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Application of a shape memory alloy to hand splinting

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Abstract

This paper describes new passive splints which have been developed using a shape memory alloy. The peculiar feature of the splints is that the way in which they change shape in use conforms to the stretching motion which it would be desirable to apply in certain conditions of deformity.

The alloy consists of 55.66% by weight Nickel and 44.34% Titanium. The heat treatment of the alloy for memorising shape was implemented at 500°C for one hour. This alloy was easily bent when cool, but the original shape was recovered on heating.

It was used as the supporting structure of the reverse knuckle bender splint and the cock-up splint. The new splints could be easily attached to the deformed limb after cooling. The splints avoided the development of spasticity, because they gradually recovered their original shapes and corrected the deformities when the heat of the room or body heat warmed the splints.

Since the shape memory alloy has the dual function of thermal sensor and kinetic power source it was a simple device. The splint was, as a result, small and smart. It was apparent from clinical use that the splint was easy to wear and could be worn with comfort for an extended period.

The design of the splints and the fabrication process are described and their application is indicated.

Introduction

Shape memory alloy has attracted the authors' attention because it can be easily bent when below the transformation temperature, but the original shape is recovered on heating.

Since the shape memory alloy was discovered by Kurdjumov in 1949, many investigators have tried to find practical applications. The alloy has a dual function of thermal sensor and kinetic power source, hence many kinds of functional devices have been developed by its use. Nevertheless, the applications are mainly for industrial purposes and it would appear that no reports on the application to splints have been published.

If the alloy is used as a splint, what kinds of benefit are there, and how should it be applied? The purpose of this paper is to answer these questions. Furthermore it is considered whether the application makes the best use of the characteristics.

Splints can be classified roughly into two groups; dynamic splints and static splints. Although it may be expected that shape memory alloy is suitable for application to dynamic splinting because it automatically moves on heating, there are many problems to solve in the application of the principle. An electric control could be considered the most effective means of activation. The transformation of electricity to heat however is most inefficient. Furthermore, the responses of the alloy to temperature rise and fall are slow. Speed of activation, is however necessary in dynamic use.

The response of shape recovery on warming by using heat from body or room is very slow. The shape memory alloy may be applied as an assist in a static splint. Since the alloy remains the same shape for a time after its shape is changed on cooling, a splint made from it is

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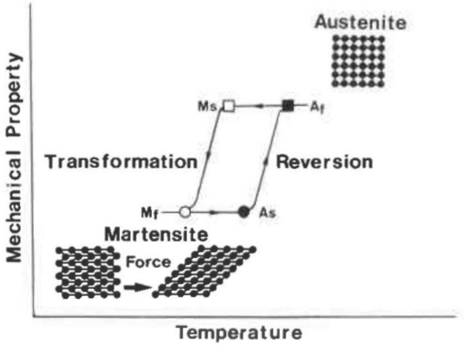


Fig. 1. Schematic representation of the mechanical property — temperature relationship for a thermoelastic martensitic transformation.
M_s: temperature starting martensitic transformation on cooling.
M_f: temperature finishing the transformation.
A_s: temperature starting the beginning of the reverse transformation.
A_f temperature finishing the reverse transformation.

easily attached to the deformed hand. The slow recovery speed on heating will not develop spasticity in the spastic hand. Accordingly, the application of the shape memory alloy to the static splint was tried. This is a preliminary report.

Methodology

Shape memory effect

In crystallography, it is understood that the shape memory effect is induced by thermoelastic martensitic transformation. The cause is explained by the fact that the crystal lattice is deformed without the diffusion of metal ions. Figure 1 shows the transformation-reversion mechanism of the shape memory effect. M_s is the temperature marking the beginning of martensitic transformation and M_f is the temperature marking its conclusion. A_s is the temperature starting the reverse transformation to the austenitic phase and A_f is the temperature ending it. If the alloy is cooled down, the martensitic transformation will start. The crystal lattice will zigzag and the alloy will be soft. In this state, the metal is easily deformed. Then, as the alloy is heated, a large stress generates and the reversion starts. The alloy "springs back" to its original shape and becomes hard.

Materials

It is widely known that Nickel-Titanium (Ni-Ti) alloy is available as a shape memory alloy. This alloy features a strong recovery force, high wear resistance, and resistance to corrosion. The safety of this alloy also has been proven in animal toxicity tests within a period as long as the splint is used. Hence, the Ni-Ti alloy has been selected as the assist of the static splint.

