Ni-Ti 合金の形状記憶効果と超弾性
Shape Memory and Super-elasticity Effects in NiTi Alloys

Summary: The equiatomic or near equiatomic NiTi is a unique intermetallic compound. It has good ductility, a shape memory effect, and a super-elasticity. The alloy undergoes a martensitic transformation at near room temperature. The low temperature phase is characterized by high damping capacity, and the high temperature phase by excellent abrasion and corrosion resistance. By a shape memory effect we mean that the alloy plastically deformed in the low temperature phase recovers its original shape in subsequent heating. Super-elasticity is a rubber-like behavior of the alloy in which a strain attained beyond the elastic limit in loading recovers upon unloading. The following is a presentation of the general properties and deformation mechanisms of the shape memory effect and the super-elasticity of the NiTi alloys including its applications such as in jointing devices, thermal actuators, and medical devices.

1. 多様な特性を持つ Ni-Ti 合金

ニッケルとチタンを原子比1:1で含む Ni-Ti 合金は、金属間化合物であるのに塑性加工が可能というめずらしい性質を持っているが、さらに、変態付近の温度でマルテンサイト変態と、これに伴って特異かつ多様な挙動を示す合金である。

まず、この合金はマルテンサイト変態温度（以下、M変態温度）を含む。M変態は、変態の形状記憶効果のメカニズムの項で説明するが、ここでは異なる温度で変化するので示さない。以下に、温度が高いほど、変化する温度が高いのでダイヤモンドタイプの変化に該当する。この温度を示すために、この合金が重要であると考えられるのである。

M変態温度より少し高い領域では、合金の変態温度が高いが、変化する温度が高くなるため、変化する温度が高いのである。

M変態温度よりずっと高い温度領域では、これまでの領域を示すが、変化する温度が高くなるため、変化する温度が高いのである。

以上、ごく簡単に述べた特性のうち、第四の特性、耐摩耗性については本誌に発表しているので、本稿では

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写真1 形状記憶合金と超弾性合金

通常の金属材料

\[ \text{引 張 る} \]

除 荷

\[ \text{加 熱} \]

超 弾 性 合 金

\[ \text{引 張 る} \]

除 荷

最近機能材料として注目されている形状記憶効果と超弾性について実用例を紹介しながら解説する。

2. 形状記憶効果と超弾性

形状記憶効果はすでに述べたように、一定の変形を生じさせた状態を記憶する性質である。加熱により変形を除去した後、冷却により元の形状に戻る。この再現性は、超弾性合金や形状記憶合金の応用に重要な役割を果たしている。

通常の金属材料では、変形を除去した後、通常は復元されない。しかし、超弾性合金や形状記憶合金では、一定の温度領域で変形を除去すると、変形を回復させることが可能である。

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COOK
Exhibit 1012-0002
のちるものではなく一種の晶変形であるが、見掛けの\centered
ずれによる変形変形を試みるところはない。しかし、\centered
これらの変形ひずみは合金をM変態温度以上に加熱する\centered
と、変形前のひずみゼロの状態に戻ってしまうのであ\centered
る。
一方、超弾性の場合はひずみの回復に加熱を必要とし\centered
ない。降伏領域まで変形した後、除荷すると、図1に示\centered
すように、ちょうど降伏現象と逆の挙動を示しながらひ\centered
ずみゼロに戻るのである。
ここで注意すべきことは、形状記憶効果や超弾性によ\centered
って回復できるひずみ量には一定の限界があり、変形の\centered
許さによっては、もとに戻らなくなることがある。この点\centered
について、高ひずみ領域の応力・ひずみ線図（図2）を\centered
によって説明する。
M変態温度以下の温度で形状記憶合金を変形すると、\centered
形態変形が試して降伏が起こり、応力はほぼ一定の値\centered
をとる。平断面の途中から除荷すると、見掛けの塑性\centered
ひずみが残るが、これはすでに述べたように加熱する\centered
と消失する。ところが、変形ひずみが増して、平断面を\centered
こえると、応力は再び増加をはじめて、加工硬化がはじま\centered
る。ある程度加工硬化した状態から除荷すると、やはりひずみが残るが、これをM変態温度以上に加熱\centered
してもひずみは完全には回復しないで永久変形とる。\centered
さらに変形ひずみが増すと、応力の増加はゆるやか\centered
になり最後に破断する。充分に加工硬化した状態⑥では\centered
加熱しても殆ど形状を回復しない。
したがって、良好な形状回復性を得るには、変形ひ\centered
ずみの量が一定の値（Ni-Ti合金では7.5%）をこえない\centered
ようにする必要がある。これらの事情は超弾性について\centered
もまったく同じである。
形状記憶効果と超弾性は、いずれも1950年代の前半に\centered
金とカドミウムの合金で偶然に発見された現象である\centered
が9). 当時は特殊な合金系であることにようからあまり注\centered
目されなかった。形状記憶効果がきちんと研究されるよ\centered
うになったのは、NOL（前述でNi-Ti合金の著者の形\centered
状記憶効果が発見されてからのことである10)。以来、多\centered
くの研究成果が発表され、形状記憶効果を示す合金もこ\centered
まれに十数種類が見つかっている。

