Shape Memory Alloy Actuator for the Tool End-Feed in Lathe Machining

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***Abstract*—A shape memory alloy (SMA) is an intermetallic compound able to recover, in a continuous and reversible way, a predetermined shape during a thermal cycle while generating mechanical work. In this paper, its use in developing an actuator for a machining process is investigated. The actuator is to drive the tool cross feed into an aluminium workpiece in a finishing lathe operation, and PID control is implemented to the power supplied to the SMA, thereby providing the position control. This study covers the first stage of the mechatronics system design and development of the actuator.**

Keywords-shape memory alloys; sma; smart actuators; machining actuators.

I. Introduction

A shape memory alloy (SMA) is an intermetallic compound able to recover, in a continuous and reversible way, a predetermined shape during a thermal cycle. SMAs have been widely used over recent history in applications ranging from static applications such as fasteners, couplings and electrical connectors, to the more recent dynamic applications such as actuators. The early dynamic applications were based on ambient temperature-controlled devices such as valves and thermostats. Over time, the inclusion of electrical control systems opened the way to more complex applications in various engineering fields, where the shape could be manipulated for a desired response. SMAs provide prominent advantages over other actuation methods that have led to their continued and inquisitive research over the years. These benefits mainly include versatility, minimal noise, space and cost [1]. Hence, their wide use in actuating and/or sensing applications. Even with all these benefits there are some significant drawbacks, such as efficiency concerns, control complexity and slow response, which give the conventional hydraulics and electric motors the edge [1].

In automated machining, electric motors are typically used as the actuators for driving tool holders. Motors are generally noisy, costly, and voluminous. They also create additional problematic variables such as vibrations. When subjected to certain thermal cycles, SMAs are able to generate mechanical work by recovering a predetermined shape. This process is continuous and reversible. Thus, an SMA actuator can be developed to drive a tool holder in a machining operation. In this work, the use of SMA to develop an actuator for lathe machining cross feeding will be investigated.

A typical SMA actuator is generally made up of several parts: the mechanical system, the SMA element, a bias element able to restore the deformed shape of SMA element, an electric control unit and a set of fixtures used to integrate the actuator into the mechanical system. These components were individually designed and/or selected. The mechanical structure must be designed and constructed, an efficient SMA element is selected based on the required force and motion, and an accurate position control system is developed. Based on the design, an SMA actuator system is to be constructed and experimentally tested. The actuator is to drive the tool cross feed into an aluminium workpiece for a lathe machine during finishing turning operation.

This study covers a mechatronics system design and development, with manufacturing application and a control system aspect, as well as materials.

II. Literature Review

A. Thermal Cycle

The SMA thermal cycle involves a crystallographic transition between the low temperature phase, martensite, and the high temperature phase, austenite. SMAs show a thermal hysteresis during transformations between the two phases. This hysteresis means the transformations from martensite to austenite and vice versa never coincide, giving the four distinct temperatures; where M_s and M_f represent the martensite start and finish temperatures while A_s and A_f are the austenite start and finish temperatures, respectively [2].

As seen in Figure 1, the shape memory element is initially in its martensite phase, which is macroscopically a relaxed state. The temperature is equal to or lower than M_f. As it is heated, the austenite phase will begin to form at A_s temperature. The percentage of austenite increases with increase in temperature. This causes the element to physically compress until the full austenite phase is reached at A_f temperature. The temperature of the element is now lowered and the martensite phase begins to form at M_s temperature. The element gradually reverts to the initial relaxed shape as the temperature is decreased to the M_f temperature.

Presented at the 4th Robotics and Mechatronics Conference of South Africa (ROBMECH 2011)
23-25 November 2011, CSIR Pretoria South Africa.