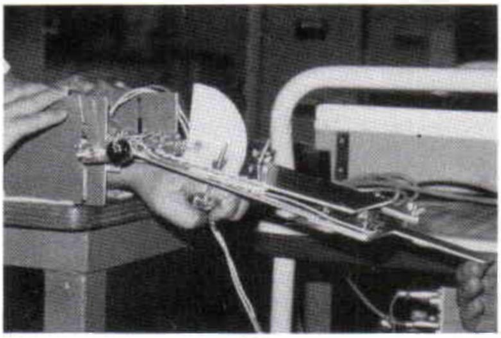
The transformation temperature is dependent upon the concentration of Ni and the temperature of the heat treatment needed to memorise the desired shape. The transformation temperature was measured with a differential scanning calorimeter. Since the transformation temperature of 55.66% by weight of Ni is close to room temperature, a Ni-Ti alloy* with this Ni concentration was chosen as the best material for the new splint. As the heat treatment temperature becomes higher, the transformation temperature drops, and the deflection range from zero load to the yield point is less. If the material is deformed past the yield point, the restoring force will not be able to correct the deformed hand. Thus, the heat treatment is implemented at 500°C for one hour. Consequently, the transformation temperature A_s is 13°C, A_f is 28°C, M_s is 24°C and M_f is 9°C.

The load versus angular movement characteristic

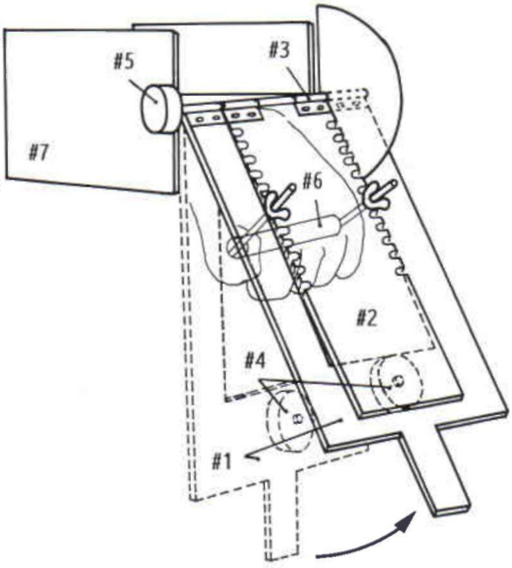
Before designing splints, it is necessary to know the bending force being exerted by the shape memory alloy to correct the deformed hand, as the size of the alloy will be determined by the force.

A device to measure the load against angular movement characteristic was constructed (Fig. 2). A duralumin frame (#1), which was cut to the shape shown in Figure 2b, and a rectangular duralumin plate (#2) was attached to a base. There was an overlapping area and they had the same axis of rotation (#3). The two plates were able to rotate smoothly about this axis. A disc load transducer (#4) was mounted in the overlapping area between the plates and a potentiometer (#5) was fixed to the shaft of the axis. The two opposite longer edges of the rectangular duralumin plate were U-notched at intervals of 1 cm. In these notches a hand rack (#6) was attached to transfer resisting force from a hand to the frame (#1). The load transducer and the potentiometer were connected by amplifier to an XY-recorder.

*Ni-Ti alloy is a product of HITACHI METALS Ltd., 1-2, 2-chome, Marunouchi, Chiyodaku, Tokyo, Japan. Tel: (03) 3284-4511.



(a)



(b)

Fig. 2. A device to measure load against angular movement characteristics using a potentiometer and a load transducer.

a) test in progress.

b) construction of the measuring device.

The deformed hand is inserted into the hand rack, and the palm or the fingers are put on its bar. The forearm is fixed to the base (#7) with the wrist joint close to the axis of the hinge. When the handle of the plate (#1) is pulled in the direction of dorsiflexion of the spastic hand by an operator, a resisting force is generated. This force is transmitted through the hand rack to the plate (#2). Pressure is applied to the load transducer which is between plates #1 and #2. The characteristic curves of the force detected from the load transducer and the angular movement detected from the potentiometer are drawn on an XY-recorder. The joint torque of the deformed hand is obtained by multiplying the force by the distance between the axis of the hinge and the hand rack.

An example of the curve of force against angular movement obtained is shown in Figure 3. The resistance shown by the joint to extension increases with increasing extension, that is, as the angle of flexion decreases. On the contrary, the restoring spring force of the shape memory alloy increases with the bending angle. Where these two curves intersect is the point at which the resistance to extension of the joint is balanced by the restoring force of the splint acting on the fingers.

