Network distribution of reinforcements in composites produced by sintering: microstructure formation and influence on consolidation behavior and properties

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Sintering of powder mixtures is one of the widely used production methods of composite materials. The distribution of the reinforcement phases in these composites is a function of both initial powder structure and sintering conditions. Based on the recent literature and experimental results obtained by the authors, this article discusses a specific type of reinforcement distribution—the network distribution—in composites produced by sintering of powder mixtures. Examples of the influence of networks of different nature on sintering of metal and ceramic matrices are presented for continuous structures composed of carbon nanotubes and quasi-continuous structures of smaller particles located at boundaries between larger particles. The principles of the microstructure formation in composites with networks formed by ceramic particles, particles of metallic glass and carbon nanotubes are analyzed. Unusual properties of composites with metal and ceramic matrices achieved by organizing reinforcements in networks are discussed.

Key-words : Reinforcement, Distribution, Network, Sintering, Ceramic, Nanotubes, Metallic glass

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1. Introduction

The character of distribution of reinforcing or toughening phases in matrices for the properties of composite materials is as important as the physical properties of the constituents. Attractive properties of composite materials are achieved by a proper selection of the matrix-reinforcement combination and their geometrical parameters as well as by optimizing the interaction at the interface and character of spatial distribution. In the great majority of studies on particle-reinforced composites, the distribution of the second phase particles is characterized as either "uniform" or "non-uniform" leaving the details of the distribution pattern out of consideration. However, there is always a question of the scale of uniformity. Along with a constant search for methods to improve the distribution uniformity of reinforcements, non-traditional patterns of organizing second phases in matrices have been recently evaluated.1-8 Non-traditional microstructures are found in trimodal composites.2,3 The concept of such composites is based on an advantageous combination of nano-grained metal regions with distributed ceramic particulates and coarse grains of a ductile metal in the microstructure. The development of metal matrix composites has also been approached from the viewpoint of creating biomimetic materials. Nacre-like structures of increased toughness were obtained in Al-based nanolaminated composites by "flake powder metallurgy approach".9-3

Organizing reinforcing elements in continuous structures is another promising trend. Based on the recent literature and experimental results obtained by the authors, this article will describe a specific type of reinforcement distribution—the network distribution—in composites produced by sintering of powder mixtures. The reinforcements can be in the form of fibers [e.g. carbon nanotubes (CNTs)9], a continuous amorphous phase10) or can present in a matrix as separate particles organized in chains or distributed along interfaces.11-16) The term "network" is also used to refer to the phases of interpenetrating phase composites.17-19) In those structures, the network elements are made of several layers of grains. These grains form walls of porous structures that can be obtained when one of the components of a composite is removed, e.g. by selective dissolution.19,20)

In this focused review, experimental approaches and processing methods will be discussed that can be used to obtain the network distribution of reinforcements in composite materials produced by sintering of powder mixtures. It will be shown that the distribution of the reinforcement phases in these composites is a function of both initial powder structure and sintering conditions. Non-reactive consolidation and reaction-accompanied sintering will be demonstrated as processing options to establish continuous or quasi-continuous distribution of reinforcement. Special attention will be given to the effect of reinforcements on the sintering behavior of the composite materials and altered microstructure of the matrix. It will be shown that by organizing reinforcements in networks, new levels of properties of composites with metal and ceramic matrices can be achieved.

2. Sintering-based preparation of composites with network distribution of reinforcements

2.1 Sintering-based processing of particle-, whisker- and nanotube-reinforced composites

Reinforcing particles can be organized in networks forming quasi-continuous structures within matrices. In such quasi-
continuous networks, the distance between particles is much smaller than the size of particle-free regions. Wong & Gupta\(^{11}\) synthesized magnesium matrix composites reinforced with nanoparticles of Mg\(_2\)Cu decorating the magnesium particle boundaries by sintering of Mg–Cu powder mixtures using microwaves. The mixtures were prepared by blending a magnesium powder with particles several tens of microns in size with a copper nanopowder. The blending operation was different from milling normally used in powder preparation: the vials without milling balls were used and no process control agent was added. Thanks to mild regimes of mixing, the magnesium particles retained their shape and size with copper nanoparticles adhering to their surface. The microstructure of the sintered magnesium composites produced from Mg–Cu powder mixtures containing 0.3 and 0.6 vol.% of copper showed Mg\(_2\)Cu particles that repeated the distribution of the copper nanoparticles in the composite powder. In a similar way, Mg–SiC were prepared showing nanoparticles of SiC along boundaries of magnesium particles.\(^{11}\)

