TEMPERATURE MEASUREMENT OF SHAPE MEMORY ALLOY WIRES WITH SPOT WELDED THERMOCOUPLES

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ABSTRACT

Shape memory alloys (SMA), materials which convert heat energy (usually through Joule-heating) to mechanical energy, provide compact and effective actuation for a variety of mechanical systems. They are attractive options to be used in an automotive context as lightweight, scalable actuators that have a very high power/weight ratio. However, the materials must be protected from overheating during actuation. This leads to the need for direct temperature measurement methods for use either in direct temperature feedback controllers or indirectly for validating models of the material’s thermo-electric behaviour. Developing a proven experimental method for measurement of wire temperature is the goal of this work.

Various methods were applied and tested, including contact methods using thermocouples and thermistors, as well as non-contact infrared thermal imaging. The latter two are briefly described, while the paper focuses on our results achieved using thermocouples. Several different methods of thermocouple attachment are also investigated: spot welding, adhesive fixturing, and mechanical contact methods. A series of experiments and theoretical calculations conducted with 500μm diameter Flexinol wire showed that the spatial offset of the thermocouple leads and the resulting ohmic drop due to current flowing in the wire causes measurement errors in the thermocouple readings. Experimental and analytical methods are proposed to compensate for these errors, resulting in a set of recommendations for thermocouple-based temperature measurement of current-carrying wires.

Keywords: Shape Memory Alloy, Temperature Measurement, Thermocouple, Actuator.
INTRODUCTION

Shape memory alloy (SMA) actuators can be an ideal substitution for more traditional actuators (e.g., magnetic solenoid) due to their unique “shape memory” property. Light, scalable and having a high power/weight ratio, these actuators are promising in a variety of mechanical systems, particularly in the automotive industry. SMA actuators rely on a reversible, thermally-driven phase transformation which occurs as the alloy temperature is cycled between approximately 30°C and 100°C. The difference in mechanical properties of the two material phases can be used to do mechanical work. Notably, the NiTi SMA commonly used for actuation has a relatively high electrical resistivity, enabling the design of electro-mechanical actuators using SMA. An actuator design typically comprises a biased wire made of SMA, which contracts in the presence of an electrical current, and expands as it cools when the current is removed. The actuator behaviour, then, can be roughly divided into the thermo-electric heating response which converts electrical to thermal energy and generates the phase transformation, and the thermo-mechanical phase transformation which causes the motion.

Research on SMA actuators has focused primarily on modelling and compensating for the nonlinear thermo-mechanical behaviour of the material, with relatively little attention being brought to bear on the heating aspects. This, despite the fact that the material must be protected from overheating during actuation in order to avoid degrading or destroying performance. This lack of attention is perhaps due in part to the inherent difficulty in measuring the temperature of the SMA wires: they are typically less than 500 μm in diameter and can carry currents on the order of several amperes.

In this work, we describe our efforts to experimentally investigate appropriate temperature measurement techniques, and the development of reliable thermocouple-based methods. Our end use for the measurements is in the laboratory validation of thermo-electric models for SMA wire heating, so a reasonable level of accuracy and precision is desirable. In addition, however, the eventual approach may also be used in direct temperature measurement in an end application, for direct temperature control of the SMA actuator.

The Background section describes the problem as evidenced by the efforts of other researchers in the area, and briefly describes our investigations with thermistors and non-contact Infrared (IR) sensing. We then provide experimental and analytical evidence of the error induced in spot-welded thermocouple readings due to current flowing in the wire under measurement. Three methods are proposed to compensate for these errors: current reversal and averaging, pulse shut-off measurement, and a zero-offset spot-welding process.

BACKGROUND

Thermocouples are a common choice for temperature measurement because of their self-energization, low cost, robust nature and wide temperature range. With minor calibration corrections, thermocouples can have accuracies of 0.25 – 0.5 °C. Michalski et al. [1] conducted research on measuring the temperature of solid bodies with a thermocouple and pointed out that temperature measurement of a solid surface has a series of possible errors.
including: temperature distortion error of the solid surface when introducing a thermocouple, and contact thermal resistance error between the solid surface and the thermocouple.

Volkov [2] proposed that thermocouple readings can be affected by current in such a way as to add an “effect voltage” $\Delta U$ to the thermo-emf of the thermocouple if it has direct contact with the current carrying surface. He concluded that the influence of current on thermocouple readings was a function of the voltage gradient along the current carrying surface. Furthermore, both [3] and [4] propose a method using two thermocouple junctions of opposing polarity, affixed next to each other on a current-carrying conductor, to measure and compensate for the current-induced error.

Kuribayashi [5] used a thermocouple twist junction attached in close proximity to the SMA wire to avoid measurement errors due to current going through the SMA wire. He also used isolation transformers to electrically separate the sensor circuit from the SMA wire heating circuit.

There is little further evidence of consideration of this problem in the literature, perhaps due to the particular nature of the SMA wire. For temperature measurement of larger-diameter conductors, electrically-insulated thermocouples are recommended [2]. However, the insulation increases the volume of the bead relative to the thin wire under test, introducing further uncertainty in the measurement.

