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Superelastic Ni-Ti Wire

The transformational superelasticity in Ni-Ti wire is about ten times higher than the elasticity in ordinary materials.

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The term "superelasticity" is used to describe the property of certain alloys to return to their original shape upon unloading after a substantial deformation. Superelastic alloys can be strained ten times more than ordinary spring materials without being plastically deformed. This unusually large elasticity is also called pseudoelasticity, because the mechanism is nonconventional in nature, or transformational superelasticity because it is caused by a stress induced phase transformation. Alloys that show superelasticity undergo a thermoelastic martensitic transformation which is also the prerequisite for the shape memory effect. Superelasticity and shape memory effect are therefore closely related. As will be shown in this paper, superelasticity can even be considered part of the shape memory effect.[1]

The shape memory and superelasticity effect are particularly pronounced in Ni-Ti alloys. We will therefore focus on these alloys. While the shape memory effect in Ni-Ti alloys has been described many times,[2] only few papers can be found describing superelasticity and its applications.

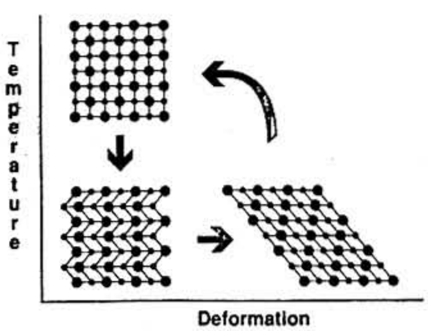


Fig. 1. Martensitic transformation and shape memory effect.

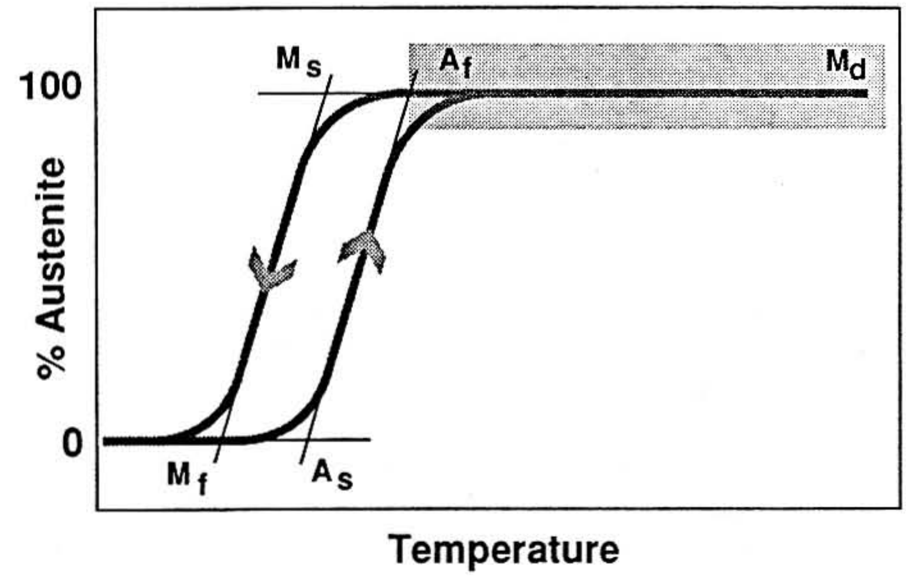


Fig. 2. Hysteresis of the martinsitic transformation (superelasticity is found in the shaded temperature range).

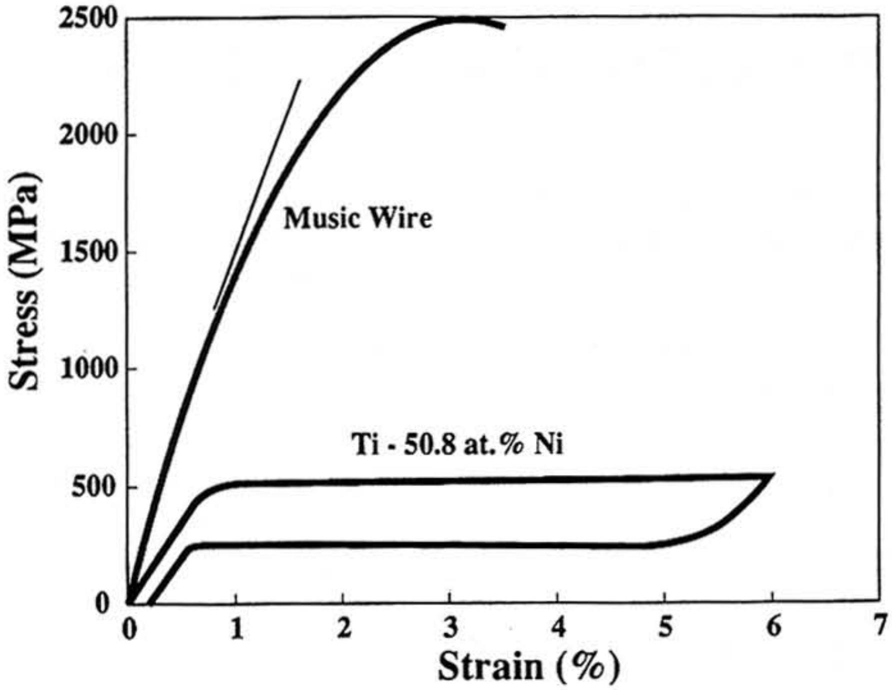
The thermoelastic martensitic transformation