Fabrication process

1) The function of the upper limbs of the patient are evaluated by an occupational therapist. Then the type of splint and corrective position are prescribed based on this evaluation.
2) The pattern of corrective force, which is the load against the angular movement, of the deformed hand is measured with the above device. The dimensions of the plate of the splint assist are chosen to give an equilibrium of forces at the angle at which correction is desired.
3) The splint assist plate is made by a machining process. Since Ni-Ti alloy is very hard, the plate is cut to the desired size from the alloy using a diamond cutter and holes are bored as required with a carbide drill. It is then formed into the required shape with forming tools. At this stage, it is necessary to keep below the limit of

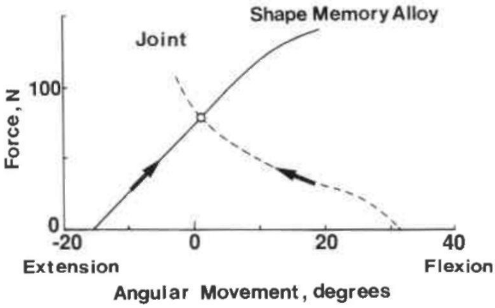


Fig. 3. An example of the curve of force against angular movement. The broken line shows the load characteristics for the metacarpophalangeal joint, and the solid line shows the characteristics for the alloy.

elasticity. Specifically speaking, the strain must be below about 6% for the bending of Ni-Ti alloy. In the case of a plate of 1.4 mm thickness, this limitation corresponds to bending with a radius of curvature of about 15 mm.

4) The shape memorising treatment is performed by fixing the shape, putting the splint assist into an electric hearth and heating for one hour at 500°C. It is then taken out and immediately plunged into cold water.

5) It is finished off into the shape required for the splint. The best connection of the plate to the substance of the splint is by a mechanical method, fastening with a bolt or rivetting for example. Connection by welding or brazing will be easily separated under a small change of temperature of the alloy and it should be avoided because the ratio of expansion or contraction is large. For example, the ratio is from 2% to 6% for Ni-Ti alloy and is approximately 0.5% for other metals in general.

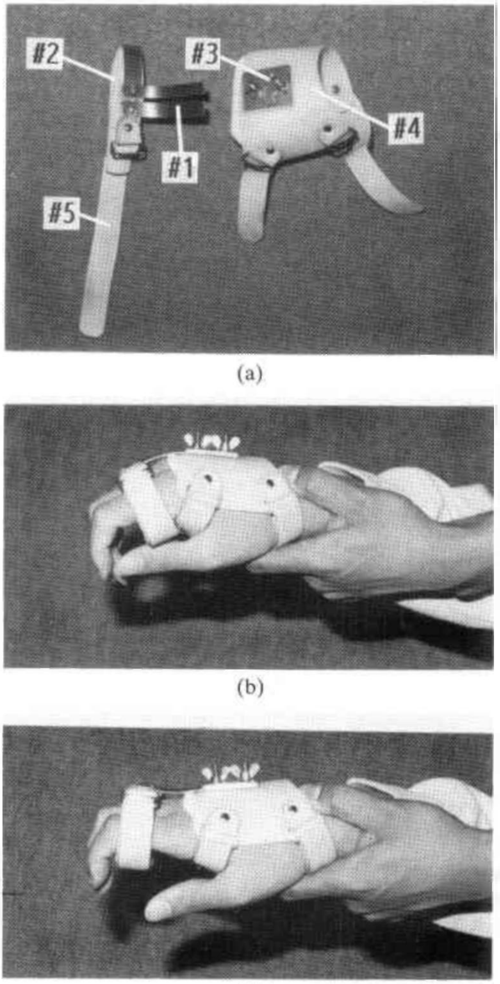


Fig. 4. A new reverse knuckle bender splint.

a) the new splint using the shape memory alloy. Two plates of the alloy are used for the finger extension assists.

b) the splint before it was activated.

c) the splint after it was activated to correct the deformed fingers.

