Nature Reviews Materials | https://doi.org/10.1038/s41578-020-0219-8 | Published online 25 June 2020

3D PRINTING

Damascus steel reloaded

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Laser additive manufacturing enables the 3D printing of metals into objects with complex shapes. Now Philipp Kürnsteiner, Eric Jägle, Dierk Raabe and colleagues, writing in *Nature*, demonstrate that it can also be exploited to locally control the microstructure, and thus the mechanical properties, of the printed alloys.

Objects fabricated with laser additive manufacturing undergo a thermal cycle that starts with a rapid quenching from the liquid state and continues with a cycle of heating made of short temperature spikes. Traditional alloys are not optimized for this type of processing, but specifically designed alloys can exploit this thermic cycling to achieve a particular microstructure. “We control the process so that instead of a homogeneous alloy, it produces a layered nanostructure that enhances the mechanical properties of the alloy,” explains Raabe. “Such nanostructures are known from ‘Damascus’ steels that were used in ancient Arabic and Japanese swords, traditionally obtained by a tedious manufacturing process involving folding two different steels over and over while forging.” By contrast, in the 3D printing process, the layered nanostructure with alternating soft and hard regions is fabricated in a single manufacturing step.

Credit: Björn Wylezich / Alamy Stock Photo

“This project started with the simple observation that some 3D printing processes introduce a significant amount of heat locally even after the initial material deposition, for instance through the building of successive layers,” comments Raabe. “We termed this phenomenon intrinsic heat treatment and set out to test our hypothesis that it could be used for local heat treatment to induce transformations that create a desired nanostructure.” To this end, the researchers developed an alloy, $Fe_{19}Ni_5Ti$ (wt%), optimized for taking advantage of the thermic cycling. The resulting material is a maraging steel, a strong and tough type of steel.

Maraging steels are obtained through the formation of a soft nickel-containing martensite phase that is then hardened by the precipitation of intermetallic compounds, transformations normally induced by costly post-process thermal treatments. When using the optimized alloy, these transformations are induced in situ during the 3D printing process, and their precise control enables the optimization of the mechanical behaviour of the material. In particular, after the deposition of 4 layers of material, the laser is switched off and the sample is allowed to cool, triggering the formation of the martensite phase. As the printing resumes, the intrinsic heat treatment induces the precipitation reaction, forming a band of hard material on top of the martensite block. Optimized timings enable the control of the thickness of these hardened bands.

The mechanical properties of the printed steel — 1,300 MPa tensile strength and 10% elongation — are comparable to those of conventional maraging steels. Some conventional maraging steels can reach higher strengths but only at 2–3% elongation. The thermal cycling is key: martensite forms only if the temperature drops below a certain value, and the precipitation reaction is triggered by the intrinsic re-heating. Without the pause between groups of layers, the temperature would keep increasing, impeding the formation of the martensite phase and of the intermetallic precipitates if not during the final cooldown, resulting in only one hardened band on top of the sample.

In this work the control knob was the pause time between layers, but many other parameters can be varied, which makes this approach applicable to many additive manufacturing processes. “The optimization of the printing process to achieve desired hierarchical nanostructures will require a deep understanding of the interplay of different types of nucleation, diffusion, phase transformation and coarsening phenomena under time–temperature profiles that are very different from those studied in the past,” concludes Raabe. “Once we know how process control translates into thermal profiles, how thermal profiles translate into phase transformations and how phase transformations translate into properties, we should be able to not only design the shape of metallic parts, but also their microstructures and properties, with local control and adjustment.”

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ORIGINAL ARTICLE Kürnsteiner, P. et al. High-strength Damascus steel by additive manufacturing. *Nature* https://doi.org/10.1038/s41586-020-2409-3 (2020)