

A legend reborn: Additive manufacturing creates Wootz-Damascus steel

rtisans in ancient India melted iron A 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 Damascuslike 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 energyconsuming heat-treatment step is thus avoided. By designing new alloys with fast precipitation kinetics, one can use the control of the timetemperature profile induced by the laser beam to obtain the desired properties after printing.

Fe19Ni5Ti (wt%) alloy where IHT can bring about the layerwise 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

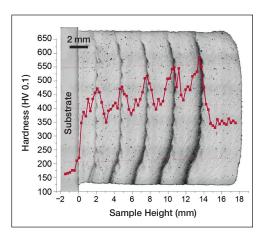
martensite transformation and precipita-

tion," Kürnsteiner says.

The researchers designed an

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 Ni₃Ti within the martensite. The Fe19Ni5Ti alloy shows fast kinetics for Ni₃Ti 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



Optical micrograph showing a layered Damascus-steellike 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.

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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