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EFFECT OF Cu CONTENT ON THERMO-MECHANICAL FATIGUE PROPERTIES AND TOTAL AVAILABLE STRAIN ENERGY OF Ti-Ni-Cu SHAPE MEMORY ALLOY

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ABSTRACT

Shape memory alloys exhibit the excellent shape memory effect and superelasticity. Ti-Ni shape memory alloy has been used for many applications. Authors have proposed a reciprocating heat engine incorporating, as an energy conversion element, shape memory alloy wires. Then, the fatigue properties is an important subject for their applications involving cyclic loading. Because the shape memory and superelastic functions are often used under cyclic conditions, the degradation of these functions and fatigue life have been important concerns. In order to improve functions and to increase fatigue life, the addition of Cu as a third element to replace Ni is an attractive option, because temperature / stress hystereses decrease, and recovery stress and strain energy increase with increasing the Cu content. In this paper, the effect of Cu content on the thermo-mechanical cyclic behaviors is investigated. Furthermore, the fatigue life is evaluated by the dissipated recovery strain energy, and the effect of Cu content on the total available strain energy to failure is also investigated.

INTRODUCTION

Shape memory alloys have been used in the field of medicine, electronic industry and mechanical engineering as sensor, actuator, spring, connector, etc. Authors have proposed a reciprocating heat engine incorporating, as an energy conversion element, shape memory alloy wires which work at low temperature and small temperature difference [1,2]. The proposed engine utilizes the balance between the recovery strain energy at heating and the deformation strain energy at cooling.

For the shape memory alloy, the recovery stress decreases and the irrecoverable strain increases with the increase in the number of thermo-mechanical cycles [3-5]. Thus, the available strain energy of the alloy varies with the number of cycles. Therefore, it is important to grasp the variations of these characteristics for determining the basic specifications of the heat engine such as the external load and the deformation strain. Furthermore, from the viewpoints of maintenance of the engine, it is important to estimate the fatigue life of alloy against the engine operation conditions. The fatigue life of Ti-Ni alloy [6-8] or of Cu group alloy **[9]** are investigated in relation to the strain amplitude, the plastic strain and the stress. The fatigue life becomes shorter as the strain and the stress become larger. Therefore, in order to design the heat engine, it is necessary to make studies taking into considerations the cyclic behaviors and the fatigue life of shape memory alloy.

It is drawn attention to be effective for the improvement of cyclic behavior and fatigue life that copper is added to the Ti-Ni binary alloy. Because the recovery stress increases with increasing Cu content, and stress hysteresis and transformation strain decrease with increasing Cu content.

In this paper, the effect of Cu content on the thermo-mechanical cyclic behaviors is investigated. Furthermore, the fatigue life is estimated by the dissipated recovery strain energy, and the effect of Cu content on the total strain energy to failure is also investigated.

EXPERIMENTAL PROCEDURES

Specimen

Ti-Ni-Cu alloy ingots are made using a high frequency induction vacuum furnace. The ingots are hot forged and hot extruded followed by cold drawing and intermediate annealing to make wires with a diameter of 1.0 mm. The alloys are composed of Ti-50Ni, Ti-45Ni-5Cu, Ti-40Ni-10Cu and Ti-37Ni-13Cu (at%). The wires are finished by cold drawing with 30% reduction and are cut to 120 mm in length. The specimens are annealed at 673 **K** for 3.6 ks as a straight wire for shape memory effect. The oxidized surface layer of specimens is removed by pickling and electropolishing except for clamping sections.

