Making Boring Cutting Edge

THROUGHOUT history, tunnels have been used for aqueduct, storm-drain, and sewer systems and for pedestrian, motor-vehicle, and rail-train passageways. In urban environments today, tunnels are often used instead of bridges for transportation because unlike bridges, tunnels hide traffic and allow land to be retained for other uses.

The development of the tunnel-boring machine (TBM) in the mid-1900s revolutionized tunnel building. A modern TBM is an enormous piece of equipment with 20 or more disc cutters mounted in a rotating circular plate 6 meters in diameter or larger. The machine advances into the tunnel in increments of 1.5 meters called “pushes.” During these pushes, the crown area of the disc cutters pulverizes the rock face. Wear on the disc cutters is so severe that they must be replaced frequently, typically every few days depending on the type of host rock, which is costly in terms of both time and money.

Attempts have been made to extend the life of disc cutters by applying hardened coatings. However, during each rotation, the disc cutters experience a combination of tensile and compressive stresses that has thwarted these attempts—that is, until these barriers were shattered with the development of the NanoSHIELD (super-hard inexpensive laser-deposited) coating. NanoSHIELD is a nanostructured protective coating that can extend the life of disc cutters by at least 20 percent, potentially saving millions of dollars over the course of a project.

The coating is created by lasers that fuse a specially formulated iron-based amorphous alloy powder onto a steel substrate, forming a metallurgical bond. While the NanoSHIELD coating was first designed to prolong the life of cutting discs used for tunnel boring, it can also be used in other applications such as rock-mixing paddles, machining tools, and geothermal drilling tools.

A team of scientists and engineers from Lawrence Livermore and Oak Ridge national laboratories and collaborators at Strategic Analysis, Inc.; Ozdemir Engineering, Inc.; Colorado School of Mines; and Carpenter Technology Corporation have won an R&D 100 Award for the technology. The team’s efforts benefited from previous work performed under the Structurally Amorphous Materials (SAM) Program, which was cosponsored by the Defense Advanced Research Projects Agency and the Department of Energy.

Glassy alloy powder is delivered onto a metal substrate and fused with it using lasers to form a NanoSHIELD (super-hard inexpensive laser-deposited) coating. (Courtesy of Oak Ridge National Laboratory.)

Exploiting Key Technologies

In crystalline alloys, atoms form an orderly three-dimensional lattice, which allows the alloy to stretch or bend. However, under high enough stress, crystalline alloys are prone to metal deformation. In contrast, structurally amorphous materials, such as iron-based amorphous alloys, have the disordered atomic structure of glass, making them harder, stronger, and more resistant to wear. The SAM Program developed innovative iron-based amorphous alloys with the correct balance of hardness, ductility, and wear resistance for tunnel-boring applications. Powder forms of SAM alloys are now commercially produced in bulk quantities via gas atomization and are used in the NanoSHIELD coating.

NanoSHIELD development also has benefited from advancements in additive manufacturing. (See *S&TR*, March 2012, pp. 14–20.) Instead of machining away material to shape a part, additive manufacturing can build components in layers from materials such as SAM powder.

A Choice of Fabrication Methods

To apply the NanoSHIELD coating onto a disc cutter, the team uses a method that involves depositing SAM powder by aspiration onto the cutter with a polymer-based binder. The binder retains the powder in place until laser fusing. The powder is applied in striped or freckled patterns, which allows for distortion or deformation of the steel substrate without disturbing the coating, similar to the use of expansion joints in concrete to accommodate thermal strains. The laser fuses the powder to the substrate, forming a strong metallurgical bond. Then the excess binder and powder are extricated by a variety of means, including scrubbing with a wire brush. This method is preferred for coating disc cutters because of their size.

Another method involves fusing the NanoSHIELD coating to a steel substrate using a direct metal deposition free-form laser and robotic system. Binders are not applied; rather, the powder is delivered to an area by argon gas where it is fused by the laser and solidified in place. The sophisticated software controlling the laser and robot allows the system to coat more complex geometries. For example, paddles used in aggregate mixers have been successfully coated with this method.

The team's experiments in laser fusing of NanoSHIELD coatings have led to unique nanocrystalline, glassy, and nanocrystalline–glassy composites with incredible metallurgical properties. For example, a sufficient coating thickness for improving the wear resistance of a cutting disc is only 0.1 to 0.7 millimeters. The coating can have from 1.3 to more than 7 times the hardness of the steel substrate without affecting the intrinsic toughness and elasticity of the substrate.

Livermore NanoSHIELD codeveloper Frank Wong.

Performing Field and Laboratory Experiments

According to the Colorado School of Mines, in over 25 years of testing and research and development on coated disc cutters, NanoSHIELD-coated discs are the first to not spall or fracture after one linear cut of granite on a linear cutting machine used for simulating full-scale rock-cutting conditions in the laboratory. The granite is cast in concrete within a heavy steel box to provide the necessary confinement during testing. After each cut, the granite is moved sideways by a preset spacing to duplicate the action of multiple cutters on a TBM. "In laboratory tests at Colorado, the coating showed no signs of spalling even after more than 100 cuts on granite," says Livermore scientist Frank Wong, who led the disc-cutter collaboration.

Following these positive laboratory tests, full-scale field tests were performed at the Combined Sewer Overflow Tunnel Project in Atlanta, Georgia. Four of the 52 disc cutters on a 9.7-meter-diameter TBM were replaced with NanoSHIELD-coated discs, adjacent to uncoated cutters. The coated cutters survived 13 pushes without cracking or spalling. Most remarkable, the coated cutters maintained their sharpness at least 20 percent longer than the uncoated cutters, resulting in less down time for disc replacement, higher penetration rates, and lower energy consumption.

—Geri Freitas

Key Words: direct metal deposition, disc cutter, glassy metal, iron-based amorphous alloy, nanocrystalline, NanoSHIELD (super-hard inexpensive laser-deposited) coating, R&D 100 Award, tunnel-boring machine (TBM).

For further information contact Frank Wong (925) 423-0763 (wong71@llnl.gov).