Effects of heating/cooling-water temperatures on output power characteristics of forced cooling pulley-type SMA heat-engine

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In this research, the effects of heating/cooling water temperatures of a heat engine on the output characteristics of the forced cooling pulley-type SMA heat-engine is investigated for the purpose of operating temperature optimization of the engine. The engine output increases almost linearly as the heating water temperature (T_H) rises. On the other hand, the engine output shows a gradual decrease as the temperature of SMA element during cooling (T_{SMA}) rises to 321.4 K and then an abrupt decrease when the $T_{SMA} = 322.7$ K. Thermal cycling tests under constrained strain conditions for the SMA element were carried out to investigate the effect of heating/cooling temperatures to generation stress ($\Delta\sigma$) and reaction velocity (V_R) of the SMA element. In result, $\Delta\sigma$ increases gradually with the increase of T_H . Besides, V_R increases almost linearly as T_H increases. This result suggests that the increase of engine output as T_H increases is mainly due to the increase of the V_R . Meanwhile, V_R increases gradually with the increase of T_{SMA} . Besides, $\Delta\sigma$ increases as T_{SMA} rise up to 318 K, above which it decreases rapidly. From these results, it may be concluded that the contributing factor to the engine output is the variation of $\Delta\sigma$ and V_R with the variation of T_{SMA} .

Key words: Shape Memory Alloy, Heat Engine, Ti-Ni-Cu Alloy, Reaction velocity

1. INTRODUCTION

For the purpose of recovering low temperature exhaust heat (less than 373 K), a pulley-type heat-engine using shape memory alloy (SMA) had been manufactured and studied [1, 2]. This choice of SMA was decided upon because the transformation temperature of Ti-Ni based SMAs are in the temperature range near/below room temperature [3, 4], and Ti-Ni based SMAs show a large recovery force (approximately 10^6 J/m³) [5]. However, the product life cycle (PLC) of the previous SMA heat-engine was too short to be of practical use.

In order to improve the PLC of the SMA heat-engine,

we proposed to use a tape-shaped SMA element instead of the wire or coil shaped SMA element [6]. Furthermore, for the purpose of improving the heat transfer efficiency, we have manufactured a pulley type SMA heat-engine with a forced cooling system using a tape-shaped SMA element, as shown in Fig.1 [7, 8]. This system is consisted of a pulley with a forced cooling system (upper pulley), a normal pulley (bottom pulley), a water bath and measuring devices (torque meter, etc). The pulley with the forced cooling system is cooled down by cooling water, and the water in the water bath is heated and stirred to maintain a constant temperature. Thus, the SMA element is heated and cooled by the heating water in the water bath, respectively. For this reason, this engine can control the heating/cooling temperature of SMA element by controlling the heating/cooling water temperatures. Moreover, the installation condition (inter-shaft distance and installation angle) of this system can be adjusted. The effect of the installation condition on the output characteristics of this pulley-type SMA heat-engine has already been investigated [8]. In this study, the effects of heating/cooling water temperatures of the heat engine on

Fig.1 The schematic drawing of pulley-type SMA heat-engine including an idler wheel with cooling system.

Table.1 Transformation temperatures of heat-treated Ti-Ni-Cu specimen measured by DSC.

Transformation temperature (K)			
M_s	M_f	A_s	A_f
320.1	306.3	328.4	341.5

the output characteristics of the engine are investigated for the purpose of operating temperature optimization of this forced cooling pulley-type SMA heat-engine.

2. EXPERIMENTAL METHOD

2.1 Tape-shaped SMA element

The chemical composition of the tape-shape SMA used in this study is Ti-45Ni-5Cu (at%). The width, thickness and length of the tape-shaped SMA for the driving element of SMA engine are 9.5 mm, 0.12 mm and 380 mm respectively. The driving element for the SMA engine is a SMA specimen heat-treated at 673 K for 3.6 ks in the atmosphere while wound around a stainless steel pipe with a 15 mm diameter. And then, the SMA specimen is welded at the leader and end parts to make an annular tape-shaped SMA. Table.1 shows transformation temperatures of a heat-treated specimen measured by a differential scanning calorimetry (DSC).