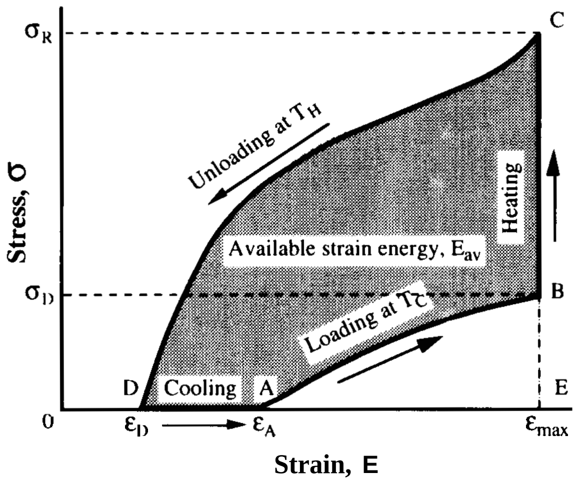


Figure 1: Schematic diagram showing stress-strain curve for a thermo-mechanical cycle

Cyclic Tests

The thermo-mechanical cycle for testing is shown in Figure 1. The specimen is first cooled from a given temperature (T,) to 293 **K** (T_C). Then, the specimen is elongated to a given strain (E,) at T, from A to point B with a stress (σ_D). Holding the strain *(E,,,),* the specimen is heated up to a given temperature (T,) by filling hot water. Due to the shape memory effect, the tensile stress in specimen increases from B to point C. After the maximum recovery stress **(a,)** is reached, the specimen is unloaded from C to D with an irrecoverable strain (ε_D). Cooling the specimen to T„ the specimen extends from D to A due to a two way strain generated by repeating the thermo-mechanical cycle. Such a thermo-mechanical cycle is repeated until the specimen fails.

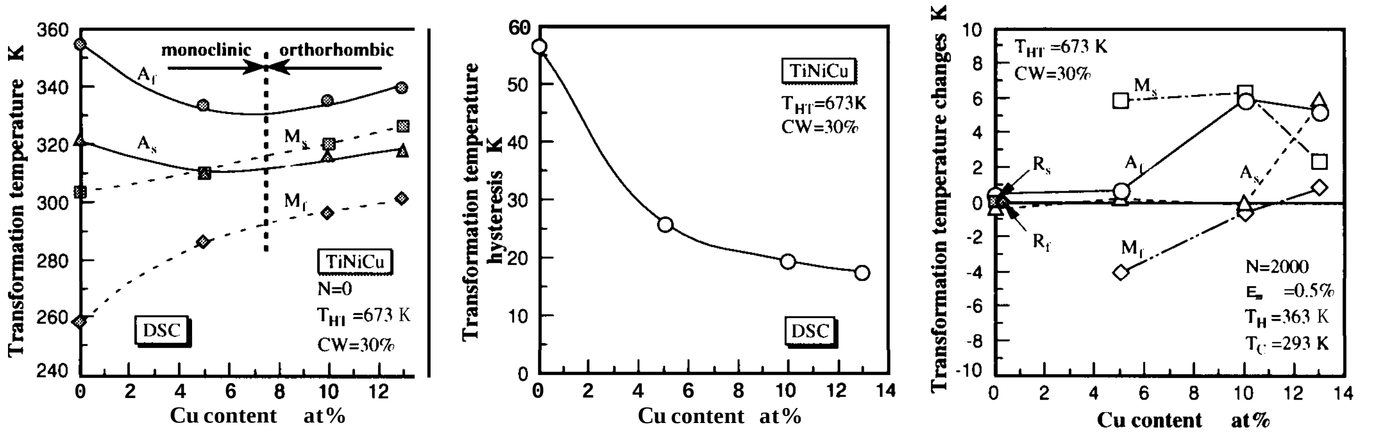
The area A-E-B-A represents the deformation strain energy (E,) per volume by loading from A to B. The area D-E-C-D exhibits the recovery strain energy (E,) per volume from C to D. The area A-B-C-D-A is defined as an available strain energy (E_{av}=E_R-E_D) per volume for a thermo-mechanical cycle. In fact, this available strain energy (E_{av}) is the work in heat engines for a thermo-mechanical cycle.

