Shape Training of Nitinol Wire using Three-Dimensional Printing (3DP) Fixtures

B. Utela*, R. Anderson*, H. Kuhn†, M. Ganter*
*Department of Mechanical Engineering, University of Washington, †The Ex One Company - ProMetal

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Abstract

The presented research focuses on work done at the University of Washington on process development for the training of nitinol shape memory alloy wire using Three Dimensional Printing (3DP). Fixtures are created using the commercial stainless steel printing system produced by Ex One. Superelastic nitinol wire is set by restraining the wire in a fixture and thermal processing. A two dimensional test array was designed and fabricated to examine the effects of fixture curvature on the final wire shape. Three dimensional coils and spheres were created to demonstrate the potential of this process for more complicated shapes.

Introduction

Nitinol belongs to a larger class of materials known as shape memory alloys due to the ability of the metal to retain a mechanical memory of a pretrained shape. It is composed of a nearly equal atomic ratio of nickel and titanium with occasional impurities added to affect the material properties. The shape memory effect is the result of two distinct and temperature sensitive crystal structures possible in the material. The higher temperature austenite state is a highly ordered crystal structure while the lower temperature martensite phase is less structured [1]. Nitinol in the austenitic state converts to the martensitic phase through physical deformation or cooling. The trained shape of a nitinol part is the natural shape of the part when fully in the austenite phase. The nitinol must be raised above the austenite start temperature (A_s) to return to the set shape. The A_s can range from -50 to 95 ˚C depending on metal processing. Alloys with an A_s below 5 ˚C are considered superelastic due to their ability to spring back from severe deformation (strains up to 7 – 8 %) at room temperature. Deformation at room temperature results in localized conversion of the crystal structure to the martensitic phase in the strained regions, but the crystal structure reverts back to the austenitic phase upon unloading and the metal returns to the trained shape. If the A_s is above the working temperature the part requires heating to return to the set shape. For certain alloys this can be done with body temperature (~30 ˚C), but the more common alloys transition between 70 and 90 ˚C. Higher temperature alloys are typically used as actuating wires and not trained to complicated shapes. For actuation the wire can be elongated at lower temperatures (elongation strain affects cycle life) and the wire contracts when heated. The force necessary to reset the wire to the initial condition after cooling is approximately 20% of the force generated during actuation.

The shape setting of the nitinol occurs when the metal is annealed in the range of 500 - 550 ˚C. A fixture is used to restrain the wire at this temperature to establish the austenitic or 'set' shape. The fixture and wire are held at this temperature briefly and then quenched or rapidly cooled in air. Traditional training involves an often iterative process of custom fixture generation. Most fixtures are metal which typically involves a machining step that can be non-trivial for complicated shapes. Ceramic fixtures are difficult to machine and require expertise to create a precise part using ceramic powder processing. The quenching process can also cause fracture problems in ceramic parts. Plastic deformation of the wire into the desired shape at room temperature is ineffective since the plastic deformation weakens the wire and the wire does not hold the deformed state while heating.

The application of Solid Freefrom Fabrication (SFF) to the problem of nitinol wire training shows several advantages over the traditional procedure, particularly in the design phases of a project. Using a ProMetal RX-D Three Dimensional Printer (3DP) it is possible to print stainless steel (SS) fixtures that can be used to train nitinol wire without the need for a machine shop or contracted machining, and design iterations from drafted fixture to set wire can be performed in under 24 hours. The fixtures fabricated in this research are not designed for heavy use, but offer the perfect opportunity for small batches and proof of concept parts. For example, SFF in the medical field allows for the possibility of easy customization of trained wire based on fixtures designed using patient specific data.

Materials and Methods

Superelastic Nitinol wire was obtained from Small Parts Inc. in 36” segments of 0.008”, 0.012”, and 0.016” wire diameters. Fixtures are designed using Rhinoceros NURBS Modeler (V3) and exported as .STL files to the 3D Printer. Parts are printed using the ProMetal RX-D using SS powder and ProMetal S-4 binder. The default SS printing parameters are used with a 100 µm layer thickness. Fixtures are cured in the powder bed to set the binder, depowdered, and sintered in a reducing atmosphere through first stage sintering. An unsintered fixture may be used for wire training, but after the training thermal cycle the fixture is weak and cannot be reused. Nitinol wire is then restrained in the fixture and is ready for thermal treatment.

