CARPENTER
ADDITIVE®

WHITE PAPER

ADDITIVE MANUFACTURING SUCCESS WITH NITINOL

Effective translation of shape memory and superelastic properties from wrought to 3D printing

SUMMARY

Nitinol (NiTi) is widely used in medical devices due to its superior superelasticity, shape memory effect, low stiffness, damping, biocompatibility, and corrosion resistance. Major applications of Nitinol include stents, guidewires, orthodontic archwires, and bone staples with new orthopedic applications being explored routinely. The functional properties of Nitinol medical device components are sensitive to composition and production thermal gradients. Subtle changes in chemistry and heat treatment can lead to large variations in austenite finish (A_f) temperature of the finished component.

Conventional subtractive manufacturing of Nitinol has several limitations, for instance machining-associated work hardening. This makes additive manufacturing (AM) of Nitinol an appealing alternative to traditional manufacturing processes. Additive manufacturing is effective in fabricating complex device geometries with pre-designed porosity, homogeneous composition, and desirable properties compared to traditional manufacturing techniques. The AM process can achieve structures with high density and near-net shape, requiring very little or no post-processing. However, a major challenge to additively manufactured Nitinol components is the effective translation of shape memory and superelastic properties primarily due to the influence of alloy chemistry on functional properties, creating a barrier to large-scale production of 3D-printed Nitinol devices. It is, therefore, critical to understand the interplay of the atomization process along with printing parameters on the additively manufactured Nitinol component.

Carpenter Technology and its branch of 3D printing experts, Carpenter Additive, carried out a study to create a systematic framework to optimize additive manufacturing for Nitinol, focusing on three factors for success:

Stringent control

Stringent control of Nitinol chemistry throughout the AM lifecycle, from feedstock to finished part

Optimized printing

Optimized printing parameter sets to enable effective control over shape memory and superelastic properties

Density

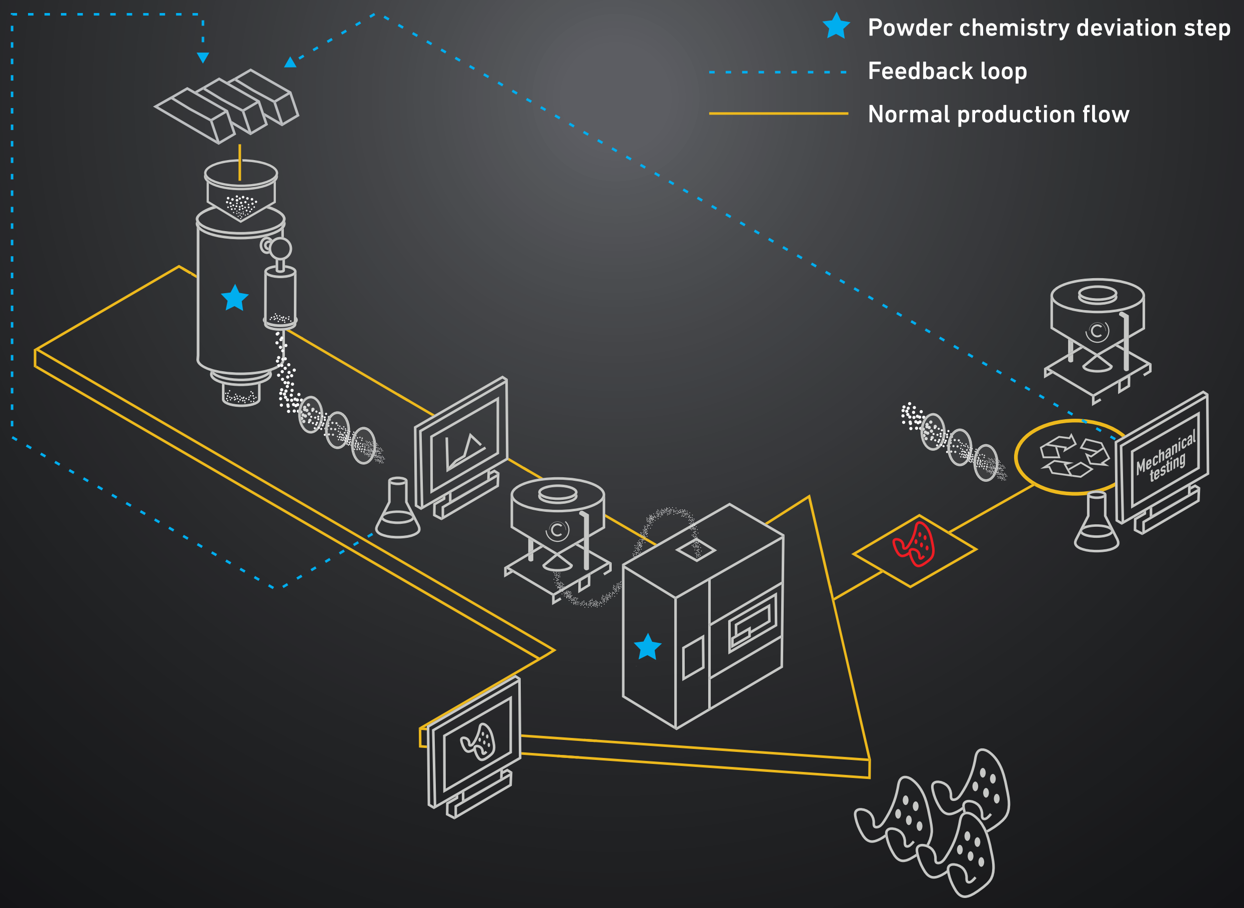
Fully dense, near-net shape Nitinol components to eliminate additional post-processing steps

