Special Interest Group Meeting on Thermal Issues
Laboratory for Machine Tools and Production Engineering (WZL) of
RWTH Aachen, Germany, February 2020
www.euspen.eu

Precision Core Temperature Measurement of Metals for Use in Manufacturing Applications

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Abstract
Core temperature variation in metals during manufacturing processes affects both the dimensional accuracy and the surface integrity of manufactured workpieces. Different types of temperature measurement techniques have been applied for obtaining workpiece temperature. However, their main limitations have been an inability to give the core temperature of the workpiece and the reduction in accuracy due to the harsh environment of some manufacturing processes. The velocity of sound in any medium of propagation is dependent on the temperature of that medium. This relationship can be used to obtain a medium's temperature, provided that the velocity of sound through the medium can be measured. This paper investigates the use of ultrasonic waves sent in the continuous mode to measure the temperature variation in a 100 mm steel sample (type EN24T) using the ultrasonic phase-shift method. Simulations and bench tests were performed to obtain a resolution and accuracy better than 0.5 °C and ±1 °C respectively. The results show that the method gives reliable results well within the target specification. Based on these results, ultrasonic thermometry experiments will be carried out during subtractive machining processes to determine the effects of the harsh environment on the accuracy of the proposed method.

Keywords: core temperature measurement; phase-shift method; manufacturing; ultrasonic thermometry

1. Introduction

The quality of manufactured products is determined by the conformance of the product to key specifications such as the dimensional accuracy and the surface integrity of the finished product. These two specifications are influenced by the temperature variation during manufacturing and inspection. Therefore, there is a need for temperature control or compensation of the thermal effects during manufacturing and measurement to produce high quality components.

No exact value is given for temperature variation during manufacturing. This is because there are many different types of manufacturing processes as well as different degrees of temperature variation for different materials. However, subtractive machining is a method in which high temperature variation can be reached. Typical temperature variation in this type of manufacturing process can reach 10 °C. In precision manufacturing, workpieces often need to be produced with dimensional error of less than 5 µm. The required temperature measurement accuracy to achieve this varies for different materials. Aluminium has a relatively high coefficient of thermal expansion compared with other common materials used in manufacturing. In order to achieve less than 5 µm dimensional error in aluminium, assuming a thermal expansion coefficient of 24 µm/m/°C, there is a need to measure temperature with accuracy of ±1 °C and a resolution of 0.5 °C. These are the accuracy and resolution this paper seeks to achieve in order to satisfy the requirement for precision manufacturing.

There have been many methods applied for measuring temperature during manufacturing processes, most of the methods described in literature deal with either the temperature of the machine [1] or of the tool [2]. Some temperature measurement methods such as the tool/workpiece thermocouple [3]–[5] and infrared thermometry [6] have been used to measure workpiece temperature. The major limitations of these and other methods previously used are the low accuracy in harsh manufacturing environments and the inability of the methods to measure the core temperature of the workpiece, which is the parameter that affects the dimensional expansion of the workpiece.

The velocity of sound in any material is dependent on the density, which is a function of temperature. This relationship can be used to obtain the temperature of any material provided that the velocity of sound through the material can be reliably obtained. Ultrasound thermometry requires sound signals at frequencies above 20 kHz. The pulse-echo method is traditionally used for ultrasonic thermometry [7]. However, the cost of pulser/receiver needed for high resolution temperature measurement is relatively high [8]. The resolution may also reduce in larger workpieces due to attenuation of the echo signal [9]. The main alternative to the pulse-echo method is the phase-shift method. In the phase-shift method, a continuous wave rather than pulses is used, the time-of-flight of ultrasonic wave is computed by measuring the difference between the phases of the transmitted and the received ultrasonic signals [10].

In this paper, the phase-shift method is used for the precise measurement of the temperature of a steel workpiece (type EN24T). Initial simulations were performed in MATLAB using the k-Wave toolbox – an open toolbox for time-domain acoustic and ultrasound simulations [11]. Based on the simulations, ultrasonic phase-shift experiments were carried out in a metrology laboratory. The results showed that this temperature variation in steel can be measured with this method with resolution of up to 0.1 °C. As part of future work, this method will be used in different manufacturing and inspection processes.

2. Materials and method

The pulse-echo method of ultrasonic measurement is widely used because of its simplicity. The method works based on the principle of time-of-flight (*tof*). The ultrasonic velocity is calculated using the time difference between sending the signal and receiving its echo [12]. The relationship between the *tof*, distance of travel and the ultrasonic velocity is given as:

$$c = \frac{d}{tof} \quad (1)$$

where *c* is the ultrasonic velocity, *d* is the distance between the transmitter and receiver and *tof* is the time-of-flight [12].