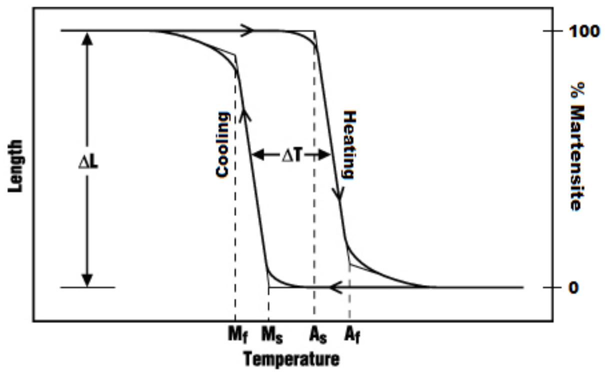

Figure 1. SMA thermo-mechanical hysteresis [1]

B. Shape Memory Alloy Actuators

Shape memory alloys are able to generate mechanical work during the phase transformation. Development of SMA actuators involves precise consideration of two parameters, the force and the displacement, produced during a heating/cooling cycle. The thermal and mechanical hysteresis are one of the factors affecting (and limiting) the precision control of SMA actuators [1]. An SMA actuator only provides force/displacement in one direction when heated. Thus, a bias (return) element must be used to restore the deformed shape after cooling. This characteristic of SMAs is known as the one-way shape memory effect. Most bias mechanisms are implemented with a conventional spring, load force or another SMA. The SMA element, usually in the form of a wire or spring, coupled with a bias element, is generally linked to an output shaft to transfer movement outside the device. The movement may be linear or rotational. Various researchers have designed and developed unique actuators using SMAs. Nespoli, Besseghini, Pittaccio, Villa, and Viscuso [1] provide a detailed review on actuators developed by various researchers and companies.

SMA actuators have a high potential for miniaturization due to high power-to-weight ratio compared to other light-weight technologies. Further advantages to the use of SMA actuators include, the simplicity of mechanism, cleanliness, silent actuation, seclusion, sensing ability and low driving voltage. SMAs also have some weak points, such as, a low energy efficiency (<10%), a strong relationship between the strain operation range and fatigue life, fairly slow response speed and nonlinear behavior [1].

The most conventional forms of shape memory material are wire, ribbon or strip, and spring. Wire is the most common and it provides the maximum amount of force per cross sectional area, matched only by ribbon form [2].

C. Heating and Cooling

Shape memory alloy actuators require a heating/cooling system as their operation is based on temperature changes. The heating can be achieved through three main methods: electric heating (Joule heating), heating element or ambient heating. Joule heating requires the current to be fed directly through the element. Though it requires the element to be electrically isolated and a large current supply due to the SMA resistivity, the simplicity of Joule heating makes it the most commonly used method. A separate heating element overcomes this disadvantage as small currents can be used with a suitable voltage to provide enough power to heat the material. Though this may seem favourable, it is not very efficient and the mass of the actuator is increased as additional components and space must now be present. Ambient heating means the SMA element operates according to the surrounding temperature. This method is most effective for applications where the SMA is used as a sensor, without any electric connectors [3].

Cooling of the SMA element can also be done using various methods but the effectiveness is application dependent. Ambient cooling can be used where the environment temperature is below the transformation temperature range and speed requirements are not critical. However, for applications where cooling speed is a critical, an active cooling element must be used to lower the temperature quickly. This can be implemented using heat sinks, forced convection (fan), or a moving liquid (oil or water). It must be noted that systems where cooling elements are continuously present require higher heating currents [3]. Furuya, and Shimada [4] used water immersion as a cooling method, which resulted in the SMA wire cooling 10 times faster than an ambient SMA wire. Asada, and Mascaro [5] used flowing water around the wire, which could be run only when the wire needed to be cooled. However, the main disadvantage of such systems is the need for pumps or compressors with sealing systems, and the increase (up to a factor of 20) in total power consumption [6].