Nitinol composition

Subtle changes in the alloy composition of Nitinol can significantly alter phase transformation temperatures. For instance, a 1% increase in Ni content decreases the transformation temperature by around 100°C along with an associated increase in the austentic yield strength. Such extreme sensitivities of austenite finish temperatures (A_f) to the base chemistry make it difficult to produce Nitinol alloys in powder form for additive manufacturing.

Figure 1 depicts the various stages in the additive manufacturing lifecycle of Nitinol from powder to part, highlighting critical steps that can lead to a change in powder chemistry. Understanding the functional performance of the finished part due to subtle changes in chemistry throughout the AM lifecycle is critical to enable large-scale additive manufacturing of Nitinol components. During atomization, the feedstock is exposed to extremely high temperatures that typically lead to the evaporation of nickel, while a loss of the element has also been observed during the 3D printing process due to exposure to high-energy laser beam.

FIGURE 1 — AM LIFECYCLE OF NITINOL



EIGA processing for Nitinol powder

Carpenter Additive produces Nitinol powder using the Electrode Inert Gas Atomization (EIGA) process that continuously melts a rotating, high-purity, pre-alloyed bar (e.g. Nitinol) into a conical induction coil to form a molten stream that falls directly into a gas nozzle to produce highly spherical powder particles (figures 2 and 3). Nitinol powder manufactured by EIGA gains as little as 100 ppm of oxygen on top of the existing oxygen levels from the feedstock (bar), depending on the size range being characterized. The EIGA processing equipment uses no refractory materials and therefore is not at risk of introducing any high-density inclusions. The use of pressurized inert gas during atomization helps control and maintain a higher level of Ni content in the powder post-atomization.

FIGURE 2—EIGA PROCESS FOR THE PRODUCTION OF NITINOL

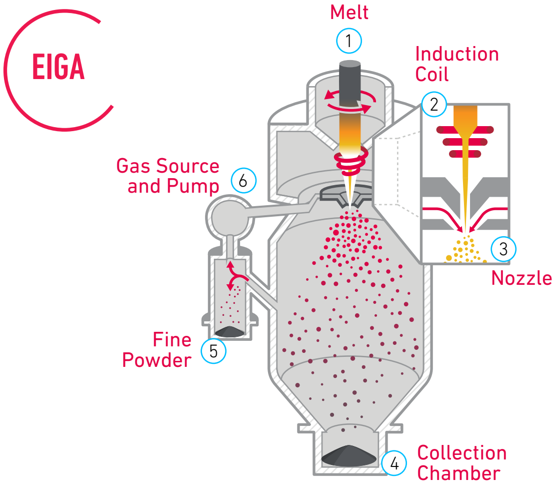
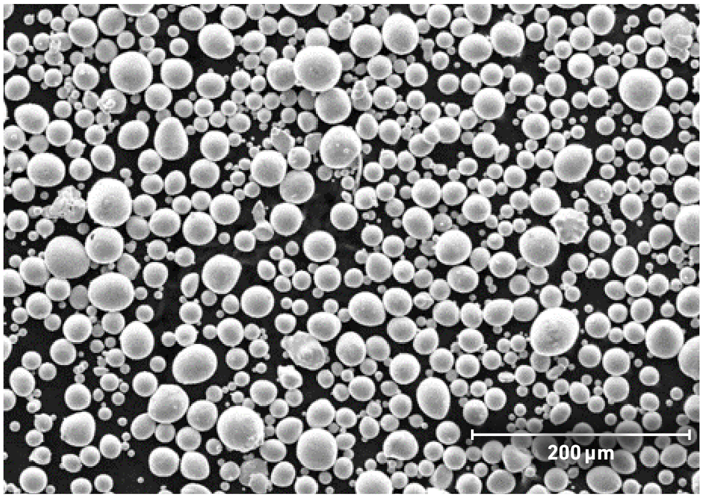