In a series of publications on titanium matrix composites reinforced with titanium carbide particles TiC\(_p\) and titanium monoboride whiskers TiB\(_w\) formed in situ in the Ti alloy matrix,\(^{14-16}\) the network distribution of the reinforcements was the goal of the chosen processing. The whiskers acted as dowel pins bonding together the particles of the Ti alloy matrix. Two types of reinforcement—particles and whiskers were also combined in a composite.\(^{15}\) The crucial factor ensuring the observed network distribution of TiC\(_p\) and TiB\(_w\) was the distribution of carbon and TiB\(_2\) reactants along the surface of the matrix alloy particles in the powder that was subjected to reaction-accompanied consolidation.

From the simple considerations of the surface area of the particles of two components, which are candidates to form a composite, it becomes clear that when the particles of the matrix material are larger than those of the reinforcing phase, the latter will have to form aggregates. However, these effects required a quantitative description. Slipenyuk et al.\(^{13}\) suggested that for a given matrix-to-reinforcement particle size ratio, there exists a critical reinforcement content, which, when exceeded, gives rise to the formation of particle aggregates, which deteriorate the mechanical properties. It was shown both experimentally and theoretically that as the matrix-to-reinforcement particle size ratio decreases, higher contents of reinforcing particles can be accommodated in the microstructure without clustering. Based on these considerations, it can be concluded that when the reinforcing particles form in situ with the components of the matrix alloy participating, the important parameters of the processing are the concentrations of the reactants in the matrix and the nucleation and growth kinetics of the reaction products, as determining the volume content and size of the in-situ formed reinforcements. The contents of the reactants in the matrix should be such that when the product particles form, they could be fully surrounded by the matrix not to clot at the boundaries between the matrix particles forming aggregates.

The in-situ formation of particles of the second phase at the inter-particle boundaries of a sintered material can occur when one of the reactants becomes available as “contamination” introduced during sintering. The modification of the subsurface layers of sintered compacts can occur during Spark Plasma Sintering (SPS) or other sintering processes that involve the use of graphite tooling. The diffusion of carbon from the graphite tooling and graphite foil along the inter-particle or inter-agglomerate boundaries during sintering causes saturation of these boundaries with carbon or results in the formation of particles of new phases, if carbide-forming elements are present in the sintered material. Zapata-Solvás et al.\(^{12}\) used elemental mapping to show the presence of carbon at the grain boundaries of zirconium diboride ZrB\(_2\) sintered in the presence of graphite foil.

In our recent studies,\(^{21}\) we observed the formation of tungsten carbide WC in the subsurface layers of a Ni–W alloy sintered by SPS with particles following a network pattern [Figs. 1(a)–1(b)]. No carbon was added to the Ni–W alloy powder before sintering. The difference of the in-situ formation of WC in such conditions from that taking place in the mixtures already containing carbon introduced into the mixture prior to sintering by co-milling its major components with carbon is in the distribution of carbon as a reactant. In the former it is a planar source of carbon covering the external surfaces of the compact that supplies the reactant. The formation of carbides in this case is connected with carbon diffusion over longer distances than in situations with sintering of powders containing admixed carbon particles. The distribution of tungsten carbide WC particles followed a pattern: the submicron particles formed networks, which corresponded to the boundaries between the agglomerates of the mechanically milled powder consolidated into a compact by solid-state sintering. The reason for this microstructure development should be sought in a specific structure of the boundaries between the initial particles in compacts that are consolidated by a fast solid-state process.\(^{24}\) These boundaries seem to present paths for faster diffusion of carbon, which favors the formation of carbide nuclei in these locations. Another carbide phase—Ni\(_4\)W\(_6\)C—was observed at larger distances from the surface of the sintered compact, with submicron particles also organized in chains. A higher transformation degree of tungsten into its carbide was associated with a higher porosity of the sintered compact: pores are visible in.

![Fig. 1. Subsurface layer of the compact sintered by SPS form Ni–15 at.%W powder produced by mechanical alloying (SPS temperature 900°C, holding time 5 min, sintering in contact with carbon foil): (a) general view of the layer in contact with carbon foil; (b) chains of WC submicron particles in the microstructure along with coarser particles (red arrows are used to mark the chains of particles).](image)
the uppermost layer of the WC–Ni composite regions of the compact while they cannot be distinguished in the layers lying underneath.

