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Achieving the desired microstructure with the digital forging lab: Resource-efficient open-die forging through predictable material properties

A new simulation model from the Fraunhofer Institute for Mechanics of Materials IWM in Freiburg predicts weak points in forged components caused by incomplete grain formation (recrystallization). Embedded in an efficient digital workflow, this creates a digital forging laboratory that enables material and energy savings in forging processes.

Rising energy costs and stricter legal requirements for climate protection are putting pressure on the forging industry. At the same time, the shift toward sustainably produced “green steel” requires a rethinking of manufacturing processes. This is because new production methods result in fluctuating chemical compositions and altered materials properties, making behavior during forging more difficult to predict. Furthermore, a defective microstructure in safety-critical components is not only a quality issue but can also lead to catastrophic failure. This conflict between greater sustainability and the highest quality requirements is putting a strain on the forging industry.

Untapped optimization potential

On its journey from blank to component, the metal undergoes numerous energy-intensive steps: heating, forming, intermediate annealing, and further forming. Each step depends on many variables, such as temperatures, degrees of forming, holding times, and pressing forces, which must be precisely coordinated. The status quo in many forging operations is based on decades of experience and costly trial-and-error cycles. However, this approach reaches its limits when it comes to managing uncertainties caused by fluctuating materials qualities. Attempts to replace real-world tests with computer simulations often fail due to a lack of models tailored precisely to the materials, insufficient data, and the difficulty of reliably translating simulation results into actionable recommendations.

The materials technology challenge

The real challenge lies in the materials themselves: During hot forming, the internal microstructure of the steel is not a rigid structure, but a dynamic system that is constantly changing. On the one hand, materials harden due to deformation; on the

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other, so-called recrystallization continuously forms new, stress-free grains in the microstructure. Subsequent grain growth can coarsen the microstructure again, while tiny particles (precipitates) can slow down this movement within the materials. All these mechanisms are significantly influenced by the temperature, the degree of deformation, and the chemical composition of the steel.

The fine art of forging technology lies in mastering this complex interplay of physics, chemistry, and mechanics. How can the machine settings on the massive forging press be linked to the development of the microscopic materials microstructure?

Digital forging laboratory in a traditionally oriented environment

This is precisely where Fraunhofer IWM comes in with a practical digital workflow that makes these complex processes within the materials calculable. At the core is a physical materials model that focuses specifically on grain formation (recrystallization). The so-called mean-field model combines the best of both worlds: It is based on thermodynamic principles and is therefore highly reliable — even under the complex, fluctuating conditions of industrial forging processes. At the same time, it is so computationally efficient that even components weighing several tons can be simulated on a computer within a reasonable time frame. Since the model is based on real physical quantities, it provides reliable predictions, even when new alloys or altered process conditions come into play.

The process begins with a material data sheet: In laboratory tests, the most important material data — such as flow behavior and grain size development under specific conditions — are first determined. Based on this, a finite-element simulation is performed, which calculates the temperatures and forces to which the materials were exposed over time, for every point in the component. This extensive data is then fed into the mean-field model, which uses it to predict the evolution of the materials microstructure. The result is a three-dimensional map of the component that shows exactly where and what grain sizes will form inside. This allows different manufacturing variants to be virtually compared and evaluated, and recommendations for defect prevention to be derived.

Demonstration of the digital forging lab's capabilities

The EU project "AID4GREENEST" demonstrated just how well this model works in practice. The goal of this project is to facilitate the processing of sustainably produced steel, whose chemical composition can vary more significantly due to materials-specific factors. To this end, the entire forging process of a 22-ton turbine shaft made of high-strength steel was simulated on a computer — a multi-hour, multi-stage process involving repeated forming and reheating.

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“Our simulation correctly identified critical zones in advance,” explains Dr. Maxim Zapara, team leader for forging at Fraunhofer IWM. “An undesirably coarse-grained microstructure was predicted for the ends of the shaft, as the material in these areas was not sufficiently deformed during the final, decisive forging step.”

The model not only predicted the weak points but also directly identified the cause: While the core of the shaft was sufficiently deformed during the final forging step and the microstructure there was completely renewed and refined, this important “reset” did not occur at the ends. This virtual prediction was later confirmed by materials analyses of the actual forged component.