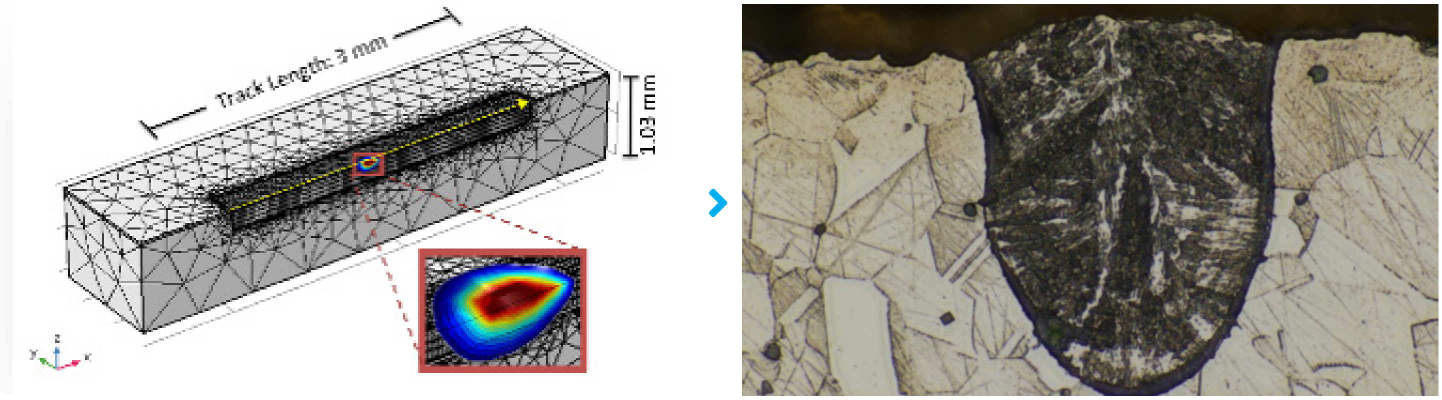
FIGURE 3—REPRESENTATIVE SCANNING ELECTRON MICROSCOPY OF ATOMIZED NITINOL POWDER



Framework for parameter optimization

Carpenter Additive collaborated to develop a unique proprietary framework for the optimization of printing parameters (figure 4). For a particular chemistry of NiTi, the initial data is obtained from finite element analysis of the melt pool thermal model for NiTi alloy systems and used to develop several initial parameter sets, combining variations of laser power vs. velocity, for a matrix of single-track printing trials.