The flow rate of hot and cold water is 80 x 10^{-6} m^3/s. The heating temperature (T,) is 363 **K** and the cooling temperature (T,) is 293 **K.** The strain rate at loading and unloading is 0.002/s. The deformation strain (E,) is from 0.7 to 6%.

CYCLIC BEHAVIOR

Transformation Temperature

The effect of the Cu content on the transformation temperatures are shown in Figure 2(a)-(c). Here, the transformation temperatures of A„ A_s, M_s and M, are measured by the stress-temperature curves and DSC method. As shown in Figure 2(a), M_s and M, points increase with the increasing Cu content. On the contrary, A_s and A, points decrease with the increasing Cu content up to approximately 7.5 at% Cu, and thereafter these values increase with the increasing Cu content. This behavior is considered to be due to the crystal structural change with the Cu content from monoclinic lattice to orthorhombic one. Figure 2(b) shows the variation of the transformation temperature hysteresis with the Cu content. The transformation temperature hysteresis of Ti-50at%Ni is about 55K. However, this becomes small with the addition of Cu to the Ti-Ni binary alloy, for example, the value of Ti-37at%Ni-13at%Cu is about 1/3 of that of Ti-50at%Ni alloy. The reduction in the transformation temperature hysteresis is very effective for application of shape memory alloy to the various



(a) Transformation temperatures (b) Temperature hysteresis (c) Temperature changes with cycles

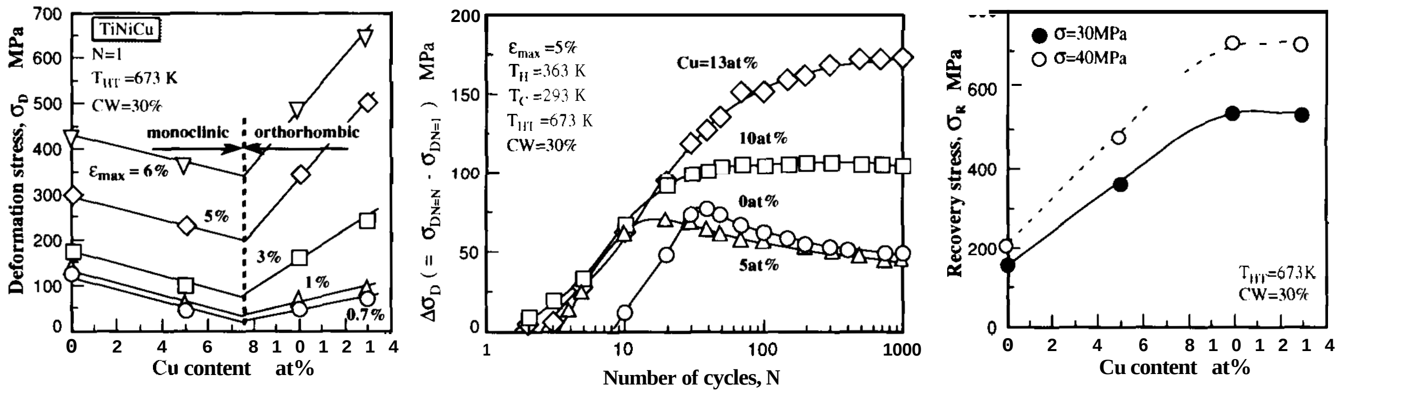
Figure 2: Variations of transformation temperatures with Cu content and cycles

actuators and thermal engines. From this point of view, the addition of Cu as an alloying element to Ti-Ni binary alloy is useful for the actual application. The transformation temperature change between one cycle and 2000 cycles is shown in Figure 2(c). The changes in these values for both M_s and M_f points become small with the increasing Cu content. On the other hand, the changes in those for A_s and A_f points show the reverse trend of those of M_s and M_f. However, the changes of these values are smaller than 6 K.

