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Thermal characteristics of a nitinol heat engine

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Temperature profiles in the nitinol working elements of a simple rocking shape-memory engine have been measured and attributed to the heat transfer characteristics of the system. The temperature extremes evidently lie between the reverse transformation temperatures A_s and A_f for the constrained wires, indicating that the device functions under the driving force generated by stress-induced formation (and reversion during heating) of a small volume fraction of martensite. Metallographic observations of relief effects associated with changes in the microstructure of wires simulating the working elements are consistent with this hypothesis.

1. Introduction

Shape recovery during the heating of a shape-memory alloy such as nitinol generates a stress which is about an order of magnitude higher than the stress required for deformation at a lower temperature. The stress differential may be harnessed as a force which will do work and convert thermal energy into usable mechanical or electrical energy.

The first patent for a heat engine based on shape-memory behaviour was issued in 1968 [1] and in the succeeding decade various designs for small engines were devised [2–4]. Further developments were reported in the 1978 Conference on Nitinol Heat Engines [5] sponsored by the US Naval Surface Weapons Center and the US Department of Energy to review the state of the art, to examine the direction of current and proposed research and to provide a forum for exchange of information.

In that conference, and elsewhere, considerable attention was directed to analyses of the efficiency of operation of various engine designs. In such analyses it is necessary to evaluate various system parameters including the extremes of temperature through which the working elements of the engine are cycled. In the absence of direct experimental data, it appears to be generally assumed that these temperatures correspond to the temperatures of the hot and cold reservoirs applied to the system. Such an assumption may not be valid for all designs, and it is the purpose of this paper to report the determination of actual temperatures in the nitinol working elements of a simple rocking shape-memory engine.

2. The nitinol engine

The engine used in this work was similar to the design described by Frank and Ashbee [6]. About 4 cm of leaf spring, 4 cm of nitinol wire, a 10 cm connecting rod (mass 35 g), another 4 cm of nitinol wire and another 4 cm of leaf spring in the same plane as the first were joined linearly. The assembly was bent at the wires into an S-shape by fixing the outer ends of the leaf springs into two metal supports mounted 14 cm apart on a 0.5 cm diameter glass axle. This axle rested across a 19 cm diameter cylindrical glass vessel located on a hotplate and containing heated water which was stirred magnetically and maintained at a constant level 4 cm below the rim of the vessel.

As one of the bent nitinol wires was dipped into the heated water it attempted to undergo shape recovery and so partially straightened. This action increased the bend in the opposing wire and, by displacing the connecting rod, displaced the centre of gravity of the assembly. As a consequence, the assembly rotated on the cylindrical axle, dipping the opposing wire into the heated water and so initiating the reverse action. Repetition of the cycles resulted in continuous rocking of the assembly provided that the temperature of the heated water was maintained between limiting values.

The hot water temperature was varied up to 100° C and measured with a mercury–glass thermometer suspended with the bulb adjacent to the path, in the water, of one of the nitinol wires. Cooling of the wires during cycling occurred in the atmosphere immediately above the water. This atmosphere was protected from disturbance due to draughts by a 40 cm high Perspex cylinder surrounding the hotplate, water container and engine. The temperature of the atmosphere was measured with a mercury–glass thermometer suspended adjacent to the axle.

Temperature variations in the nitinol working elements were measured during cycling using a copper–constantan thermocouple made from stripped 0.33 mm diameter wires spot-welded on to one of the elements. Welding did not appear to have any detrimental effect on the function of that element. The copper thermocouple lead was attached with nylon thread to both the connecting rod and the other nitinol element to preserve the symmetry and balance of the assembly. Both leads were arranged in such a way as to offer least mechanical resistance to the cyclic motion and were connected, through a cold junction, to a sensitive storage cathode-ray oscilloscope. During operation of the engine the thermal waveform generated by cycling was stored for later recording and determination of the temperature extremes in the wires.