In near-equiatomic Ni-Ti alloys martensite forms on cooling from the body-centered cubic high temperature phase, termed austenite, by a shear type of process. This martensitic phase is heavily twinned. In the absence of any externally applied force the transformation takes place with almost no external macroscopic shape change. The martensite can be easily deformed by a "flipping over" type of shear until a single orientation is achieved, as illustrated in Fig. 1. This process is also called "detwinning."

If a deformed martensite is now heated, it reverts to austenite. The crystallographic restrictions are such that it transforms back to the initial orientation, thereby restoring the original shape. Thus, if a straight piece of wire in the austenitic condition is cooled to form martensite it remains straight. If it is now deformed by bending, the twinned martensite is converted to deformed martensite. On heating, the transformation back to austenite occurs and the bent wire becomes straight again.

The transformation from austenite to martensite and the reverse transformation from martensite to austenite do not take place at the same temperature. A plot of the volume fraction of martensite as a function of temperature provides a curve of the type shown schematically in Fig. 2. The complete transformation cycle is characterized by the following temperatures: austenite start temperature (A_s), austenite finish temperature (A_f), martensite start temperature (M_s) and martensite finish temperature (M_f).

Fig. 2 represents the transformation cycle without applied stress. However,



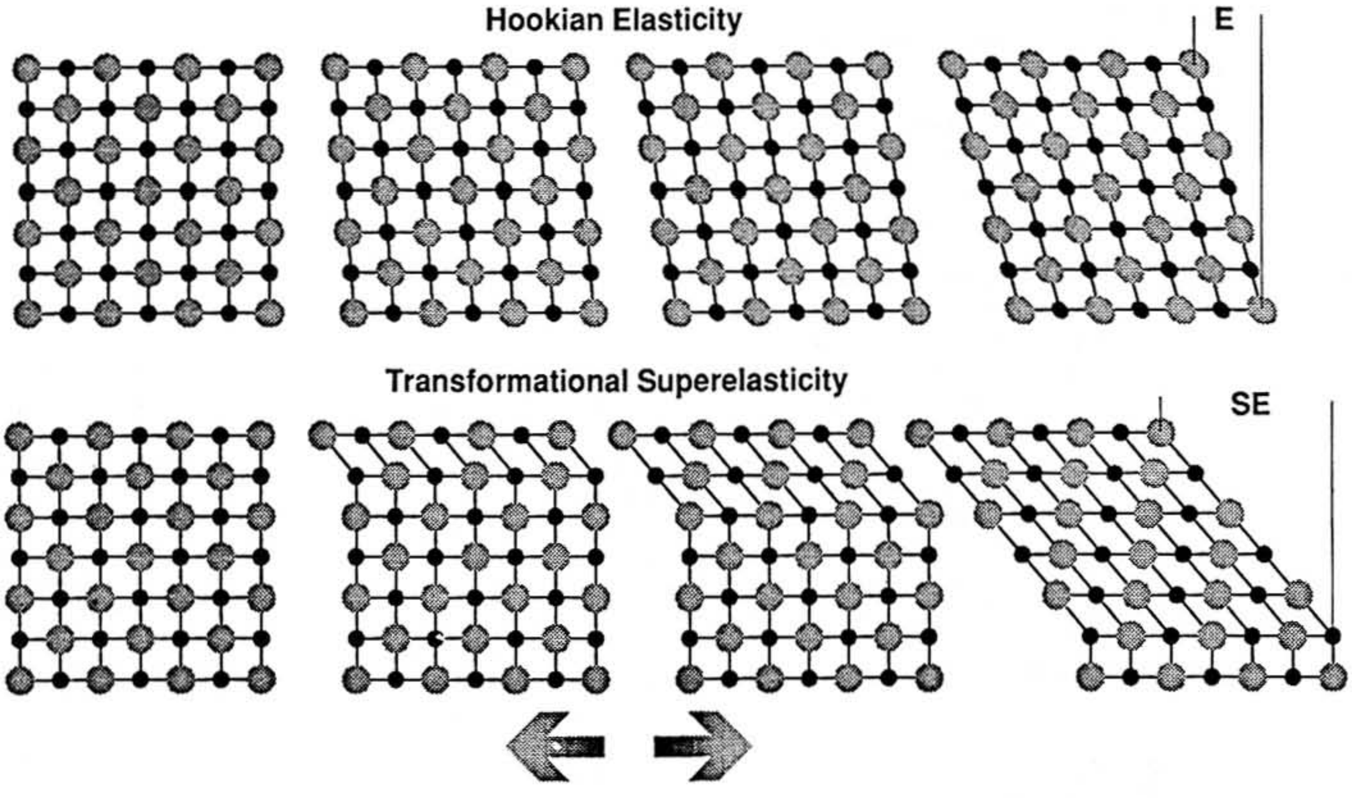


Fig. 3. Tensile behavior of steel and a Ni-Ti superelastic alloy and mechanisms of elastic deformation.

if a stress is applied in the temperature range between A_f and M_d (which has yet to be defined) martensite can be stress-induced. The stress induced martensite is then immediately deformed by detwinning as described above. Less energy is needed to stress induce and deform martensite than to deform the austenite by conventional mechanisms.