The thermoelectric effect (Seebeck-Peltier) has also been researched as a means of heating/cooling and improving dynamic performance of SMA actuators. Romano, and Tannuri [6] made use of a thermoelectric tablet within a heat sink in permanent contact with the SMA wire. This eliminates the need for complex accessories like pumps or compressors but still increases power consumption as the wire requires additional heat to overcome the continuous cooling. Peltier elements provide an effective means of achieving active heating and cooling. The heating or cooling occurs depending on the polarity of the voltage fed into the Peltier element. As with heating/cooling elements, this increases the mass and space required for actuator unit [3]. The main advantage of this system is the heating and cooling is provided through the same source and is not applied on the material simultaneously, but the contact surface area with the SMA tends to be insufficient resulting in poor efficiency.

Another method that combines heating and cooling involves control of the medium in which the SMA material lies, and adjusting it between martensite and austenite temperatures. The main disadvantage of this method is the high operating temperature range. This in turn involves the complexity of building a precisely controlled heat exchanger [2].

As mentioned, hysteresis and nonlinearity of SMAs poses difficulties in applications which require the displacement of actuator generating linear motion. Therefore, in such applications, most SMA actuators are on/off controlled with only two determined positions of movement. This is achieved by maintaining the austenite phase through constant heating and maintaining the martensite phase through constant cooling. To achieve controlled linear motion with variable displacements, a control system based on a precise model must be implemented.

D. Control

The main challenge in shape memory alloy actuator control is precisely regulating the element temperature for position control. The modelling and consequent control of SMAs remains challenging primarily due to the nonlinear hysteretic thermo-mechanical behaviour. The hysteresis behaviour can lead to a loss in position precision with up to a 50% error [7]. Various methods of control have been applied to SMA actuators. Sittner, et al. [8] proposed phase transformation kinetic and three-dimensional models for the thermo-mechanical behaviour of SMAs. These complex models, though precise, require finite element code computation which is not suitable for real time control [9]. Majima, et al. [10] used a feedforward neural network which obtained its command using a Preisach model for the hysteretic effect. Dutta, et al. [11] used a similar feedforward scheme but utilised the Duhem differential hysteresis model. These hysteretic models make controller synthesis complicated and time consuming requiring substantial computational time. Simpler and classical models have also been applied to SMA actuators and improved by various researchers. DaSilva [12] used variations of linear proportional integral derivative (PID) control approaches. Ahn, and Nguyen [13] developed a control algorithm that tuned the parameters of a PID controller thereby producing an adaptive fuzzy PID controller. The use of empirical information for fuzzy control provides a convenient method for constructing nonlinear controllers [13]. PID controllers are often tuned with linear models which are preferred in industry [9]. Gharaybeh, and Burdea [14] used pulse width modulation (PWM) to vary the average current flowing into the shape memory element, thus controlling its thermoelectric state.

E. Metal Cutting

Since shape memory alloy actuator is designed to drive the tool holder for a machining (turning) operation, it is important to understand the process of metal cutting and the forces involved. The tool is usually wedge-shaped and the removed material is sheared in the form of a chip. When cutting occurs, three main forces act on the tool [15]:

- *Tangential force* – acts in a direction tangent to the revolving workpiece. This is the workpiece resistance to rotation. It accounts for 99% of the total power required by the operation.
- *Longitudinal force* – acts parallel to the workpiece longitudinal axis. This force opposes the tool’s longitudinal feed. It is 50% of tangential force and accounts for 1% of the total power required by the operation, as feed velocity is low compared to the workpiece rotational velocity.
- *Radial force* – acts in a radial line from the centre of the workpiece. It is the smallest of the forces, being 25% of the tangential force.

The resultant of these three components is the total force acting on the cutting tool. The radial force is of most concern when designing the actuator for realising the cross feed of the tool holder. The actuator must be sufficiently stiff to overcome this force and drive the tool into the workpiece.