図1 形状記憶合金、超弾性合金と通常の金属材料の応力・ひずみ線図

ところで、Ni-Ti合金の発見当時はこの合金が超弾性\centered
を持つことは判っておらず、超弾性は形状記憶効果とは\centered
別個の現象としてCu-Al-Ni合金などを中心に研究がな\centered
されていた。Ni-Ti合金の超弾性現象が見つけられたの\centered
は、1970年代に入って両者の現象がいずれも塑性型M\centered
変態によって起こることが解明される直前にのことであ\centered
る1112)

一方、高強度の耐摩耗は形状記憶効果などの\centered
機能材としての興味とはまったく独立に、構造材として\centered
開発がすすめられ、機能材としてよりずっと早い時期に\centered
実用化され、現在に至っている。

3. 形状記憶効果と超弾性のメカニズム
形状記憶効果や超弾性が何故起こるかということ、これが
一方、超弾性もやはりM変態に伴う現象であるが、形状記憶効果におけるM変態が熱帯で温度変化によって引き起こされるのに対して、超弾性では応力によって引き起こされる点で異なる。この型のM変態は応力誘起変態と呼ばれ、AF点よりも若干高い温度でA相に応力を加えたとき、主にせん断応力が駆動力となってM相に変態するものである。その際、同じ応力によってM相とA相の変形が変わることで、図4の破線で示すようにA相から一挙に変態M相に移行する。これを除荷した後、またA相に戻すと、よりもとその温度（AF点以上）で安定なA相に戻ることになるが、ここででも結晶間のつながり方が保たれ、変形が逆に生じることが解消されるのである。

ところで、M変態はNi-Tiのような特殊な合金にだけ見られる現象ではない。鉄鋼をはじめ、多くの金属、合金で見られるポピュラーな現象である。しかし、鋼も最も典型的なM変態を示す合金なのであるが、形状記憶効果を観察することはできない。一部のTi合金やCo合金はある温度でひずみを回復するが、不完全である。これらの違いの原因は変態の際に相と相の境界面の変化性にあると考えられている。完全性のあるNi-Ti合金などのM変態（熱弾性型M変態と呼ばれる）の場合はA相に戻るときに、原子がそれぞれその配置に戻る形で変形を回復するが、鉄鋼などのM変態は必ずしもA相の位置に戻らない、エネルギー的に有利な配置がA相に帰る。したがって、多少形状が変化することはあっても、完全に変形前の形状に戻ることはない。これら変態の整合性に加えて、規則構造の形成によってM相とA相（結晶の形が同じで方位だけは異なる相）の数が制限されることも原子がその位置に固定されるための重要な要因となっている。これらの要因のすべてが満たされたときには、精密な形状記憶特性や超弾性特性が得られるものである。

4. 形状記憶Ni-Ti合金の応用

形状記憶Ni-Ti合金の実用化第1号はバイブ接続14である。接続には動作温度が低い（-150°C位）合金を用い、内径をバイブ外径よりやや小さく作ってある。接続作業はまず接続を液体空気中に浸し、内管にブラシを押込むことで内径を拡げてやる。次に、図4のように両側からバイブ

図3 形状記憶効果と超弾性のメカニズム（概要図）
Ni-Ti合金は体への適合性が高いので、体内に埋め込んで使用するインプラント材として期待されている。折れた骨をギプスによらずボルトなどで生体で固定する内