Thermal training of the wire is performed using a ProMetal RX-F dental furnace. The wire and fixture are heated using the maximum ramp rate of the furnace to 540 ˚C for 10 minutes and then immediately quenched in water. This method allows a clear delineation between the austenite and martensite phases, and avoids aging effects as well as extended heating of nitinol which can affect the material properties as well as potentially change the transition temperature of the wire. After quenching, the wire is removed from the fixture and can be further processed as desired.

Experimentation

Successful training of wire into both two and three dimensional shapes was performed. Two dimensional post arrays were created to examine the curvature ranges possible for a variety of different thickness wires. The arrays consist of posts of decreasing diameter (range 2 – 8 mm) that each have a small lip to help restrain the wire in the z-direction. The measured diameters of the posts as printed were larger than as drafted. The difference ranged from 0.10 mm to 0.36 mm with an average of 0.22 mm. In this initial work, there was no correlation between the difference and increasing post diameter.

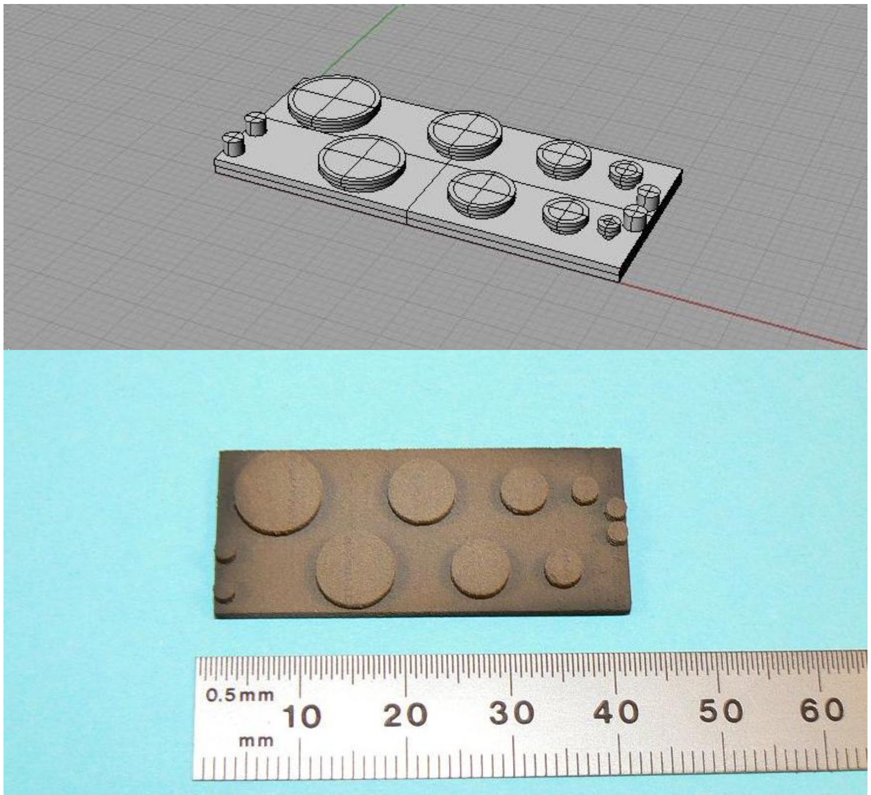

Figure 1: One version of curvature test array as modeled and printed

Wire of three different diameters was wrapped around the fixture shown in Figure 1. Posts of 1 and 1.5 mm were printed in different arrays, but were always damaged during fixture handling. This does not mean that diameters smaller than 2 mm are not possible with this training method, but designs requiring a smaller diameter will require more robust posts that exhibit varying curvatures.

