Study and Design of Nitinol Engine

Sanket M. Lahamge[1], Saurabh P. Nikam[2], Manoj R. Bhingare[3], Akash S. Bachhav[4],

Prof. Kishor R. Kumbharde[5]

[1,2,3,4]BE, Department of Mechanical Engineering, S.N.D. COE & RC, Yeola, Maharashtra, India
[5]Asst. Prof. Kishor R. Kumbharde, Dept. of Mechanical Engineering, S.N.D. COE & RC, Yeola, Maharashtra, India

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Abstract - *A new design is proposed for thermo mechanical energy conversion by use of shape memory wires. A prototype of this new heat engine has been built; it converts low-temperature heat into mechanical work .This work presents a novel approach to arranging SMA (NITINOL) wires into a functional heat engine. Notable contributions include the design itself, a preliminary analytical model and the realization of a research prototype; thereby, laying a foundation from which to base refinements and seek practical applications. Shape memory alloys are metallic materials that, if disfigure when cold, can forcefully recover their original, "memorized" shapes, when heated. The proposed engine consists of set of NITINOL wires stretched between two crankshafts, synchronized to rotate in same direction. Cranks on the first crankshaft are moderately longer than cranks on the second. During operation, the engine is positioned between two distinct thermal reservoirs such that half of its wires are heated while other halves are cooled. Wires on the hot side try to contract, driving the engine in the direction that relieves the heat-induced stress. Wires on the cold side soften and stretch as engine rotates. Because the force generated during heated rehabilitation exceeds that required for cooled deformation, the engine is capable of generating shaft power. Limited experimental measurements of shaft speed were performed. An analytical model of the engine forecasts that the maximum output power for the prototype, under test conditions, should be 0.75 W. Prospective applications may involve the conversion of waste heat into shaft power.*

***Key Words*: Nitinol, NiTi, Titanium Nickel, NiTi based alloys, Superelaticity, Shape Memory Alloy (SMA).**

1. INTRODUCTION

Most heat engines make use of the liquid-vapour phase transformation, because the addition and withdrawal of the latent heat creates big changes in volume which may be used to produce work. The change of length of wires may in principle be used for the same cause. However, for a long time such length changes had to depend on the minimum thermal extension of wires and not much work could be produced in that way. This has changed with the appearance of shape memory materials, in which a martensitic austenitic phase transition creates strains up to 10%. While this is still Nitinol compared to the 20.000 % volume change of liquids upon evaporation, the forces exerted by the solids are considerable. Therefore, from their beginning, shape memory alloys have been used to construct heat engines. So far, however, nothing much more than toys have been built. In the present paper we present details of a prototype engine that generates a torque of 15 Nm and revolves with 20 rad/min. Revealed and explored within, is a novel scheme for arranging shape memory alloy (NITINOL) wires into a functional heat engine. This work chronicles the design, evolution and subsequent realization of a research prototype; thereby, laying a foundation from which to base refinements and seek practical applications. Notable contributions of this effort include:

- The introduction and evolution of an engine design that uses straight wire in place of coiled springs
- An analytical model to simulate presentation of the proposed engine
- A exhibited working prototype

1.1 Objectives

As stated, this machine is only valuable in cases where thermal energy is abundant and cheap; Evidence of thermal energy is the shimmering look of a parking lot in the sun, or the steam avoidance from a utility vent. Both cases represent untapped or otherwise wasted resources. Volcanoes are evident thermal sources, so are hot springs and some undersea vents. Many industrial facilities generate waste heat. Then there are forms of energy that are more moveable, but easy to convert to heat. Any temperature difference is a probable source of thermal energy. It is nearly infinite and often free. There are expenses related with equipment and complications with channeling heat into the engine. Then there are problems of energy density and storage; running the prototype requires a larger temperature difference than is commonly available between outside air and the average basement. The technology is not prepared to revolutionize the power generating industry, but there is possible, and beginning to exploring that potential is the motivation for this work.