Deformation and Recovery Stress

Figure 3(a) shows the deformation stress (σ_D) at the first cycle in relation to the Cu content. In the ε_{max} lower than 1%, the σ_D has the small dependency on the Cu content. However, in the ε_{max} larger than 3%, the CT, has the remarkable Cu content dependency. The effect of Cu content on the σ_D is different near the about 7.5 at% Cu point where the crystal structural change from monoclinic lattice to orthorhombic one occurs, just like the aspect in the transformation temperature change. The deformation stress difference (ACT,) between N(=2000) cycles and the first cycle is shown in Figure 3(b). In each Cu content, $\Delta\sigma_D$ increases linearly with the increasing cycles up to each cycle which are different from the Cu content. Thereafter, $\Delta\sigma_D$ shows the saturated value with cycles, and the saturated $\Delta\sigma_D$ increases with the higher Cu content. The above behavior of the deformation stress may be due to the work-hardening effect of this material. Therefore, the addition of copper to Ti-Ni binary alloy causes the decrease of fatigue life.

Figure 3(c) shows the variations of the recovery stress (σ_R) with different initial applied stresses. The σ_R increases with the increasing initial applied stress and with the higher Cu content. The σ_R becomes almost constant at Cu content over about 10%.These behaviors may be due to the difficulty of the reverse phase transformation.



(a) Deformation stress (b) Stress changes with cycles (c) Recovery stress

Figure 3: Variations of deformation and recovery stresses with Cu content

Irrecoverable Strain

The low irrecoverable strain is required for the large available strain energy (E_{av}) per volume in heat engine. Figure **4** shows the Cu content effect on the irrecoverable strain *(E,)*, and ε_{max} is 6% in this case. The *E,* decreases monotonously with the increasing Cu content up to about 10 at% Cu content, and thereafter the *E,* value becomes almost constant. Generally, the *E,* represents the residual strain and the large *E,* is also caused by the large applied stress which induces the plastic deformation. From this point of view, the addition of Cu to this Ti-Ni alloy is desirable for keeping the performance of this material.

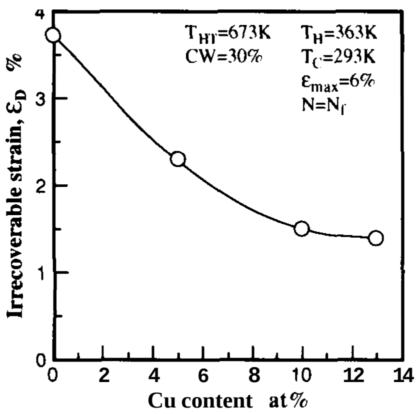
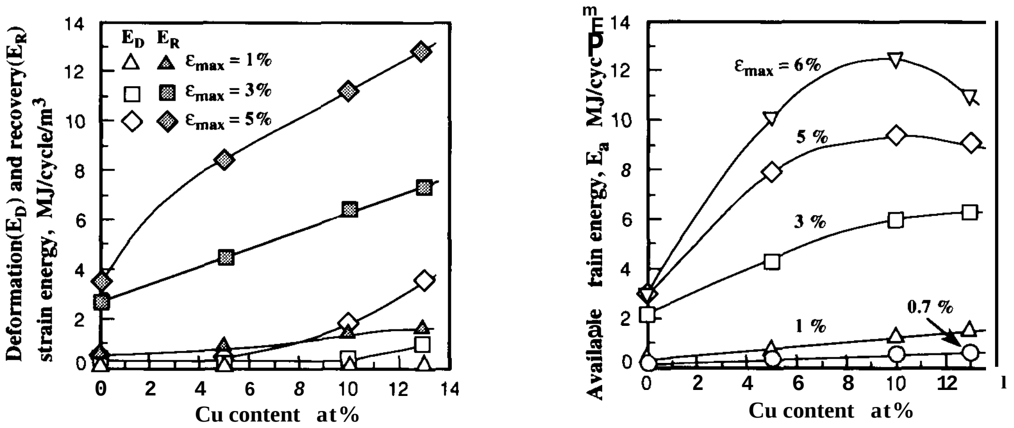