図4 形状記憶NiTi合金を用いたパイプ維手の原理図

図5 形状記憶合金を用いたIC素子パッケージのシーリング

図7 バイスバネによる二方向性形状記憶素子の動作原理図

固定接骨法に使用する接骨板は広く研究されているものの一つである。同じ様な用途に適応びや人工関節等基部の固定法がある。变动した維手に直線状を記憶したNi-Ti合金を沿って固定し、外部から加熱し維手を直ぐにする側面の治療法は形状記憶合金ならではの方法である。

さて、これまで述べてきた形状記憶効果はいずれも一方性(One way)と呼ばれる現象である。つまり合金を低温で変形した後に加熱すると一回だけ元に戻る現象で、これを再び低温にしても低温で変形した形にはならない。しかし、能動素材は一般的に一方性をより繰返し動作をする二方向性(Two way)の素材の方が機能的に有利であり、応用範囲も広い。このため、形状記憶合金についても二方向性特性を得る方法がいろいろ考えられているが、その一つにバイアス力を用いた方法があな。これより形状記憶合金が高温で強く(硬く、降伏応力が高い)、低温で弱い(軟かく、降伏応力が低い)という性質を利用したもので、例えば図7のように、形状記憶合金のコイルと通常のコイルバネを互いに押合うようにした素材の場合、低温では形状記憶合金がバネの力に負けて左側に押付けられているが、温度が上るとバネの力に打勝って右側へ動くわけである。

二方向性素材としては、これに差動式二方向性素材が良く使われる。これは高温と低温における形状記憶合金の力の差を出すもので、例えば図7のコイルを両共形状記憶合金で作るとこのタイプの素材になる。一方のコイルを加熱すると温度の上ったコイルが対側のコイルを押込んで力の出発。コイルの加熱を止めて反対側のコイルを加熱すれば逆方向へ動くのである。

二方向性の温度変化素材としては、昔からバイメタルが良く知られているが、形状記憶素材は発生する力が大きいこと、形状変化が特定の温度で急に起こり変形量が非違に大きい点でバイメタルよりすぐれている。特に発生力の子供化は、温度検出部（センサー）と駆動部（アクチュエータ）を一つの素子で兼ねることができのに、この素子の最大の利点となっている。ただ、駆動源が熱であるため大きな出力を出すとして寸法の大
きな要素を使用すると動作速度がどうも遅くなるという点は注意すべきである。

Ni-Ti合金は耐食性が良いのでこれを用いた製品は温度以外の環境や雰囲気に対しても良い。さらに、モーターなどと違って可動制御部（シール）を必要としないので、環境条件の厳しい場所や外皮に装置されている場所での使用に適しており、実際に、高真空や原核内の応用が検討されている。

二方向性要素の応用例として、ベンレコーダーの駆動装置がある。これは図11に示す構造をもっており、ステンレス鋼で構成された直線状のNi-Ti合金ワイヤーに通電加熱して動作させる。ベンの位置はフィードバックされたヒステリシスや温度変化による誤差を生じないように設計されている。

図9はコネクターで、前述のパイプ構造を連続して二方向性動作をし、何故でも複数で動作できる。内部のベリリウム鋼製のスリープには向上が入っており、フリーナ状態では先端が開いている。スリープの外側に、室温から冷却してから挿入し、室温で閉じる

5. 超弾性Ni-Ti合金の応用

超弾性の実用化第1号は、眼鏡のフレームである。
超弾性 NITi 合金は図11に示すようにレンズを固定するワイヤとして使用されている。従来、このような金属や合成樹脂のワイヤでレンズを吊って固定する方式のフレームは、広くて視野が広いという利点の反面、レンズを抜いたとき、線でレンズが収縮したときに外れるなどの問題があり、充分に機能したフレームを作ることができなかった。開発されたフレームでは、レンズを強く抜いたり、温度変化しても超弾性ワイヤが浸透して保持することによりこれまでの欠点をすべて解決している。

