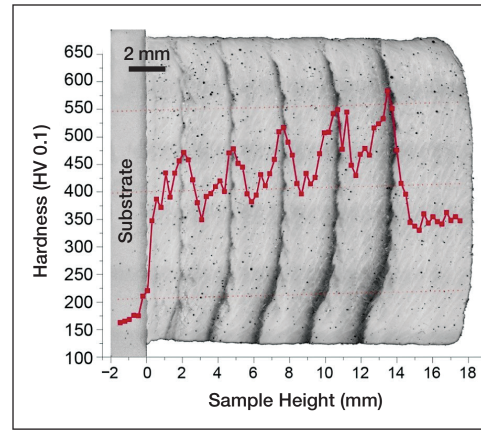
A legend reborn: Additive manufacturing creates Wootz-Damascus steel

Artisans in ancient India melted iron with woodchips as sources of carbon in clay crucibles and produced a hypereutectoid steel (C content ~1.5% by weight) called Wootz steel. Their technique, perfected over centuries, resulted in steels of high strength and ductility. These steels were traded in Damascus and spread to many countries, which turned them into swords of amazing performance with aesthetically pleasing wavy patterns on the surface. Combining the expertise of researchers at the Max Planck Institute for Iron Research in alloy design with that in laser processing by a team at the Fraunhofer Institute for Laser Technology, a new Damascus-like steel has now been created by additive manufacturing (AM), commonly known as three-dimensional (3D) printing. The key to the success of this work, as reported in a recent issue of *Nature* (doi:10.1038/s41586-020-2409-3), is the innovative use of the digital capabilities of AM to introduce a controlled hierarchical structure without the need for post-treatment.

Directed energy deposition (DED) is an AM technique that uses alloy powder fed by a carrier gas and a computer-aided design file to produce a near-net component in a single step. The alloy powder is injected into a melting pool of the same composition, heated by a laser beam. Then a subsequent layer is deposited and melted and thus the process is continued layer by layer. Interestingly, while a new layer is being deposited, the previously synthesized layer below gets heated up as well. The researchers call this effect "intrinsic heat treatment" (IHT).

"We exploit this IHT to trigger precipitation hardening reactions already *in situ* during the AM process. Via a precise control of the IHT we can digitally control the microstructure layer by layer in order to produce a steel with locally adjustable properties," says Philipp Kürnsteiner, the lead author of the study. A time- and energy-consuming heat-treatment step is thus avoided. By designing new alloys with fast precipitation kinetics, one can use the control of the time-temperature profile induced by the laser beam to obtain the desired properties after printing.



Optical micrograph showing a layered Damascus-steel-like structure consisting of a sequence of soft and hard bands. The precipitates are confined to the thin, dark layers by a precise control of the intrinsic heat treatment during the additive manufacturing process. The red line shows the increase in hardness in the dark layers due to precipitation hardening. Credit: P. Kürnsteiner and M. Wilms.

The researchers designed an Fe19Ni5Ti (wt%) alloy where IHT can bring about the layer-wise formation of two distinct structures that, in combination, enhance the mechanical performance of the alloy. "We use the digital access to the AM process parameters to precisely regulate the time-temperature profile of the IHT. This allows us to control the sequence of the desired phase transformations, namely martensite transformation and precipitation," Kürnsteiner says.

First, the researchers triggered the formation of martensite by pausing the DED process to cool down the material below the martensite start temperature (M_s). During re-heating by IHT, a hard layer was formed due to the precipitation of the intermetallic compound Ni_3Ti within the martensite. The Fe19Ni5Ti alloy shows fast kinetics for Ni_3Ti formation enabling *in situ* precipitation during the short temperature cycles of IHT. One can control which layer is to be hardened by adjusting the time of laser melting and pausing.

The researchers created a material formed by successive hard (precipitation hardened) and soft layers, giving the steel a pattern that resembles that of Damascus steels. More importantly, the hard layers gave the strength and the soft layers ductility to the steel. The product had a strength of 1.3 GPa and 10% elongation for the case of samples produced using DED pauses of 90 s between layers, comparable to those of conventional maraging steels. Guillermo Requena, who heads the Department of Metals and Hybrid Materials at the German Aerospace Center, and who did not participate in the research, says, "The beauty of the work is that they reach comparable properties with a much simpler chemistry and during production (without the need for further heat treatments)."

This work suggests that, in the future, new alloys tailored to the parameters of AM can be designed by integrating a fundamental understanding of thermodynamics and kinetics of phase transformations. The Wootz-Damascus steel has moved from the crucible to the laser room and from manual control to digital.

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