The microstructure evolution during sintering can result in the formation of a network in immiscible systems. Such an effect was observed when a mechanically milled nanocomposite powder of 50 vol.% Fe–50 vol.% Ag composition was Spark Plasma Sintered.25) Silver streaks are seen at the inter-agglomerate boundaries in the microstructure of the compact (Fig. 2).

The first step in the preparation of composites with CNT networks distributed in matrices by sintering is their dispersion over the surface of the particles of the matrix material. Several methods have proven suitable to disperse CNTs in different matrices. In addition to dry ball milling,26) ultrasonic treatment and wet milling can be used. An intertwining network of CNT in the alumina matrix (Fig. 3) was successfully obtained using ultrasonication combined with ball milling in alcohol, as is described in ref. 27). However, CNT agglomerates can be sometimes found in the microstructure of the sintered compacts.28) A uniform distribution of CNTs over the surface of particles of alumina was achieved by Huang et al.29) who used a non-covalent functionalization approach. The method of functionalization was shown to effect mechanical properties of ceramic matrix composites containing CNT, as will be discussed below in section 3. The sintering temperature is a key factor that should be carefully chosen to keep the CNTs intact in the composites. It was found that CNTs contained in an alumina matrix tend to transform into graphite at temperatures exceeding 1150°C during SPS.28),30)

2.2 Sintering-based processing of interpenetrating phase composites

Interpenetrating phase composites with ceramic networks can be obtained by consolidation of metal-ceramic powder mixtures containing high volume percentage of ceramic phases.18,19) Figure 4 shows the microstructure of the 57 vol.% TiB2–Cu nanocomposite powder obtained by a combination of the self-propagating high-temperature synthesis using Ti and B reactants in a copper matrix and ball milling. In order to characterize the structure of the ceramic network (skeleton) formed within the microstructure of consolidated composites, electrochemical etching was used to remove copper from a surface layer of the compacts. Porous TiB2 layers formed on the 57 vol.% TiB2–Cu compacts consolidated from the powders by SPS and shock wave are shown in Figs. 5(a) and 5(b), respectively. It is important to note that these strong and robust porous layers could not be formed when the composite powders were conventionally sintered by heating cold-pressed pellets of the same phase composition in a furnace at the same sintering temperature as was used in the SPS (950°C). This shows the significance of the high relative density of the compact for the formation of a strong and self-supporting TiB2 skeleton. The size of the TiB2 grains is also an important parameter, as finer grains forming the walls of the porous structure possess a larger inter-particle contact surface, sintering along which will ensure a higher mechanical stability of the porous structure.

The network of grains organized in walls can be formed by an in-situ process during consolidation involving chemical reactions or phase transformations. In ref. 20), this route was evaluated for nickel-graphite composites. The powders were subjected to treatment in a high-energy ball mill to achieve intimate mixing and refine the microstructure of nickel. The consolidation was accompanied by in-situ graphitization of amorphous carbon. Figure 6(a) shows the fracture surface of the 50 vol.% nickel–50 vol.% graphite composites obtained by SPS of nickel-amorphous carbon mixtures. Selective dissolution of nickel from the compact allowed obtaining porous graphite (Fig. 6(b)) that was self-supporting at the macroscale (in the form of disks of 10 and 20 mm diameter).
2.3 The influence of the network distribution of reinforcement on the sintering behavior of powder mixtures

Networks of ceramic particles or fibers usually make the sintering process more difficult. The presence of CNT in alumina required a higher sintering temperature to reach the same relative density.29) While CNT-free alumina powder could be fully densified by SPS at 1200°C, composites containing 5 wt.% of CNT required sintering at 1300°C to be fully dense. A higher sintering temperature was needed for densification, as the CNT network acted as an obstacle for diffusion of aluminum and oxygen of the alumina matrix.

On the other hand, when the reinforcement is more susceptible to the physical treatment imposed to induce sintering of powder mixtures, its presence and distribution can influence the outcome of the sintering procedure, making sintering more efficient in terms of reaching higher relative densities. Wong & Gupta31) attributed improved yield strength, ultimate tensile strength and ductility of magnesium matrix composites Mg–SiC to a beneficial property of the SiC reinforcement to be a better microwave susceptor and heat faster compared with magnesium. Due to the network distribution of the SiC susceptor particles, enhanced interfacial integrity was achieved in the composite as a whole. Lahiri et al.31) suggested that the presence of CNT in ceramic matrices helps establishing more uniform heating of the compacts during SPS than in the case of CNT-free ceramics. However, this effect should also be considered from the viewpoint of what happens to the CNTs and to what extent they can be preserved when they have to carry a major fraction of the electric current. Because of a large difference in the electrical conductivities of CNTs and ceramics, at the scale of ceramic grain size/CNT diameter, the electric current will be distributed non-uniformly.

