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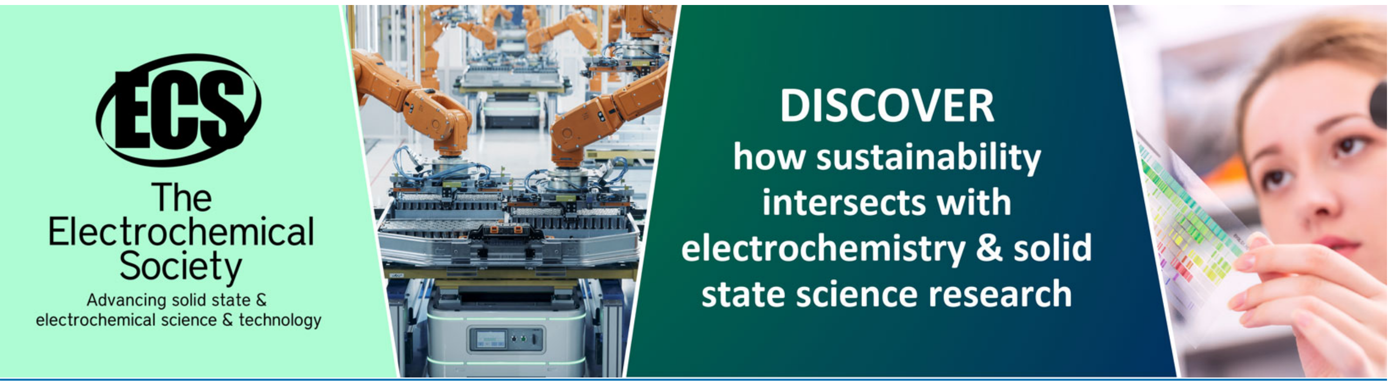

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Cold Forming of Ni-Ti Shape Memory Alloy Sheet

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Abstract. Ni-Ti shape memory alloy has two specific properties, superelasiticity and shape memory effect, and thus is widely applied in diverse industries. To extend its further application, this study attempts to investigate the feasibility of cold forming its sheet blank especially under a bi-axial tensile stress state. Not only experiments but also a Finite Element Analysis (FEA) with DEFORM 2D was conducted in this study. The material data for FEA was accomplished by the tensile test. An Erichsen-like cupping test was performed as well to determine the process parameter for experiment setup. As a result of the study, the Ni-Ti shape memory alloy sheet has a low formability for cold forming and shows a relative large springback after releasing the forming load.

1. Introduction

Shape memory effect was found in Au-Cd alloy by Ölander [1]. The shape memory effect is actually generated by phase transformation between austenite at high temperature and martensite at low temperature [2]. The shape formed in austenite at high temperature will be recovered, if the part is deformed in martensite at low temperature and the deformation load is released, by raising the temperature, at which the austenite is stable. Shape memory alloys, which have the shape memory effect, possess a rubber-like behavior as superelasticity as well by phase transformation between austenite and martensite at high temperature where the austenite is table [3]. With these two distinguished properties, shape memory alloys can be implemented as dampers, devices, sensors, actuators, and so on [4]. However, not until Buelher and his colleague found the same effect in Ni-Ti alloy [5] would the application of this effect be expanded in the other industries [6], especially in medical devices [7].

Traditionally to secure or to memorize the shape of Ni-Ti shape memory alloy parts, they need further precipitation treatment at a relative high temperature. It cannot be avoided that tool sets are needed to clamp the parts to keep their shapes during the treatment at high temperature. Thus the thermomechanical process is commonly used to make Ni-Ti shape memory alloy parts by forming the alloys in hot state with a subsequent precipitation treatment, which is a cost intensive process and needs lots of investment for the tool sets [8]. Fann and Huang [9] therefore proposed a cold forming process, in that the shape memory alloys are first solid solutionized, then formed at room temperature, and thereafter aged for shape memory again at high temperature. Even this process would lose part of the shape formed at room temperature during the precipitation treatment, it is still worth to use it to form the shape memory alloy parts for saving the cost of the tool sets. This proposed process encourages researchers to explore the feasibility of forming Ni-Ti shape memory alloy sheets, which are usually formed at room temperature because of their geometrical characteristics to easily dissipate the heat. This article is therefore aimed to investigate the behavior of Ni-Ti shape memory alloy sheets during cold forming at room temperature, especially under a bi-axial tensile stress state.