Leading up to our thermocouple-based results which are the focus of this paper, we investigated the use of thermistors and non-contact infrared sensing. A thermistor is a device whose electrical resistance varies in a predictable way with temperature. Thus, a thermistor located at a spot under test can be used in a resistance bridge to measure temperature. Typical thermistors are more stable and can be orders of magnitude more precise than thermocouples [6]. However, the smallest thermistors which are readily-available are still larger than a small thermocouple bead [e.g., 7] and have a significant influence on the local temperature of the SMA wire during measurement. IR measurement was attempted and eventually found to be too cumbersome due to the need for specialized lenses given the target size, the difficulty accounting for background effects, the limited accuracy (approximately $\pm 2^\circ C$, [8]), the need to accurately know the SMA wire emissivity and the effects of wire curvature on IR temperature measurement. In addition, while successful IR measurements could be used in the lab for model development and validation, they could never be implemented in situ in our eventual application.

SMA WIRE CURRENT INFLUENCE ON THERMOCOUPLE READINGS

In an early experiment comparing thermocouple attachment methods, two 500mm long samples of 500$\mu$m diameter SMA wire (Flexinol, from Dynalloy) were prepared by affixing seven 36AWG type-T thermocouples along the wire length at regular 50mm separations between 100mm and 400mm along the wire. On one wire, the thermocouple beads were spot-welded, while on the other they were affixed with adhesive gel (QuickTite, from Loctite). Examples are shown in Fig. 1.
A current of 250mA was applied to each of the wires, first in one direction then in the opposite, and the steady-state readings from all thermocouples recorded. The results are shown in Fig. 2. For the glued thermocouples, measurement differences along the length of the wire can be easily ascribed to thermocouple accuracy and variability in the gluing process as evidenced by comparing Fig. 1(a) and Fig. 1(b). The difference in readings when current is reversed is minimal. The spot-welded thermocouples, on the other hand, show wider variability between thermocouples. In addition, the current direction has a large influence on readings, producing mirror-image curves which appear symmetric about approximately 26°C. The average reading from the glued thermocouples is also about one degree lower than the average from the spot-welded thermocouples, which is not unexpected given the greater thermal resistance of the adhesive.
wire temperature, this offset should have no influence on the thermocouple emf. However, we hypothesize that the wire current induces an ohmic drop proportional to the lateral separation of the leads. This additional voltage corrupts the thermoelectric voltage generated by the thermal field, leading to an erroneous reading which deviates from the average reading of 26°C. The fact that the error-induced offset reverses its sign when the current is reversed supports this hypothesis.

![Images of spot welded TCs](a), TC 1 spot welded (b), TC 3 spot welded (c), TC 4 spot welded

Fig. 3: Spot welded TC

To further verify this idea, we can calculate the lateral offset suggested by the observed errors, by comparing the measured thermocouple voltages with the expected emf for a T-type thermocouple at 26°C. The equation is

\[ U_{26°C} - U_{\text{measured}} = I \cdot \rho \cdot \Delta x \]  

where \( U \) is the T-type thermocouple emf, \( I \) is the wire current (250mA), \( \rho \) is the linear resistance of the wire (6.3 \( \Omega \)/m [9]), and \( \Delta x \) is the thermocouple lead separation. T-type thermocouple emfs for TC 1 readings from Fig. 2 were computed from thermocouple coefficients in the NIST ITS-90 database [10], and are given in Table 1.

<table>
<thead>
<tr>
<th>Temp (C)</th>
<th>( U ) (mV)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.0</td>
<td>1.033</td>
<td>average reading</td>
</tr>
<tr>
<td>26.8</td>
<td>1.066</td>
<td>reverse current</td>
</tr>
<tr>
<td>25.2</td>
<td>1.000</td>
<td>forward current</td>
</tr>
</tbody>
</table>

The lateral offset between the leads in TC1 can then be estimated using (1), giving a separation of 21\( \mu \)m. Similarly, the offsets of TC3, TC4 and TC7 can be estimated at 17\( \mu \)m, 61\( \mu \)m and 9\( \mu \)m respectively. It can be seen from this experiment and analysis that even very small offsets can introduce significant measurement error, particularly at relatively high currents and temperatures close to room temperature. Since currents of 250mA or higher, and room temperature operation are very normal conditions for an SMA actuator, it is important to develop a method to account for these current-induced measurement errors.
COMPENSATING FOR CURRENT-INDUCED MEASUREMENT ERROR

Three methods are proposed and have been verified, to compensate for measurement errors induced in thermocouples spot-welded to current-carrying conductors.

Current reversal and averaging

Since the error component of the measured thermocouple voltage is due to an ohmic drop, its sign is dependent on the direction of current flow, as seen in Fig. 2. One approach to compensate which has been previously proposed is to use a “compensated thermocouple” comprised of three thermocouple leads [4]. Two leads of a similar metal are affixed to the surface under measurement, and the third lead, of a dissimilar metal, is affixed in the centre. This creates two thermocouple junctions which will have opposite current-induced errors, and the average voltage can be read to get the “true” temperature. This approach still relies on the precise relative positioning of the leads on the surface, but residual errors due to lateral spacing differences would be smaller than the original current-induced errors.

