The Advanced Photon Source

Complex 3-D Graphite Structures in Cast Iron

Cast iron is an alloy of iron, carbon, silicon, and other elements with numerous industrial and consumer applications. The carbon content of cast iron — generally higher than that of steel — appears mostly in the form of distinct graphite particles. Materials scientists have long known that the sizes and shapes of these graphite particles critically affect cast iron's strength, brittleness, and other key properties. Characterizing the graphite in cast iron has traditionally relied on surface (two-dimensional; 2-D) imaging techniques. In this research, high-resolution three-dimensional (3-D) imaging of cast iron samples was achieved using synchrotron x-ray tomography performed at the X-ray Science Division beamline 1-ID-B,C,E at the APS.

The tomography revealed striking details of graphite particle distribution, size, and morphology inaccessible to 2-D imaging. Graphite content ranged from nodular, micron-sized particles, to complex coral-like structures spanning more than a millimeter. This research is part of a collaborative effort led by Caterpillar Inc., which supplied the cast iron materials, with funding from the DOE. The goal is to develop higher-strength cast iron for engine blocks and other components used in heavy-duty equipment. By increasing cast iron strength, engine size and weight can be reduced, thereby improving fuel economy while lowering emissions.

Prior to this research, 3-D imaging of cast iron was achieved using particle-beam tomography. Focused ion beam and transmission electron microscopy, utilizing beams of ionized atoms and electrons, respectively, have imaged cast iron microstructure three-dimensionally. However, these particle-beam techniques require laborious and extensive sample preparation, resulting in time-consuming and expensive experimental setups. They also destroy the probed area, which limits follow-up testing. By contrast, the x-ray tomography used in this research is non-destructive and requires little sample preparation, thereby reducing experiment duration and cost.

Cast iron can be classified according to its graphite inclusions. Ductile cast iron possesses more-or-less rounded particles called nodular graphite. Compacted-graphite iron (CGI), the type examined in this research, contains a mixture of nodular graphite and the more irregularly-shaped compact-graphite. Figures 1(b) and 1(c) show the rounded and irregularly-shaped particles typical of compacted-graphite iron.

The CGI sample consisted of a rod approximately 2 mm in diameter [Fig. 1(a)]. An x-ray energy of 70 keV maximized contrast between the cast iron and its graphite particles. To limit computer processing requirements, a small (1 mm^3) volume was imaged. Specialized software programs combined multiple 2-D x-ray slices to form a single 3-D image. Cross-sectional images of some of the graphite particles were found to be part of the coral-like structure in Fig. 1(d). The results demonstrate that synchrotron x-ray tomography can quickly reveal the intricate and extensive graphite structures present in cast iron using minimal sample preparation. Figure 1(e) highlights the benefits of 3-D imaging. Depending upon the orientation of the 2-D image, the same graphite particles could be interpreted as nodular graphite or compact-graphite. However, in three dimensions, the particle types are unambiguous.

The researchers expect their 3-D imaging techniques will help resolve several outstanding questions. For instance, do complex graphite particles, like the one in Fig. 1(d), originate from a single particle that grows as the sample cools? Or do many smaller particles merge during cooling? Importantly, the 3-D tomography techniques used in this study are applicable to other alloys, for instance aluminum alloys. Moreover, the availability of greater computational power will allow the imaging of larger sample volumes. *— Philip Koth*