2. Methods and setup

2.1. Material
The material acquired for this study was a Ni-rich (50.0-50.8at% Ni) Ni-Ti shape memory alloy sheet having a thickness of 0.9 mm. The chemical compositions of the alloy sheet used in this study was determined by a glow discharge spectrometer and had 50.67at% Ni and 49.24at% Ti after converting weight percent (wt%) to atomic percent (at%). The content of Fe is as little as 0.10at% and can be regarded as a minimal contaminant during casting, so that the material can be considered as a pure binary Ni-Ti system.

2.1.1. Tensile Test. The Ni-Ti shape memory alloy sheet was placed in a heated furnace at 800°C for one hour and subsequently quenched in water, which served as a solid solution process affiliated to an annealing process [9]. Specimens are prepared according to the subsize defined by ASTM E8 [10] with a gauge length of 25 mm and width of 6 mm. Figure 1 shows the engineering stress strain curve obtained by tensile test after the unloading of an initial 12% tensile strain. This at 800°C solid solutionized Ni-Ti shape memory alloy sheet showed a low Young’s modulus around 41 GPa at room temperature in austenite, started the martensitic transformation under the strain about 1.3% and a plateaus strength about 530 MPa. Once the strain reached about 11% the sheet metal started yielding and deformed plastically. After unloading at the stain of 12%, the sheet shows a further low Young’s modulus about 21 GPa. This alloy could have a maximum elongation of 21% without necking, if its specimen was tested until failure. It means that this alloy has ductility to deform.

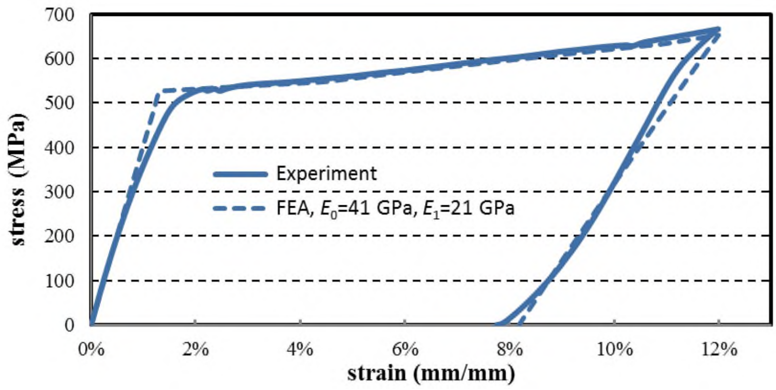


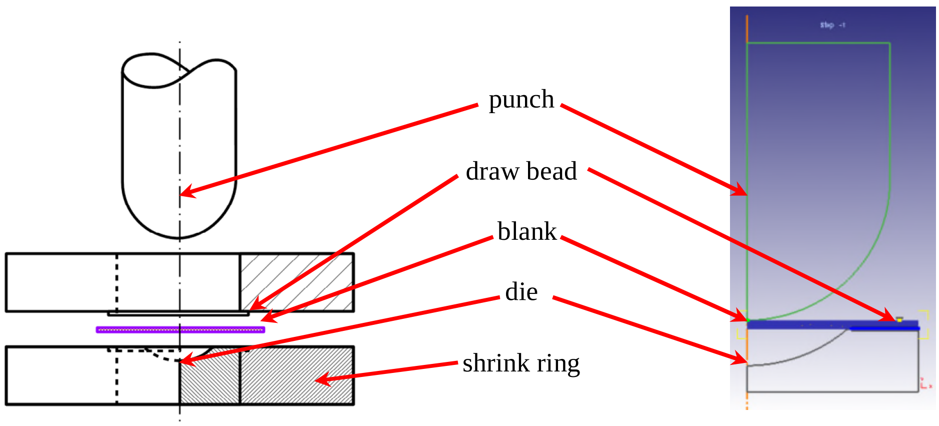
Figure 1. Stress strain curve of Ni-Ti shape memory alloy obtained by a tensile test and FEA.