Often, the amplitude or pulse-width modulation (PWM) duty cycle of the current in an SMA wire is controlled by a computer or embedded microcontroller, in order to control temperature and hence actuator motion. The greater the amplitude or duty cycle, the more power is delivered to the wire and the faster the heating. In this case, another approach using a single traditional thermocouple can be used to reduce or eliminate current-induced measurement errors. Since current direction does not affect heating, the control electronics can be used to alternate current direction while achieving the same overall desired control. If temperature measurements are synchronized with the current reversals, the average thermocouple emf can be used to eliminate the effects of the ohmic drop on the temperature reading.

Pulse shut-off measurement

The pulse shut-off method takes advantage of the fact that the electrical time constant is much smaller than the thermal time constant of the system: the problematic ohmic drop disappears as soon as the current is removed, while the wire takes longer to cool. This is illustrated in Fig. 4, which shows the response of a 40AWG K-type thermocouple spot-welded to a 500μm diameter Flexinol wire. Thermocouple readings were recorded during two trials, in which 750mA was run through the wire, in opposite directions in each trial. At steady state with current flowing, the measured thermocouple temperatures are -4°C with current in one direction, and 78°C after the polarity is switched. When current is shut off, the thermocouple reading in both cases jumps almost immediately to 37°C, the average of the two. The jump is followed by an identical slow decrease in measured temperature as the wire cools to ambient temperature.
By synchronizing the temperature measurement with the removal of the current in the wire, a single spot-welded thermocouple can be used to get an accurate reading, avoiding errors induced due to ohmic drop. This is particularly suited to SMA actuator applications where heating is controlled using a PWM current signal, as the measurement can be synchronized with the off-cycle of the control signal.

To further confirm the validity of the averaged and pulse shut-off measurements, we can use a first-order heating model accounting for Joule-heating and convection, to approximate the expected steady-state temperature of the wire in our experiments [11]:

\[ T_{ss} = T_{\infty} + \frac{\rho}{h \cdot \pi \cdot d} I^2 \]

where \( T_{ss} \) is steady-state temperature, \( T_{\infty} \) is ambient temperature, \( I \) is the wire current (250mA), \( \rho \) is the linear resistance of the wire (6.3 \( \Omega \)/m, [9]), \( d \) is the wire diameter (500mm), and \( h \) is the convection coefficient (75 W/m\(^2\)C, [11]). Equation (2) confirms that at a measured ambient temperature of 23\(^\circ\)C, the steady state temperatures for our wire at 250mA and 750mA are approximately 25\(^\circ\)C and 38\(^\circ\)C respectively. Within thermocouple measurement error, these are the two average temperatures observed in Fig. 2 and Fig. 4.

**Zero-offset spot-welding process**

Different from the two methods above, zero-offset spot weld method focuses on the joint point where thermocouple is attached on the SMA wire and eliminates the ohmic drop through improved spot welding techniques. In the conventional spot welding of thermocouples, a bead is made from two thermocouple wires and then the bead is welded to the SMA wire. This method cannot eliminate the voltage drop between two thermocouple
wires associated with the current flow in the SMA wire. The challenge is to properly spot weld thermocouple wires on the SMA surface, minimizing lateral offset to reduce the current’s influence, yet providing better thermal contact than a glue-affixed or insulated thermocouple. This problem can be resolved by first attaching one thermocouple wire to the SMA and subsequently attaching the second thermocouple wire to form the measurement bead. Being a purely mechanical solution, this approach does not depend on the presence of a computer or microcontroller being used for SMA actuator control.

After attaching a thermocouple onto the SMA wire by the zero-offset spot welding, either the average reverse current method or pulse shut off method can be used to examine if there is an ohmic drop on the thermocouple leads. For example, Fig. 5 illustrates that four 40AWG E-type thermocouples spot welded to the SMA wire using the zero-offset process, have no ohmic drop when they are subject to the pulse shut off test. In these figures, when temperatures go above 100°C, the power is shut off by computer and all temperatures decrease smoothly (curve in circle in TC 1), without showing a steep drop or jump as observed in Fig. 4. If the observed offset error is too large, the attachment can be removed and redone. If this is not feasible, either of the two previous compensation methods can be used.

Fig. 5: Zero-offset spot welded thermocouples are examined by pulse shut off method
CONCLUSION AND FUTURE WORK

Based on the above experimental and theoretical analysis, it can be concluded that a combination of improved spot welded thermocouple on the SMA wire, pulse shut off method and average reverse current method is the best practice for laboratory temperature measurement of SMA wires using thermocouples. We give guidance on the selection of the appropriate method depending on the application and type of control.

Future work on temperature measurement will focus on using IR imaging to investigate the error induced by thermal conductance down the thermocouple leads (the “fin effect”). The described measurement techniques will also be applied in our efforts to develop more detailed thermo-electric models of SMA and obtain heat-transfer coefficients.

REFERENCES