Figure 4: Effect of Cu content on irrecoverable strain

Strain Energy

Figure 5(a) shows the Cu content effect on both the deformation strain energy (E_D) and the recovery strain energy (E_R) in relation to the various ε_{max}. The higher Cu content increases the strain energy, and this becomes remarkable for the high ε_{max} and also especially for the E_R. Figure 5(b) represents the available strain energy (E_{av}) which is induced from the difference between E_D and E_R ($=E_R - E_D$), as shown in Figure 1. The E_{av} increases with the higher ε_{max} and also with the high Cu content up to approximately 10 at% Cu. This result suggests that the addition of the around 10 at% Cu to the Ti-Ni alloy is very effective for obtaining the high energy from this energy-conversion system.



(a) Strain energy E_D and E_R

(b) Available strain energy

Figure 5: Effect of Cu content on the strain energy per cycle

FATIGUE PROPERTY

Generally, stress amplitude or strain range is used to correlate fatigue life. Although the number of cycles to failure generally increases with the decrease in the recovery stress, but the different fatigue lives occur at different heating temperatures for $\varepsilon_{max} > 4\%$. Therefore, the recovery stress (maximum stress) is not the parameter controlling the thermo-mechanical fatigue life. The irrecoverable strain represents the residual strain by the plastic deformation during a thermo-mechanical cycle, but it is also not the parameter controlling the thermo-mechanical fatigue life [10]. It is thought that fatigue life (N_f) is physically the exhaust of the recovery strain energy (i.e., the dissipated strain energy) during the thermo-mechanical cycles.

Figure 6 shows the relationship between the dissipated strain energy ($\Delta \overline{E_R}$) and the number of cycles to failure (N,) for each Cu content. The $\Delta \overline{E_R}$ is a reduction of recovery strain energy per cycle and can be expressed by the following equations.

$$\Delta \overline{E_R} = \frac{1}{N_f} \sum_{i=1}^{N_f} \Delta \sigma_{R,i} \qquad (1)$$

$$\Delta \sigma_{R,i} = \int_{\varepsilon_D}^{\varepsilon_{max}} \sigma_{R,i}(\varepsilon, T_H) d\varepsilon - \int_{\varepsilon_D}^{\varepsilon_{max}} \sigma_{R,i+1}(\varepsilon, T_H) d\varepsilon \qquad (2)$$

All the data fall on the two straight lines separated by a critical strain ε_{max} of **4%.** This means that the dissipated strain energy is a life-controlling parameter of Ti-Ni-Cu shape memory alloys. When ε_{max} **> 4%,** slip deformation is thought to be the thermo-mechanical fatigue damage mechanism. And in this strain range, the data with different Cu contents fall on the same line. However, when ε_{max} ***c* 4%,** the fatigue life decreases with an increase in Cu content under the same dissipated strain energy. The addition of Cu promotes the ability of reverse phase transformation and therefore increases the phase transformation dominated fatigue damage.