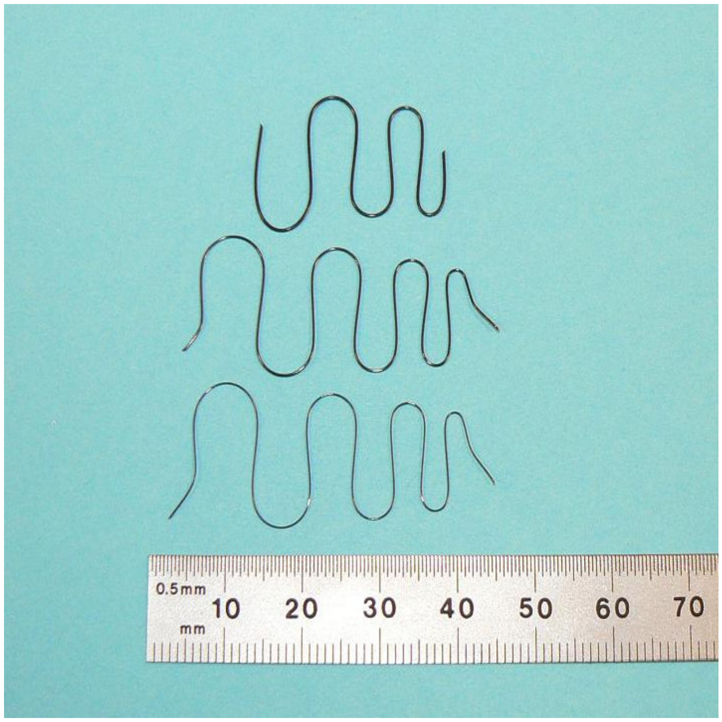

Figure 2: Wires trained by curvature test array (top - bottom 0.008", 0.012", and 0.016" diameters)

Table 1: Comparison of trained wire diameters with the drafted and printed post diameters

Trained wire results			
	Average differences (mm)		
	Wire measurements		
Wire	.008"	.012"	.016"
Drafted diameter	0.103	0.106	0.004
Printed diameter	-0.121	-0.118	-0.216
	Correlations (R-squared)		
	Wire measurements		
Wire	.008"	.012"	.016"
Drafted diameter	0.02	0.71	0.04
Printed diameter	0.10	0.11	0.00

An example of the trained wires is shown in Figure 2. Each of these three wires was trained using the same fixture but the fixture was damaged during the setting of the 0.016" wire so the two extreme diameters were not correctly generated. The curve diameters are measured with calipers at the widest section of the curve in the horizontal direction as oriented in Figure 2. Results of the wire training experiments are shown in Table 1. The differences between the trained shape and the drafted and printed dimensions are minimal with average differences of 0.075 mm and -0.145 mm respectively. There is very little correlation between the differences and the post diameters with the lone exception being the correlation between the measured curve diameters of the 0.012" wire and the drafted dimensions of the array. The R^2 value of

0.71 in this case remains somewhat inexplicable given the next highest correlation value of 0.11.

Qualitatively there are observable differences when training wire of different diameters. A close look at Figure 2 shows that the curves of the 0.016" exhibit a non-uniform curvature over some of the curves. Unless pulled tightly against the fixture post the thicker wires tend to separate slightly from the outer edge of the post and only make contact with the fixture on the sides of the post. Since the measurements are taken in this region of the set wire the thicker wires exhibit the correct horizontal diameters but do not have the constant curvature over the arc that is desired.

Several three dimensional wire shapes have been created that demonstrate the potential of the SFF training technique. Drafting in three dimensions adds an element of complexity to the fixture creation process, but the fixtures can be more intuitive to design. A wire path containing no inflection points can consist of a fixture that is a solid object with a guide channel marking the desired path of the wire. Tension in the wire holds it to the surface of the fixture so restraining the wire ends fully constrains the nitinol. A sphere drafted in Rhino 3 can be seen in Figure 3.