2.2 Pulley-type SMA heat-engine including the idler wheel with a cooling system

The diameter of the upper and bottom pulley of the SMA heat-engine (as shown in Fig.1) are 78 mm and 25 mm respectively. The distance in a straight line between the center of upper pulley and bottom pulley is set at 105 mm. The angle formed by the straight line passing through the center of each pulley and the hot-water surface is set at 90 deg. The SMA annular belt made of the tape-shaped SMA is installed over both these pulleys. The SMA elements are heated by immersing the bottom pulley in hot water inside the water bath, and then the engine operates by the shape recovery force of the SMA elements. The output power of this engine is transmitted to the output measuring device by the power transmission belt attached to the upper pulley. The constant load for torque measurement is generated by the electric motor. Temperatures of the heating water (T_H) and cooling water (T_C) are varied from 343 K to 363 K and from 293 K to 313 K, respectively.

2.3 Thermal cycling tests under constrained strain condition

In order to investigate the effect of the heating/cooling temperatures on the output characteristics of SMA element, thermal cycling tests under constrained strain condition for SMA element were carried out. Fig.2 and Fig.3 show schematic drawings of thermal cycling tests under constrained strain condition and the stress-strain curve in the thermal cycling test under constrained strain condition, respectively. The width, thickness and length of the tape-shaped SMA for thermal cycling tests are 9.5 mm, 0.12 mm and 50 mm respectively. In addition, this SMA specimen is heat-treated at 673 K for 3.6 ks in the atmosphere for the shape-memory treatment for achieving linear shape. The SMA element was loaded to the given 1.2 % pre-strain in the cooled oil bath, as shown in Fig.2(a) (Fig.3 (a) A→B). The 1.2 % strain is the maximum applied strain during an engine operation. The cooled oil temperature (T_{CO}) is controlled within the range of T_C mentioned at 2.2. And then, the specimen is immersed in the heated oil bath as shown in Fig.2 (b). The heated oil temperature (T_{HO}) is controlled [at the range of within the range of T_H mentioned at 2.2. Since the stress increases due to the austenitic transformation (Fig.3 (a) B'→C), the specimen was heated rapidly under constrained conditions. In this study, the stress difference between the maximum stress at T_C and the stress that rapidly increased linearly by heating is defined as the generation stress ($\Delta\sigma$). Moreover, to investigate the reaction velocity of SMA element, the time constant (τ) is defined. Fig.3 (b) shows the enlarged view of the (a) heating part of the stress-strain curve. The stress difference between the heating start (B') and the endpoint of the linear stress increase (C') is defined as the $\Delta\sigma'$, and the time constant (τ) is the period from the heating start time to the arrival time of the stress reaching $0.632\Delta\sigma'$ ($1-\exp(-1) \cong 0.632$). In this study, the reaction velocity of the heated SMA element (V_R) is expressed as the reciprocal of τ .

Fig.2 Schematic drawings of thermal cycling tests under constrained strain condition.

Fig.3 The stress-strain curve in the thermal cycling test under constrained strain condition.

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3. RESULTS AND DISCUSSION

3.1 Effects of heating/cooling-water temperatures on engine output of SMA heat-engine

Figure 4 shows the relationship between engine output and T_H , when the $T_C = 293$ K. The engine output increases almost linearly as T_H rises. Fig.5 shows the relationship between the engine output and T_C , when the $T_H = 363$ K. The engine output shows a gradual decrease up to 308 K and then an abrupt decrease when the $T_C = 308$ K. In this experiment, the SMA element makes contact with the heating water directly, but does not make contact with the

Fig.4 The relationship between engine output and T_H , when the $T_C = 293$ K.

Fig.5 The relationship between engine output and T_C , when the $T_H = 363$ K.

cold cooling water directly. Therefore, it is thought that the temperature of SMA element is almost equal to the T_H when the SMA is heated, but the temperature of the SMA element is not equal to the T_C when the SMA is cooled. For this reason, the temperature of SMA element during cooling (T_{SMA}) is determined by thermographic measurement, and the relationship between engine output and T_{SMA} was investigated. Fig.6 shows the relationship between engine output and T_{SMA} . The T_{SMA} varies from 314.4 K to 324.3 K. The engine output shows a gradual decrease up to 321.4 K and then an abrupt decrease. In addition, the inflection point temperature exists in the vicinity of M_s .

These tendencies are thought to be caused by the variation of generation stress ($\Delta\sigma$) and reaction velocity (V_R) of the heated SMA element with the variation of T_H and T_C . Accordingly, to investigate the effects of T_H and T_C on $\Delta\sigma$ and V_R of SMA element, thermal cycling tests under constrained strain condition were carried out.

