Development of Reciprocating Heat Engine Using Shape Memory Alloy*
-Ratchet Type Drive System with Self-Drive Rotational Valve-

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Abstract
This research aims at developing the heat engine system using Shape Memory Alloy (SMA) wires, which work by alternating supply of hot/cold water through the newly developed automatic valves. The SMA wire is connected to the chain and sprocket system having the ratchet type bearing and the spindle with the flywheel. The valves for supplying hot/cold water to the SMA wires are driven by the flywheel, so no outside power is necessary. Output power of the developed heat engine with two φ 0.3 mm SMA wires is 0.1W at 30~40 rpm. The SMA wire used in the developed heat engine was produced by the Furukawa Electric Co., Ltd.. The wire shows the fatigue life of more than 10^5 cycles under conditions of 150 MPa in loading and heating/cooling cycle rate of 0.5 Hz in the cyclic transformation fatigue tests. The heat engine system works without any adjusting process of a length of SMA wire and water supplying timing. The stress of the SMA wire is kept to be rather higher during working because that the engine has no crank system. So, the developed heat engine system is hopeful to use in recovering energy from waste hot water.

Key words: Energy Conversion, Waste Heat Recovery, Shape Memory Alloy, Phase Transformation, Cyclic Transformation Fatigue, Ratcheting Drive System, Self-Drive Rotational Valves, Heat Engine

1. Introduction
At the ironworks and the electric power plants and so on, huge amounts of warmed coolant under 100 ℃ are usually wasted with no use. It is very useful in efficient use of natural resources and energy to do heat-recovery from the coolant and reuse it. The heat-recovery is thought to be possible by the heat engine using the shape memory alloy (SMA), because the SMA deforms alternately by the small difference in temperature at rather low temperature. Some researchers have investigated about several types of the heat engine using SMA (1)~(5). Cyclic phase transformation properties of the SMA wire also has been investigated to use it in developing the heat engine (6). For applications of such heat engine, there are a lot of difficult problems to be solved.

We also have developed various types of SMA heat engine as the pulley type, the bevel circular plate type and the reciprocating type. The reciprocating type heat engine is found to be the best of all, because that only a small amount of SMA is necessary, a recovery force is converted effectively into rotational force, and a cyclic deformation of the SMA is controlled by supplying coolant as well as warm water.

In this report, the heat engine of the reciprocating type using SMA wires is developed, which moves by supplying only warm and cold water without other outside control systems as a solenoid operated valve, and the performance of the engine system is investigated.

2. Specification of the newly developed heat engine
The target of this study is to increase the efficiency in power transfer of SMA into rotational power. So, the new reciprocated heat engine of ratchet type which is shown in Fig.1 is developed and the output power of the system is investigated.
2.1 Action mechanism of the heat engine

SMA wires are heat treated as to be shrink at temperature of $A_s$ and elongate due to tension by a bias spring below the temperature of $M_f$. Due to alternating supply of hot and cold water, SMA-wire shrinks with strong recovery force and elongates by the small tensile load, alternately. When the SMA wire shrinks, a chain which is wound around a sprocket is pulled through a swing arm as shown in Fig. 2. Then the sprocket which has a ratchet system, rotates intermittently in one way.

Hot and cold water are supplied alternately through the newly developed valves which are driven by the power of the heat engine itself.

![Fig.1 The newly developed heat engine of the reciprocating type using SMA wires](image)

Fig. 2 Action mechanism of the heat engine

2.2 SMA wire

SMA wires used in the experiment are $\phi 0.058 - \phi 0.3$ mm in diameter made by the Furukawa electric Co., Ltd (NT-H7-TTR). The $A_s$, $A_f$ and $M_s$, $M_f$ temperatures of $\phi 0.2$ mm wire are 53.0, 66.8°C and 43.7, 29.7°C, respectively.