1.2 Methodology

The prototype consists of a set of NITINOL wires stretched between two synchronized crankshafts. When heat is applied, the engine rotates. Any heat source, of enough temperature, may be used. Unfortunately, the low thermal efficiency of this type of device transfers its use to applications where thermal energy is abundant and inexpensive. For those applications, this machine's simplicity and flexible power necessities could make it an attractive alternative to existing sources of shaft power.

1.3 Ni-Ti Material

Nickel titanium, also called as **Nitinol** (part of shape memory alloy), is a metal alloy of nickel and titanium, where the two elements are present in roughly equal atomic percentages e.g. Nitinol 55, Nitinol 60. Nitinol alloys show two closely related and unique properties: shape memory effect (SME) and superelasticity (SE; also called pseudo elasticity, PE). Shape memory is the ability of nitinol to undergo misshaping at one temperature, and then recover its original, undeformed shape upon heating above its "transformation temperature". Superelasticity occurs at an inadequate temperature range just above its transformation temperature; in this case, no heating is necessary to cause the undeformed shape to recover, and the material exhibits extensive elasticity, some 10-30 times that of ordinary metal.

Table -1: Physical Properties of Nitinol[2]

Density	6.45gms/cc
Melting Temperature	1240-1310° C
Resistivity (hi-temp state):	82 uohm-cm
Resistivity (lo-temp state)	76 uohm-cm
Thermal Conductivity:	0.1 W/cm-° C
Heat Capacity	0.077 Cal/gm-° C
Latent Heat	5.78 Cal/gm; 24.2 J/gm
Magnetic Susceptibility (hi-temp):	3.8 uemu/gm
Magnetic Susceptibility (lo-temp):	2.5 uemu/gm

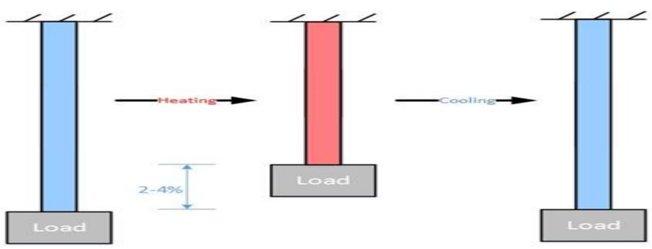

Fig. -1: Work cycle from heating and cooling Shape Memory Alloy[4]

Table -2: Mechanical Properties of Nitinol[2]

Ultimate Tensile Strength	754 - 960 MPa or 110 - 140 ksi
Typical Elongation to Fracture	15.5 percent
Typical Yield Strength (hi-temp):	560 MPa, 80 ksi
Typical Yield Strength (lo-temp):	100 MPa, 15 ksi
Approximate Elastic Modulus (hi-tem):	75 GPa, 11 Mpsi
Approximate Elastic Modulus (lo-temp):	28 GPa, 4 Mpsi
Approximate Poisson's Ratio	0.3

1.4 History

The word Nitinol is extract from its composition and its place of discovery: (*Ni*ckel *Ti*tanium-*N*aval *O*rdnance *L*aboratory). William J. Buehler along with Frederick Wang fined its properties during research at the Naval Ordnance Laboratory in 1959. Buehler was attempting to make a better missile nose cone, which could resist fatigue, heat and the force of impact. Having found that a 1:1 alloy of nickel and titanium could do the job, in 1961 he presented an illustrative at a laboratory management meeting. The sample, folded up like a concertina, was passed around and flexed by the participants. One of them applied heat from his pipe lighter to the sample and, to everyone's surprise; the accordion-shaped strip stretched and took its previous shape. [1]

While the potential applications for nitinol were realized instantly, practical efforts to commercialize the alloy did not take place until a decade later. This delay was largely because of the remarkable difficulty of melting, processing and machining the alloy. Even these efforts confront financial challenges that were not readily overcome until the 1980s, when these practical difficulties finally began to be resolved. The unearthing of the shape-memory effect in general dates back to 1932, when Swedish chemist Arne Ölander[6] first observed the property in gold-cadmium alloys. The same effect was detected in brass in the early 1950s. [1]

