Study on shape memory effect of hot deep-drawn Ni-Ti shape memory alloy sheet part

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Abstract. This study investigates the properties of Ni-rich Ni-Ti shape memory alloy sheet parts during and after deep drawing process at an elevated temperature, which is under a plane tensile-compressive stress state. According to the results, the sheet metal shows superelasticity and ductility at 500°C, 550°C, and 600°C. In the hot deep drawing process, the working parameters affect the result. The higher the forming temperature and the longer the holding time at the bottom dead center of the punch or the longer the ageing shape memory treatment, the greater the height of the drawn part and the lesser the springback. The results of the subsequent free recovery experiment show that the deep drawn sheet part without ageing treatment still possesses the shape memory effect. It also shows in the further constraint recovery experiment that in a wide temperature span the deep drawn sheet part possesses a different recovery load when reacting to the phase transformation of the shape memory alloy. Furthermore, the higher the forming temperature and the shorter the ageing treatment, the greater the part recovery load.

1. Introduction
Recently, since the Ni-Ti based shape memory alloy has shown good compatibility and corrosion resistance in organisms as well as some particular characteristics in superelasticity and shape memory effect [1], it has been widely used as biomedical materials, such as stents [2], bone rivets [3], orthodontic wires [4], etc. At the same time, with the free recovery and constraint recovery functions of the shape memory effect, there are many industrial applications [1], such as fixed pins, pipe joints, and disc springs, etc.

The above-mentioned Ni-Ti shape memory alloys are mostly made using wire as blank materials. The main reason is that the material does not have good machining properties but could be formed from braided wires into shapes. However, because the Ni-Ti shape memory alloy is superelastic at room temperature, it can easily springback after forming. Therefore, the shaping is mostly done by hot forming [5]. However, the whole process must be done with a die, resulting in high tool costs. In contrast, sheet metals that can be used for mass production must be formed while cold because of their geometrical characteristics for heat transfer. However, Ni-Ti shape memory alloys are hard to form while cold because of their poor formability at room temperature [6]. These two factors hinder usage of Ni-Ti shape memory alloy sheets and thus cause the production of Ni-Ti shape memory alloys to be limited to wires as the blank materials. In view of potential applications for the future, this article attempts to apply the hot forming technology [5] along with the subsequent recovery [7, 8] on the deep drawing process, which is one of the basic methods of sheet metal forming, to explore the hot forming and the subsequent shape memory processing characteristics of Ni-Ti shape memory alloy sheet under a plane stress state in tension.
2. Experiment setup
Before the high temperature experiment with Ni-Ti shape memory alloy sheets, this study explored the mechanical characteristics of the alloy sheet in a hot state as well as to provide a reference for setting the blankholder force required for the subsequent deep drawing experiment. Figure 1 (a) shows the setup of tensile test in a high temperature uniaxial tensile testing machine (4505,Instron, Norwood, MA) along with its heating furnace and fixture, while Figure 1 (b) shows the dimensions of the specimen used in the tensile test, which was acquired as 50.67at% Ni having a thickness of 0.85±0.02 mm (Zhongrui, Tainan, Taiwan) and was cut by waterjet. The temperature for the uniaxial tensile test was set at 500°C, 550°C, and 600°C [5], and the strain rate was set to 0.001 s⁻¹ in accordance with ASTM E8 [9].

![Figure 1](image1.jpg)