超弾性 NITi 合金は形状記憶材と同じように医療関係に応用されている。その一つは咬合の改善で、いわゆる歯の酸化に関するものである。不正咬合をワイヤの弾性によって改善するフルダウンシステムはすぐれた方法であるが、通常の金属ワイヤ（ステンレス鋼、Co-Cr合金など）では弾性範囲が小さいため治療の進行に従って何度もワイヤを交換しなければならなかった。また、弾性範囲を拡げるためにループを作ったりすると装着中の不快感が増す欠点もあった。超弾性ワイヤを使用すればこれからの問題を解決でき、さらに応力・ひずみ線図から予想されるように、咬合が進行しても酸化力が低下しないという大きなメリットが生ずる。このため、ワイヤ特性の改善の他、ワイヤと骨の固定、美術アーチ形状など、それら特性を生かすための総合的な研究が進められている。

超弾性 NITi 合金ワイヤは溶接ではすでに半分近くの鈍化錳に使用されているが、これは NITi 合金のM相を加工硬化して弾性範囲を拡げたもので本来の超弾性とは若干その特性や使い方が異なる。

整形外科関係では、骨の結合後に応用例がある。一般に生体組織は外部からの荷重を自動的に緩和する作用があり、骨の場合はステンレス系などで強く結合すると骨組織が溶洗作業で溶け出し、結果状態を長期間保持することができない。これに超弾性ワイヤだと、骨が溶け出しても超弾性の範囲内でのみでであれば追従し、治療期間中の良好な結果が得られるのである。ところが、超弾性ワイヤにも問題がないわけではない。例えば通常のワイヤのようにベンチでよじって最小限に付けようとしても元に戻って固定することがない。この問題は細いパイプにワイヤを通し、カシミで固定することで解決した（写真2）。この結果法はすでに臨床で使われている。

超弾性合金は通常のパネ材より一桁も大きなくびり回復能力がある。したがって、溶洗のパネ材として期待されている。また、超弾性パネは本質的に非線形パネなので、非線形性をうまく利用すれば機能性パネとして活用できる。その反面、弾性ひずみは少ないため剛性率やパネ定数から荷重と変位の関係を求めることは簡単ではない。ひずみ量が大きく、ねじりモーメントでコイルパネのひずみ状態を近似することに無理がある。パネの設計上の難しさがある。このため、加工法、熱処理法などのハード技術と並行して、パネ設計法を中心としたソフト面の開発が進められている。

超弾性合金には、ひずみ回復能に加えて、応力・ひずみ曲線上のヒステリシス特性から入る大きな振動減衰性能があるため、その特性を積極的に利用すること、例えばチャングレイン防止機能を持つ接点パネに使用することが、精密機械関係の分野で検討されている。
6. おわりに

以上述べたように、Ni-Ti合金の形状記憶効果と超弾性は一部は実用化されているというもので、まだ開発段階にあり、ハードウェア面を含む応用的に完成されたものとは言い難い。しかし、数パーセントにおよぶ変形ひずみが回復するユニークな性質は、機能材料としてきわめて好ましいものであり、多くの分野で広範な応用が期待されている。

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Shape Memory and Super-elasticity Effects in NiTi Alloys

Yuichi Suzuki

Summary: The equiatomic or near equiatomic NiTi is a unique intermetallic compound. It has good ductility, a shape memory effect, and a super-elasticity. The alloy undergoes a martensitic transformation at near room temperature. The low temperature phase is characterized by high damping capacity, and the high temperature phase by excellent abrasion and corrosion resistance. By a shape memory effect we mean that the alloy plastically deforms in the low temperature phase and recovers its original shape in subsequent heating. Super-elasticity is a rubber-like behavior of the alloy in which a strain loading beyond the elastic limit recovers upon unloading. The following is a presentation of the general properties and transformation mechanisms of the shape memory effect and the super-elasticity of the NiTi alloys including its application such as in jointing devices, thermal actuators, and medical devices.

1. Ni-Ti alloys have various characteristics

A Ni-Ti alloy containing nickel and titanium in the atomic ratio of 1:1 shows unique characteristics. Although it is an intermetallic compound, it can be worked plastically. Furthermore, the alloy undergoes a martensitic transformation at a certain temperature near room temperature. The alloy shows various unique forms of behavior in accordance with the martensitic transformation.