In traditional combinations of metal matrices and ceramic or intermetallic reinforcements, the second phase is usually a higher-melting point material. When clustered, the reinforcing particles poorly sinter with each other, and, as a result, the areas of agglomeration contain porosity that cannot be eliminated in the optimal sintering conditions normally selected based on the physical properties of the matrix.21),32) In a ceramic composite, the phase with a higher melting temperature also comprises most of the porosity, if it forms agglomerates, as has been shown for TiB2–B2C composites with boron carbide acting as a matrix toughened by higher-melting point titanium diboride.33) If the matrix and the reinforcement could sinter within the same temperature range, it would be much easier to produce pore-free compacts. The network distribution of particles that can act as a binder in composites during sintering is beneficial for eliminating porosity uniformly throughout the microstructure. In metal matrix composites reinforced with particles of metallic glass, the latter perform both functions being a binder at the sintering temperature and a hard reinforcement in the composite at its service temperature.34)–37) The role of a binder can be played by metallic glass thanks to the existence of the supercooled liquid region \( \Delta T_g = T_x - T_g \), where \( T_x \) is the crystallization temperature and \( T_g \) is the glass transition temperature of the metallic glass), within which the metallic glass becomes soft. Distributed along the boundaries of the alloy matrix particles, the metallic glass particles help fully eliminate the porosity during consolidation, as was suggested in ref. 34). In that work, the Al6061 alloy matrix composite reinforced with particles of a FeCo-based metallic glass was developed using the above described concept. The volume content of metallic glass particles was 15%. The Al alloy particles ranged...
from 10 to 50 μm while the metallic glass particles were an order of magnitude smaller. During co-milling of the powders, the size of the Al alloy particles did not change significantly. The main result of co-milling was distribution of smaller particles of metallic glass over the surface of coarser particles of the matrix alloy.

In an aluminum matrix composite reinforced with a Zr-based metallic glass developed by Scudino et al.\textsuperscript{38)} using the same considerations of possible benefits from combining a metal and a metallic glass, particles of the latter formed a network of a different kind: as the volume content of the metallic glass was high (60 vol.%), the reinforcing phase created constraints for deformation of the aluminum phase. The resultant composite was, therefore, close in structure and behavior to interpenetrating phase composites.

2.4 The influence of the network distribution of reinforcement on the microstructure of the matrix

Annealing of defects introduced into aluminum during its co-milling with CNTs has been recently studied by Selyutin et al.\textsuperscript{26)} by means of the in-situ X-ray phase analysis using synchrotron radiation. By measuring the microstrain stored in aluminum from the shape of the X-ray profiles, it was found that during annealing of Al–3 wt.% CNT composite particles containing 10 nm-diameter multi-walled CNTs obtained by high-energy mechanical milling of Al–CNT mixtures, the level of microstrain remains unchanged up to a temperature of 500°C, while exposure of the CNT-free aluminum to this temperature led to a significant reduction in the value of microstrain in the powder. When CNTs of a larger diameter (20 nm) were used in the same weight percentage, annealing of defects started at a lower temperature—at about 150°C due to a smaller number of nanotubes present in the same volume of the aluminum matrix.

The presence of CNT influences the grain size of the sintered metal and ceramic matrices by hindering grain growth.\textsuperscript{39,40)} Non-covalent functionalization of both Ni (initial particle size 120 nm) and CNT in ref. 39) helped distribute the CNTs along boundaries of Ni nanoparticles and efficiently hinder grain growth during sintering. Another example of hindering grain growth during sintering of CNT-containing mixtures was demonstrated by Shen et al.\textsuperscript{40)} The grain size of ZrO\textsubscript{2} in the compact Spark Plasma Sintered at 1300°C without CNT addition was 230 nm, while grains of ZrO\textsubscript{2} in the composite containing 5 vol.% of CNT were much smaller—150 nm—and close in size to the initial powder. It was suggested that the differences in the sintering behavior of ZrO\textsubscript{2} and ZrO\textsubscript{2}-based CNT-containing composites are due to a change in the densification mechanism from grain boundary sliding to grain boundary diffusion caused by the pinning effect of CNTs.