Cutting speed, tool feed and depth of cut are the major factors affecting the turning operation. These cutting conditions are the root parameters in calculating turning performance parameters such as cutting force and power. The cutting force is calculated as,

$$\mathrm{F_c = k_c \times a_p \times f} \tag{1}$$

where k_c is the specific cutting force, a_p is the depth of cut, and f is the feed per revolution.

The specific cutting force of aluminium alloys with Si < 13% and Si > 13% as 500-700 N/mm^2 for a new tool and 700-1050 N/mm^2 for a worn tool, respectively [16].

In finish cuts for aluminium using high-speed steel toolbit, the cutting speed is 93 m/min, feed is 0.13-0.25 mm/rev, and the depth of cut is up to 2 mm [17].

III. Design and Development

A. Preliminary Design

The actuator must be designed and constructed with the following considerations:

- Cutting force must be overcome.
- Linear displacement.
- Stroke must achieve the required depth of cut.
- Uniform current supplied to SMA element.
- Wire configuration must maximize the heat transfer surface area.
- Wires must be attached such that they can be easily replaced, also allowing for a range of diameter wires to be used, making the actuator versatile over a range of forces.
- Components must be easy to assemble and disassemble for easy accessibility and maintenance.

The physical structure must overcome the total cutting force while the actuator wire only needs to overcome the radial cutting force. By calculating the typical cutting force in turning an aluminium workpiece and taking 25% of the result, the radial force can be approximated. For this to be calculated, cutting conditions must be selected. Although, most of the conditions are machine and tool dependent, some preliminary values were selected as a starting point for force calculation. From the researched data values collected, the following finish cutting conditions were selected: depth of cut 1 mm, feed 0.25 mm/rev, and specific cutting force of aluminium alloys 1050 N/mm^2. The cutting force from (1) was calculated as 265.5 N, approximated to 300 N. Thus, the radial force that the actuator wires must to overcome was 75 N.

Flexinol shape memory alloy actuator wires, manufactured by Dynalloy, were selected. Flexinol wires are composed of nickel-titanium. Dynalloy provides a range of Flexinol wire sizes with diameters from 0.025 mm to 0.508 mm. The Flexinol wires are available in two categories, HT (high temperature) and LT (low temperature). The main difference being that HT wires have an austenite finish temperature of 90°C, while LT wires have an austenite finish temperature of 70°C. The most efficient wire was selected based on the power requirements. Smaller diameter wires have a higher surface to volume ratio giving them better heat transfer characteristics. Though smaller diameter wires provide higher performance, the large number of wires required in parallel increase the complexity of the actuator and the power requirements will thus be too excessive. The 0.381 mm diameter wire was therefore selected to maintain a high efficiency and minimize the bundle size.

A preliminary requirement was to achieve a thrust force and power similar to that on small-to-medium manufacturing machines. A single Flexinol wire cannot produce the required force, thus a wire bundle must be used to improve the force capabilities. By assembling the wires mechanically in parallel a greater force can be achieved. The total force of the actuator is expressed as

$$F_{total} = F_{bias} + F_{net} \tag{2}$$

where F_{bias} is the bias force used to restore the actuator to its martensite state and F_{net} the force exerted by the actuator. The wire manufacturers recommend an approximate bias force of two-fifths the total load. Applying the required force of 75 N, the total force was calculated from (2) as 125 N and the bias force as 50 N. The selected 0.381 mm wire is rated to provide a pulling force of 2250 g. To achieve the required force, approximately 6 wires were required in the bundle.

The stroke determines the movement of the actuator shaft, which in turn is the depth of cut. The manufacturer approximates a 3% to 4% stroke with a normal bias spring setup. The appropriate wire length must be selected to achieve the desired stroke. The stroke was selected based on the selected depth of cut of 1 mm. Thus, the wire length should have a minimum length of 33.3 mm.