It has been known that this alloy has a great damping capacity at temperatures below martensitic transformation temperature (abbreviated to M-transformation temperature hereinafter; this M-transformation will be described in the section on mechanisms below, but it is to be understood here to be a certain temperature or the like.1) The alloy was developed by the Naval Ordnance Laboratory (NOL) as a soundproofing material for submarines as a countermeasure against SONAR. The damping capacity can be called the first feature. The damping characteristic could therefore conceivably be used as a damping material or a soundproofing material.2)
The second feature of the alloy is characterized by a shape memory effect which appears when the M-transformation and a reverse M-transformation are cycled in a temperature domain near the M-transformation temperature, precisely speaking, one that straddles the M-transformation temperature. This phenomenon is characterized in that when the alloy is heated to a temperature higher than the M-transformation temperature after it has been deformed at a temperature lower than the M-transformation temperature, its shape recovers to its original form.

The third feature of the alloy, super-elasticity appears in a temperature domain slightly higher than the M-transformation temperature. This is a rubber-like behavior in which a deformation strain of several percent which significantly exceeds the yield point is recovered only upon unloading, so this behavior is sometimes called false elasticity or rubber elasticity.

Although these unique phenomena do not appear in a temperature region much higher than the M-transformation temperature, these characteristics of the alloy become significantly advantageous in a structured material having both excellent corrosion and abrasion resistances. The fourth feature has been previously made use of in certain portions of chemical plants or the like where rubbing takes place and where corrosion resistance is required.
Since the fourth feature consisting of corrosion and abrasion resistances as described above has been previously disclosed in this magazine,\textsuperscript{7} the shape memory effect and super-elasticity which have recently become of major interest for functional materials will now be described with introducing practical examples.

2. Shape memory effect and super-elasticity

As described above, the shape memory effect and super-elasticity are phenomena in which a deformation strain exceeding the yield point can be reversed only by heating or unloading. These phenomena will now be more specifically described with reference to actual photographs and stress-strain diagrams (Fig. 1).

On the other hand, a super-elastic alloy does not require heating for recovering from strain. If the load is removed after the alloy has been deformed to the yield region, the strain, as shown in Fig. 1, returns to zero, exhibiting a behavior which is the opposite of the yield phenomenon.

It must be noted here that the amount of strain which can be reversed by the shape memory effect or super-elasticity has a certain limitation. Strain sometimes cannot be recovered from, depending on the manner of deformation. The point will now be described with reference to a stress-strain diagram covering a high strain domain (Fig. 2).\textsuperscript{8}

When a shape memory alloy is deformed at a temperature below the M-transformation temperature, yield occurs after elastic deformation \textsuperscript{1}, and the stress becomes approximately constant. If the load is removed at an intermediate portion of the flat portion \textsuperscript{2}, apparent plastic strain \textsuperscript{3} remains, but this strain is removed by heating, as mentioned above. However, if the deformation strain increases so as to exceed the flat portion, the stress again begins to increase, and work hardening begins. If the load is removed when the work hardening has progressed to a certain degree \textsuperscript{4}, the strain \textsuperscript{5} also remains, but this strain cannot be recovered from by heating to a temperature beyond the M-transformation temperature, resulting in a permanent deformation \textsuperscript{6}. If the deformation strain further increases, the increase in stress becomes moderate, and finally the material breaks. A material which has been extensively work-hardened \textsuperscript{7} will not recover its shape by heating.

Therefore, it is necessary to restrict the amount of strain to below a certain value (7.5% in Ni-Ti alloy) in order to obtain an excellent shape recovery characteristic. This is exactly the same as the condition for super-elasticity.

Both the shape memory effect and super-elasticity were accidently discovered in an alloy consisting of gold and cadmium in the early 1950s,\textsuperscript{9} but they did not attract much attention at the time because of the rarity of the alloy. The shape memory effect was not studied much until after significant shape memory effects were discovered in Ni-Ti alloys by the NOL (as described above).\textsuperscript{10} Since

![Fig. 1 Stress-strain diagrams of shape memory alloy, super-elastic alloy, and normal metallic material](image1)

![Fig. 2 Stress-strain diagram of shape memory Ni-Ti alloy](image2)
then, numerous research results have been disclosed, and more than a dozen alloys having the shape memory effect have been discovered.

However, when this effect was discovered in Ni-Ti alloys, the fact that these alloys have super-elasticity was not known. Therefore, super-elasticity has mainly been studied in Cu-Al-Ni alloys as a phenomenon which is independent from the shape memory effect. The super-elasticity of the Ni-Ti alloys was discovered at the beginning of the 1970s, immediately before it was clarified that the two phenomena are complicated, and not many details have been clarified scientifically. Therefore, only the mechanism which has been clarified will now be simply described (see Fig. 3).