3. Promising properties of composites achieved by the network distribution of reinforcements

Depending on the nature of matrix and reinforcement, the continuity of the latter in the microstructure can have different consequences for the material evolution during processing and resulting properties. In metal matrix composites, the most significant aspect of the distribution of reinforcing particles along the boundaries of the matrix is particle-free (particle-lean) regions that can help maintain ductility of the composites—through the mechanisms of crack blunting and lowering its propagation rate—while reaching desirable strength levels.\textsuperscript{1)} In interpenetrating phase composites, the high strength of the composite is provided by the thick-walled skeleton of ceramics. Indeed, the 57 vol.% TiB\textsubscript{2}–Cu composite with a fine-grained TiB\textsubscript{2} network interpenetrating the copper phase showed a higher yield strength (540 MPa\textsuperscript{42)} than its counterparts produced by simple mixing and hot pressing (300 MPa\textsuperscript{42}) when tested in compression.

In CNT-containing composites, the reinforcement networks allow achieving principally new levels of properties. Interestingly, not only CNT that are structures with high aspect ratios can form networks imparting conductivity to ceramics. Ahmad et al.\textsuperscript{43)} obtained a 3D interconnected nanosheet architecture from graphene distributed in an alumina matrix, which resembled a network of CNTs. The room temperature electrical conductivity of about 800 S·m\textsuperscript{−1} was achieved in a composite containing 5 vol.% of graphene, which is close to values reported by Zhan & Mukherjee\textsuperscript{27)} for alumina reinforced with 5.7 vol.% of SWCNTs. Agglomeration of CNTs is an important factor for the electrical conductivity of ceramic-based composites. Shen et al.\textsuperscript{49)} observed an increase in electrical conductivity of ZrO\textsubscript{2}–CNT composites with increasing volume content of CNTs up to 5% followed by a decrease in electrical conductivity when the content of CNT reached 10%. The observed trend was explained by a poorer distribution of CNTs contained in the ZrO\textsubscript{2} matrix at high volume percentages.

When electrical conductivity of CNT-ceramic composites needs to be tailored, percolation threshold for CNT should be determined.\textsuperscript{49)} Reaching the percolation threshold in ceramic matrix composite by nanotubes is also key for developing microwave absorbing materials.\textsuperscript{45)} As was shown by Chojnacki et al.\textsuperscript{46)} alumina matrix composites containing multi-walled CNTs possess attractive properties for microwave absorbers in 1–40 GHz frequency range when the CNT content in the composite reaches 1–2.5 wt.%, which is just above the percolation threshold.

Related to electrical conductivity of CNT-ceramic composites is their potential for thermoelectric applications. In this regard, Zhan et al.\textsuperscript{47)} suggested a possibility of tailoring the electrical to thermal conductivity ratio by adjusting the CNT content and porosity of CNT-ceramic composites. With increasing concentration of CNT, the electrical conductivity of the composites could be increased, while the manageable porosity of the composite as a whole would reduce the thermal conductivity of the material. In such situations, the pores should not disrupt the continuity of the CNT networks.

An interesting feature of CNT networks in the sintered compacts is in that they can have certain orientation relative to the compact axes. Zhan et al.\textsuperscript{48)} showed that mixtures of Al\textsubscript{2}O\textsubscript{3} and single-walled CNTs form anisotropic compacts when consolidated by SPS. Ropes of single-walled CNTs were aligned mostly perpendicular to the pressing direction during SPS. In this “in-plane” direction, the thermal conductivity of the sintered composite decreased only slightly relative to that of pure alumina, while it showed a 2–4 fold decrease in the transverse direction (parallel to the pressing axis during SPS). Indentation fracture toughness of 5 vol.% double-walled CNT-alumina composites measured on the cross-section was higher than that measured on the surface normal to the pressing direction.\textsuperscript{49)} Measurements of the lengths of the cracks emanating from the corners of Vickers indents obtained on cross-sections of alumina-CNT compacts produced by SPS showed that cracks propagating in the pressing direction were shorter than those that were perpendicular to the pressing direction, which was attributed to residual stresses and preferential alignment of CNTs.\textsuperscript{50)} The achievable level of toughening of ceramics by CNT networks is a matter of debate, as was discussed by Thomson.
et al. An interesting effect of reduction of fracture toughness of Al₂O₃ to 10 vol. % Nb composites upon the introduction of CNTs shows that mutual interaction between the toughening phases should be taken into account in multi-phase composites. Based on refs. 27, 49, it can be concluded that CNT networks can be introduced into alumina ceramics resulting in the formation of composites with increased electrical conductivity relative to pure alumina, beneficial anisotropic thermal properties and fracture toughness that remains at the level of pure alumina or exceeds it.