Usage

1) The splint assist is cooled in a refrigerator at 0°C for about ten minutes, and becomes soft. Rapid cooling may be achieved by using a spray type freezing gas, such as Three Bond PANDO-29C®.
2) The shape of the splint is then adjusted to fit the deformed wrist or hand snugly. The splint is then ready to be worn.
3) When the splint is worn, the heat of the room or body warms the splint and it recovers its original shape gradually; the recovery time is about 5 minutes. A heater or hot water may also be used as the means of warming the splint. The higher the temperature, the faster will be the recovery speed.
4) Care should be taken not to bend the splint assist until its temperature decreases below M_s, nor to warm it above A_f in use, since these cause loss of shape memory.
5) The splint is detached from the hand by loosening the straps which attach the splint to the hand.

Clinical applications

Reverse knuckle bender splint

The patient is a male, 27 years old, with quadriplegia caused by head trauma. His hand is in the fourth stage of the Brunnstrom's recovery stage. The MP joints are moderately deformed by spasticity of the flexors. The purposes of the splint prescription are to prevent the aggravation of spasticity and to improve the functions of the hand.

Figure 4a shows a new splint using the shape memory alloy. Figure 4b shows the splint before activation and Figure 4c shows the splint after activation to correct the deformed fingers. Two pieces of plate of the shape memory alloy were used for the finger extension assists (#1). The dimensions of each plate were 10 mm wide, 40 mm long, and 1.4 mm thick. An MP bar (#2) was made of duralumin plate and was connected to the assists.

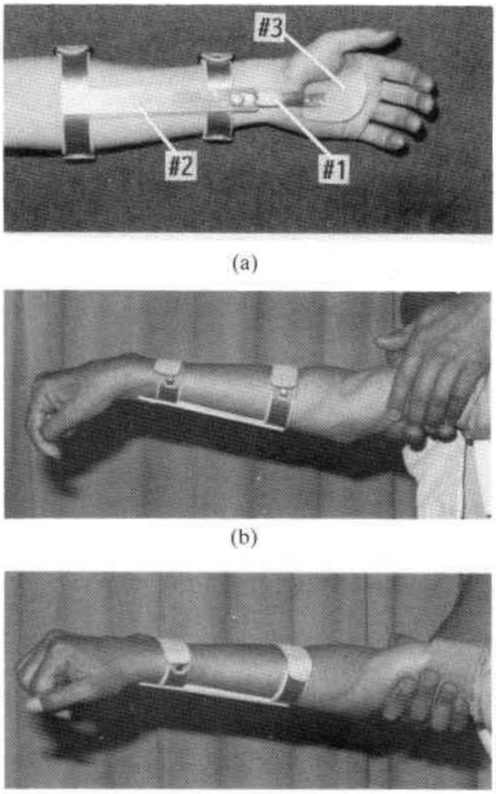
To obtain the optimum fitting position, a removable MP bar and a "slide fix" type mounting was adopted. The MP bar could slide along the attachment base (#3) and was bolted to it. Hence the MP bar could be attached rapidly to the base and the shape memory alloy could be easily cooled. The lateral sides of the splint were opened for easy insertion of the deformed hand. When the hand is dorsiflexed, there is a tendency for the transverse arch to flatten. To maintain the arch, the attachment #4, which was made of thermoplastic sheet was shaped to the transverse arch of the hand by casting. The MP bar is also shaped to the transverse arch. The wrist edge was trimmed to permit the range of movement of the wrist. VELCRO® straps (#5) were positioned so that they did not prevent the flexion of the MP joint. Urethane sponge sheets were pasted on the internal surface of the splint to distribute the pressure, and all rough edges were trimmed, and smoothed to prevent the tissue from being injured.

The new splint was easily attached to the deformed hand and was well fitted. Consequently, no pain was noted and the tissue did not turn red. The patient was able to wear the splint for a long period. After using the new splint, for 4 months the patient could extend his fingers fully. The spasticity decreased and the hand was improved from a non-functional hand to a functional assistive hand.

Cock-up splint

The patient, is male 66 years old, with left hemiplegia caused by subarachnoid haemorrhage. His hand is in Brunnstrom's third stage of recovery. The wrist joint is deformed severely by painful spasticity and contracture of the flexors. The purpose of the splint prescription is to correct the deformity.

Figure 5a shows a new splint using the shape memory alloy. Figure 5b shows the splint before activation and Figure 5c shows the splint after activation to correct the deformed wrist. A plate of the shape memory alloy was used for the wrist extension bar (#1). The size was 12 mm wide, 45 mm long, and 1.4 mm thick. The plate was fixed to the forearm piece (#2) by riveting. The forearm piece was made of duralumin plate with felt pasted on the inside surface and two VELCRO® straps added. A palm pad (#3) to distribute the pressure was fixed to the wrist extension bar by riveting.