2. METHODS OF MANUFACTURING NiTi ALLOY

Forming and preparation for the manufacture of Nitinol components with the desired SME is of great importance. As far as fabrication of NiTi alloys is concerned, the two methods systematically used involve specific casting methods or powder metallurgy methods followed by other mechanical processes such as Hot or Cold Working, Surface

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Treatments and Heat-Treatments ,with the latter having an significant role in the shape setting of the Nitinol.[4]

2.1 Cast-Produced Ni-Ti

The first method to be discussed involves producing the NiTi component via a casting process. The raw materials must be of as high purity as possible, since the existence of impurities and non-metallic elements can seriously affect the unity and homogeneity of the alloy, thus create uneven composition distribution and change essential properties of the material. More specifically, the techniques that are used include Vacuum Induction Melting (VIM), Vacuum Arc Melting (VAM) and Electron Beam Melting (EBM). The basic results, in terms of material and properties.[3]

2.2 Ni-Ti Produced via Powder Metallurgical Methods:

The second method that is used to fabricate the NiTi alloys involves several powder metallurgical methods. In this case a variety of different techniques can be used in order to produce the NiTi alloy using powders of Ni and Ti elements as the starting material which is produced using rapid solidification processes such as Gas Atomization. The powder used may also be prealloyed which improves the composition homogeneity of the final product. The basic steps to be followed in most methods contain; a) Powder Blending, b) Mold Compaction and c) Sintering in a furnace. To begin with, the first step invloves blending the desired powders in order for a uniform distribution of each components' ingredient to be achieved (this step is used for elementary powders since in prealloyed ones the appropriate proportion is already present in each of the particles). Furthermore, after getting the desired distribution, the parts are consolidated via high pressing methods in molds and dies which consequently create very densified, but never the less still not completely compact, components said to be in a green state. At this point the components are only prepared for handling resolutions and any additional loads applied can take the component apart. The third step, intended to be used in order to achieve the density required for the actual component to be usable, includes heating the material in a sintering furnace at a temperature high enough (but bellow melting point of the materials) so diffusion of each of the ingredients from one particle to the other can take place. More specifically, with the increase in temperature, atomic diffusion leads to the formation of necks between the particles which grow larger as time passes and bring about the desired density increase. It is important to note that the driving force for densification is the decrease of Gibbs free energy due to the decrease in surface energy because of the formation of the neck that has a shape which has less surface energy than the almost spherical spheres used in the first place. Additionally, the more dense and with more uniform pores the material is before sintering, the faster is the porous destruction since in this case particle boundaries are closer to each other so the diffusion distance is shorter.

In general, the fundamental benefits that derive from this method include very good composition homogeneity throughout the material compared to those acquired via vacuum melting techniques and the production of NiTi alloys with great porosity, a property that is critical for the biocompatibility of NiTi in biomedical uses. In terms of specific techniques that can be used to produce NiTi alloys, they can be divided into two major categories based; Conventional processes and Rapid Manufacturing processes.[3]

3. LITERATURE REVIEW

SMA heat engines convert heat energy into mechanical energy using shape memory alloy material. The state of the art in SMA heat engines has been resolute by a systematic patent search. The engine concepts can be divided into four categories: offset crank engines, turbine engines, field engines and miscellaneous engines. While reviewing patents, it is found that convenient to separate the concepts into six categories based on their driving mechanism. These rough differences as the engine type: Crank pulley, field, and swash plate, reciprocating and sequential. Descriptions of each type are involved in the following sections. Journal articles related to crank and pulley engines were reviewed to match the patent results. The prototype is a crank engine; accordingly, the crank section is conversed in some detail.