Up to 10 percent strain can be accommodated by this process (single crystals of specific alloys can show as much as 25 percent pseudoelastic strain in certain directions). As austenite is the thermodynamically stable phase at this temperature under no-load conditions, the material springs back into its original shape when the stress is no longer applied. Fig. 3 shows stress/strain curves for a conventional material and a superelastic Ni-Ti alloy as well as a comparison of the microstructural mechanisms of the elastic deformation.

As will be shown later, it becomes increasingly difficult to stress-induce martensite at increasing temperatures above A_f. Eventually, it is easier to deform the material by conventional mechanisms (movement of dislocations, slip) than by inducing and deforming martensite. The temperature at which martensite is no longer stress-induced is called M_d. Above M_d, Ni-Ti alloys are deformed like ordinary materials by slipping.

Production of superelastic Ni-Ti, alloys

Melting of Ni-Ti alloys is usually carried out by vacuum melting techniques such as electron-beam melting, vacuum arc melting or vacuum induction melting. In all cases contamination of the melt with carbon, oxygen etc. has to be avoided. The cast ingot is press-forged and/or rotary forged prior to rod and wire rolling. Hot working to this point is done at temperatures between 700°C and 900°C.[3]

Cold working of Ni-Ti alloys is rela-

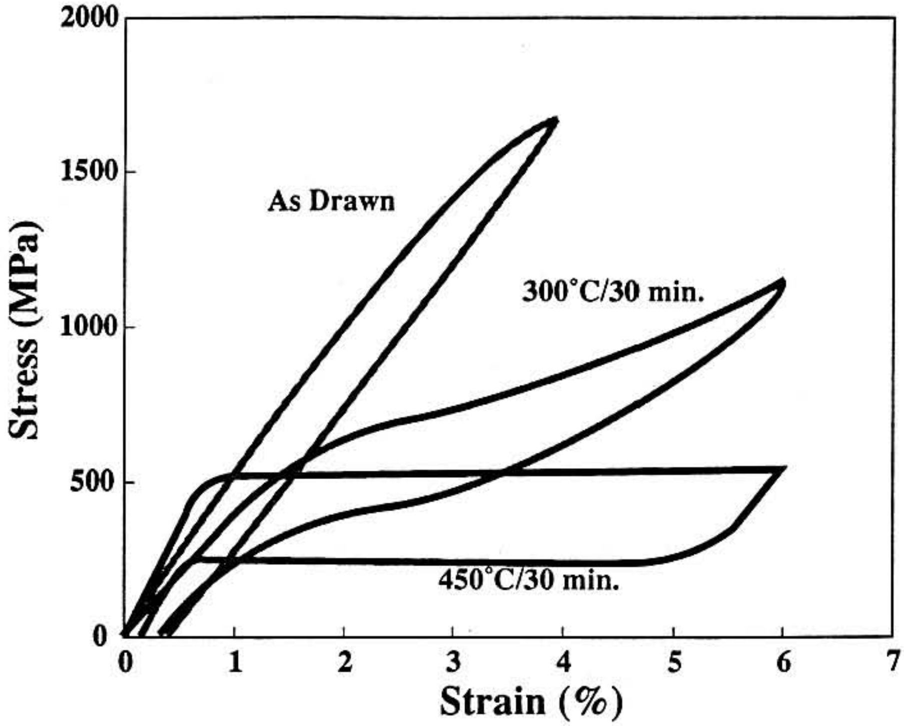


Fig. 4. Tensile behavior of a Ni-Ti alloy in different conditions.

tively straightforward, using basically the same procedures as in titanium wire fabrication. Typical reduction in area between anneals during wiredrawing is about 30 percent in some cases up to 60 percent. Interpass annealing is carried out at temperatures between 600°C and 800°C usually in air. An oxide layer on the wire improves the adhesion of the lubricant. Using carbide dies for diameters larger than about 0.050″ (~1.25mm) and diamond dies for smaller diameters, superelastic Ni-Ti wires with diameters as small as 0.003″ (~0.075mm) have been produced.

