive or magnetic nanofillers in a polymer matrix. Nanoscale coatings improve the corrosion resistance of components or improve lubrication. Using nanomaterials in paints and surface treatments is particularly appealing for the automotive and aerospace industries, with scratch resistance or self-cleaning properties.

The adoption of nanomaterials is accompanied by environmental challenges and safety concerns (Barhoum et al. 2022). The novelty of engineered nanomaterials makes these aspects a somewhat unknown factor, with research gaps in the impact and use of these materials over a longer timeframe. Reducing environmental impacts and recycling of products with nanostructured materials is an important aspect of their utilisation, especially given the increasing importance of these factors in society. However, there are other environmental aspects of using high performance materials. Improvements due to better fuel efficiency in the automotive industry may be enormous, with a large beneficial impact on the use of less energy, the increased wear resistance means fewer replacements or repairs of products, improved thermal insulation exhibited by some nanomaterials again reduces the use of energy, and so on.

In the medical sector, nanomaterials are researched for several diagnostic and treatment services with the use of various nanoparticles and nanostructured materials. The high mechanical properties of nanostructured materials are beneficial for wear resistance and the miniaturisation of bodily invasive instruments, devices, implants, fixings and elements, along with other characteristics that these materials exhibit, such as corrosion resistance, or special coatings (Gautam et al. 2022).

The sports industry is a leading user of advanced nanostructured materials (Song and Cai 2012), incorporating them into high-end performance products, where exceptional mechanical properties are required. However, the high costs of these products mean that they are not intended for mass markets, but for customers willing to pay a premium for an improvement in sports performance. Examples include high performance bicycles, golf clubs, sail boats, safety helmets, ski equipment, tennis racquets, hockey sticks, camping gear, climbing gear, diving gear, archery bows, protective equipment, and others.

Nanostructured materials are also well suited for the arms and defence industries for bulletproof armour and improved weaponry (Koch 2007), sensors, etc. Applications for nanostructured materials are truly numerous, but are currently economically less accessible, due to being technologically sophisticated. The increase in performance as compared to conventional materials must thus justify the highly increased costs. In most economies, cost effectiveness is a key factor for product design, presenting a barrier for the introduction of new materials in a broader manner. Nevertheless, some users accept these costs for the added benefits, such as in the aerospace, medical, or sports industries, driving forward the development of these materials and lowering their costs of production for a more widespread adoption (Figure 10).

Conclusions

The mechanical and functional performance of nanostructured materials are the result of their nanosized grains and structure features. Material advancements and technologies, along with the development of characterization abilities, have enabled the engineering of these materials, manipulating their structures to achieve a desired outcome for designing high-end products. Achieving a nanosized grain structure is a challenge, as larger crystals are thermodynamically more favourable, wherein the atoms are arranged in an orderly manner, according to their interatomic bonds. Reducing grain sizes to the nanoscale increases the volume fraction of grain boundaries in which the atoms are in a disordered, amorphous, or glassy structure. Grain boundaries then have a dominating role in the plastic deformation, and the conventional mechanisms of plastic deformation with dislocation activity is restricted. A number of different production processes and their combinations are possible for the production of nanomaterials, nanostructured materials, and materials incorporating nanoscale features. Restricting grain growth and the stability of these materials presents one of the main difficulties in the widespread adoption and production of bulk nanostructured products for advanced applications. As technology advances, these materials are increasingly being used in all areas of modern life, and new nanomaterials are being developed with promising properties for additional improvements to existing products and services.

Fig. 10. Examples of products with nanostructured materials

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