Reverse Engineering of Nitinol Vena Cava Filters

Material Science 102 Semester Project
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Performance of Nitinol in Vena Cava Filters

To treat pulmonary embolism, it is necessary to remove blood clots from a patient's blood stream. Generally this is done by injecting anticoagulants into the blood, but sometimes introducing a clot filter into the vena cava is preferable. A new vena cava filter is being developed using the shape memory alloy Nitinol. The metal memorizes the shape of the filter shown, which consists of a low turbulence mesh and a series of hooks to keep the filter in place within the vein. Once the shape has been memorized, the filter is cooled to room temperature. It is then deformed into straight wires, and loaded into a catheter with cold saline. The Nitinol wires are then inserted into the vena cava along with a continuous flow of saline to keep the alloy cool. Once the wire bundle is inserted, the patient's blood warms the wires and causes to return to their memorized filter shape inside the vein. Thus far the reliability and effectiveness of the Nitinol filter has been significantly better than other conventional filters. Nitinol itself is flexible, durable, corrosion resistant, and biocompatible.

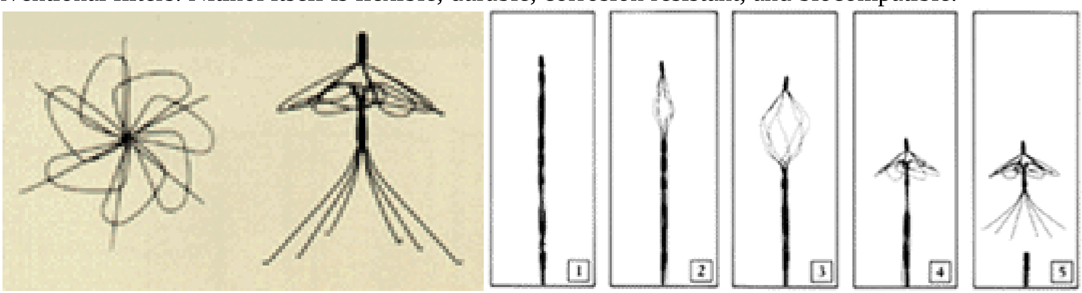

Figure 1: Nitinol Vena Cava Filter

Structure of Nitinol

Nitinol is a binary nickel-titanium alloy. The shape memory properties of Nitinol arise from a change in the crystal structure between the austenite and martensite phases. In the high temperature austenite phase, NiTi assumes a rigid BCC structure. However, in the martensite phase, the crystal structure of NiTi becomes orthorhombic; that is, the lattice parameters a, b, and c are generally different. It is in the martensite phase that NiTi is most readily deformed. The shape memory effect occurs when the NiTi is heated to the austenite finish temperature, at which point all of the deformation retained from the martensitic phase is recovered.

Crystal Structure Changes

Nitinol alloy can exist in a two different temperature-dependent crystal structures. At lower temperatures, it is martensitic, and is austenitic at higher temperatures. Figure 2 (right) illustrates the temperature dependent crystal structure change from martensite to austenite.

where:
As = austenite start temperature
Af = austenite finish temperature
Ms = martensite start temperature
Mf = martensite finish temperature
Md = Highest temperature to strain-induced martensite

In practical applications, Nitinol can have three different forms: martensite, stress-induced martensite (superelastic), and austenite. When the material is in its martensite form, it is soft and ductile and can be easily deformed. Superelastic Nitinol is highly elastic, like rubber, while austenitic Nitinol is quite strong and hard, exhibiting properties similar to titanium.

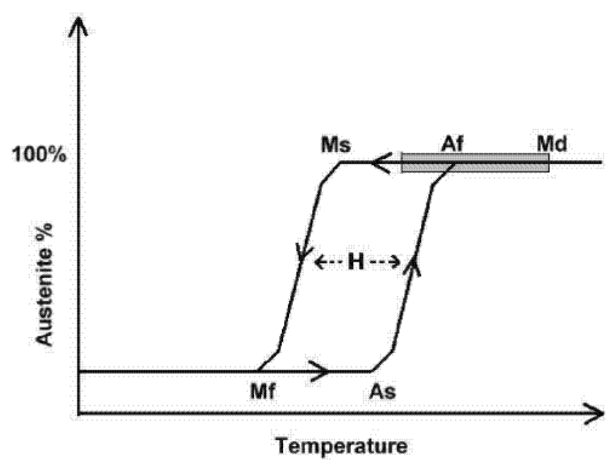

Figure 2: Martensite – Austenite Hysteresis

Thermal/Mechanical Properties of Nitinol

Hysteresis Loop and Thermoelastic Transformation

The temperature range for the martensite-to-austenite transformation that takes place upon heating is somewhat higher than that for the reverse transformation upon cooling. These differences in temperatures create a hysteresis. This difference is usually around 20-30°C, defined from 50% transformation points on the hysteresis loop.