3. Results

The effectiveness of operation of the engine was

TABLE I Experimental parameters for 1.23 mm diameter wires*

T_H (°C)	T_{MAX} (°C)	T_A (°C)	T_{MIN} (°C)	f (min^{-1})
50†		25.0		
55‡	54.3	25.2	50.0	95.3
60	58.6	26.8	53.3	95.7
65	64.3	27.6	56.7	95.5
70	69.5	28.2	60.5	95.3
75	73.4	29.0	63.3	93.9
80	78.5	30.7	67.5	93.2
85	83.4	34.5	69.4	91.2
90	88.5	35.5	70.5	88.0
95	93.5	39.0	72.8	91.0
100	~ 100.0	~ 100.0		

* T_{MAX}, T_A, T_{MIN} reproducible to within ± 1° C; f accurate to within ± 1 min^{-1}.
†Engine would not operate.
‡Intermittent operation.

strongly dependent upon the diameter of the nitinol working elements. With 0.5 mm diameter wires, insufficient force was generated to rock the assembly against the resistance of the attached thermocouple. With 1.65 mm diameter wires, non-recoverable strain occurred during bending of the assembly into the S-shape and performance was poor except for water temperatures in excess of 90° C. Performance was excellent with 1.23 mm diameter wires and Table I lists the temperature limits (T_{MAX}, T_{MIN}) in the wires, the atmosphere temperature (T_A) and rocking frequency (f) as functions of the hot water temperature (T_H).

It is evident from Table I that the engine operated effectively for water temperatures in the range 55 to 95° C. Operation ceased at 100° C as there was no temperature differential with the atmosphere, and at temperatures less than about 50° C, presumably because the driving force at these low temperatures was insufficient to overcome the mechanical resistance offered by the attached thermocouple.

4. Engine characteristics

4.1. Temperature profile

The thermal wave profile measured in the working elements was similar at each operating temperature as shown in Fig. 1. Clearly, the wave is non-sinusoidal and comprises an input pulse generated as the wire entered the hot water and a logarithmic decay as cooling occurred in the atmosphere. Both the pulse and the decay are distorted, possibly by the sinusoidal variation in angular velocity during operation.

To determine whether the profile was unique to the shape-memory working elements, the nitinol wires in the rocking assembly were replaced with non-shape memory wires of the same diameter. This device, with attached thermocouple, was manually cycled at a frequency of about 95 min^{-1} and in Fig. 2 the associated temperature profile is compared with the profile generated by the nitinol engine operated at the same hot-water temperature (85° C). The similarity of the profiles strongly suggests that the waveform is not associated with shape-memory behaviour of the nitinol, but is determined by the heat-transfer characteristics of the system.

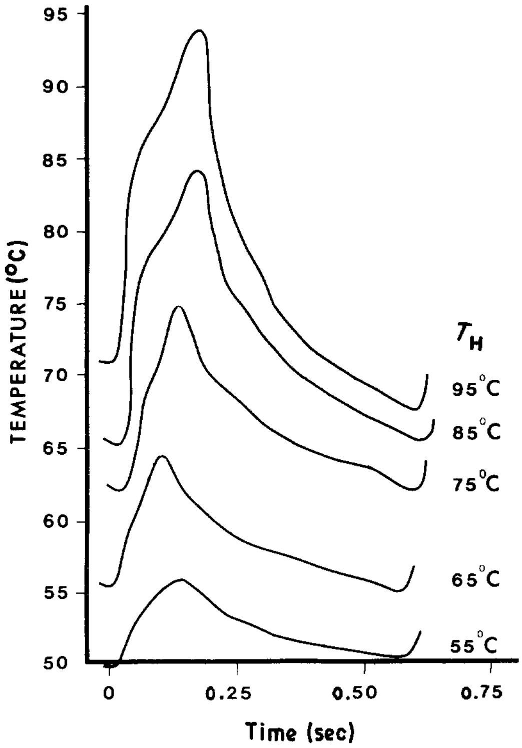


Figure 1 Diagram showing the similar temperature profiles generated during operation of the engine at temperatures between 55 and 95° C.

4.2. Internal temperatures

The thermocouple, being spot-welded to one of the nitinol working elements, monitored only the surface temperature of that wire. To determine whether the temperature profile within the mass of the wire was similar to that at the surface a thermocouple was embedded in a hole spark-machined through 0.75 of the wire diameter at the point of maximum curvature. The centre and corresponding surface profiles, compared in Fig. 3, show that (as expected) the heating and cooling rates at the centre of the wire were lower and, as a consequence, the temperature differential was less. Nevertheless the profiles are sufficiently similar to suggest that the surface temperatures, which are easier to measure, are adequate for analyses of engine characteristics.