FIGURE 4 — CARPENTER ADDITIVE FRAMEWORK FOR PRINT PARAMETER OPTIMIZATION

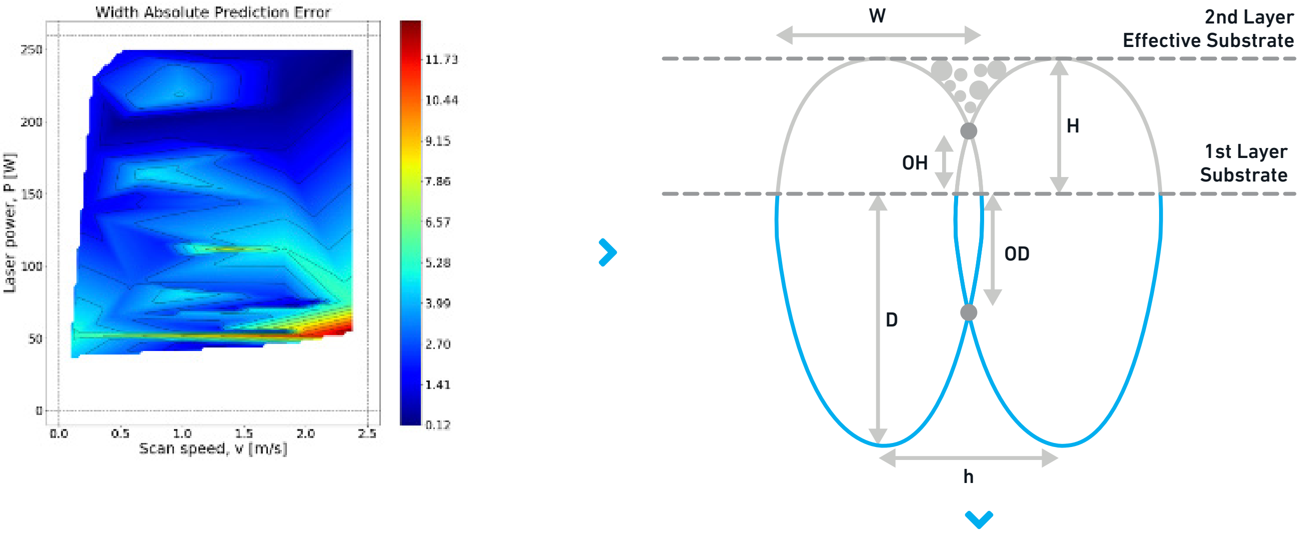


Melt pool thermal model
FEA—high-fidelity, slow; or Analytical—low-fidelity, fast

Single-track sampling
Design of experiments

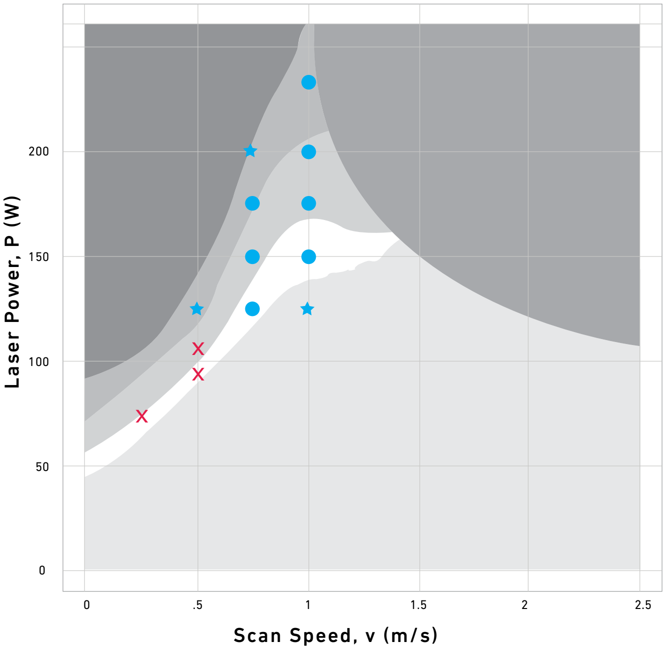
Statistical calibration of the thermal model

Hatch spacing criterion

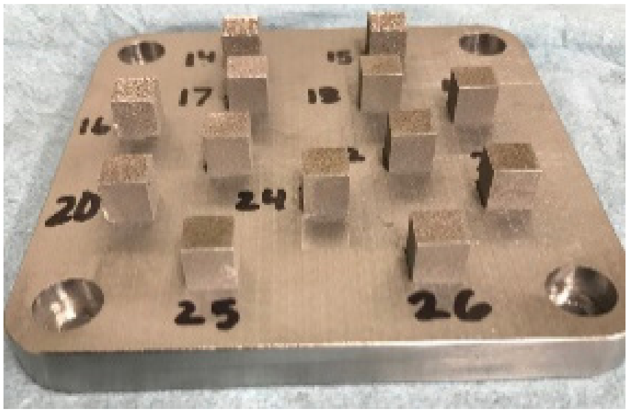


Construction of printability maps

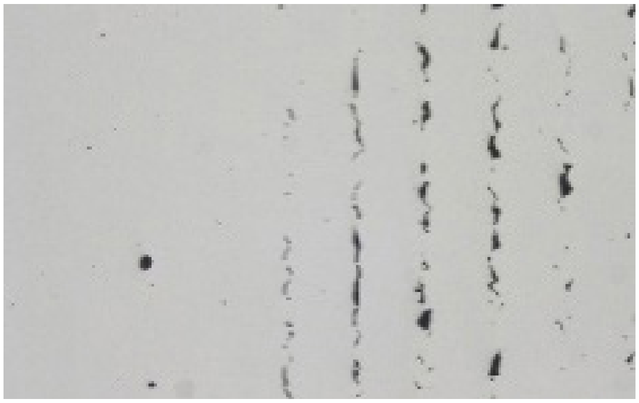
Parameter selection for bulk sample fabrication



