High-speed video analyzes microcracking during additive manufacturing of tungsten

Most of our day-to-day encounters with tungsten metal are limited to seeing its glowing coils in outdated incandescent light bulbs. However, the exceptional thermal conductivity and excellent radiation shielding properties of this very dense metal suggest that it is ideally suited to use as a plasma facing material in containment systems in emerging fusion reactors. In order for that to happen, however, researchers must overcome a critical roadblock. When tungsten cools down—from either high-temperature processing or after use in extreme environments—it stops being ductile and becomes brittle. In turn, the material develops microcracks and loses its strength. This is particularly problematic for the additive manufacturing of tungsten components, which uses laser heating to melt this metal and conform it to custom curvatures and shapes. Moreover, while researchers have examined failed tungsten articles and analyzed the networks of fractures that had formed, postmortem analyses have not provided much insight into the mechanisms that drive microcrack formation.

Researchers from Lawrence Livermore National Laboratory decided to use advanced videography to address this characterization challenge. Their efforts combine high-speed optical imaging of tungsten surfaces as they undergo laser melting with a thermomechanical model to provide key fundamental explanations for their observations. Bey Vrancken, Rishi Ganeriwala, and Manyalibo Matthews published their approach and findings in a recent issue of *Acta Materialia* (doi:10.1016/j.actamat.2020.04.060).

The researchers combined experimental videos with thermomechanical modeling using a Diablo finite element code they developed. "The observations and models were even sensitive enough to capture the effect of local strain rates, which are directly influenced by the processing parameters," say the researchers. "We are now using this technique to evaluate the efficiency of different crack-mitigating strategies, such as alloying and baseplate preheating. Ultimately, our goal is to produce tungsten parts that can withstand structural and thermal loading in extreme environments, for example in fusion reactors," they say.

The researchers set up a camera with a 50,000 cycle per second frame rate and used several laser emission sources to illuminate the sample and highlight emerging cracks. Continuous 200–500 W power laser heating combined with scan speeds between 50 and 500 mm/s created localized small pools—less than 100 µm wide—of molten tungsten. Increased applied heating power increased the depths of resulting melt pools. As the tungsten cooled, it formed transverse cracks on the surfaces of the resulting solids. Higher applied laser power increased spacing between cracks from 250 µm to 600 µm until longitudinal cracks, which ran deeper into the bulk of the material, appeared and relieved resulting stress. Researchers were also able to derive the ductile-to-brittle transition temperature range of 450–650 K for tungsten, during which cracks formed long after solidification.

The researchers were able to extract key data from their thermomechanical model that describes how the laser power and scan speed influence the residual stress and strain in molten tungsten. These affect the ductile-to-brittle transition, and, in turn, crack formation. In particular, a key derivation was the exponential correlation between the activation energy of the transition and the strain rate. The results predict that cracks initiate below surfaces and, following the paths of least resistance along the grain boundaries, emerge on the surface.

The heating rate and material composition, including impurities in the material and in the production environment, globally affect the structural integrity of resulting additively manufactured tungsten components. Specific alloy compositions can lower the ductile-to-brittle transition and strengthen grain boundaries, while preheating of the tungsten will lower thermal gradients and similarly mitigate embrittlement. The diagnostic tools that the researchers developed in this work will help monitor the additive manufacturing processing of tungsten and help bring forth crack-free, strong parts for emerging high-end applications.

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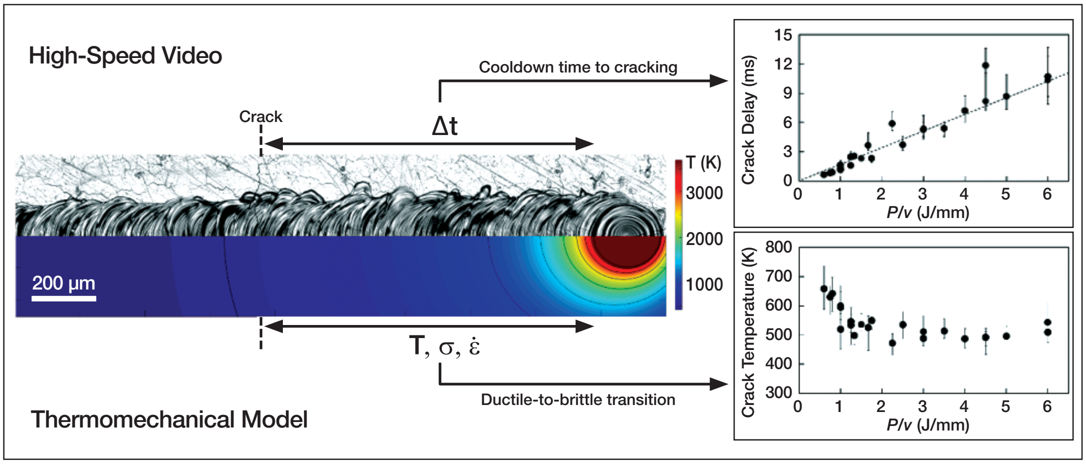

The reported technique captured high-speed video of the cooling of laser-induced molten tungsten patterns, and resulting data were fed into the thermomechanical model that derived relationships between the heating rates and crack formation and properties. Credit: Bey Vrancken, Rishi Ganeriwala, and Manyalibo Matthews.