Zapara continues: “This use case demonstrates that the model not only simulates materials behavior but can also identify process defects before they occur in actual production. We can now test different approaches virtually: A simple adjustment to the final forging step in the simulation directly resulted in a completely fine-grained, defect-free component. In practice, this saves enormous amounts of materials and energy.”

Innovation opportunities

The digital forging lab opens up new innovation opportunities: The focus shifts from post-production quality control to predictive process planning. Instead of noticing defects only on the finished component, they can be predicted and avoided on the computer. Instead of months of test series for new materials, hundreds of scenarios can now be run through virtually within a few hours.

Understanding the relationships between machine settings and materials properties enables optimized processes. For example, heating cycles can be shortened and pressing forces reduced. More precise, near-net-shape manufacturing also lowers energy consumption, machine utilization, and the effort required for subsequent finishing.

In the future, every forged component could even be issued a “digital passport” — a complete record of its internal structure that verifies its quality and safety from production through to final use.

Note: The research results were obtained in the EU Horizon Europe project AID4GREENEST (Grant Agreement No. 101091912)

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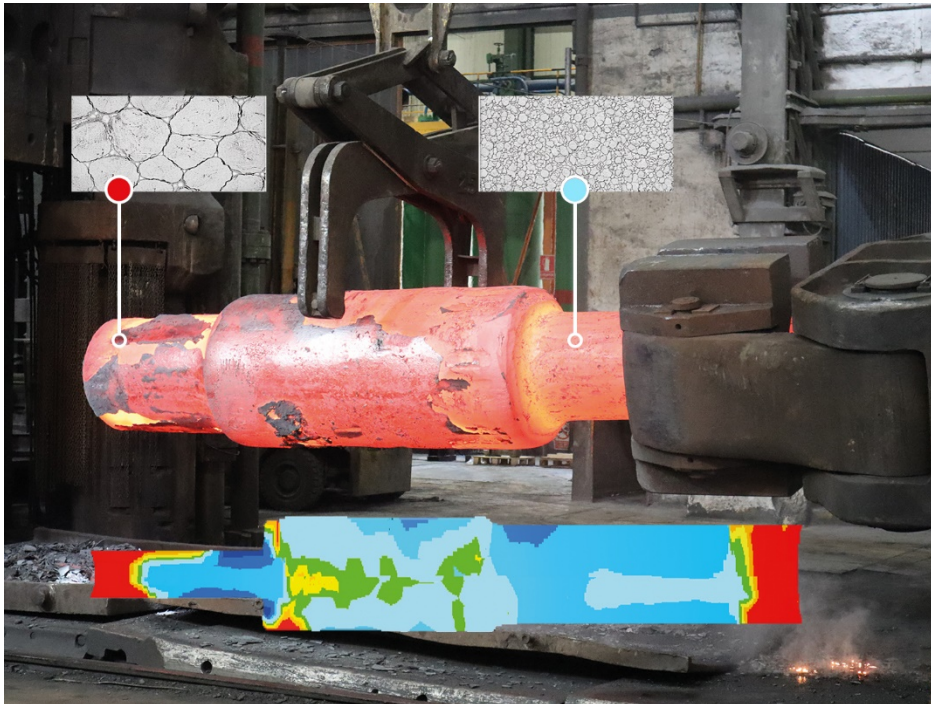
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The forged (red-hot) turbine shaft exhibits a coarse-grained microstructure at both ends and a fine-grained microstructure in the central region. This was analyzed after forging. The coarse-grained microstructure has lower strength and toughness.

The simulation model correctly predicts the measured microstructure distribution (bottom). In the red areas, the microstructure is coarse-grained; in the blue/green areas, the microstructure is fine-grained.

The **Fraunhofer Institute for Mechanics of Materials IWM** works on sustainability in industrial value creation. Through its research and development activities, it opens up new opportunities for its partners to achieve durability and safety in components, resource efficiency in process chains, and energy efficiency in machines. To this end, the institute makes the behavior and properties of materials in process chains, components, and machines predictable.

The **Fraunhofer-Gesellschaft**, headquartered in Germany, is one of the leading organizations for applied research. It plays a central role in the innovation process—with research focusing on future-relevant key technologies and the transfer of research results to industry to strengthen our economic position and for the benefit of our society. Founded in 1949, the organization currently operates 75 institutes and research units in Germany. Its nearly 32,000 employees, most of whom have backgrounds in the natural sciences or engineering, generate an annual budget of €3.6 billion. Of this, €3.1 billion is allocated to contract research.

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