**Figure 1.** Setup of the tensile test in a high temperature uniaxial tensile testing machine (a) with a specimen (b).

The deep drawing experiment for the Ni-rich Ni-Ti shape memory alloy sheet is then conducted with a die set, shown as in Figure 2 (b), which is enclosed in a temperature-controllable heating chamber (Risen, Taoyuan, Taiwan) with a jacket water circuit to arrest the heat out of the chamber, as shown in Figure 2 (a). The forming process with a stroke of at least 4 mm is done at a punch speed of 6 mm/min by a uniaxial tensile testing machine (2402, Hunta, Taichung, Taiwan) having a load capacity of 5 tons. The temperature in the heating chamber is set at 500°C, 550°C, and 600°C according to [5]. After the deep drawing process, the entire condition of the chamber, such as the temperature and the punch stroke, is held for 3,600 s to serve as the ageing heat treatment for shape memory. In the die set, the punch has a circular cylinder with a diameter of 20 mm and a fillet radius of 3.5 mm, and the die has a fillet radius of 2 mm. A blankholder is used to clamp the workpiece blank with a nickel-based superalloy Inconel 718 disc spring set (Bauer, Pittsburgh, PA) providing an appropriate and secured blankholder force at the high temperatures. The blankholder force is determined by the mechanical properties of the material obtained from the previously conducted uniaxial tensile test and the force conversion formula in the handbook [10]. The blank is cut into a circular sheet with a diameter of 36 mm by waterjet.

3. Results and discussion
Figure 3 shows the stress-strain curve of a Ni-Ti shape memory alloy sheet from its tensile test with a 3 mm wide and 20 mm gauge length at a strain rate of 0.001 s⁻¹ at different temperatures. Figure 4 is a diagram of the fracture specimen after the tensile test at various temperatures.

Since nickel-rich Ni-Ti shape memory alloys are usually in the austenitic phase at relatively high temperatures, if a considerable stress during the elastic deformation is imposed to the alloy at a high temperature, a stress induced martensitic phase might appear in the alloy, which would cause a large strain within a small amount of stress increment and be shown as a plateau on the stress-strain curve generated by the tensile test. The plateau is an elastic deformation because the strain is recovered if the load on shape memory alloy specimen is released. However, as the elastic strain found in shape memory alloy is much greater than 0.2%, the elastic limit for general metals, this material is called superelastic. Because the superelasticity is induced from the phase transformation rather than the distance increase
between atoms, it is also called pseu
deelasticity. Once the transformation of the whole austenitic phase into the martensitic phase is completed, the stress-strain curve would turn from the plateau into another elastic deformation from the martensitic phase and further act as a common metal, followed by plastic deformation with strain hardening or strain softening after the elastic limit of the martensitic phase is achieved.

![Figure 2](image1.png)

**Figure 2.** Setup of the hot forming experiment in a uniaxial tensile testing machine with a heating chamber (a) enclosing a die set (b).

![Figure 3](image2.png)

**Figure 3.** Stress-strain curves in the tensile test of Ni-Ti shape memory alloy sheet at 500°C, 550°C, and 600°C.

![Figure 4](image3.png)

**Figure 4.** Specimen after the tensile test of Ni-Ti shape memory alloy sheet at 500°C, 550°C, and 600°C.

At 500°C, the shape memory alloy specimen first undergoes an elastic deformation. Afterwards, the stress reaches the plateau at about 60 MPa, with a slight superelastic phenomenon having a strain of 0.5%, and then enters plastic deformation. The stress rises sharply. When the strain reaches 15%, the maximum stress or tensile strength is 229 MPa and necking begins to occur at the same time. The stress therefore drops until it breaks, and the maximum strain or ductility of 42% can be obtained. In an environment of 550°C, the material acts similar to when it is at 500°C for strain levels less than 6%. However, when the strain reaches 6%, the maximum stress of 178 MPa appears and the stress drops sharply until it breaks, so that a discontinuity of the slope of the stress-strain curve appears, which is different to that at 500°C having a continuous change of its slope. Such an appearance is a typical strain softening phenomenon and might be caused by recrystallization at such high temperatures. It might lessen the ductility, which is 33% in this case. As for at 600°C, the sheet has an obvious plateau at the stress of about 32 MPa. Again, as it deforms plastically, a strain softening takes place at the strain of 7%, where the maximum stress of 129 MPa shows. Even when the maximum strain of 35% is obtained, the ductility seems to not better than that at 550°C, because the pseudo-elastic strain is already 3%.