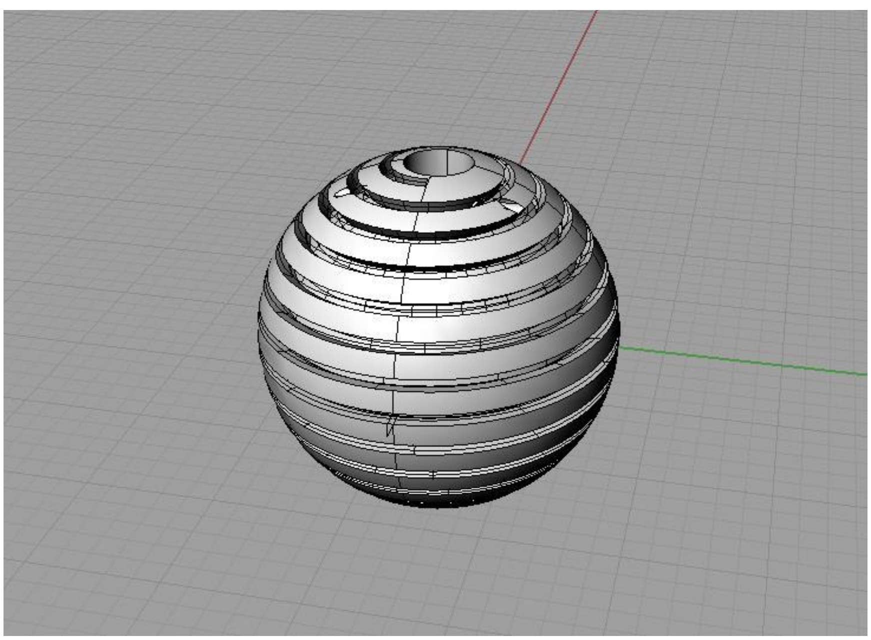

Figure 3: 17 mm Rhino 3 generated sphere with guide channel

Two fixtures used to train wire into three dimensional shapes are shown in Figure 4. The sphere on the left was printed using the .STL file generated by the model shown in Figure 3. Both fixtures are generated from guide curves that contain no inflection points so during training the wire is in contact with the fixture over the entire length. Figure 5 shows the trained shapes resulting from the fixtures in Figure 4. The 0.008" wire trained by the hemisphere capped cylinder is flexible enough that the trained structure self deforms slightly, but the 0.012” wire is thick enough that there is no observable self deformation due to gravity.

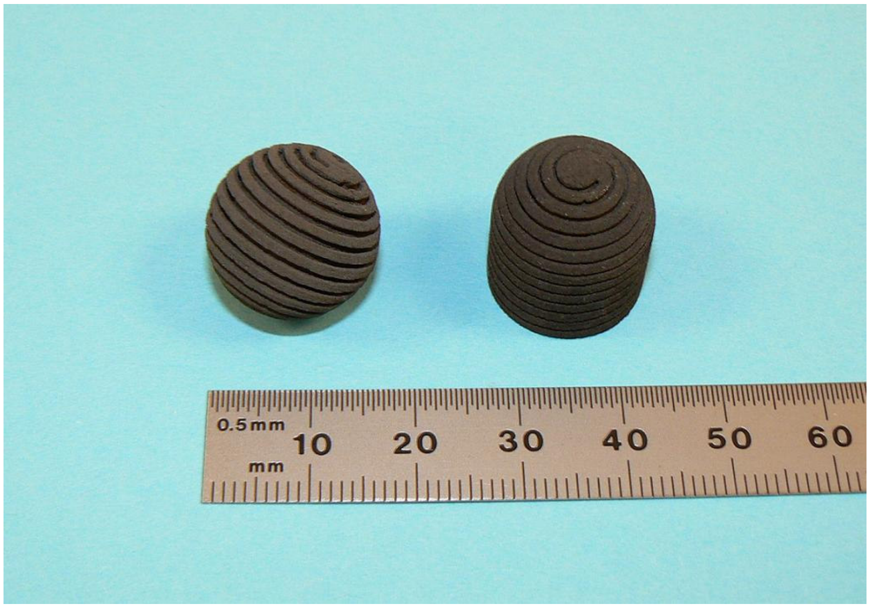

Figure 4: Printed SS fixtures. The sphere diameters 17mm, and the hemisphere capped cylinder height and diameter are 17 and 16 mm respectively

