

Cray-2 supercomputer used liquid immersion cooling (10).

Recently, chilled-liquid cooling was reintroduced in high-end mainframes and densely packed servers to cope with the high heat fluxes. Yet, liquid cooling can be taken further if we consider a microfluidic heat sink (11) (see the figure, panel C). Microchannel heat sinks can be designed such that the thermal resistance between the transistor and the fluid is reduced to the extent that even cooling-water temperatures of 60° to 70°C ensure no overheating of the microprocessors. This hot-water cooling has compelling advantages. First, chillers are no longer required year-round and thus the data-center energy consumption plummets by up to 50%. Second, and perhaps most important, direct utiliza-

tion of the collected thermal energy becomes feasible, either using synergies with district heating or specific industrial applications. With such an appealing waste-heat recovery system, the green diligence of data centers would be upped substantially.

Reducing the energy consumption of data centers and concomitantly restraining costs, while curtailing carbon emission, is achievable. Despite power dissipation in microprocessors continuing to be a source of severe concern, liquid cooling and deploying waste heat appear to become imperative in the drive for improving the data-center energy efficiency.

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MATERIALS SCIENCE

The Future of Metals

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On 15 December 2009, the world's most fuel-efficient commercial jetliner—the Boeing 787 Dreamliner—completed its first flight. The airliner is mostly made from carbon fiber–reinforced polymeric composites (50% by weight, up from 12% in the Boeing 777) (1). Traditional metals are substantially replaced by composites with higher strength/weight ratios; aluminum usage has dropped to 20% (versus 50% in the 777). Ever since the 1950s, when “engineering materials” mainly meant metals (2), the share of metals in engineering materials has been diminishing. What are the reasons behind this trend, and which applications are likely to stay in the domain of metals?

The main property limitation of metals as structural materials is their low specific strength (the strength/weight ratio). Most engineering designs call for structural materials that have high strength, fracture toughness (a measure of the energy required for propagating cracks), and stiffness while minimizing weight. Most metals have high strength and stiffness, but because they are dense (steels are several times as dense as ceramics and polymers), their strength/weight and stiffness/weight ratios are low relative to competing materials (see the figure). This is a key reason for replacing metals in aircraft and sporting goods, where weight is a primary

concern. Some metals such as aluminum and magnesium are light, but they are too soft for many applications and have low toughness and stiffness. Titanium alloys partly overcome these problems: They are about half as dense as steels, have higher strength, and are very tough. Titanium was first used in airliners in the 1960s in the Boeing 707 and its use has increased to 15% in the Boeing 787 (1).

Metals can be strengthened through controlled creation of internal defects and boundaries that obstruct dislocation motion (3). But such strategies compromise ductility and toughness, in contrast to the increasing toughness at higher strength seen with polymeric composites (see the figure). Strengthening may also compromise other metal properties, such as conductivity and corrosion resistance. One method for strengthening metals without losing toughness is grain refinement (grain size reduction), but when the grain sizes fall below ~1 μm, strengthening is usually accompanied by a drop in ductility and toughness (4). A recent study points the way to overcoming this problem: In a low-alloy steel containing ultrafine elongated ferrite grains strengthened with nanosized carbides, toughness and strength both rose when temperature was lowered from 60° to –60°C (5). In contrast, conventional metals become strong but brittle at lower temperatures. The authors attributed the observed toughening to the unique hierarchical anisotropic nanostructures in their steels.

Nanotwinned metals are another example of hierarchical nanostructured metals

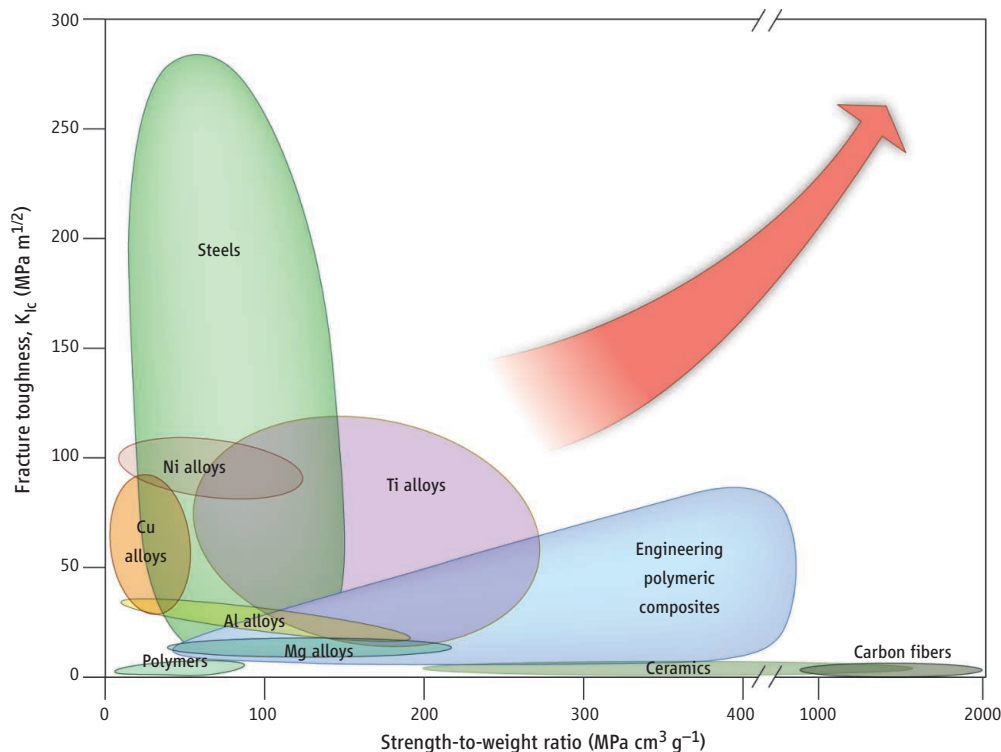
Despite advances made in composite materials, metals remain irreplaceable in many important applications.