It can be summarized from the tensile tests at 500°C, 550°C, and 600°C that as the temperature increases, the strength of the Ni-rich Ni-Ti shape memory alloy decreases, the superelastic plateau stress decreases,
its superelastic strain span increases, and its plastic strain before failure decreases. Special attention must be paid, if the material is used at 550°C or 600°C, to avoid making the sheet unstable due to strain softening characteristics. By contrast, the sheet at 500°C still exhibits strain hardening characteristics. Whether strain hardening or softening occurs, the shape memory alloy at the three temperatures has a considerable plastic strain after necking. It is hard to distinguish from the appearance of the specimen after fracture in Figure 4 in which local necking is caused by strain hardening or softening.

After the Ni-Ti shape memory alloy sheet blank is clamped between the blankholder and the die with a blankholder force of 210 N, 136 N, and 101 N respectively, determined according to the handbook [10], and the heating chamber is carried out at 500°C, 550°C, and 600°C for at least 15 minutes to reach the desired soaking temperature, the blank sheet is then pressed by the punch with a stroke of 6 mm at a speed of 6 mm/min, and then the punch is returned to its starting point to take the sheet part off the die set in the heating chamber. Figure 5 shows the load stroke diagram of the hot forming process. There is not a significant difference among them, such that it is not hard to describe the effect of the forming temperature on the load. According to the results from the tensile test, only at 500°C does the Ni-Ti shape memory alloy sheet have different mechanical properties than at other temperatures, which may make the formability worse. It can be seen in Figure 5 that the blank broke at 500°C (red line) when the drawing stroke was just 5.82 mm.

![Figure 5. Load stroke diagram in the hot forming process of Ni-Ti shape memory alloy sheet at 500°C, 550°C, and 600°C.](image)

It can be seen as well from the unloading stroke after the unbroken stroke of 6 mm at 550°C (blue dash line) and 600°C (yellow line) in Figure 5 that the punch strokes are 3.11 mm and 3.59 mm, which means that the springback amounts are 2.89 mm and 2.41 mm, respectively. The springback rate $p$ is then defined as the ratio of the springback amount $\Delta h$ to the forming stroke $s$, that is $p = \Delta h / s \times 100\%$. Thus the springback rates are 44.8% and 40.1%, respectively.

To serve as the shape memory process, this research also tried to hold the punch when it reaches the bottom dead center in accordance with [5], in order to keep the shape memory alloy part in the formed shape with the die set at the same forming temperature environment during the ageing heat treatment. The hold time of the punch at its bottom dead center as the shape memory process time is 900 s and 3,600 s. Figure 6 shows the load evolution during the forming process and the following shape memory process for 3,600 s at the above-mentioned processing temperatures. Except for the abrupt drop in load at 500°C, when the drawing depth is less than 6 mm and the part is broken, at the temperatures 550°C and 600°C the punch load drops sharply by about 2 kN in a very short time (at about 10 s) and then at about 400 s drops further slightly to the minimum punch load, with a total drop of about 3.5 kN to 4.9 kN. At about 2,400 s, it increased slightly again, with an increase of about 1.3 kN to 1.9 kN, and finally decreased again until the end of the experiment, with an insignificant decrease of only about 0.01 kN to 0.30 kN. From Figure 6 it can be clearly seen that the load decreases more at 600°C compared to the memory heat treatment at 550°C. It is obvious that the temperature and time of the shape memory process have a certain effect on the change of material structure, which is further exposed in the mechanical properties.
Figure 6. Load evolution by holding the punch after the hot forming process of Ni-Ti shape memory alloy sheet at 500°C, 550°C, and 600°C.

Figure 7 shows the appearance of the drawn parts under different hold time and process temperature. Except for the three formed parts that broke at the drawing depth of less than 6 mm at 500°C shown in the upper row of Figure 7, the rest parts shown in Figure 7 are arranged in order of the hold time and process temperature, where the hold time of 0 s corresponds to the case shown in Figure 5 as a pure forming process without holding the punch at its bottom dead center.

