Two discoveries advance basic and applied additive manufacturing research

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A research team led by Tao Sun, associate professor of materials science and engineering at the University of Virginia, has made two discoveries that can expand additive manufacturing in aerospace and other industries that rely on strong metal parts.

Additive manufacturing has contributed to aircraft production for years, as reported by the Association for Manufacturing Technology. However, additive manufacturing also generates defects in the microstructure of a finished part, limiting its role to the fabrication of ductwork, interior components and other non-critical parts. Additive manufacturing of safety-regulated parts will help the industry achieve its aspirations for efficient and stable supply chain management, as well as fuel savings and emissions reductions that accompany a lighter aircraft.

Sun's team and collaborators have discovered why structural defects occur during the additive manufacture of parts made from a high-strength, light-weight titanium alloy widely used in aerospace applications. They present a process map—the blueprint the machine uses to create a part—to help manufacturers avoid generating defects during a common additive manufacturing technique called laser powder bed fusion.

The team's paper, Critical Instability at Moving Keyhole Tip Generates Porosity in Laser Melting, is published in the Nov. 27 issue of *Science.* Cang Zhao, who was a post-doc in Sun's research group at Argonne National Laboratory and now a faculty member in the Department of Mechanical Engineering at Tsinghua University in Beijing, first-authored the paper with colleagues from Argonne, Carnegie Mellon University, the University of Utah and UVA. The second author, Niranjan D. Parab, was also one of Sun's Argonne National Laboratory post-docs, who has since joined Intel.

The research team focused on the two most important conditions of the additive manufacturing process, laser power and scan speed. How these two conditions are set and interact is captured in a power-velocity process map. Similar to a conventional map, the power-velocity map sets boundary lines between areas in which to work and areas to avoid.

The power-velocity map can be divided into a good zone and three bad zones. If the manufacturer stays in the good zone, the build will likely yield a high-quality part on a consistent basis. Two of the bad zones are easy to recognize. One is represented by a lack of fusion, evidenced by unmelted powder because of deficient laser power density. A second bad zone is represented by balling, when a single printed line rolls up on itself, signaling that the laser is moving too fast.

Sun and the team focus on zone four. In this zone, parts come out of the build process with tiny holes, a structural defect called porosity. These tiny holes appear inside the material, making it hard to see and control. "You could print multiple test lines, and you still would not know by examining the part surface if porosity is occurring underneath," Sun said.

Porosity defects remain a challenge for fatigue-sensitive applications, such as aircraft wings. Some porosity is associated with deep and narrow vapor depressions called keyholes, which occur under high-power, low-scan-speed laser melting conditions.

Sun and the team discovered how porosity occurs and were able to characterize materials' transformation during the 3-D printing process with very high spatial and temporal resolutions. They used an imaging technique, called high-speed synchrotron X-ray imaging, that monitors the formation of the pores frame-by-frame throughout the laser printing process. Images are captured at microsecond intervals, far beyond what the human eye can capture or the human brain can process.

High-speed synchrotron X-ray imaging is the only available method to qualitatively measure and describe what happens when the laser beam is exposed to the metal powder bed. In addition to melting powder, the laser also vaporizes some metal. The high-velocity vapor escaping the melt pool surface creates a small cavity called a keyhole.

The formation and size of the keyhole is a function of laser power and the materials' capacity to absorb laser energy. If the keyhole walls are stable, it enhances the surrounding material's laser absorption and improves laser manufacturing efficiency. If, however, the walls are wobbly or collapse, the material solidifies around the keyhole, trapping the air pocket inside the newly formed layer of material. This makes the material more brittle and more likely to crack under environmental stress.

Sun described the boundary between the good zone and the bad, porosity zone as smooth and sharp. "A very narrow laser condition, the specific combinations of power and speed, separates a good part and a part with pores. Just stepping across the line between the good and bad zones will determine whether your part carries this structural defect," Sun said. Based on the physics of such a smooth and sharp boundary, Sun knew that a subprocess was at play.

The team eventually discovered that the laser-metal interaction generates acoustic waves.

Sun explains that an acoustic wave can interact with a gas bubble in a liquid in different ways. Driven by the acoustic force, a bubble can move, deform, split and even collapse. In this study, the team found that under laser conditions near the porosity zone boundary, the acoustic force plays a critical role in pushing the pore away from the keyhole tip. Without the generation of acoustic waves in the melt pool, the pore will be pulled back to the keyhole.

"This is rather surprising," Sun said. "Short-pulse lasers were believed to be the source for generating acoustic waves in liquid, but we observed acoustic effects while using continuous-wave lasers. Apparently, there are still many intriguing problems that demand more research."

The two discoveries described in the *Science* paper have immediate impact on laser additive manufacturing of metals on both basic and applied research fronts. The well-defined porosity zone boundary in the power-velocity map provides more confidence for laser powder bed fusion practitioners to identify good printing conditions. Meanwhile, the new observations afforded by synchrotron X-ray imaging open up exciting multidisciplinary research areas that will attract more scientists to perform fundamental studies on laser additive manufacturing.

Sun's research team at UVA will continue to apply state-of-the-art characterization techniques for in-depth studies of additive manufacturing processes and materials. Additive manufacturing technologies hold the promise to completely revolutionize the way we make things.

"Additive manufacturing can only reach its full potential after the research community pieces together all the beautiful physics governing the complex energy-matter interactions involved in the printing process," Sun said.

More information: Cang Zhao et al, Critical instability at moving keyhole tip generates porosity in laser melting, *Science* (2020). DOI: 10.1126/science.abd1587

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