The cycle rate is the amount of time needed for the shape memory element to contract and relax. The contraction is solely due to heating and the relaxation is solely due to cooling. The cycle rate is thus entirely dependent on the rate of heating and cooling of the Flexinol wire. Direct electric heating was the chosen method as it is the most advantageous and convenient method to implement. The 0.381 mm Flexinol has a rating of 2.25 A of current for the wire to contract within one second. For the entire bundle to contract within one second, six times this current (13.5 A) is required. The selected Flexinol wire (0.381 mm) takes 10.5 seconds and 8.8 seconds for the low temperature wire and high temperature wire to relax, respectively. The high temperature wire was selected due to the shorter cooling time.

The wire will be quickly heated to contract to a defined length and held in that position for a period of time. This requires control of the driving current, with a large current to heat the wire and a smaller current to keep it hot without overheating it. Closed loop position control will be implemented where PID control is applied to a PWM signal duty cycle. The PWM signal is the input of a MOSFET switching circuit which controls the power supply to the SMA wires, controlling the heating and the subsequent wire contraction and displacement of the shaft. Based on the feedback, the PWM duty cycle will be varied accordingly to achieve and maintain the desired position. Feedback will be provided through displacement, current and temperature sensors. The relation between input power and output position will be used to estimate the power needed to keep the actuator in the desired position. The control system is depicted in Figure 2.

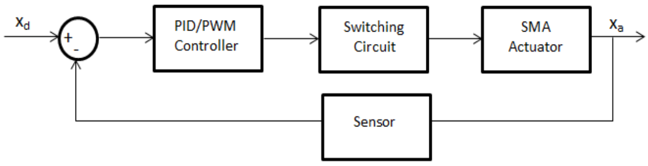

Figure 2. Actuator control system.

B. *Final Design*

Based on the preliminary design, a concept was developed then improved and finalised. The design involves transferring the force and displacement produced by the SMA wires to a shaft.

The structure design involves having one end of the SMA wires attached to a stationery block and the opposite end attached to a moveable block. The shaft is fixed on the moveable block and extended through the stationery block which also acts as guide. The entire configuration is fixed onto a firm base block. The structure design is depicted in Figure 3. The moveable block moves along a fixed shaft protruding from the base block. A compression gas spring is attached to the blocks as shown in Figure 3 to provide the bias force.

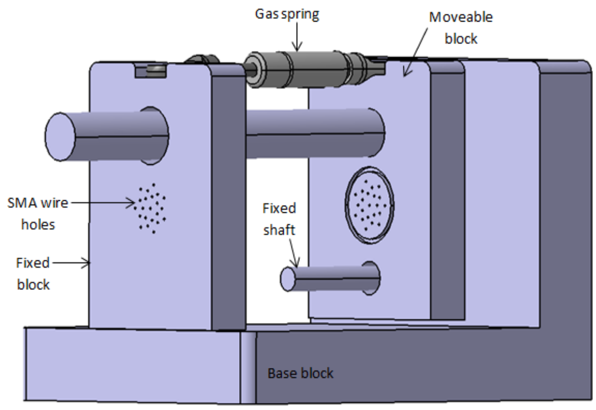

Figure 3. Actuator structure final design.

A bundle of 6 Flexinol 0.381 mm actuator wires are fixed in a circular pattern onto the blocks by vented screws and crimped. Camshaft bushes are selected to provide frictionless movement of the shafts.

The actuator design is such that the length of the wire is restricted by the length of the gas spring, thus the gas spring selected could not be shorter than the minimum length of 33.3 mm if the required stroke was to be achieved. Stabilus Lift-O-Mat spring is used to provide the bias force and linear motion. The gas spring has a force of 50 N, an extended length of 200 mm and a stroke of 60 mm. Thus, the wire length is 200 mm and the stroke was 6 mm.

The switching circuit is responsible for varying the power being supplied to the wires. A MOSFET is used as the switching device, which is controlled by a logic-level signal. The circuit schematic is shown in Figure 4.