4.3. Two-way shape-memory

The engine was operated at a hot-water temperature of 90° C for about 8 h. During the sequence of about

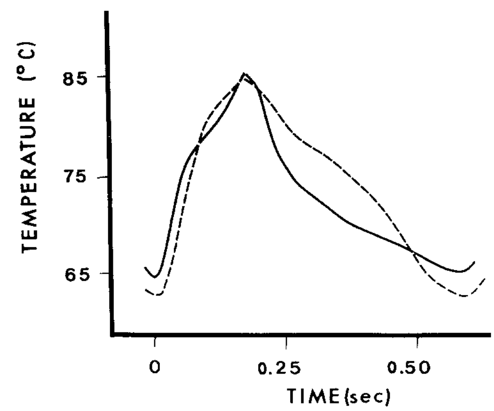


Figure 2 Diagram showing the temperature profiles generated in (—) nitinol and (– – –) non-shape-memory wires during operation at 85° C.

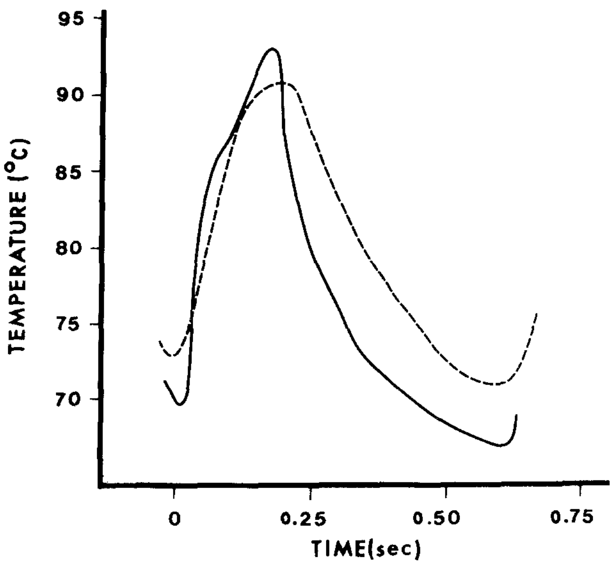


Figure 3 Diagram showing the temperature profiles generated at (—) the surface and (---) the centre of a nitinol working element during operation at 95° C.

24 000 cycles the frequency increased from an initial value of 94 min^{-1} to 100 min^{-1}, presumably due to the gradual development of two-way shape-memory capacity.

4.4. Wire temperature

From the experimental measurements listed in Table I it is evident that the maximum wire temperature was about 1° C lower than the hot-water temperature, indicating that the heating efficiency was high. On the other hand, cooling was most inefficient as the minimum wire temperature was about 30° C above the atmospheric temperature.

It is significant to compare the temperature extremes with the reverse transformation temperatures A_s and A_f measured under constraints similar to those imposed on the working elements of the engine. In making the measurements it was assumed that shape recovery commenced at A_s and was completed at A_f. Thus, the progress of shape recovery was at least approximately proportional to the fraction of parent β_1 phase formed by re-transformation of the deformed martensite. For unconstrained wire A_s was 29° C and A_f was 40° C, but

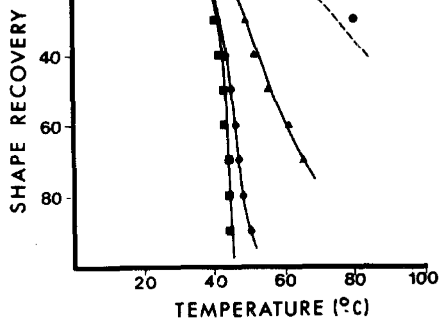


Figure 4 Diagram showing the effect of constraint on the progress of shape recovery of a bent nitinol wire. Load (g): (■) 0, (♦) 200, (▲) 300, (●) 500.

whereas constraint had no apparent effect on A_s, the A_f temperature increased as the magnitude of the constraint increased as shown in Fig. 4. Since the working elements were highly constrained by the design of the engine it is probable that under all operating conditions the wire temperature was always between A_s and A_f, with the consequence that the microstructure of the wire consisted of b c c β_1 phase and martensite.

Additionally, it is clear from Fig. 4 that for high constraints very little reversion occurred at temperatures below 50 to 55° C. Under these conditions the available driving force would be very small, thereby explaining the failure of the engine to operate in the lowest temperature range.