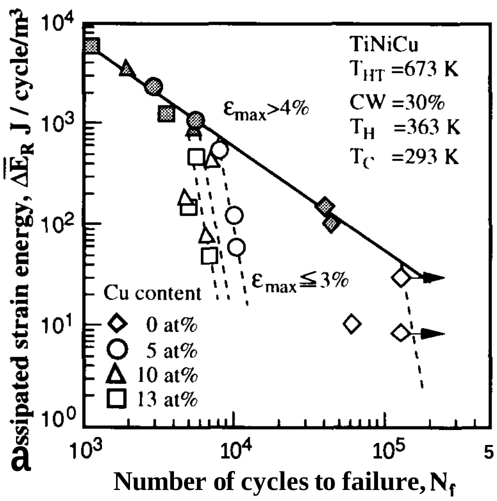
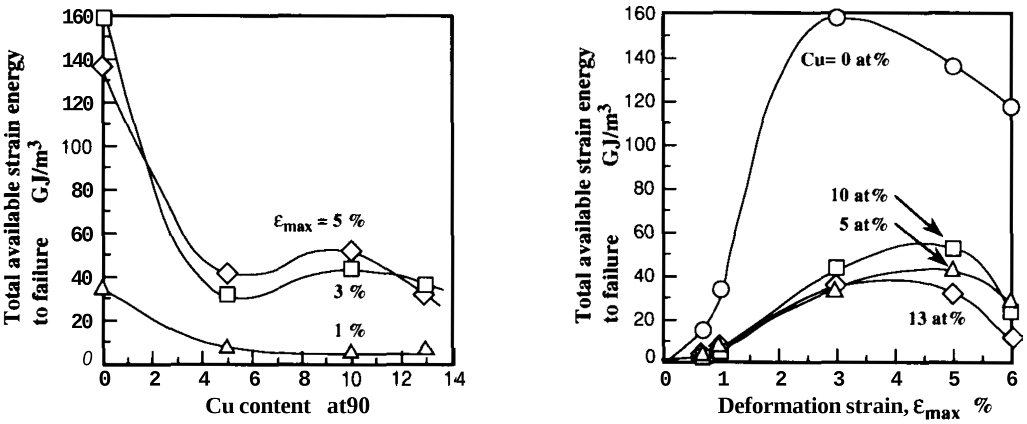


Figure 6: The effect of Cu content on number of cycles to failure

TOTAL AVAILABLE STRAIN ENERGY TO FAILURE

When the shape memory alloy is applied to actuators, heat engines and so on, the available strain energy per cycle is desired to be large. At the same time, the fatigue life of shape memory alloy is also desired to be long. Therefore, the total available strain energy to failure is desired to be large. Figure 7(a) shows the Cu content effect on the total available strain energy (total output work) to failure in relation to the ε_{max}. The total available strain energy to failure increases with the increasing the ε_{max} and also decreases with the increasing Cu content up to approximately 5 at% Cu., and thereafter it shows almost the constant energy value of about **40** GJ/ m^3. Figure 7(b) shows the total available strain energy to failure in relation to the deformation strain of the ε_{max} and also with the Cu content. The maximum total available strain energy to failure of the Cu-free Ti-Ni alloy is obtained at about the **3%** ε_{max}. On the other hand, that of Cu-containing Ti-Ni alloys shifts to the higher ε_{max} of about **4%** - 5%. These results suggest that the higher total available strain energy to failure depends on the heating condition, deformation strain and also Cu-content. Furthermore, the life controlling parameters such as fatigue, corrosion and others should be clarified in detail for the high performance of this shape memory alloy.



(a)Effect of Cu content (b) Effect of deformation strain

Figure 7: The effect of Cu content and strain ε_{max} on the total available strain energy to failure

CONCLUSION

The followings are the main results obtained from the experiments concerning the Cu-content effect on the thermo-mechanical behaviors and the total available strain energy to failure of the Ti-Ni shape memory alloy.

(1) Transformation temperature hysteresis becomes small with the increasing Cu- content. This Cu-additive effect is very important for the actual application of the shape memory alloy to the heat engines and others.

*(2)*The irrecoverable strain at the ε_{max} which is applied to the material in the thermo-mechanical process decreases with the increasing Cu content monotonously up to about 10 at% Cu, and thereafter that value becomes constant. This characteristics is desirable for keeping the material performance.

*(3)*The available strain energy per cycle increases with the increasing ε_{max}, and also with the higher Cu-content up to about 10 at% Cu. This is very important for the effective energy-conversion.

*(4)*The addition of Cu accelerates the fatigue damage which may be induced by the reverse phase transformation.

(5) The total available strain energy to failure increases with the larger the ε_{max} ,and decreases with the increasing Cu content up to about 5 at% Cu, and thereafter it shows almost the constant energy value.

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