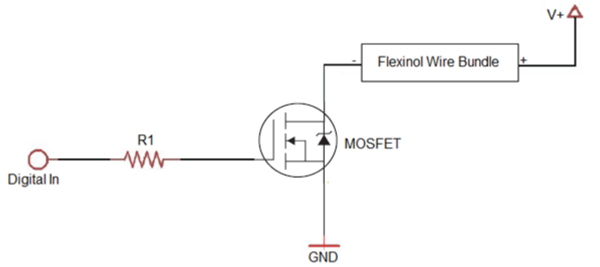

Figure 4. MOSFET switching circuit

A current sensor will monitor the current being supplied to the SMA wire bundle. A Honeywell Micro Switch CS series linear current sensor will be selected. The sensor will incorporate a linear output Hall effect transducer that outputs a percentage of the supply voltage in proportion to the sensed current.

A thermocouple in contact with the wires will be used to monitor the temperature. An RS J-type welded tip PTFE insulated thermocouple will be selected. The thermocouple has a sensing tip of 0.2 mm and a temperature range of -50°C to 260°C.

Displacement will be measured using a linear potentiometer. The Opkon LPT linear motion transducer is selected. The transducer has a measuring stroke of 50 mm.

Force will be measured using a force gauge. The force gauge will be attached to the moveable block and the force will be recorded as the actuator wires are activated.

The signals from the sensors must be fed into software for data processing and analysis. The data acquisition (DAQ) module is the bridge that links the sensors to software. The National Instruments Compact DAQ (NI cDAQ) was selected. The NI cDAQ consists of a chassis with slots for hot-swappable I/O modules with integrated signal conditioning. Four modules were selected: NI 9211 thermocouple input module for temperature measurements, NI 9215 analog input module for receiving the signals from the sensors, NI 9263 analog output module for providing power to additional system peripherals, and NI 9472 digital output module for generating PWM signals and switching tasks. The NI cDAQ is connected, via USB, to a PC running National Instruments Labview software. The data collection, PWM generation and PID control is implemented in within the Labview software.

The entire system block diagram is depicted in Figure 5 below.

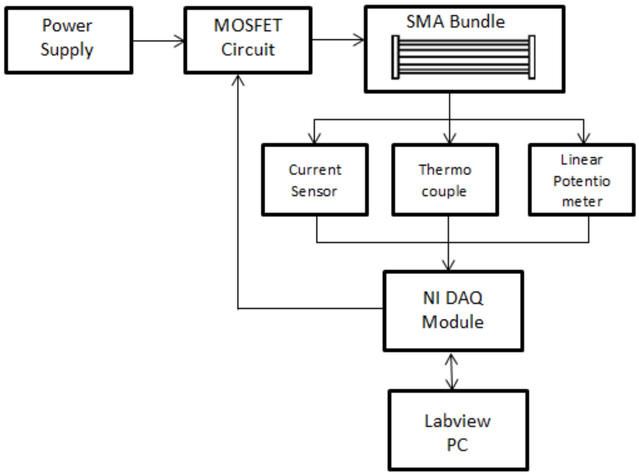

Figure 5. Actuator system block diagram

IV. Conclusion and Future Work

Research suggests shape memory alloy actuators may have significant advantages over conventional actuators. The purpose of this research was to investigate whether these advantages can be applicable in machining and provide an alternative method to drive the tool-end feed.

Based on the foundation set out on this paper, future work involves developing the experimental setup to determine the performance of the actuator. The experimental setup involves the fabricated actuator structure with sensors fitted, connected to a PC running Labview. Tests involve implementing open-loop and closed-loop position control, and graphing the actuator's response. Finally, the actuator will be fitted onto a lathe machine behind the toolpost, by means of an adapter plate, and a finishing turning operation will be performed on an aluminium workpiece. Based on the results, the advantages and disadvantages of SMA actuators in turning processes will be evaluated and the feasibility of their use determined.

Acknowledgment

Particular thanks to the DST/TIA for the financial help of the current work.

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