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Nitinol Engine Development

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NITINOL ENGINE DEVELOPMENT*

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OBJECTIVE

The objective of this project is to determine the feasibility of applying the shape-memory effect in certain intermetallic compounds (particularly "55-Nitinol") [1] to the conversion of low temperature heat energy to mechanical work by means of solid state heat engines. A primary milestone is the development of a prototype Nitinol engine on a scale suitable for powering a moderate-sized residential air conditioner with solar-heated hot water.

CONCEPT

It was readily established at the outset of this project that Nitinol wire could be used as the working element in a thermodynamic stress-strain cycle operating between hot and cold temperature baths to generate net work output. The essence of this project is to determine whether this phenomenon is merely a laboratory curiosity or whether it can be used in fact as the basis for production of practical working engines.

The basis for using Nitinol as a working medium of a heat engine originates in a "martensitic" phase transformation that gives rise to a mechanical shape memory effect. In order to use Nitinol to its best advantage, it is important to have a basic understanding of its properties and the mechanisms involved relative to the following performance criteria:

(1) Thermodynamic conversion efficiency;
(2) Work output per unit mass;
(3) Fatigue life.

Accordingly, the main thrust of the LBL effort has been directed toward determining, through theoretical and experimental investigations, whether Nitinol heat engines have the potential for achieving a cost of power production that is competitive with existing technologies that utilize small temperature differences (such as Rankine cycle turbines) at relatively low temperatures.

SUMMARY

Operational testing of the original LBL prototype Nitinol heat engine [2] established that Nitinol working elements can withstand, at relatively low levels of stress and strain, continuous cycling on the order of tens of millions of cycles without observable deterioration in the shape-memory effect. Subsequent tests using more efficient engine designs indicated that the cost of the Nitinol elements would not be the dominant factor limiting development of practical heat engines, and revealed some of the sensitive parameters of an engine cycle using a polycrystalline solid as the working medium. Recent work has concentrated on theoretical and experimental quantitative determinations of thermodynamic conversion efficiency, within the constraints of practical values of work output per cycle and fatigue lifetime. A key piece of experimental apparatus--an electronically controlled cycle simulator -- has been developed to carry out systematic measurements of work output and conversion efficiency.

TECHNICAL ACCOMPLISHMENTS

- An electronically controlled cycle simulator has been designed and constructed to facilitate the testing of Nitinol wire elements subjected to specific stress-strain-temperature cycles. This cycle simulator, which is shown in Fig. 1, can be preprogrammed to execute several types of thermodynamic cycles, such as isothermal, "stress limited", etc. Test parameters, which can be varied singly or in combination, include stress levels, stress rates, percent of elongation of the wire, temperature levels, heating and cooling rates, cycling speeds, etc. Efficiency values and work output as a function of these parameters will serve for the identification of the most useful thermodynamic cycle.

- The isothermal engine cycle, the one most commonly used in various Nitinol heat engines, has been studied in some detail on the cycle simulator. Repeatable performance data have been obtained over the range of test parameters investigated. Efficiency data were obtained for two ways of heating the Nitinol wire: a) by submerging the wire into hot liquid, and b) by passing a pulse of electric current through the wire. Analysis of these data is proceeding.

- A "stress limited" cycle is also being investigated. The advantage of this type of cycle is that the wire element can be subjected to lower peak stresses and higher elongations than in the isothermal cycle, and therefore a longer life of the wire may result.

- Mechanical properties of the material, particularly recovery stresses developed on heating, yield strengths, and their dependence on effects of cycling and previous heat-treatment, have been measured.

- A relationship has been developed which allows prediction of the recovery stresses as a function of temperature and strain given a certain set of experimentally measurable properties. A comparison between predicted and measured properties has been initiated.

- The thermal conversion efficiency has been studied with reference to an ideal cycle and a relationship has been developed that gives the efficiency as a function of a certain set of experimentally measurable materials properties.

- Transformation temperatures and their functional dependence on external strees, cycling, and previous heat-treatment have been measured.

- A determination of the effect of strain-temperature cycling on the microstructural features, on the fine scale of transmission electron microscopy, has been initiated.

- A method has been devised to determine the equilibrium transition temperature from the experimentally measured effective transformation temperatures.

- The latent heat of the transformation, which constitutes part of the heat input, has been determined from the observed rate of change of the transformation temperatures, using a modified Clausius-Clapeyron equation.

FUTURE ACTIVITIES

Contract Activities. The current contract has essentially ended at this time. The analysis of the efficiency and work output measurements taken to date with the cycle simulator will be completed and an attempt will be made to reconcile any discrepancies between the experimentally measured and theoretically predicted cycle performance.

Post-Contract Activities. Assuming continued support by other DOE Divisions, the experimental and theoretical program will proceed to determine practical limits of work output, conversion efficiency and wire lifetime using diverse types of thermodynamic cycles. In addition, experimental measurements will be made using new samples of Nitinol wires being fabricated under controlled conditions by the Naval Surface Weapons Center. A set of realistically achievable performance goals will be established using the results of these cycle measurements and our independently determined basic Nitinol materials properties. This will allow a realistic determination of the commercial potential for Nitinol engines, and those applications that are most appropriate for this technology.

PUBLICATIONS/REFERENCE

(1) "55-Nitinol": a homogeneous nickel-titanium alloy; the numerical prefix indicates the nominal percentage (by weight) of nickel. The alloy takes its name from the elements nickel, titanium and the initials of the Naval Ordnance Laboratory (Silver Spring, MD, now the U.S. Naval Surface Weapons Center) where the shape-memory properties were first observed.

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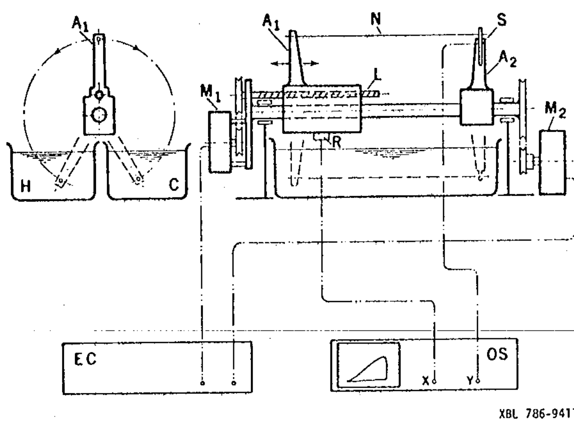

Fig. 1 Cycle simulator experimental system.

A test sample of Nitinol wire N is stretched between arm A_1, axially sliding on a rotating shaft, and arm A_2, solidly attached to the same shaft. Strain gage S measures the force exerted by the Nitinol wire N. The axial motion of arm A_1 is effected by a lead screw L which is driven by servomotor M_1. The position of the arm A_1 in respect to arm A_2 is transmitted by means of a potentiometer readout R to the oscilloscope OS as a horizontal deflection of the electron beam. The vertical deflection of the beam is effected by an amplified signal from the strain gage S. The stress-strain diagram displayed on the oscilloscope screen is recorded by means of a video camera and stored on a video tape.

The transfer of the Nitinol wire N back and forth from the hot reservoir H and cold reservoir C is effected by a 300^{o} rotation of the shaft which is driven by the servomotor M_2. The clockwise and counterclockwise rotation of the shaft as well as of the lead screw L are electronically controlled by two linear servoamplifiers in the electronic control system EC. The sequence of events, of positions, and of the speed of motion is programmable to permit simulation of a desired thermodynamic cycle.

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