When a shape memory alloy which is in an austenitic phase (abbreviated to A phase hereinafter) at a high temperature is cooled and the alloy passes a certain temperature (M-transformation start temperature, called the Ms point), the alloy M-transforms from the A phase to the M phase. The M phase is a well-known phenomenon which occurs when steels are rapidly cooled down. This phase also occurs in metals such as titanium or zirconium, or in alloys. This phenomenon is due to a phase transformation in which the crystal structure changes mainly by shear transformation, without any accompanying diffusion, with the solid phase thereof retained. When the M phase is heated to a temperature at which the M phase is returned back again to the A phase (This temperature is slightly higher than the Ms point reached during cooling, and is called the Af point), the A phase is again realized. If no external force is applied, the macrostructure of the alloys are not changed by this cycle consisting of transformation and inverse transformation. However, the case is different if an external force is applied to the M phase. In this case, if the stress exceeds the yield-stress, apparent plastic deformation occurs as mentioned above, but this deformation is a sort of hemitrope deformation in which the crystals change their direction (azimuth) to absorb the deformation. Therefore, in contrast to the deformation which is proceeded by displacement slip, in which the arrangement of the crystals is changed, the connections between the crystals are the same before and after the deformation. If the M phase which has been transformed as described above is heated, it transforms back to the A phase. However, since the connections between the crystals remain as the material returns to the A phase, the overall shape of the crystals recovers its original form.

Super-elasticity is also a phenomenon which depends upon M-transformation. However, the M-transformation which generates super-elasticity is caused by stress. The M-transformation which is independent from the shape memory effect is caused by heat, that is, a change in temperature, while the M-transformation which generates super-elasticity is caused by stress. The M-transformation which is described above is called stress transformation, in which stress, mainly shear stress, acts to transform the A phase to the M phase when a stress is applied to the A phase at a temperature slightly higher than the Af point. In this case, since the stress also causes transformation to the M phase, the A phase suddenly shifts to a transformed M phase, as shown by the dashed line in Fig. 3. The removal of the load, that is, the removal of the stress, causes a return to the A phase which is originally stable at this temperature (above the Af point). This return to the A phase maintains the connections of the crystals, and so releases the strain.

M-transformation is not a phenomenon displayed only by special alloys such as Ni-Ti alloys. It is a phenomenon displayed by many types of metal such as steels and alloys. Although steel is an alloy which typically exhibits M-transformation, it does not display any shape memory effect or super-elasticity. Some Ti alloys and Co alloys exhibit stress recovery to a certain extent, but this is not complete. The reason for this difference is considered to depend on the consistency of the phase boundaries between the A phase and the M phase. In M-transformation (called thermal elastic M-transformation) in an extremely consistent Ni-Ti alloy, when the M phase returns to the A phase the atoms return to their original arrangement, so that the shape can be recovered. However, in M-transformation in steel or the like, the atoms do not necessarily return to their original positions; they return to a suitable sort of A phase in which they are arranged advantageously from the energy point of view. Therefore, the shape can be recovered to some extent, but it cannot be completely recovered. The fact that the number of hemitrope phases of the M phase (in which the shape of the crystals is the same, but only their azimuths differ) is limited by the way in which the super lattice is formed is an important factor, in addition to the consistency of the phase boundaries. An excellent shape memory effect and super-elasticity can be obtained only when all of the conditions are satisfied.
realized by pipe joints. An alloy of a low working temperature (approximately -150°C) is used for such a joint, and its inner diameter is slightly smaller than the outer diameter of the pipe. When pipes are to be connected, the joint is first immersed in liquid air and a plug is forced into the inside of the joint to expand its inner diameter. Then, as shown in Fig. 4, the pipes are inserted from both sides, then the joined pipes are left at room temperature until the diameter of the joint recovers to its pre-expansion dimensions. As a result, the pipes are clamped. More than 100,000 joints of this type are used in the hydraulic systems of F-14 jet fighters, and they have caused no problems such as oil leaks. Similar methods have been applied to various seals and clamps (Fig. 5 and Fig. 6).