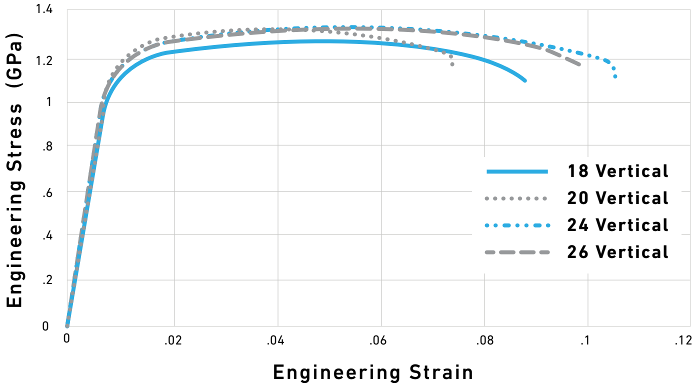
Print bulk samples



Density analysis



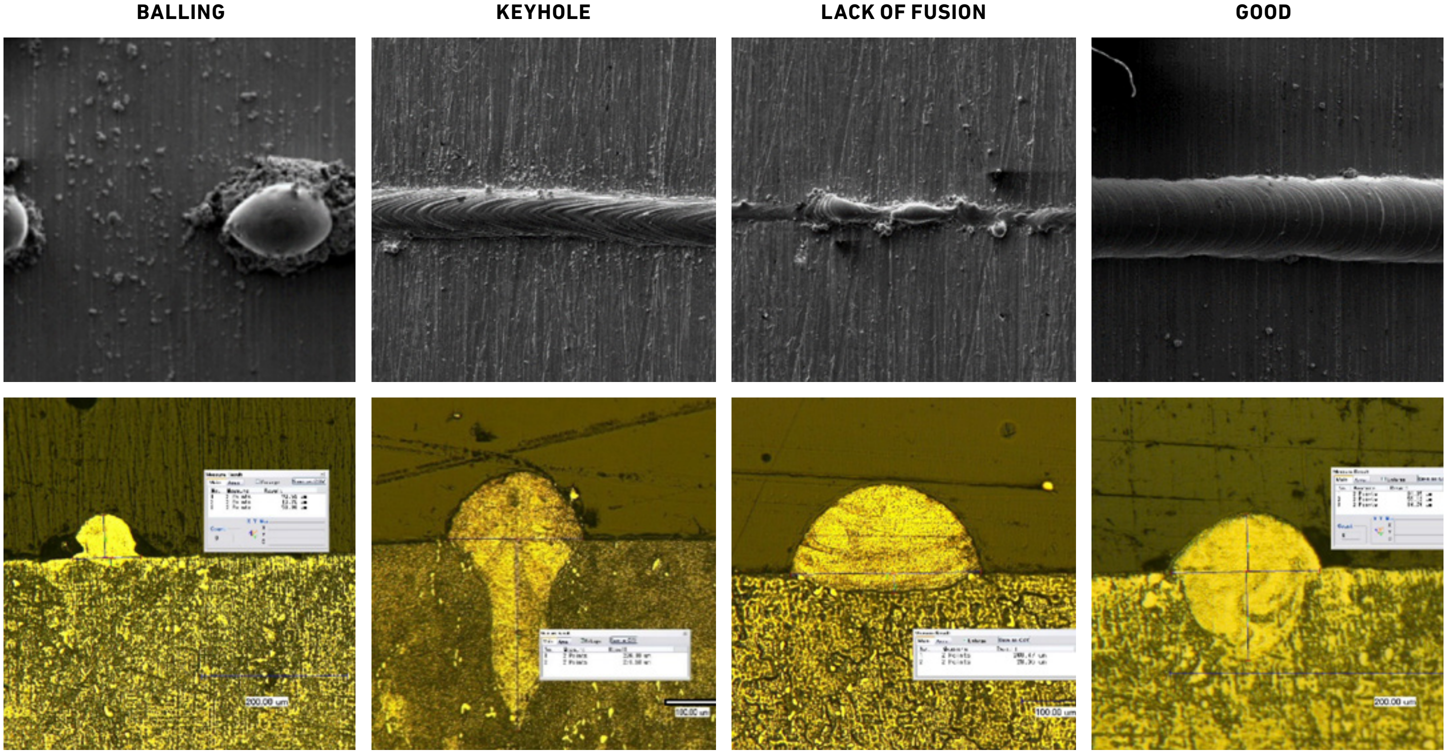
Characterization of properties



The results from these trials are used to further refine the model to eliminate those parameter sets that lead to artifacts, such as lack of fusion, keyholing, or balling. This exercise typically provides a region of parameter sets that result in optimal single-track builds (figure 5) and facilitates the determination of boundary conditions of the processing parameters.