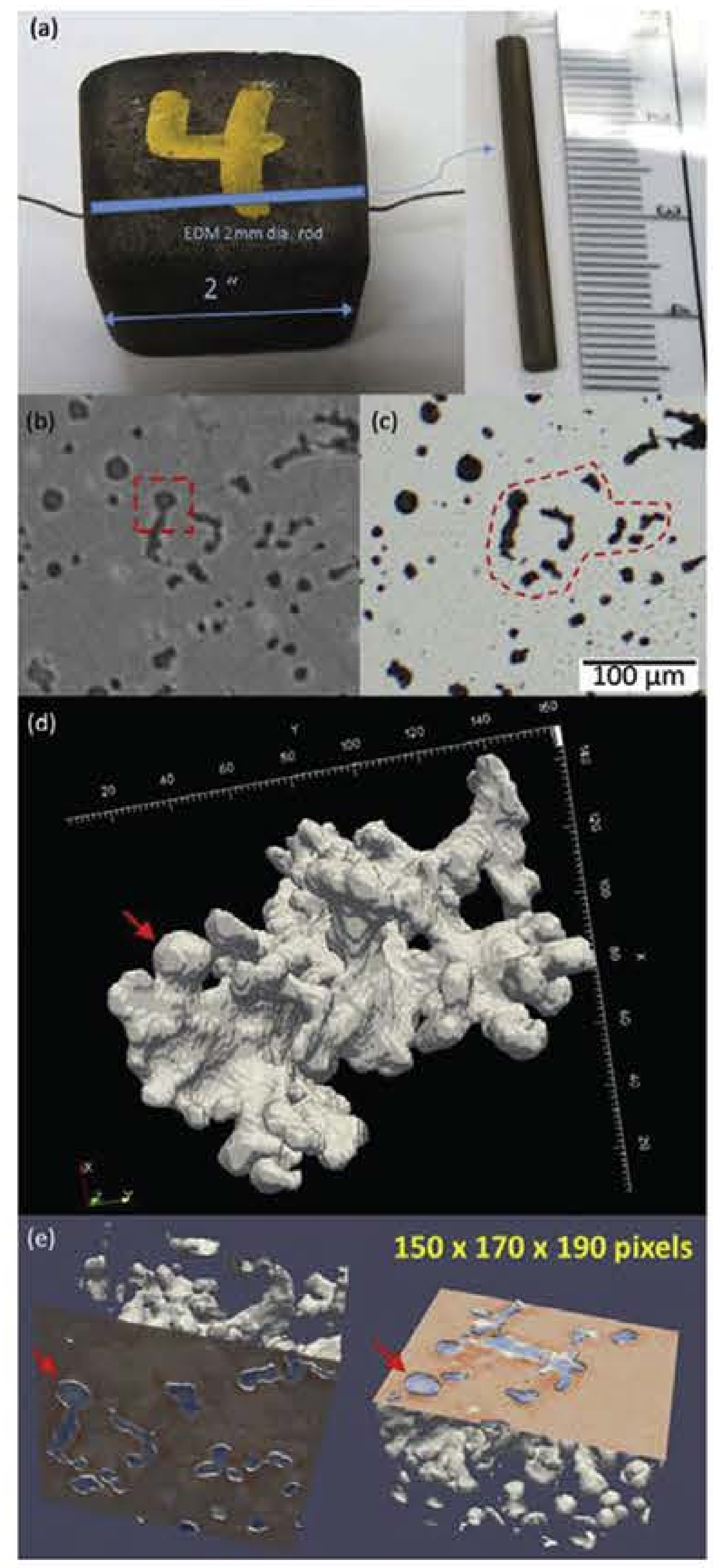

Fig. 1. At left in panel (a) is the cast iron block from which the ~2-mm-diameter rod used for measurements was cut. Panel (b) shows a 2-D x-ray slice. Panel (c) After cutting the rod at the precise location of the x-ray slice in panel (b), an optical image of the surface confirms x-ray image quality. Panel (d) is a reconstructed 3-D model of a coral-like structure with flat, rounded branches spanning two-tenths of a millimeter within the iron matrix.

See: C. Chuang[1], D. Singh[1*], P. Kenesei[1], J. Almer[1], J. Hryn[1], and R. Huff[2], "3D quantitative analysis of graphite morphology in high strength cast iron by high-energy X-ray tomography," Scripta Mater. **106**, 5 (2015).
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