For medical applications the surface of the wires has to be free of oxides and contaminations. For this purpose, the wires are descaled and cleaned.

Ni-Ti wires in the as drawn condition do not show the "flagshaped" stress/strain behavior. In order to achieve maximum superelasticity the material has to be heat treated at temperatures between 400 and 600°C. However, for certain applications deviations from the flag shape are

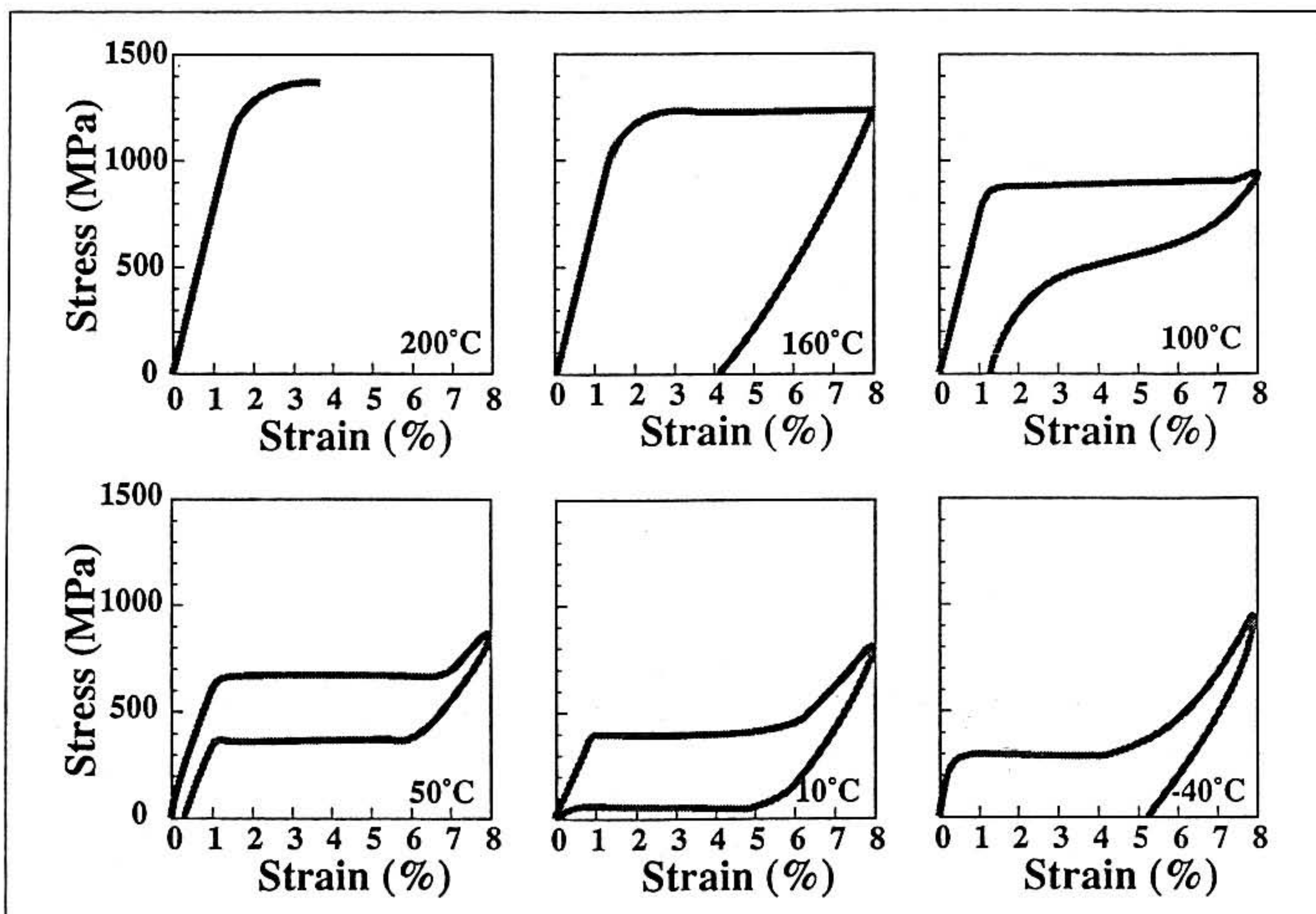


Fig. 5. Tensile behavior of a binary Ni-Ti alloy at different temperatures.