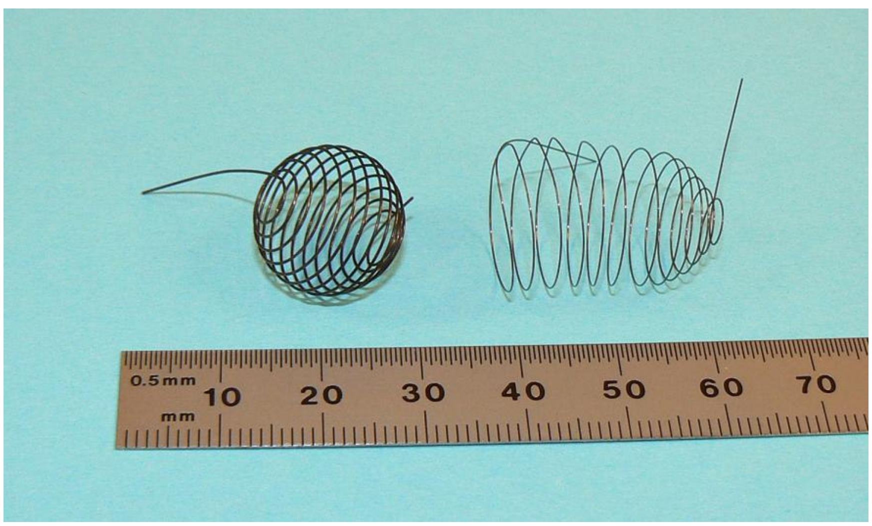

Figure 5: Trained sphere and capped cylinder. The wire diameters are 0.012" and 0.008" respectively

Discussion

Research to date has been focused on proof of concept work and initial quantification but during this process the basic design rules for successful 3DP fixtures have been established. Most important is a thorough understanding of how the curvature and inflection points of the desired wire path affect the placement of fixture features. This logic is not necessarily different than that needed for traditional fixture creation, but the resulting design does not have the restraint of being necessarily machinable. Holes, channels, and undercuts can all be integrated into one fixture as necessary. The other set of design rules concern the physical durability of the printed fixtures. Since only first stage sintering occurs in the SS there is still considerable porosity and the sintered strength is far less than that of a fully dense metal. Posts that are too thin for the wire can be damaged or broken and sharp edges and undercuts may lose edge definition. The durability of the fixtures could be greatly increased by infiltrating the SS fixture with another metal. The ProMetal printing process includes the materials and methodology to infiltrate the SS, but this requires an additional furnace cycle that was deemed unnecessary for this experimentation. The effect of the metal infiltration process may also soften some of the fine features designed into a fixture so these potential effects would also need to be examined.

The next step of the fixture generation process is to attempt the integration of an analytical examination of the desired wire path with partially automated drafting. Rhino has the ability to show the curvature of the wire along the path, but no ability for automated decision making. With the proper analytical software a parametric analysis of the wire path should be possible with the goal of automatically determining where in the wire path the wire needs supporting and which side of the wire the support should be on. This is a relatively simple process to complete manually, but becomes time consuming during multiple design iterations.

The benefit of the SFF based nitinol training method is that there is nothing fundamentally different than the traditional process. Any fixture design complicated enough to require machining should have an associated CAD model that can instead be used to generate a .STL file. While metal 3DP was discussed in this paper, other SFF technologies such as SLS and SLM could also be used to generate fixtures of sufficient precision and durability. Use of this methodology has the potential to simplify the training process, increase the potential for fixture complexity, and significantly decrease the time from inspiration to creation of trained nitinol wire parts.

References

1. Ford, D.S., White, S.R., Thermomechanical behavior of 55Ni45Ti Nitinol, Acta mater. Vol 44 (6), 2295 – 2307, 1996