Since the drawn parts shown in Figure 7 are not easy to distinguish in appearance, the springback rate \( p \) is then shown in Figure 8, which is calculated as the ratio of the height reduction of each part to the punch stroke after measuring their height. It can be seen from Figure 8 that the springback rate for the hold time of 0 s is different than that obtained from Figure 5, 42.5% instead of 44.8% for 550°C and 39.7% instead of 40.1% for 600°C, respectively. That means that a further springback or deformation is brought into the part when the blankholder force is released by detaching the part from the die set. It can be further observed from Figure 8 that the longer the hold time, the lower the springback rate and the higher the height. That means that the hold time can reduce the springback, which might be caused by creep characteristics of the part material to produce further plastic deformation under internal stress during the hold time at that temperature. There is no linear relationship of the springback rate to the hold time. That is, there should be a saturated springback rate, so that no significant springback occurs even with a significant increase of hold time. In addition, Figure 8 also shows that the temperature has an effect on the reduction of the springback as well. The higher the temperature, the smaller the springback. This result shows that increasing the process temperature and hold at the bottom dead center of the punch for a period of time can improve the shape accuracy of the drawn part.
One characteristic of the shape memory alloy is the shape memory effect, which is that the alloy can recover its shape once it is heated to a higher temperature in the austenitic phase, after the alloy is deformed at a lower temperature in the martensitic phase. The principle of such effect is that the alloy is subject to a shape memory treatment at high temperature in the austenitic phase first. When the temperature of the shape memory treated alloy drops to a low temperature, the alloy is transformed to the martensitic phase, but its shape remains the same as that at the high temperature, in that the martensitic phase is in the state of twin crystals. Applying a load to the alloy to deform it, the alloy will change the shape of its lattice in a way of de-twinning to thereby easily achieve the deformation. When the load is removed, the de-twinned martensitic crystals do not return to the twin crystal form and the deformation is kept. Once the temperature rises to the high temperature, the internal stress of de-twinning deformation in the lattice is released and the martensitic phase in the twin crystal is retrieved, and at the same time it is transformed to the high-temperature austenitic phase, so that the shape before the deformation under the load at the low temperature is restored. Thus, the recovery process by heating the alloy part, which has been formed at high temperature and flattened at low temperature, is usually used to evaluate how well the shape memory treatment of the alloy part performs. To do this, this study first immerses the formed alloy part into a liquid, in which 95% ethanol is impregnated with dry ice to have a constant temperature of -50±2°C for a while, so that the Ni-Ti shape memory alloy is ensured to have completely transformed into a martensitic phase. Subsequently, the alloy part is pressed by the two flat plates of the testing machine to totally flatten in that environment, and finally the flattened part is taken out from the plates into a room temperature environment to have the part recover via phase transformation to the austenitic phase as well as to the previously formed shape while the temperature rises. This recovery process is called the free shape recovery process, as there is no any external force on the part during the recovery. If the height $h_0$ of the top on the symmetry axis of the deformed alloy part before the free recovery process is compared with the height $h_1$ of the top on the symmetry axis of the retrieved alloy part after the free recovery process, the free shape recovery rate $r$ can be defined as $r = h_1/h_0 \times 100\%$. For different hot forming temperatures and the hold time of the punch at its bottom dead center, the free shape recovery rate for each case can be calculated by the above formula from the experimental results, as shown in Figure 9.

![Figure 8. Springback rate of the part drawn at different temperature and held for different time interval at the bottom dead center of the punch](attachment:image.png)
Figure 9. Shape recovery rate of the part drawn at different temperature and held for different time interval at the bottom dead center of the punch.