3.2 Effects of heating/cooling temperatures on generation stress and reaction velocity of SMA element

Figure 7 shows relationships between $\Delta\sigma$ and V_R of the heated SMA element and T_{HO} , when the $T_{CO} = 293$ K. The $\Delta\sigma$ shows a sharp rise at 343 K, and it increases gradually up to 363 K, above which it is saturated. On the other

Fig.7 Relationships between $\Delta\sigma$ and V_R of heated SMA element and T_{HO} , when the $T_{CO} = 293$ K.

Fig.6 The relationship between engine output and T_{SMA} , when the $T_C = 293$ K.

hand, the V_R increases almost linearly as temperature rises. From these results, the variation of engine output with the variation of T_H is thought to be mainly caused by the variation of V_R with the increase of T_H . Fig.8 shows the explanatory drawing of the variation of $\Delta\sigma$, V_R and engine output with T_H . The temperature dependence of $\Delta\sigma$ is weaker than that of V_R , when the T_H is above 340 K. Therefore, the engine output increases almost linearly as temperature rises. From these results, it is concluded that the higher the T_H , the higher engine output.

Fig.8 The explanatory drawing of the variation of $\Delta\sigma$, V_R and engine output with T_H .

Fig.9 Relationships between $\Delta\sigma$ and V_R of heated SMA element and T_{CO} , when the $T_{HO} = 363$ K.

Figure 9 shows relationships between $\Delta\sigma$ and V_R of the heated SMA element and T_{CO} , when the $T_{HO} = 363$ K. The $\Delta\sigma$ increases as temperature rises up to 313 K, above which it decreases rapidly. In contrast, the V_R is almost constant as the temperature rises up to 303 K, and then it increases with the increase of temperature. From these results, the variation of engine output with the variation of T_{SMA} is thought to be caused by the combined factors (which is) of the variation of $\Delta\sigma$ and V_R with the increase of T_{SMA} . Fig.10 shows the explanatory drawing of the variation of $\Delta\sigma$, V_R and engine output with T_{SMA} . Since $\Delta\sigma$ and V_R are almost constant up to 313 K, the engine output is almost constant up to 313 K. However, the $\Delta\sigma$ decreases with the increase of T_{SMA} when the T_{SMA} is above 313 K. In contrast, the V_R increases when the T_{SMA} is 318 K ($\cong M_s$). Therefore, the engine output is approximately constant as T_{SMA} rises up to M_s . Furthermore, the V_R is almost constant when the T_{SMA} is from 320 K to 323 K, and then the engine output drops. Moreover, the engine output becomes constant again when the T_{SMA} is above 323 K because the V_R increases again when the T_{SMA} is above 323 K. From these results, it is desirable that the SMA element be cooled down to a temperature M_s for the increase of engine output.

4. CONCLUSION

The effect heating/cooling-water temperatures on output power characteristics of forced cooling pulley-type heat-engine using a tape-shaped SMA element were investigated. The obtained results are summarized as follows:

- (1) The engine output of the SMA heat-engine increases almost linearly as the temperatures of the heating water (T_H) rises. On the other hand, the engine output shows a gradual decrease as the temperatures of the cooling water (T_C) rises up to 303 K, and then an abrupt decrease when the $T_C = 308$ K.
- (2) The temperature of the SMA element during cooling (T_{SMA}) is determined by thermographic measurement, and the relationship between engine output and T_{SMA} was investigated. In result, the engine output shows a gradual decrease as T_{SMA} rises up to 321.4 K, and then an abrupt decrease when the $T_{SMA} = 322.7$ K.
- (3) Thermal cycling tests under constrained strain

Fig.10 The explanatory drawing of the variation of $\Delta\sigma$, V_R and engine output with T_{SMA} .

conditions for the SMA element were carried out to investigate the effect of heating/cooling temperatures on generation stress ($\Delta\sigma$) and reaction velocity (V_R) of the SMA element. In the results, it was observed that $\Delta\sigma$ increases gradually with the increase of T_H . Besides, V_R increases almost linearly as T_H increases. This result suggests that the increase of engine output as T_H increases is mainly due to the increase of V_R of SMA element, and it is concluded that the higher the T_H , the higher the engine output is.

(4) V_R increases gradually with the increase of T_{SMA} . Besides, $\Delta\sigma$ increases as T_{SMA} rise up to 318 K ($\cong M_s$), above which it decrease rapidly. From these results, it is concluded that the contributing factor of the relationship of T_C and the engine output is due to the variation of $\Delta\sigma$ and V_R with the variation of T_{SMA} , and it is desirable that the SMA element is cooled down to a temperature M_s for the increase of engine output.

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