The model then incorporates hatch spacing as an additional criterion to construct guides for parameter selection of bulk sample fabrication (figure 6).

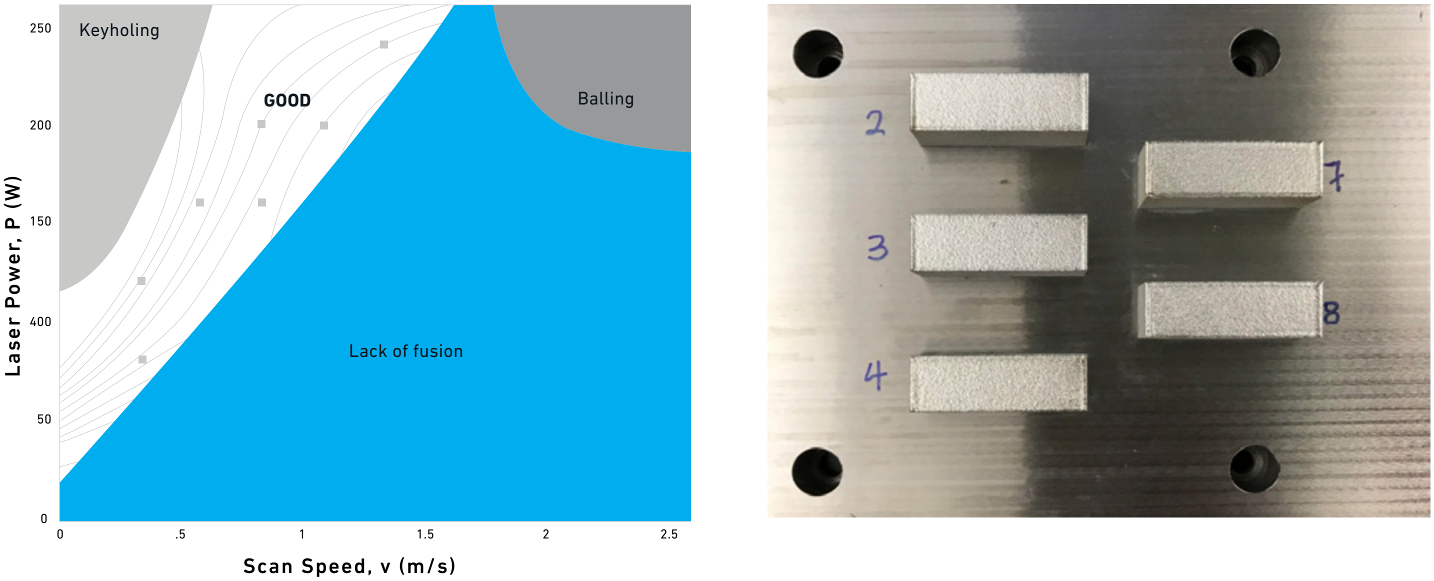
FIGURE 5 — SINGLE-TRACK EXPERIMENTS WITH TYPICAL FAILURE MODES AND A GOOD PRINT



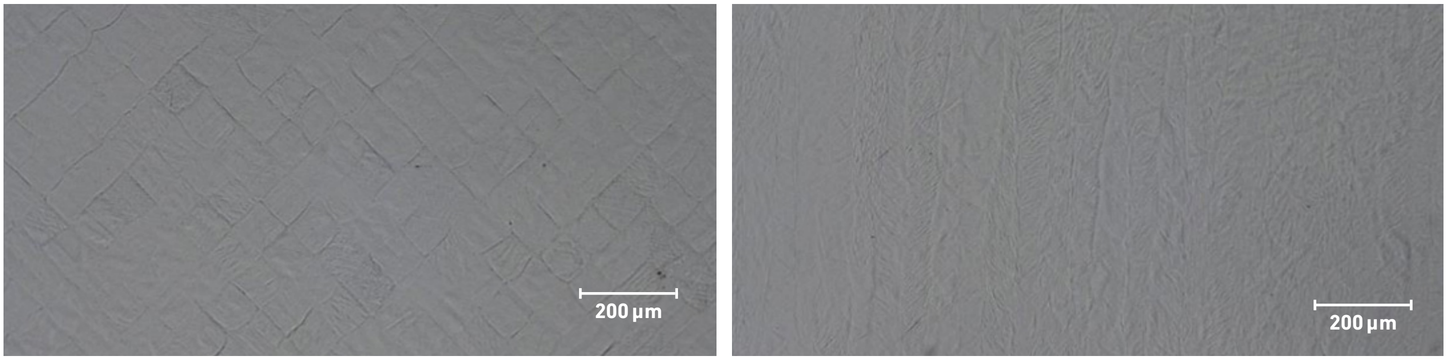
BALLING **KEYHOLE** **LACK OF FUSION** **GOOD**

FIGURE 6 — PARAMETER SELECTION OF BULK SAMPLE FABRICATION

Representative printability map depicting a region of good parameter sets — i.e., optimal combination of laser power, scan speed, and hatch spacing — with the highest probability of resulting in a build with ~99.9% density.