(a) (b) (c)

Fig. 5. A new cock-up splint.

a) the new splint using the alloy. One plate of the alloy is used for the wrist extension bar.

b) the splint before it was activated.

c) the splint after it was activated to correct the deformed wrist joint.

The palm pad was made of thermoplastic sheet and was made in the shape of the arch of the palm by casting. The outline of the pad was trimmed to avoid the ball of the hand. The corners were rounded, and all edges smoothed off.

No pain was noted when the new splint was attached to the deformed hand, and the splint was well fitted. The slow gradual stretching of the splint prevented the development of spasticity. The splint exerted sufficient force to correct the deformity, and expanded the range of motion (ROM) of the wrist after a few months.

Discussion

It is worth noting that the new splint prevented the development of spasticity.

The discharge in Ia fibres activates agonistic muscles and as a result, inhibits antagonistic muscles at the same time. It enhances agonistic muscle tone. On the other hand the activation of Ib fibres inhibits agonist and facilitates antagonist. Consequently they have a relaxation effect on the agonistic tone. The Ib fibres fire more slowly than the Ia, and the excitation continues for a time after stretching. When a muscle is stretched quickly, the Ib fibres hardly become sensitive to stretching and the Ia fibres fire, but when the stretching is performed slowly, the Ib fibres are excited and the agonistic tone is decreased. That is to say, when a spastic hand is moved suddenly, a spasticity occurs easily. If the deformed hand is corrected gradually, the occurrence of spasticity decreases.

The method of stretching by using this splint agrees well with the above-mentioned theoretical grounds. This is a peculiar feature of the new splint. The splint is attached to the deformed hand and stretches it slowly while being warmed by the heat from the environment.

Firstly, the Ib of flexor is fired for a while by using this splint, and subsequently, the extensor should be exercised voluntarily to strenghten it. Because it is necessary to increase the Ia fire of the extensor to decrease flexor spasticity more.

The recovery speed of the shape memory alloy is proportional to the rate of its increase in temperature. Since the temperature of a body or a room, which is the heat source to heat the alloy, is not high, the speed of temperature rise is slow and the recovery time is long. The speed can be slowed down by decreasing the conduction of heat to the alloy. Covering the surface of the alloy with a heat insulator is one of the methods for delaying recovery, and increasing the heat capacity by increasing the dimensions of the alloy is another.

For the purpose of decreasing spasticity, it is desirable that the wearing period is lengthy and the splint can be used during sleeping at night as described by Kaplan (1962) and Snook (1979). Although patients can understand the usefulness of a splint, in practice many of them hate it and are used to life without it. If a splint is small, smart and easy to attach, more patients might use it. These are important factors to continuous wear. Since the splint changes the shape gradually by gaining heat, it can correct the deformed hand while the patient is sleeping.

Furthermore, no assistant is needed to help the patient to extend the wrist or the finger joints before wearing the splint, since the new splint can be put on to the hand in the deformed state and the hand position corrected automatically. It is easy to wear independently. With other methods, it is necessary for a therapist to correct the deformed hand forcibly or to do ROM exercises sufficiently before wearing the conventional type splint.

As shown in both cases of reverse knuckle bender splint and cock-up splint, the shape memory alloy improved the wearing procedure of the splint and extended its wearing term. Since the alloy has a dual function of heat sensor and kinetic power source, it can eliminate components such as an electric motor and mechanical gears along with a sensor system, and the correcting mechanism of the splints is simple and small.

On the other hand, the high cost is one of the shortcomings of the shape memory alloy. Mass production will make the price lower, and the total cost of the splint can be decreased by using the minimum amount of the alloy required. Another shortcoming is that cutting and drilling of Ni-Ti alloy are difficult, because the alloy is harder than duralumin.

Particular attention is also needed in fabrication. Welding and brazing should be avoided as mentioned above. For the same reason, covering the alloy with a heat contractible tube is a better way of coating it.

The safety of Ni-Ti alloy has been proven in animal toxicity tests extended over some weeks. A thorough check over a long duration would also be necessary to confirm bio-compatibility.

Conclusion

The authors especially emphasize the point that using a shape memory alloy as the assist or the extension bar of a splint may be the most desirable method of correcting a deformed hand with spasticity. The present experience is not sufficient to prove this fact statistically. More practical research is required.

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