2.1.2. FEA of Tensile Test. To prepare the material module for the Finite Element models later to analyze the deformation of the Ni-Ti shape memory alloy sheet during cold forming, an elastic-plastic Finite Element model was created to simulate the above mentioned tensile test of a 12% strain by DEFORM 3D. The commercial software DEFORM 3D can formulate the stress strain relation during the martensitic transformation because of its similarity to classic plasticity [11, 12]. The stress strain curve obtained from the FEA is shown as the dash line in figure 1. It matches very well the stress strain curve obtained by the experiment. Thus the idealized stress strain curve with the Young’s modulus of 41 GPa for loading (E_0) and 21 GPa for unloading (E_1) as well as the software should be suitable for analyis of cold forming Ni-Ti shape memory alloy sheet.

2.1.3. Experiment Setup of Cold Forming. The cold forming of Ni-Ti shape memory alloy sheets in this study was a kind of stretch forming, in which the sheet was clamped around and its deformation came from the reduction of its thickness under a bi-axial tensile stress state. Figure 2 (a) shows the schematic experiment arrangement used in the study. A bottom die with a specified cavity depth was inserted into a shrink ring under an interference fit, so that the compression load of the punch could be borne by the bottom die with the support of the ring. The sheet blank was then clamped by a V shaped draw bead of the blankholder around the ring circumference at the diameter of 32 mm. Subsequently a hemispherical punch with a diameter of 30 mm descended with a traveling speed of 10 mm/min through the hole of the blankholder on the blank as well as into the cavity of the bottom die. Once the punch reached its bottom dead center, it returned upwards to its original top dead center and the blankholder as well as the formed sheet metal was then removed.

2.1.4. Erichsen-Like Cupping Test. The Erichsen-like cupping test was actually served as a pre-test for preparing the tools of experiments by seeing how deep the Ni-Ti shape memory alloy sheet could be formed under the experiment setup as above mentioned. Because the dimension for the cupping test deviated a little bit from the standard Erichsen cupping test [13], it was called in this study as Erichsen-like cupping test. Besides the punch diameter and the clamping method, the hole diameter in 28 mm of the shrink ring without the bottom die was different to the standard as well.

The Erichsen-like index from the five Erichsen-like cupping test results was located between 4.1 mm and 4.2 mm. The location of the fracture appeared always around the corner radius of the bottom die. It seems that the maximum strain occurred there.



(a) (b)

Figure 2. Cold forming Ni-Ti shape memory alloy sheet:
(a) schematic setup of experiment (b) rotation symmetrical model for FEA.

2.1.5. Process Parameter of Cold Forming. Based on the above obtained Erichsen-like index, the process parameter or the cavity depth of the bottom die for the cold stretch forming in this study was therefore set as 1 mm, 2 mm, 3 mm, and 4 mm, respectively. Assuming that the sheet was well clamped and the deformation of its portion contacting to the punch was homogenous and barely raised from the reduction of its thickness, the apparent strain e of the cold forming process is then defined as

$$e = \frac{a_1 - a_0}{a_0} \times 100\% \qquad (1)$$

where a_0 and a_1 are the area of the thickness middle layer associated with deformation before and after cold forming. For the hemi-sperical punch used in this study, the apparent strain could be theoretically determined for the die cavity depth 1 mm, 2 mm, 3 mm, and 4 mm as 4.9%, 8.6%, 13%, and 17%, respectively. According to the stress strain curve in figure 1, the above listed apparent strains show that the deformations were at the stage of just matensitic transformation, midway of martensitic transformation, just plastic deformation, and midway of plastic deformation, respectively.

2.1.6. Modeling for FEA of Cold Forming. To detail the deformation of the Ni-Ti shape memory alloy sheet during cold forming, elastic-plastic rotation symmetrical Finite Element models were established by DEFORM 2D, in which the tress strain relation beyond the martensitic transformation was regarded as a plastic deformation based on [11]. Figure 2 (b) shows one of the models, which has the depth of the die cavity in 4 mm. The material for the FEA was set as that for figure 1. There were 4,559 elements and 4,965 nodes generated for the anlaysis model. The friction coefficient for the contact between the sheet and the punch as well as the die was set as 0.07, which is normally used in cold stamping process. The draw bead is fixed on the top of the blank.

3. Results and Discussion

3.1. Formed Profile

The solid line shown in figure 3 is the profile of the cold formed sheet measured from a symmetry plane through the top of the dome with a coordinate measurement machine, while the dashdotted line is the die geometry having the forming depth of 4 mm regarded as target geometry to compare. It can be observed that the dome of the formed sheet is relative flat and low by springback, because the material has the superelastic property. Further compared with the dashed line obtained by FEA, in which the dome height is much higher than that from experiment. It can be attributed to that the boundary condition in Finite Element modeling might be deviated from the reality, especially the draw bead around the bottom die and the shrink ring.