2.3 Deformation and fatigue strength properties of the SMA wires

Deformation properties and fatigue strength were investigated experimentally. Figure 3 shows the experimental apparatus for these tests. In the experiments, the SMA wires are heated by the introduction of electric current and cooled by the fan. Temperature of the SMA wires is measured by using a thermo-couple which is attached to the center of the SMA wire. Deformations of the SMA wires are measured by using a differential censor. The SMA wires are tensile loaded by a dead weight.

Figures 4 (a) and (b) show the relationship between the differential strain and temperature for various loading conditions at cooling and heating, respectively. We can see that the amount of the differential strain and transformation temperatures change depending on loading conditions. That is, the differential strain increases with increasing tensile stress.
Fig. 3 Experimental apparatus of SMA wire fatigue test

Fig. 4(a) Relationship between strain and temperature of SMA-wire at cooling stage

Fig. 4(b) Relationship between strain and temperature of SMA-wire at heating stage

and the transformation temperature increases with increasing stress. Figure 5 shows the relationship between temperature and differential strains of the SMA wires for various tensile stresses. In this result, it is found that the thin wire deforms quickly at rather low temperature. But, the thick wire is better to get large power in application to the heat engine. It is not so good to bundle many fine SMA wires to get much power, because that temperature change delays at inside of the bundle and wires in the bundle deform not
uniformly. Figures 6 (a) and (b) show the effects of cyclic phase transformation on the amounts of differential strain of the SMA wire, so called “training effect.” In the results shown in Fig.6 (a), the differential strain generally decreases with an increase of number of cycle for more than 3.5% of the strain range and for heavy load of 400MPa. (Cyclic rate is rather high in these experiments) On the other hands, if the load stress is controlled to be less than 150 MPa, the differential strain is kept constant for more than $10^5$ cycles especially for the case of slow heating, as shown in Fig.6 (b).
Figure 7 shows S/N curves obtained by fatigue tests of SMA wires for various heating conditions in the cyclic phase transformation. In the fatigue test, the differential strain is controlled to be around 4% even for changing in applied stress by controlling the heating electric power and time. Effect of heating rate on fatigue life is also investigated in the tests. As the results of the fatigue tests, we can see that quick heating bring about shorter life in cyclic phase transformation and the effect of heating rate is much larger for a thick wire than for a fine wire. This result means that temperature difference occurs between inside and outside of a wire in heating/cooling process, and so local thermal stresses must be much higher than mean stresses measured in the tests. Accordingly, much slow heating/cooling will enable SMA wires to have about a million times of fatigue life even for the loading conditions of more than 100MPa in tensile stress and around 4% of the difference strain range. We have a test data of 0.6 million times and more in fatigue life in fact.

2.4 Characteristic points of the engine

2.4.1 Ratchet driving system

Reciprocating motion of the SMA wire must be transfer into rotational motion. There are a ratcheting system and a crank system as the possible system. About the crank system, efficiency of transfer is not so high at around both upper and lower dead points and it is difficult to control the timing of deformation of SMA wire with crank angle. On the other hands, the ratcheting system using a one way clutch with a chain and sprocket system which is similar to a rack and pinion system, has many good points. That is, recovery force of the SMA wire is transferred perfectly into rotational power through the clutch and sprocket system as shown in Fig.2, and there is no problem about timing of rotational angle with recovery deformation of SMA wire.

2.4.2 Valves supplying hot/cold water

In this study, the new valve is developed to supply hot/cold water to SMA wires alternately. This valve is driven by the heat engine itself and moves smoothly with small
Fig. 9 The hot/cold water ducts of tournament branches type

Fig. 10 The output power meter

energy loss. There are two rotating cam pusher and ball plug systems inside the valve, as shown in Fig. 8. When the cam pushes the ball which works as the plug of the outlet hole, hot/cold water flows into the ducts which have SMA wires inside.

2.4.3 Multi-cycle system
The developed heat engine has two sets of SMA wires. Phase difference of the valves supplying hot/cold water is 180° in this case. Multi cycle system which has many sets of SMA wires is possible to design. The multi cycle system will bring about much smoother and continuous rotational power.