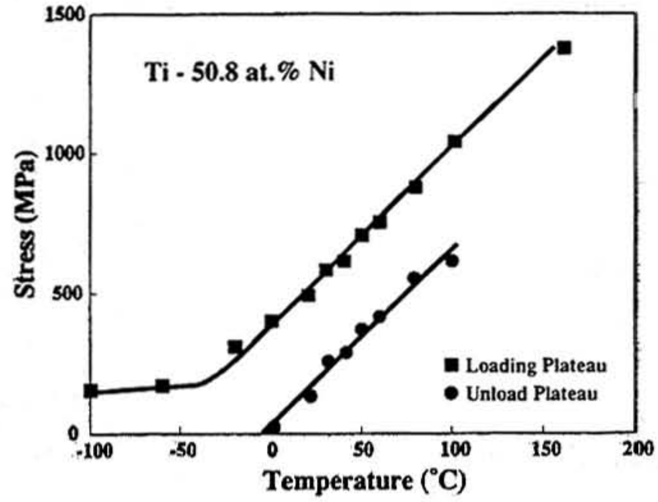


Fig. 6. Influence of temperature on the loading and unloading stress of a binary Ni-Ti alloy.

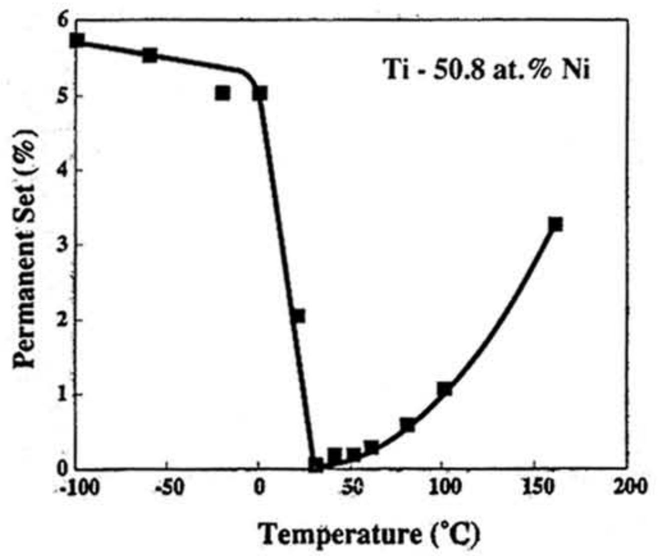


Fig. 7. Influence of temperature on the unresolved strain (permanent set) after straining to eight percent (binary Ni-Ti).

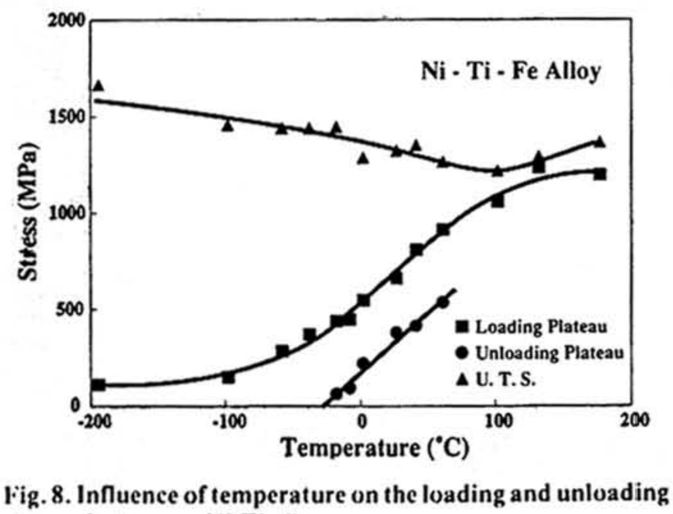


Fig. 8. Influence of temperature on the loading and unloading stress of a ternary Ni-Ti alloy.

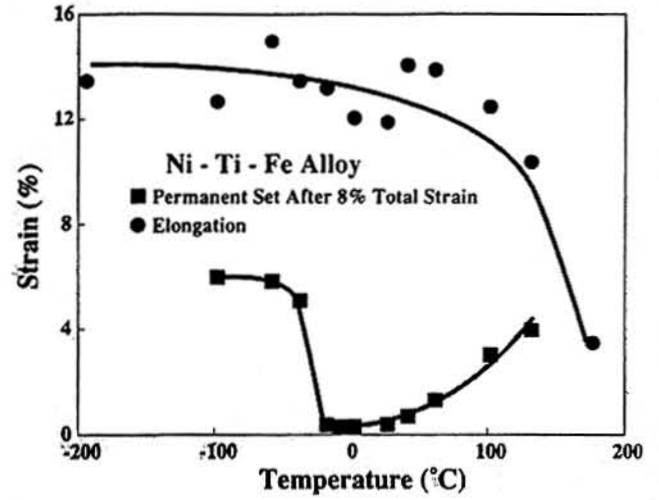


Fig. 9. Influence of temperature on the unresolved strain (permanent set) after straining to eight percent (ternary Ni-Ti).

