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ABSTRACT

A recent calculation of the thermal efficiency of a solid-state engine made with a Ni-Ti alloy (Nitinol) has been criticized with reference to the origin of the work output and the deformation behavior of the material.

In a recent publication, Golestaneh[1] has calculated the thermal conversion efficiency of a solid-state heat engine comprising the shape memory alloy Ni-Ti (Nitinol) as a working medium. The cycle considered by the author consists of deforming the material at a temperature T_o below the transformation critical temperature T_c and then bringing the deformed material rapidly to a hot reservoir at a temperature $T > T_c$ (the stress-strain temperature path of the cycle has not been given) under constant applied load.

The analysis of the energetics of the cycle as presented, however, is misleading and suffers from serious difficulties that could lead to erroneous conclusions about the efficiency. This analysis and the conclusions reached by the author were based on the assumption that the useful work output can be expressed as:

$$W = \alpha m \, \Delta H - W_D \qquad (1C)^1$$

where W_D is mechanical energy consumed in generating martensites of mass m at temperature T_o, α is the volume fraction of martensites transformed to the parent phase at temperature T, and ΔH is the latent heat of the transformation.

In principal, this equation is incorrect as the enthalpy does not act as a potential for work in that system and it even contradicts the author's own assumptions, as shown below. Golestaneh[1] assumes that the latent heat of the $P \rightarrow M$ transformation at the temperature T_o is equal to that of the $M \rightarrow P$ transformation at the higher temperature T. Since equal and opposite amounts of heat will be required to heat and cool the material between the temperatures T_o and T, energy conservation leads to the conclusion that

$$W = - W_D$$

rather than to the incorrect equation $1C^1$. In effect, the

author's cycle and assumptions lead to no net useful work output.

In addition to the above serious difficulty that negates the conclusions reached about the efficiency, the author has introduced physically unfounded parameters implied to be characteristic properties of the material. It was stated on page 1242 that "we define W_D as a fraction α' of the thermal energy $\alpha m\ \Delta H$ which is released during the shape recovery". There is no obvious justification, except in a purely algebraic sense, for the assumption that W_D can be expressed as a fraction of $\alpha m\ \Delta H$, therefore α' cannot be assumed constant. It has been observed experimentally[2] that in an initially partially-transformed Ti-50.3 at. pct. Ni alloy, a strain within the recoverable range is accommodated by reorientation and growth of the most favorably oriented martensite variants with respect to the applied stress. This occurs by stress-induced migration of twin boundaries. Therefore, the mechanical energy W_D is consumed in overcoming the internal frictional forces which oppose motion of twin boundaries. Accordingly, the parameter β defined by the author as $\beta = 1 - \alpha'$ (β was assigned a value of 0.90 - 0.95) is physically unfounded and thus cannot be considered as a characteristic property of the material. The author also did not show how β was estimated. Furthermore, general observations concerning the relative merits of the type of deformation (linear, flexural) cited by the author in reference (2) do not support the quantities assigned to the parameter β and the derivation of this parameter developed in the presented argument.

It should be realized that the feasibility of converting heat into mechanical energy in that system is essentially based on the effect of martensite transformation on the stress-strain-temperature behavior of the material as illustrated in the following: It is well known that there exists a one-to-one correspondence between shape recovery and the $M \rightarrow P$ transformation which occurs upon heating. For the purpose of this

discussion we assume that the shape memory element is fully transformed to martensite (thermally induced martensite) at the temperature of the cold reservoir T_o. The stress required to induce a given strain within the recoverable range at T_o where the martensite phase is thermodynamically stable is smaller than that at a higher temperature T within the M → P transformation temperature range. This behavior which gives rise to a net work output originates from two factors: (1) reversability of the deformation modes that accommodate a strain within the recoverable range,[2] and (2) increasing thermodynamic instability of the martensite phase as the temperature increases. Thus, the recovery stress developed gradually by the material as it recovers its shape originates from the driving force of the M → P. This force arises from the free energy difference between the two phases. Therefore, it is free energy, namely Helmholz free energy of the phase change that acts as a potential for work in that system.

Finally, we would like to point out that the data used by Golestaneh to calculate the efficiency are not based on experimental measurements of a particular alloy, but rather seem to have been chosen arbitrarily.

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1. A. A. Golestaneh, J. Appl. Phys. 49, 1241 (1978).
2. H. A. Mohamed and J. Washburn, J. Mater. Scien. 12, 469 (1977).

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