4.5. Metallography

It has not yet been possible to make direct observation of the microstructure of the working elements or changes in the microstructure during engine operation. However, some simulation studies suggest that the proposal that the wire had a duplex microstructure is valid.

In the first study, a straight piece of nitinol wire was polished as described previously [7] to provide for metallographic observations of changes in microstructure associated with shape-memory behaviour. As shown in Fig. 5, bending of the wire in the plane of polish at ambient temperature generated relief effects associated with deformation processes in the fully martensitic structure. During heating of the bent wire to above A_f the relief effects disappeared as the deformed martensite reverted to β_1 phase and concomitant recovery of the original straight shape occurred.

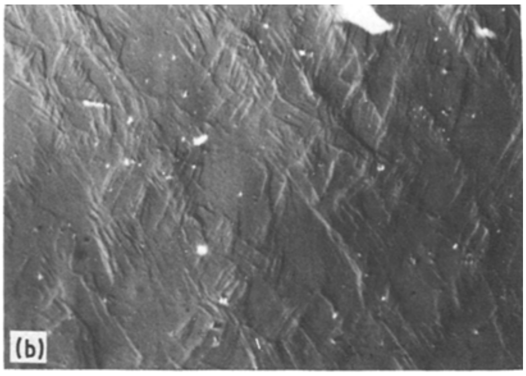
In the second study, a polished (unconstrained) wire was heated above A_f to 60° C and then bent. As shown by the relief effects in Fig. 6, the bending strain was accommodated by the stress-induced formation of martensite indicating that the maximum temperature for stress-induced transformation M_d, was higher than 60° C. Release of the bending stress was accompanied by disappearance of the relief as the reverse transformation progressed and shape recovery occurred by what was evidently superelastic behaviour.

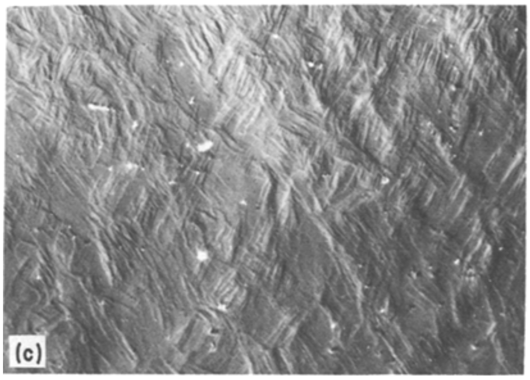
Alternatively, relief effects remained present during heating of the bent wire under load to about 100° C, which therefore must be lower than A_f for the constrained condition.

4.6. Driving force

It is now possible to use the measurements of temperatures in the wires and observations of relief effects in the simulation studies to deduce the changes in microstructure and associated forces that drive the engine.

Clearly the wires comprised b c c β_1 phase and martensite during the entire cycle of operation. In the cooling part of a cycle, the bending stress applied by straightening of the opposing (hot) wire caused a small volume fraction of stress-induced martensite to form to accommodate the increase in bending stress. On entering the hot water, the increase in temperature caused that small volume fraction to revert to the β_1





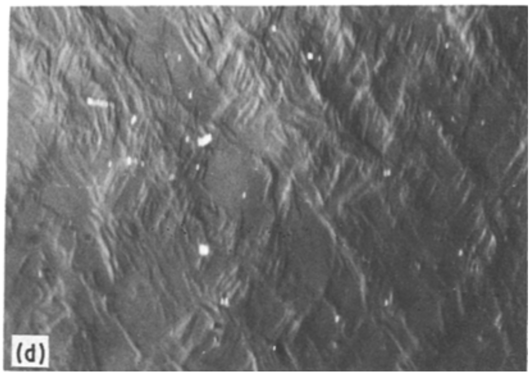


Figure 5 Photomicrographs showing (a, b, c) the development of relief during the bending of a nitinol wire at ambient temperature, (d, e) and the disappearance of the relief as reverse transformation occurred on heating to above A_f; unetched, oblique illumination; × 250.