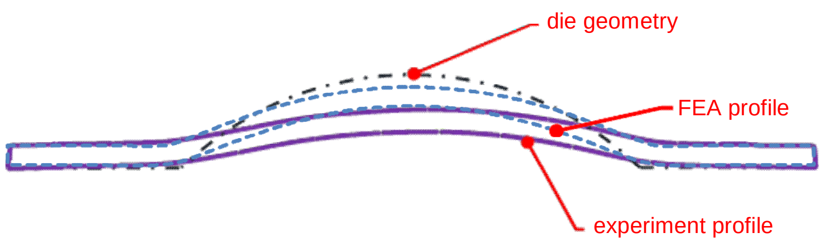


Figure 3. Profile of Ni-Ti shape memory alloy obtained by experiment and FEA in comparison to the die geometry.

3.1.1. Forming Loads. The solid lines in Figure 3 show the punch load over the stroke during cold forming the Ni-Ti shape memory alloy sheet to the bottom die with different depths. After reaching their maximum, the load drops quickly and then slows down as the punch returns upwards. At the depth of 0.16 mm, the punch load vanishes for cold forming with the bottom die having cavity depth of 1mm. That means that the deformation of the cold forming almost totally springs back. Forming with dies with deeper cavity had smaller springback. For the sheet formed with die cavity depth of 4 mm, the load vanished at 2.23 mm. Similar results could be found in the FEA results. The maximum load computed by FEA is about one and a half times that from experiment, because the modeling of the boundary conditions was moderately idealized in FEA as mentioned above.

3.1.2. Springback Rate. The springback rate *r* after cold forming can be defined as

$$r = \frac{h_0 - h_1}{h_0} \times 100\% \tag{2}$$

where h_0 and h_1 are the die cavity depth and the dome height of the cold formed sheet after removing the forming load. According the data accessed from figure 4, it can be worked out from equation 2 that the springback rate for the depth of 1 mm, 2 mm, 3 mm, and 4 mm is 84%, 66%, 50%, and 44% from the experiments as well as 81%, 54%, 44%, and 34% from the FEA, respectively. It seems that the springback is still large for the maximum achievable dome height. Thus, cold forming might not be applicable for Ni-Ti shape memory alloy sheet, which has superelasticity and low formability.

4. Conclusions

This study has accomplished the tensile test of an at 800°C solid solutionized Ni-rich Ni-Ti shape memory alloy sheet at room temperature and formulated a material model for the FEA. Both of its

Young's moduli before and after martensitic transformation must be separately considered in the FEA of elastic-plastic forming process, because the modulus for loading is twice as high as that for unloading. This shape memory alloy sheet shows a relative low Erichsen-like index as 4.1 mm for the cupping test conducted in this study. Experiments for cold forming such alloy sheet were performed with the dies having depths of 1 mm, 2 mm, 3 mm, and 4 mm, respectively, which have low average strains of 4.9%, 8.6%, 12.6%, and 16.8%, respectively. As a result, both experiment and analysis show that cold forming might not be practical for Ni-Ti shape memory alloy sheet, because the springback is still too high for a maximum achievable deformation under bi-axial tensile stress state.

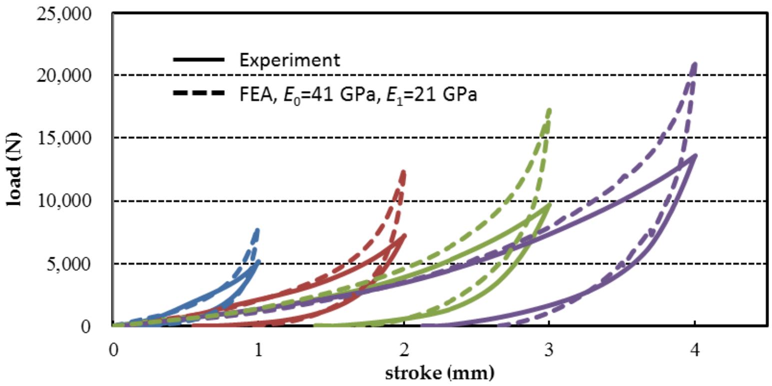


Figure 4. Punch load over stroke of Ni-Ti shape memory alloy obtained by experiment and FEA.

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