Zhou et al. found that non-covalent functionalization of CNT introduced into alumina makes composites more deformable compared with pure alumina, while covalent functionalization produces an opposite effect. The introduction of functionalized CNT networks into ceramics was, therefore, suggested as an effective approach to grain boundary engineering. The authors argued that the content and distribution of CNTs in ceramics impact the grain boundary sliding during deformation. Huang et al. showed that the presence of boron nitride BN nanotubes in alumina enhanced the superplastic behavior of the composite through the mechanism of inhibition of both static (in the as-sintered composite) and dynamic grain growth (after compressive deformation) in the ceramic matrix.

4. Future research directions in the area of composites with network distribution of reinforcements

Significant advances made in recent years in the processing of composite materials have solved many practical tasks. At the same time, they opened new avenues for developing new materials with sets of properties that have not existed before. One of the possibilities of fine property tuning of composites produced by sintering is an adjustable second phase distribution achieved through variation of the initial particle morphology.

The networks of the second phase have a potential of increasing the efficiency of inter-particle sintering. The network distribution of conducting phases in powder mixtures is crucial for electric current-assisted sintering, when heating-induced processes in the sample depend on the presence and distribution of a conducting phase in the powder compact. In high-voltage electric pulse sintering, the physical processes can be spatially inhomogeneous, as the density fluctuations in the powder compacts due to agglomeration cause fluctuations in electrical conductivity. The paths of the least resistance can form a channel throughout the compact volume suffering from overheating. As a result, a short circuit forms leaving the rest of the sample poorly sintered. In high-voltage processes relying on a single electric pulse or a sequence of a several pulses, the formation of the preferred current paths is especially important. The networks of CNTs introduced into the compact to be sintered by high-voltage consolidation could be a solution to improve the sintering uniformity.

The challenges of dispersing CNTs in different matrices have been solved to a great extent by covalent and non-covalent functionalization. Usually, once a high degree of the distribution uniformity is achieved, the composite mixture is used for further sintering studies and property measurements. However, it is of interest to track the dependence of the properties of composites on the degree of dispersion of CNTs.

5. Summary

In this article, the principles underlying the microstructure formation in composites with networks formed by ceramic particles, particles of metallic glass and carbon nanotubes were analyzed. The network distribution is one of the possibilities to spatially organize the reinforcing phases in composites to achieve specific properties. Networks can be formed by particles located at grain or particle/agglomerate boundaries, fiber-like components extending through the boundaries between many pairs of grains or can present multi-grain skeletons with thick walls making the reinforcing structures self-supporting upon removal of the other phase. The consequences of the continuity of the reinforcement phase are used to achieve a new level of properties of the composites or derivatives that are produced from them upon further processing. The presence of reinforcing phases forming networks influences the sintering behavior and impacts specific properties to the sintered composites:

1) reinforcing particles can be more susceptible to micro-waves and promote sintering of the surrounding regions of the composites;
2) networks of metallic glass particles can efficiently glue together particles of matrix alloys provided the optimal time-temperature sintering regimes are selected;
3) networks of CNTs hinder grain growth of metal and ceramic matrices;
4) networks of CNTs can impart electrical conductivity to otherwise non-conductive compacts without sacrificing toughness of the materials;
5) networks made of CNT ropes orient perpendicular to the pressing direction during uniaxial pressure-assisted consolidation of powder mixtures, which results in the property anisotropy of the sintered composites;
6) networks of CNT can mediate superplastic behavior of ceramic-based composites;
7) networks in the form of thick-walled skeletons can be part of interpenetrating phase composites; such networks of ceramic grains impart increased strength to metal-ceramic composites; they can also serve as a basis for designing porous materials by selectively removing the other phase to obtain a self-supporting network structure.

Future research in the area of sintered composites with network distribution of reinforcements may be directed to finding ways of increasing sintering efficiency using metallic glass as an inter-particle binder for a greater variety of materials and improving sintering uniformity of non-conductive materials during electric current-assisted sintering through incorporating networks of conducting fibers into the compacts.

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