with extraordinary mechanical properties (3). When a high density of twin boundaries (highly symmetrical interfaces between two grains of the same lattice structure) is incorporated into polycrystalline copper grains, with boundary spacing in the nanometer scale, the material becomes stronger than coarse-grained copper by a factor of 10; it is also very ductile. The ultrastrong nanotwinned copper has an electrical conductivity comparable to that of high-conductivity copper (6) and a much enhanced resistance against electromigration (7). It has great potential for applications in microelectronics.

Corrosion is another headache for metals (8). To protect metals from corrosion, they are commonly coated with a layer of corrosion-resistant material. The Hangzhou Bay Bridge in China is an outstanding example of this technique. This 36-km-long bridge—the world's longest to date, with a design life of 100 years—is supported by several thousand pillars made of concrete-filled steel tubes ~80 m in length. The tubes are protected against corrosion in the harsh ocean environment by a coating of novel polymeric composites combined with cathode attachments.

Metal corrosion can also be resisted by forming a continuous protective passivation layer on the metal surface. For example, Yamamoto *et al.* (9) have added 2.5% Al to conventional austenitic stainless steels, resulting in the formation of a protective aluminum oxide layer that can resist further oxidation at elevated temperatures. Given their enhanced

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oxidation resistance, these steels could be used at the high temperatures and aggressive oxidizing conditions of energy conversion systems to replace the currently used expensive nickel-based superalloys (metals specifically developed for high-temperature applications). Another route to enhancing the corrosion resistance of metals is to modify the chemical composition of surface layers. But most such processes require high temperatures that may cause serious deterioration of the metal substrates. The processing temperatures can be lowered substantially if the grains of surface layers are refined into the nanoscale via surface mechanical attrition treatments (10).

Metals also get soft at elevated temperatures; they can rarely be used above 1000°C with useful strengths. Superalloys have higher operating temperatures (up to ~1150°C for nickel-based superalloys), enabling their use in high-temperature applications such as jet turbine engines. Superalloys for higher operating temperatures, based on metals with higher melting points such as molybdenum and niobium, are under investigation (11).

Despite these limitations, metals are still the major workhorse of our society and will remain so in the future, thanks to unique properties that make them irreplaceable.

First, metals have a much higher fracture toughness than other materials (see the figure); steels are the toughest known materials. Therefore, metals are usually used for key

components with the highest requirements for reliability and durability, such as bridge cables, concrete reinforcement in buildings, and vehicle body frames. The Boeing 787 contains a considerable amount of metals (45%), mainly in critical parts with the highest reliability requirements, such as engines, wings, and alighting carriage.

Second, the properties of metals are uniform in all directions, and their strength is the same in tension and compression. Also, the strengths of metals are usually predictable. These features are critically important for predicting fracture in engineering structures. In contrast, it remains very difficult to predict fracture of composites and ceramics; their fracture is often catastrophic (the material fails all at once) and may cause serious economic loss and even loss of life. Hence, many advanced technologies continue to rely on high-performance metals. For instance, only extremely tough metal alloys can survive in the harsh irradiation and temperature conditions in the next generation of nuclear power stations. Body implants must sustain severe corrosive and loading conditions that also call for advanced tough metals.

Third, most metals are more conductive than ceramics and polymers. Copper and aluminum remain the best materials for overhead electricity transmission lines. Conducting lines and thermal spreaders used in information technology are mostly made from copper and its alloys. Metals also have unique

Competing materials. Steels have the highest toughness, whereas carbon fibers have the highest strengths. Titanium alloys and polymer composites are increasingly used in aircraft and sporting goods because of their outstanding combination of properties. Research on advanced materials for structural applications aims toward the upper right corner. [Data from (2)]

magnetic properties that are not easily reproduced in other materials.

Fourth, metals have the best overall mechanical properties at temperatures up to a few hundred degrees. This window covers most of the operation temperatures in chemical engineering processes, power stations, and various engines. Finally, most metals are recyclable, making metals more competitive for quantity applications.

Modern technologies not only strongly rely on these unique properties of metals, but urgently call for even better metals. Increasing the strength of metals without sacrificing other properties is critical for their competitiveness. Multiscale hierarchical structures provide a possible route to optimizing overall properties. Metals may also be mixed with other materials in a controlled way to form composite structures. Assembling metals with other components in this way—for example, in novel reinforcements or hierarchical assemblies—may shift their strength/toughness ratios toward the upper right corner in the figure. Developments in different material families may thus benefit from each other.

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