Since Ni-Ti alloys do not react with organic substances, it is expected that they will be used in implants in living tissues. One application which is being widely studied is a bone setting plate that is used to provide internal bone setting in which a broken bone is fixed not by plaster but by bolts or the like. Methods of fixing intramedullary nails and base portions of artificial arthroses can also employ similar means. A method of curing scoliosis, in which a Ni-Ti alloy which retains the memory of a straight line is fixed in such a manner that the alloy is placed along the spine is then heated in order to straighten the spine, is a method which fully utilizes the characteristics of a shape memory alloy.

All of the shape memory effects mentioned above exhibit a phenomenon which is called the one-way effect. That is, when the alloy is heated after being deformed at a low temperature, the alloy recovers its shape once. Even if it is again cooled to the low temperature, it will not recover the shape it previous had when deformed at that low temperature. However, in general, a two-way device which repeatedly recovers is more advantageous from the functional viewpoint, and its range of applications is wider than that of a one-way device. Therefore, various methods by which two-way characteristics can be provided for shape memory alloys have been studied. One such method involves the use of a bias force. This method utilizes the characteristic of a shape memory alloy that it is strong at high temperatures (where it is hard and has a high yield stress), but it is weak at low temperatures (where it is soft and has a low yield stress). For example, in a device in which a coil spring formed of a shape memory alloy and a normal coil spring are abutted against each other, as shown in Fig. 7, the shape memory alloy is pressed to the left at low temperature because the normal coil spring is stronger, while the shape memory alloy becomes stronger than the normal coil spring as temperature rises and forces it to the right.
A differential two-way device is well known as another type of the two-way device. This device utilizes the difference in force exerted by a shape memory alloy at high temperatures and low temperatures. For example, if shape memory alloys are used for both of the coils shown in Fig. 7, a differential two-way device is realized. When one of the coils is heated, the heated coil presses against the other coil to exert a force upon it. When the heating of the first coil is terminated and the other coil is heated, the coils move in the opposite directions.

A bimetal is well known as a two-way temperature detecting device. A shape memory device would be significantly superior to a bimetal because the shape memory device would be able to generate a large force, the shape change would occur rapidly at a specific temperature, and the magnitude of the change would be significantly large. In particular, the ability to generate a large force is the most important advantage for this type of device, because a single device has both a temperature detecting portion (sensor) and an actuating portion (actuator). It is important to consider that if a large device is used in order to obtain a large force, the actuation speed will inevitably become low because the actuating source is heat.

Since Ni-Ti alloys have excellent corrosion resistances, a device of this type would have a very good resistance to the environment and the atmosphere except the temperature condition. Since the movable shaft sealing portions (seals) which are necessary in motors are not needed if a Ni-Ti alloy is used, these alloys are suitable for use in extreme environmental conditions or in places which are isolated from the atmosphere, and, in practice, applications in hard vacuum and nuclear reactors have been investigated.\(^\text{15}\)

The driving device of a pen recorder is an application of a two-way device. As shown in Fig. 8, the structure of the driving device is such that a straight Ni-Ti alloy wire is tensioned by a bias spring coil and a current is passed through it to heat it for operation. The pen recorder is designed so that the pen position is fed back so that no errors are generated by hysteresis or temperature changes.

Fig. 9 shows a connector\(^\text{16}\) which can be repeatedly used because it has a two-way operation, while the pipe joint described above has a one-way action. A beryllium sleeve on the inside of the connector is provided with slits in such a way that the front end of the connector is opened in the free state. A ring of a Ni-Ti alloy, whose actuating temperature is lower than room temperature, is installed around the sleeve. The front end is opened at low temperatures by the spring force of the sleeve, but at room temperature the ring recovers its shape so that the ring clamps a mating conductor. Spraying of gas is usually employed for obtaining the low temperature. Other two-way devices which have been disclosed include various thermal switches, circuit breakers and fire safety devices.

The use of shape memory alloys in automobiles has been...
suggested, especially in radiator thermostats and fan clutches. A radiator thermostat is a device which cools engine cooling water by introducing the cooling water into the radiator only when the temperature of the cooling water rises. A fan clutch is a device which provides cooling by connecting a cooling fan to a rotary shaft when the engine reaches a predetermined temperature. Both devices were developed to reduce the warming-up time and save energy. Another proposed device is an injection nozzle of a carburetor which is designed to always provide the most suitable mixture ratio using a shape memory device which compensates for differences in the viscosity of gasoline at different temperatures.