2.4.4 Water duct of tournament branches type
Water ducts have some branches like the tournament so as to make temperature of the whole SMA wires change uniformly and quickly, as shown in Fig. 9.

3. Evaluation of the heat engine

3.1 Evaluation terms
To evaluate the performance of the newly developed SMA heat engine, the following terms were investigated experimentally.

i) Temperature change at inside of valve and duct
ii) Relationship between output power and the moment of inertia of flywheel
iii) Relationship between power properties and temperature of hot water
iv) Relationship between power properties and load/rotational speed

3.2 Power meter
Figure 10 shows the power meter used for estimating the output torque in the investigation. The power meter is composed of a rotary encoder, a flywheel and a force lever to measure a rotational speed and a tangential force.

The output power is calculated by using the following expression.
4. Experimental results and discussions

4.1 Temperature in the ducts

Figure 11 shows measured temperatures of water at outlet of the duct. Temperatures of hot water and cold water at inlet of each valve are 85 °C and 23 °C, respectively. Temperatures of water in the ducts 1 and 2 are found to change in a uniform range from 25 °C to 83 °C, repetitiously, which means that the newly developed valves and the ducts work well.

4.2 Effect of capacity of the flywheel on output power

Figure 12 shows the results on output power obtained for three kinds of capacity in moment of inertia of the flywheel. Not so much difference can be seen among these data. But, it is found that more stable power can be obtained for rather larger capacity of the flywheel.

4.3 Effect of temperature of hot water on output power/torque

Figures 13 and 14 show the output power and the torque, respectively, for three kinds of temperatures of hot water. These figures show that both power and torque increase with an increase in temperature of hot water. It is because that high temperature water enables the SMA wires to change quickly in temperature and deformation, and so the larger tensile load and stroke can be obtained.

4.4 Effects of rotational speed and load on output power

Figure 15 shows the results on effects of rotational speed and load on output power. In this test, the rotational speed of the water valves was controlled by using the electric motor. It is
Fig. 13 Effect of temperature of hot water on output power of the heat engine.

Fig. 14 Effect of temperature of hot water on output torque of the heat engine.

Fig. 15 Effect of load on output power of the heat engine at various rotational speeds.

Fig. 16 Effect of load on stress-strain curve of SMA-wire of the heat engine.
found that the output power increases with an increase of rotational speed, except the cases of heavy load, and too heavier load inhibit the power even in the case of low rotational speed. This is because that SMA wire can not have an enough recovery strain against so heavy load and SMA wire can not get an enough temperature increase so as to phase transform at rather high rotational speed.

4.5 Effects of rotational speed and load on stress of the SMA-wire

Figure 16 shows stress-strain curves for three kinds of amount of loading weight in the power meter shown in Fig.10. The stress of SMA-wire increases firstly and decreases gradually after showing the maximum stress at heating stage. At cooling stage, the stress keeps itself low and the SMA-wire elongates up to zero in strain. The maximum stress and the maximum shrinking strain increase with increasing load. The output power per unit volume of the SMA-wire equals to the area of these stress-strain loops, so the maximum stress is expected to be higher much more and the strain also is expected to be much larger to get much more output power. But, thinking of fatigue life of the SMA-wire, the maximum stress and the maximum strain must be controlled to be around 100 MPa and less than 4 %, respectively.

5. Concluding remarks

The reciprocating heat engine using SMA-wires was newly developed, which was a closed system with no outer energy except hot/cold water. Output power of the engine and fatigue properties of the SMA-wire were investigated for various conditions. Concluding remarks are as follows,

(1) The newly developed engine system is simple and reliable for working. So, it is now near at hand that such heat engine will be put to practical use.

(2) The high rotational speed brings the high power, but also the early fatigue failure of SMA-wires, simultaneously. So, the low rotational speed and high torque system is superior from the long term view point.

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References