Shape Memory

Nitinol is very sensitive to temperature, and is able to convert its shape to a preprogrammed structure. While Nitinol is soft and easily deformable in its martensite form, it resumes its original shape and rigidity when heated to its austenite form. This is called the one-way shape memory effect. This is illustrated in the Figure 3 below.

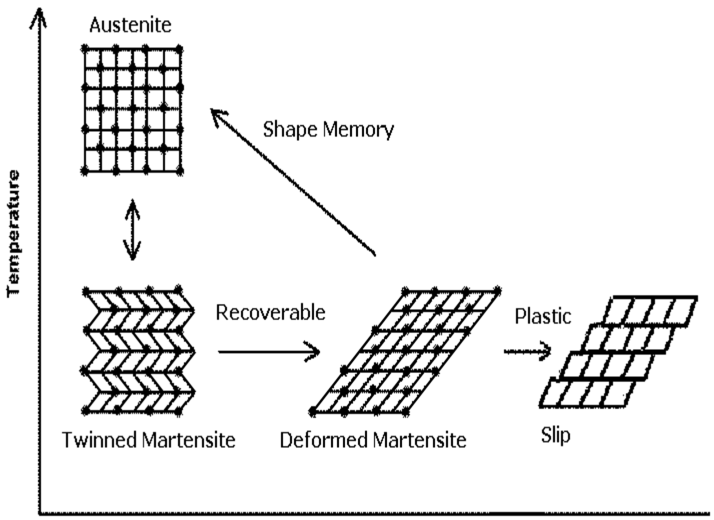

Figure 3: Mechanism for Shape Memory Effect

The unique behavior of Nitinol is based on the martensite-to-austenite transformation on an atomic scale, which is also called thermoelastic martensitic transformation. Shape recovery is the result of the crystal lattice structure accommodating to the minimum energy state for a given temperature. The symmetries between the two phases lead to a highly ordered transformation, where the displacement of individual atoms can be accurately predicted and eventually lead to a shape change on the macroscopic scale.

A Nitinol specimen will deform until it consists only of the corresponding variant which produces maximum strain. However, deformation beyond this will result in a classical plastic deformation by slip, which is irrecoverable and therefore has no memory effect.

Superelasticity

Nitinol has the ability to return to its original shape upon unloading after a substantial deformation. This ability is referred to as superelasticity, and is based on a stress-induced martensite formation. About 8% strain can be recovered by unloading and heating. This is remarkably high, since most materials have maximum elastic strains of less than 1%. Strain above the limiting value will remain as a permanent plastic deformation.

The application of stress on a sample of Nitinol causes martensite to form at temperatures higher than the martensite start temperature. The macroscopic deformation is accommodated by the formation of martensite. When the stress is released, the martensite transforms back into austenite and the specimen returns back to its original shape. This transformation can only be observed over a specific temperature area though, between As and Md.

Synthesis & Processing of Nitinol

A 1% change in the nickel content of Nitinol can alter Ms and Af values by 100K, so the composition of the alloy is very closely controlled. Most Nitinol alloys in use are within a few percent of 50% nickel by number. At the temperature necessary to melt titanium it oxidizes easily, so the melting must occur in an inert atmosphere and crucible. Once the alloy is formed, an internal stress has to be introduced to the austenite phase for the shape memory effect to work correctly. This means that the austenite has to be heavily cold worked before being manipulated into its final desired shape. The desired remembered shape has to be fixed to a jig and then annealed for 10-100 minutes at between 623K and 723K to complete the shape memory treatment. The remembered shape can be changed by repeating the annealing process. Each step in the processing can alter the transformation temperatures or the transformation stresses in the alloy, so the last step is to test the transformation temperatures and stress-strains curves of the austenite and martensite of the Nitinol alloy.

References

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