Since differential shape memory devices can generate large forces and have high energy conversion ratios, they can not only be utilized in various actuators and manipulators for robots or the like, but they are also expected to be applied to heat engines in which mechanical energy is obtained from low grade energy sources such as exhaust heat (Fig. 10). Although such a heat engine has yet not been produced, it has been the subject of intense research, and a heat engine conference was held in the U.S. in 1978.\(^{17}\)

5. **Application of super-elastic Ni-Ti alloys**

The first practical usage of super-elasticity is in the frames of spectacles.\(^{18}\) A Ni-Ti alloy is, as shown in figure 11, used as wire for fixing lenses. A conventional frame in which the lenses are suspended by wire made of a metal or synthetic resin, has the advantage of enabling a lightweight and a wide field of view, but it has the disadvantage that the lenses can easily fall out when they are wiped or when they contact at a temperature. The newly developed frame completely overcomes this problem, even if the lenses are strongly wiped or the temperature changes, by the use of an super-elastic wire for supporting the lenses.

Super-elastic Ni-Ti alloys are used in medical fields, in the same way as shape memory alloys. One application is in the correction of abnormal occlusion, that is, in the straightening of teeth. Although a full-band system which corrects abnormal occlusion by utilizing the elasticity of a wire is an excellent method, normal metal wires (made of stainless steel, Co-Cr alloy, or the like) have a poor range of elasticity, so the wire must be changed many times as the treatment progresses. If loops are made to increase the elastic range of the wire, the disadvantage arises that the patient feels discomfort. The use of a super-elastic wire can overcome these problems, and provide a great advantage, as can be expected from its stress-strain diagram, in that correcting force of the wire does not drop as the correction progresses. In order to use such characteristics, comprehensive research into improving the wire characteristics, fixing the wire to bone, and the most suitable shapes of arches or the like have been progressing.\(^{19}\) In the U.S, Ni-Ti alloy wires are used by nearly half the dentists for correcting abnormal occlusion. This method uses super-elastic characteristics and usages which are slightly different from those of basic super-elasticity, because the method is characterized in that the M phase of each Ni-Ti alloy is work-hardened to increase the elastic range.

Ni-Ti alloys are applied to methods of clamping bones in plastic surgery.\(^{20}\) In general, since living tissues automatically adjust to externally-applied loads, if a bone is strongly bound by stainless steel wire or the like, the tissues of the bone creep as they adjust to the load. Therefore, it is impossible to keep the bone clamped for a long period of time. If a super-elastic wire is used it can follow the contraction of the bone within its super-elastic range as the bone creeps, so that firm clamping can be maintained during the treatment. However, super-elastic wires have a problem. For example, such a wire cannot be fixed because it recovers its original form when an attempt is made to twist it by pliers, as if it was normal wire. This problem has been solved by caulking the wire after it has been passed through a thin pipe (photograph 2). This method of clamping has already been utilized clinically.

Since a super-elastic alloy has an excellent strain recovery ability
which is an order of magnitude larger than those of normal materials for springs, it is of course expected to become a general-purpose material for springs. Furthermore, since a super-elastic spring is basically a non-linear spring, skillful use of this non-linearity will enable its use as a functional spring. However, such a spring does not exhibit any elastic strain, which will present some design problems. It will be difficult to obtain a relationship between load and displacement by using its rigidity and spring constant, and it will be difficult to simulate the strained state of the coil spring with the use of torsional moment because of the large magnitude of the strain. In order to overcome these problems, research is under way into software which provides methods to design springs together with hardware techniques such as working methods and heat treatments.

Since super-elastic alloys have a damping ability caused by the hysteresis characteristics seen in their stress-strain curves in addition to the stress recovery ability, positive utilization of this feature in, for example, a contact spring which is able to prevent chattering, has been examined in the precision instrument field.

6. Conclusion

As described above, although the shape memory effect and super-elasticity of Ni-Ti alloys have been partially utilized, these efforts are still in the development stage. The hardware and software techniques required for realizing the utilization of these alloys have not yet been developed. However, since the unique feature of these alloys of being able to recover from strains of several percent raises strong demand for their use as functional materials, it is expected that they will be used in many fields.

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