3.1 Crank Engines:

Crank engines convert the reciprocating linear motion of an SMA actuator into constant rotary motion, by eccentrically connecting the actuator to the output shaft.

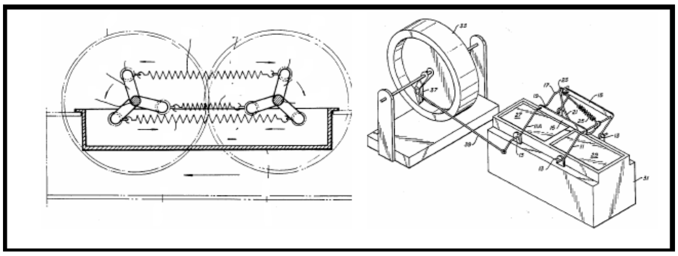

Fig -2: Patented crank engines

3.2 Pulley Engines:

Pulley engines use constant belts of SMA wire as the driving mechanism. A pulley engine can be unsynchronized or synchronized.

Fig -3: Unsynchronized Pulley Engine

3.3 Field Engines:

This type contains engines that work against a recovering force, such as a gravitational or magnetic field

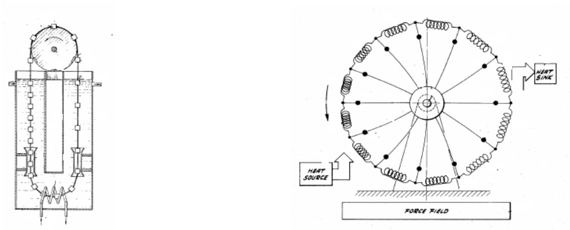

Fig -4: Field Engine

3.4 Swash Plate Engines:

Swash plates are related to cranks except that their axis of rotation is unevenly parallel to the direction of the applied force, instead of perpendicular as for cranks.

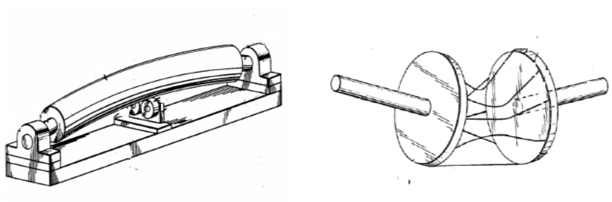

Fig -5: Swash Plate engine

3.5 Reciprocating Engines:

Reciprocating engines work linearly, in a back-and-forth approach, as different to cyclically. SMA's are best suited for axial strain and regaining.

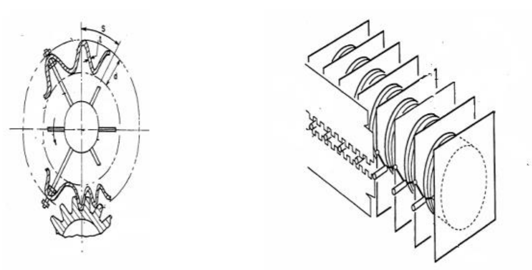

Fig -6: Reciprocating Engine

3.6 Sequential Engines:

Sequential engines move with lesser, powerful steps, which sum to considerable displacements. They work like an inchworm, spreading the front part by a lesser step and then pulling the back part along. With the back part adjacent, the front part can spread again. Figure is a hollow, tubular gear, made from SMA

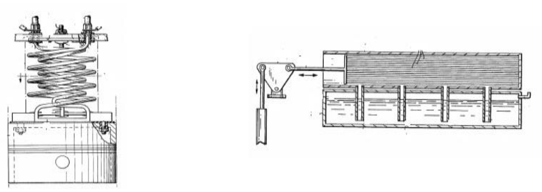

Fig -7: Sequential Engines

4. CONCLUSION

A novel design has been proposed for creating a heat engine from shape memory alloy contractile wire. Following a review of alloy behavior and the prior art of SMA engines, it was suggested that this design advances that art. Subsequent analysis and creation of a working prototype helped to substantiate the claim, though additional experimentation will be needed to make a conclusive determination.

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