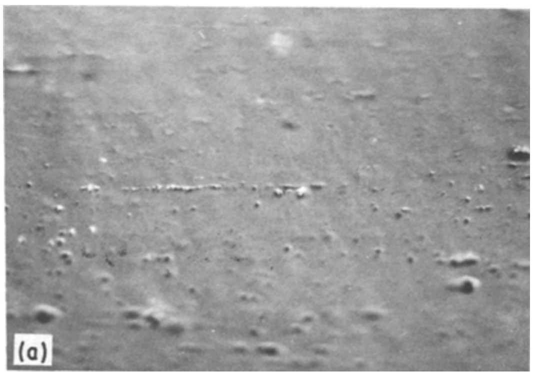
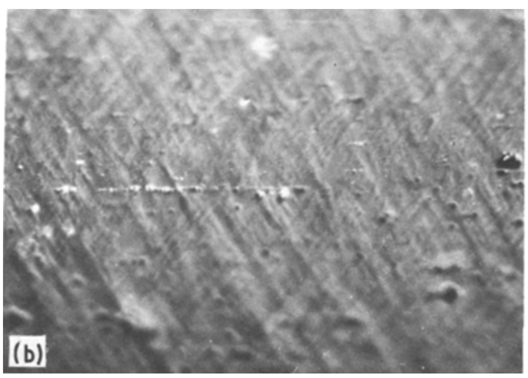
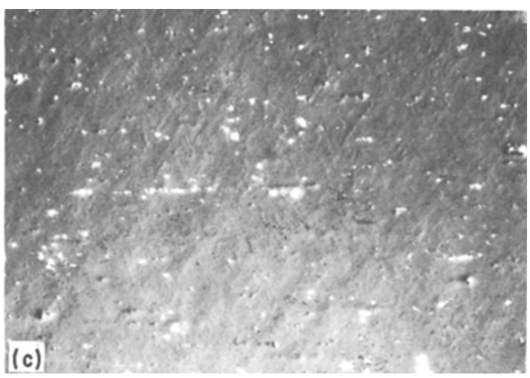


Figure 6 Photomicrographs showing (a, b) the development of relief associated with stress-induced transformation of β_1 phase to martensite at 60° C, and (c) disappearance of the relief as reverse transformation occurred during release of the load; unetched, oblique illumination, × 250.





phase and the associated shape-memory behaviour, in slightly straightening the wire, generated the bending stress and stress-induced martensite in the other (now cold) wire. Thus, the driving force operating the engine was provided by the shape-memory behaviour associated with the formation and reversion of only a small volume fraction of martensite.

Further, due to the stress distribution in a bent cylindrical wire it is probable that the small volume fraction of martensite was located only in the surface layers of the wire.

5. Conclusion

From measurements of temperature through which the nitinol working elements cycled in a simple rocking shape-memory engine it is obvious that heating in the hot-water reservoir was efficient and effective. On the other hand, cooling in the atmosphere above the water was inefficient and the temperature differential in the elements was considerably less than the temperature differential of the reservoirs.

It seems evident, however, that if both hot and cold reservoirs had high heat transfer characteristics, as in many designs, the heating and cooling efficiency would be high and the two temperature differentials would be very similar.

As the working elements of the engine operated under severe constraints the effective A_f temperature was much higher than A_f for unconstrained wire, and the microstructure was β_1 phase and martensite during the entire cycle. The engine operated under a driving force generated by stress-induced formation of martensite while in the cold reservoir, and reversion of that martensite to β_1 phase with concomitant shape recovery while in the hot reservoir.

Acknowledgements

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References

1. W. J. BUEHLER and D. M. GOLDSTEIN, US Patent 3403238 (1968).
2. R. BANKS, in "Shape Memory Effects in Alloys", edited by J. Perkins (Plenum Press, New York, 1975) p. 537.
3. A. D. JOHNSON, in Record of the Tenth Intersociety Energy Conversion Engineering Conference, Newark, Delaware August, 1975, Paper No. 759082, p. 530.
4. B. CUNNINGHAM and K. H. G. ASHBEE, *Acta Metall.* **25** (1977) 1315.
5. Proceedings of the Nitinol Heat Engine Conference, US Naval Surface Weapons Center, Maryland, 1978, Report No. NSWC mp 79-441, edited by D. M. Goldstein and L. J. McNamara.
6. F. C. FRANK and K. H. G. ASHBEE, *Inventus* **4** (1976) 22.
7. L. A. MIDDLETON, N. F. KENNON and D. P. DUNNE, *Metallography* **18** (1985) 51.

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