Representative micrographs of Nitinol test coupons. Porosity was determined by Archimedes' principle and image analysis.



POROSITY%=0.01%

POROSITY%=0.01%

With an optimal combination of laser power, velocity, and hatch spacing, Carpenter Additive has achieved ~99.9% dense 3D-printed NiTi components.

The framework optimization model is universal, and this systematic approach to determine optimum build parameters can be utilized for any Nitinol chemistry, accelerating initial development and leading to significant cost savings by reducing trial and error with repeated Nitinol builds.

Process optimization

Additive manufacturing enables production at near-net shapes to minimize, or in some cases eliminate, post-processing steps. Nitinol has a significant work-hardening rate, often leading to challenges in the fabrication of components through conventional machining methods. NiTi alloys also cause significant tool wear, so the reduction of secondary machining operations improves production efficiency.

By producing fully dense, near-net shape geometries directly through 3D printing, manufacturers can reduce complications that arise from traditional machining of Nitinol components.

Successful shape memory and superelastic effect

Using this systematic approach, Carpenter Additive printed NiTi samples of varying compositions—samples exhibiting shape memory and superelasticity at room temperature. These samples were subsequently subjected to cyclic tension testing at room temperature. Initial results from the shape memory composition show ~6% of recoverable strain upon heating. The superelastic NiTi also showed reversible strain of ~6%. More work on this study is currently underway.

FIGURE 7—CYCLIC TENSION TESTING OF A 3D-PRINTED NITINOL COMPONENT

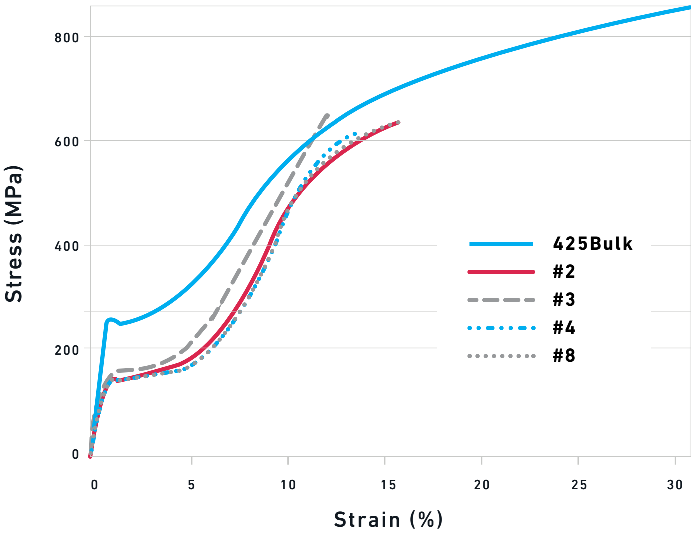
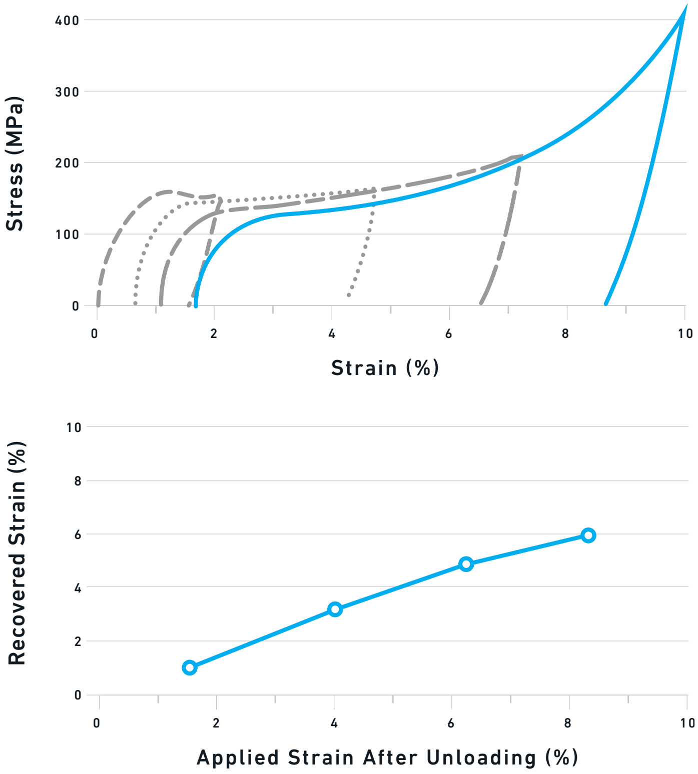