The free shape recovery rate shown in the red bar in Figure 9 is directly taken from the formed alloy part after the drawing depth of 6 mm without holding the punch at its bottom dead center for shape memory heat treating. The green and purple bars are the free recovery rates obtained from the alloy part by drawing it with a depth of 6 mm and holding the punch at its bottom dead center for a period of time, 900 s and 3,600 s respectively. Obviously, the free shape recovery rate of the formed alloy part that has not been held at the bottom dead center of the punch for shape memory heat treatment is not as good as those of the formed parts with a shape memory heat treatment by holding the punch at its bottom dead center for a certain period. However, it seems that there is no significant effect of the shape memory heat treatment on the free shape recovery rate, if the processing temperature is at 550°C. That means that there still exists a considerable shape recovery effect of the forming process at the high temperature, regardless of whether it is held at the bottom dead center of the punch for shape memory heat treatment. From the results shown in Figure 9, it can be observed that the higher the processing temperature, the higher the shape recovery rate.

When the aforementioned shape recovery on the testing machine is performed by soaking the formed alloy part in a basin filled with ethanol and dry ice and by pressing it back into a flat state, the flattened state is maintained and at the same time hot water is poured into the basin to gradually bring the temperature back to the room temperature. The above procedure is called constraint recovery of a shape memory alloy part. During the temperature rise, the temperature of the flattened alloy and the force exerting to the two pressing plates are recorded. The curves of recovery force versus temperature in the constraint recovery test of the formed alloy parts in different temperature and shape memory heat treatment is shown in Figure 10.

Figure 10. Force-temperature diagram during the constraint recovery test of the part drawn at different temperature and held for different time interval at the bottom dead center of the punch.
The recovery force shown in Figure 10 at low temperature is the load required by the two flat plates to press the shape memory alloy sheet into a flat state at low temperature. When the flattened state is maintained and the ambient temperature rises, the plate load is increasing. The higher the forming temperature, the higher the recovery load on the plates, and additionally the shorter the hold time at the bottom dead center of the punch, the higher the recovery load. Furthermore, it can be seen that the recovery load of the alloy part made without hold time and with a hold time of 3,600 s at the bottom dead center of the punch is almost constant for the low temperature span below 0°C, while all the temperature span has a significant effect on the recovery load of the alloy part made with a hold time of 900 s. A larger temperature span on the significant change of the recovery load can help to extend the applications of the Ni-Ti shape memory alloy.

4. Conclusion
In this study, a Ni-rich Ni-Ti shape memory alloy sheet with a thickness of 0.85 mm was subjected to tensile tests at 500°C, 550°C, and 600°C, respectively. The results show that the sheet is still superelastic in the hot environment and has a sufficient ductility. The sheet has significant strain hardening characteristics at 500°C, but has a strain softening behavior at 550°C and 600°C.

The alloy sheet blank with a diameter of 36 mm was drawn to a depth of 6 mm by a cylindrical punch with a diameter of 20 mm and held at the bottom dead center of the punch for 0 s, 900 s and 3,600 s as a shape memory heat treatment in an environment of 500°C, 550°C, and 600°C respectively. The results show that, although the punch load required for drawing at different temperature is similar, the alloy sheet is broken before reaching a depth of 6 mm at 500°C. The higher the forming temperature, the smaller the springback of the formed alloy part, and the longer the hold time at the bottom dead center of the punch, the smaller the springback.

The material has an austenitic phase at room temperature and a martensitic phase in an environment of being soaked in ethanol with dry ice. The free recovery results show that the shape memory effect exists even if no hold time at the bottom dead center of the punch is conducted as a shape memory heat treatment. At 550°C there is no significant influence of the shape memory heat treatment on the shape recovery rate, while at 600°C the heat treatment has a significant influence, in that the longer the shape memory heat treatment, the higher the shape recovery rate.

The results of the shape memory constraint recovery show that the formed alloy part with a hold time of 900 s at the bottom dead center of the punch has a wider temperature range for operating the recovery load than those without hold and with a hold time of 3,600 s. In addition, the higher the forming temperature, the higher the recovery load, and the shorter the hold time at the bottom dead center of the punch as shape memory heat treatment, the higher the recovery load.

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