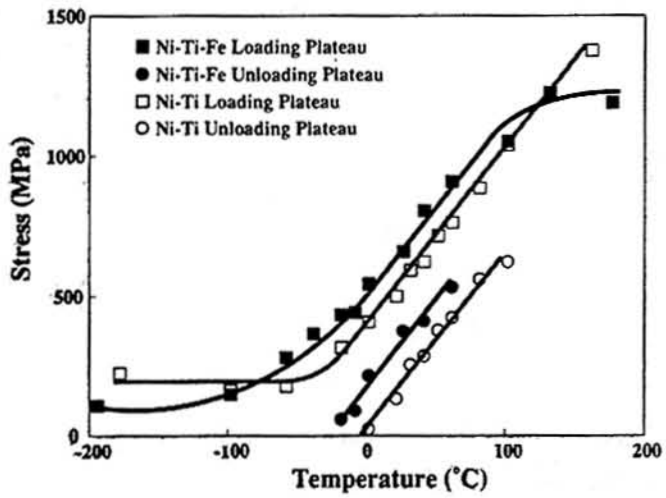


Fig. 10. Comparison of the loading/unloading stress of a binary and a ternary Ni-Ti alloy.

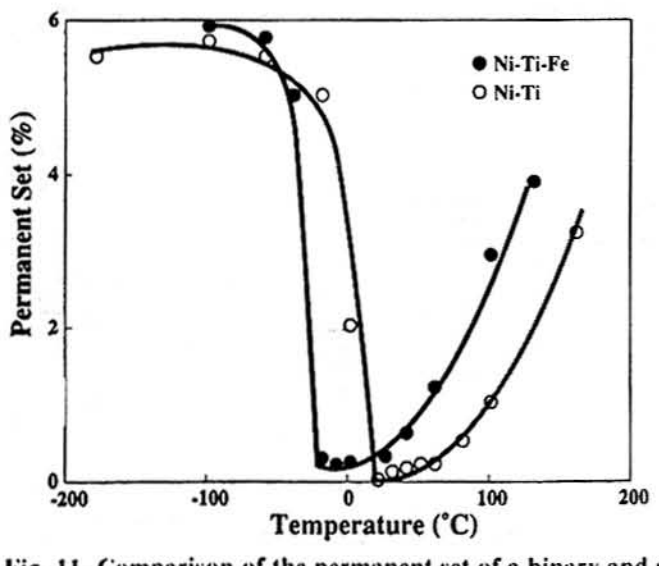


Fig. 11. Comparison of the permanent set of a binary and a ternary Ni-Ti alloy after straining to eight percent.

desirable. In these cases the heat treatment is done at lower temperatures. Fig. 4 shows stress/strain curves for the as drawn, the "flag annealed" and an intermediate condition. It has to be mentioned, however, that certain geometrical configurations, like perfectly straight wires, can only be achieved in the flag annealed condition.

Properties of superelastic Ni-Ti wires

Superelasticity is only observed over a narrow temperature range: below A_s, the material is martensitic. Deformations up to approximately eight percent can be recovered thermally, but not elastically. Above M_d, the material is deformed by conventional mechanisms, i.e. slip occurs after Hookian elasticity. The stress/strain curves of a binary Ni-Ti alloy at different temperatures are shown in Fig. 5. The largest flag is found at temperatures just above A_f, where strains up to eight percent can be recovered with almost no permanent set. Loading and unloading stresses increase with increasing temperature, but so does the permanent set after loading and unloading.

Fig. 6 shows the temperature dependence of the loading and unloading stresses of a binary Ni-Ti alloy, the transformation temperature A_f of which is approximately 10°C. This means that maximum elasticity and minimum permanent set is found near room temperature. Plotting the unresolved strain after unloading from a strain of eight percent vs. temperature results in a curve shown in Fig. 7. The minimum is found at 20°C. At higher temperatures the unresolved strain is equivalent to permanent deformation, but it is still only 0.5 percent at approximately 50°C. At temperatures below the minimum, the unresolved strain is caused by deformation of the martensite. A substantial part of it can be recovered by heating above A_f.