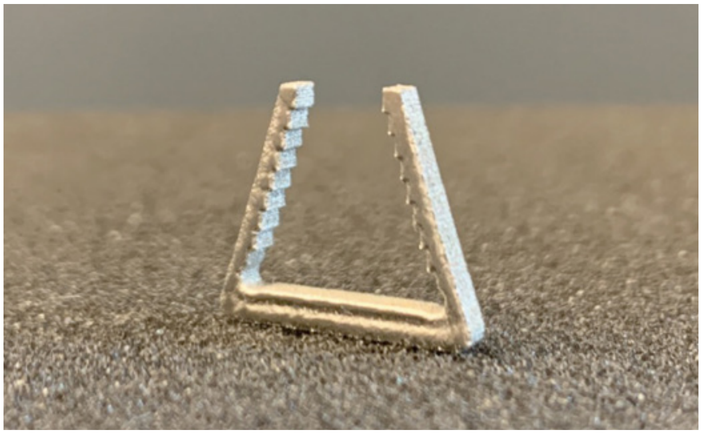
FIGURE 8—CYCLIC TENSION TESTING OF A 3D-PRINTED SUPERELASTIC NITINOL COMPONENT

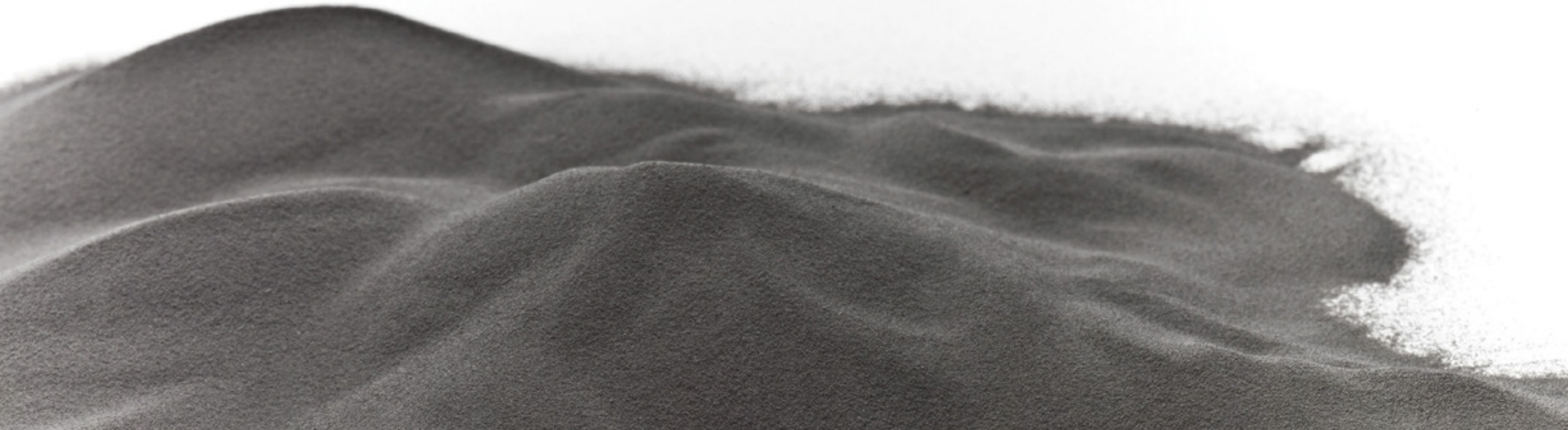


Carpenter Additive used an in-house produced Nitinol composition to demonstrate the shape memory effect in a 3D-printed Nitinol bone staple for orthopedic applications (figure 9), highlighting how understanding the material properties of Nitinol solutions can enable large-scale additive manufacturing of components for the medical device industry.

FIGURE 9 — PROTOTYPE NITINOL BONE STAPLE

Produced via additive manufacturing utilizing the in-house powder-to-part workflow in conjunction with the Nitinol parameter optimization model.





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