For many applications higher stresses at operating temperatures are desirable. For example, eyeglass frames should exhibit some stiffness even at temperatures below 0°C. This can be achieved by using alloys with a lower transformation temperature. Fig. 8 shows the temperature dependence of the loading and unloading stress of a iron doped Ni-Ti-alloy, the transformation temperature A_f of which is near -20°C. At room temperature the loading stress is approximately 95 ksi (650 MPa) and unloading stress approximately 55 ksi (370 MPa). However, unresolved strain at room temperature after straining to eight percent is approximately 0.5 percent (compared with 0.2 percent for the binary alloy).

The temperature dependence of the unresolved strain after straining to eight percent for this alloy is shown in Fig. 9. It is obvious that the superelastic window has shifted to lower temperatures. A comparison of the loading and unloading stresses of the binary and the ternary alloy is shown in Fig. 10, while Fig. 11 compares the unresolved strains of these two alloys.

Applications of superelastic Ni-Ti wires

Superelasticity is an isothermal event.[4] Therefore, applications with a well controlled temperature environment are especially successful. As body temperature is extremely well controlled, superelastic wires have been used for medical applications first. Even today, most applications of superelastic Ni-Ti wires are related to the human body in one way or another.

The first superelastic application was as orthodontic archwire (Fig. 12). The biggest advantages that Ni-Ti provides over conventional materials obviously are the increased elastic range and a nearly constant stress during unloading.[5] The first reduces the need to retighten and adjust the wire and provides the clinician with a greater working range. The second tends to decrease treatment time and increase patient comfort. Temperature changes induced during the ingestion of cold or hot food change the stress level of the wire, which apparently can accelerate tooth motion.

Fig. 12. Application of superelastic Ni-Ti wires for orthodontics.[11]

Recently, superelastic coil springs made from Ni-Ti wires have been introduced to the orthodontic profession for treatment for either opening or closing of extraction spaces. The superelastic springs provide greater efficiency in tooth movement than coil springs made from stainless steel or Cr-Co-Ni alloys.5

Another successful superelastic application is the Mammalok® needle wire localizer (Fig. 13), used to locate and mark breast tumors so that subsequent surgery can be more exact and less invasive.[6] A hook shaped Ni-Ti wire straightens when it is pulled into a hollow needle. The needle is then inserted into the breast using a mammogram as a guide to the location of the lesion. At the right location the wire is pushed out of the needle, thereby deploying itself around the lesion. If the mammogram after placement shows that the needle was improperly positioned, the superelastic hook can be pulled back into the needle and repositioned. This is done in radiology. The patient is then taken to the operating room for surgery.

A third successful medical application is the guidewire, which is passed through blood vessels and used as a guide for catheters.[7] These wires must be extremely kink resistant and flexible, and thus Ni-Ti has provided large advantages over stainless steel or titanium. Straightness of the wires is extremely important to achieve optimum torquability (the ability to translate a twist at one end of the guidewire into a turn of nearly identical degree at the other end). Superelastic Ni-Ti wires can be thermally shape set to meet this requirement.

The kink resistance and resistance to take a permanent set is also a major advantage of superelastic Ni-Ti suture needles for less invasive orthopedic surgery.[7]

Another recent application is the suture anchor (Fig. 14): a small arc of Ni-Ti straightens when it is pushed through a hole drilled into the bone with a guiding device. When it reaches the softer core of the bone it springs back to its arc configuration and anchors itself into the bone. A suture tied to the anchor is then used to reattach ligaments to the bone. This sort of surgery has proven to be far less invasive than conventional methods using large stainless steel screws.[8]

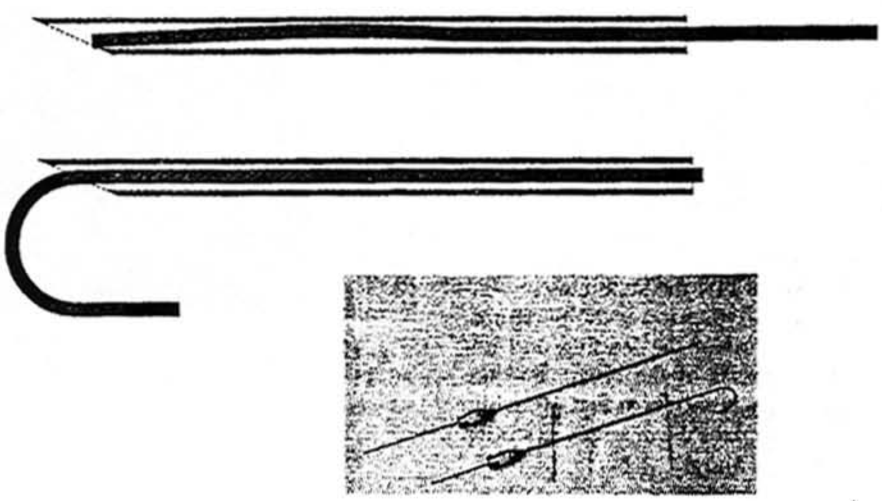


Fig. 13. Mammalok® needle wire localizer (photo) and schematic function.[6]

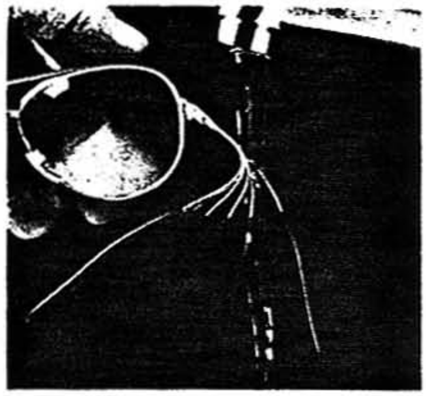


Fig. 15. Thermal recovery of a Ni-Ti eyeglass temple.[9]

Eyeglass frames using temples and bridges made from superelastic Ni-Ti wires are getting increasingly popular, particularly for sports and children's glasses. For the temples, the pieces that set over the ear and along the side of the head to connect to the front of the frame, a material with sufficient stiffness at temperatures down to -20°C (e.g. for skiers) is desirable. For certain models, the material of the temple is selected and processed in such a way that a combination of superelasticity and shape memory is achieved (Fig. 15).[9] The bridge, the part that connects the two glass rims, on the other hand should show maximum elasticity to prevent permanent distortion of the frame when accidentally deformed.

Finally, one of the most publicized applications is the Ni-Ti underwire brassiere. In many reports the shape memory of the brassiere is described as the unique feature. In reality, it is the superelasticity of the underwires that makes the bra comfortable to wear. These bras have been very successfully marketed in Japan.[10, 11]

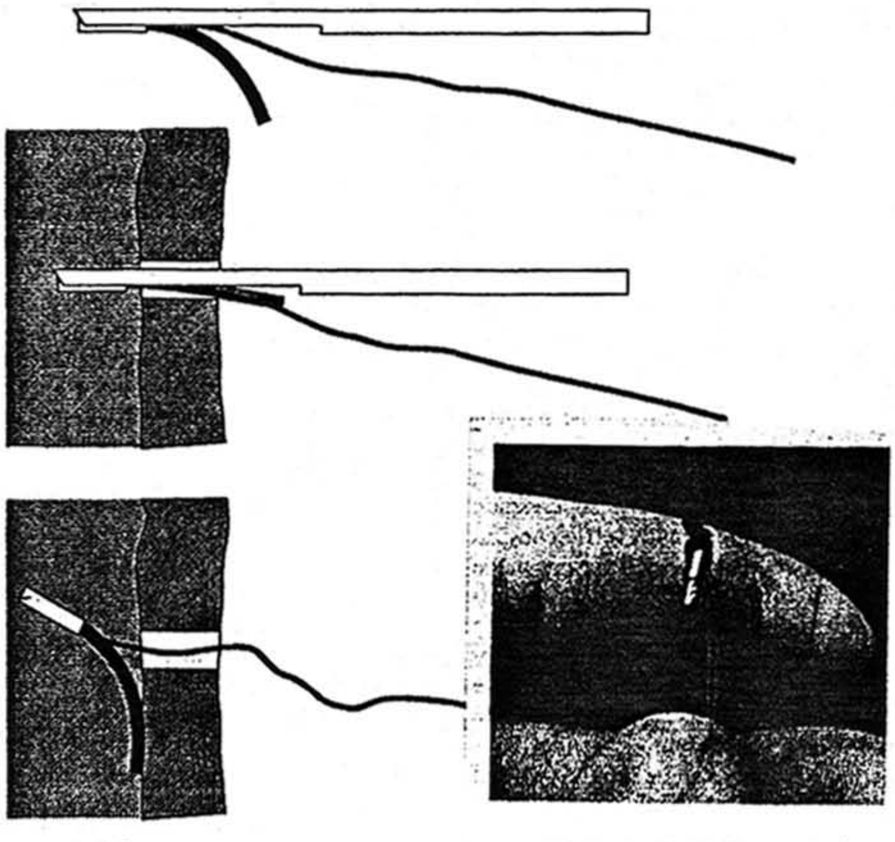


Fig. 14. Schematic function and original size (photo) of a Ni-Ti suture anchor.

Conclusion

Superelasticity in Ni-Ti wires caused by the formation of stress induced martensite. This transformational superelasticity is about ten times higher than the elasticity in ordinary materials. It is strongly temperature dependent. Therefore, the most successful applications of superelastic wires are medical or other applications that work in a narrow temperature range.

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