The Phase-shift method is another technique for ultrasonic measurement. To obtain the ultrasonic velocity, the phase-shift method uses the difference between the phases of the sent and received signal of a continuous ultrasonic wave. The relationship between the phase-shift and the velocity of a steady state frequency ultrasonic wave is governed by the following equation:

$$c = \frac{Lf}{\left(n + \frac{\phi}{2\pi}\right)} \quad (2)$$

where *L* is the path length between the ultrasonic transmitter and receiver, *n* is the integer number of wave periods, ϕ is the phase-shift, *f* is the ultrasonic frequency and c is the ultrasonic velocity.

2.1. Simulations

The pulse-echo and the phase-shift methods were both simulated to choose the most appropriate method for core temperature measurement of metals. The simulation was done in MATLAB R2017b using the k-Wave toolbox. Steel was chosen as the medium of propagation. For the pulse-echo simulation, the *tof* technique was used to resolve 0.1 °C. The k-Wave grid (Nx) was set as 6.561e+3 grids, the spacing (dx) was set as 1.2e-4. The ultrasonic velocity used for the simulation is based on the temperature-velocity relationship given by Ihara et al [13] which is given as:

$$c(T) = -0.636T + 5917.6 \quad (3)$$

Where c(T) is the temperature dependent ultrasonic velocity and T is the temperature.

To achieve a 0.1 °C resolution, a 1.2 MHz tone burst and 10 GHz sampling frequency were used. Figure 1 and Table 1 show the tone burst and the *tof* for the whole simulation respectively.

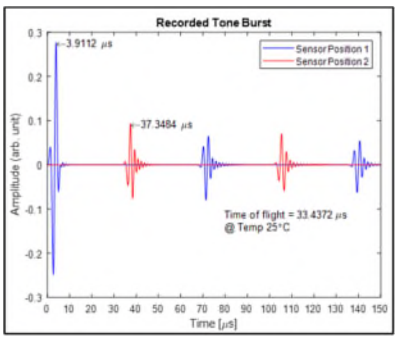

Figure 1. Recorded tone burst at 25 °C

Table 1. Time of flight at different material temperature.

Temperature (°C)	Velocity (m/s)	Tof (μs)
25.0	5901.70	33.4372
25.1	5901.63	33.4376
25.2	5901.57	33.4380
25.3	5901.51	33.4384
25.4	5901.45	33.4388
25.5	5901.38	33.4392

The phase-shift method was also simulated, using a frequency of 5 MHz, 0.1 °C change was successfully resolved and this is shown in table 2.

Table 2. Phase-shift simulation result.

Temperature (°C)	Phase-shift (5 MHz) (°)	Used ultrasonic velocity (m/s)
20	167.64	5894.0
20.1	168.83	5893.9
20.2	170.02	5893.8
20.3	171.21	5893.7
20.4	172.40	5893.5
20.5	173.59	5893.4

Both pulse-echo and phase-shift methods resolved 0.1 °C change in temperature. However, the resolution of the pulse-echo method may reduce due to attenuation [9]. However, with the phase-shift method, resolution of 0.1 °C can be achieved even with attenuated echo signal. Also, to use the pulse-echo method, a pulser/receiver of sampling frequency of approximately 10 GHz needs to be used, the cost of such device can be as high as €20,000. However, using the phase-shift method requires the use of a phase detector just under €400. Because of these, the phase-shift method was chosen over the pulse-echo method. The experiments described in the next section are based on the phase-shift method.

3. Experiments

The ultrasonic phase-shift thermometry experiment was set up as shown in figure 2.

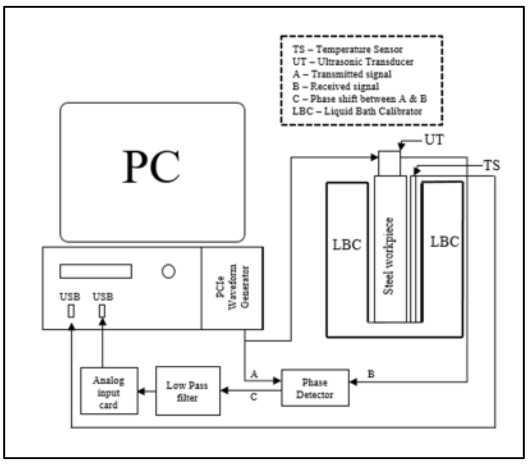

Figure 2. Ultrasonic phase-shift thermometry experimental setup.

For the phase-shift thermometry experiment, a sinusoidal waveform was generated using a Spectrum M2i.6022-exp arbitrary waveform generator (Spectrum Instrumentation, Ahrensfelder, Grosshansdorf, Germany). The signal was then sent to the transmitter probe of a transducer (5 MHz centre frequency and bandwidth of ±1 MHz) and the input A port of an Analog Devices AD8302 (Analog Devices, Norwood, MA, USA) phase detection board using a 100 mm steel sample (EN24T) - as the medium of propagation. Using a single transceiver on a 100 mm sample has the equivalent path length to the simulation, where a transmitter and receiver were at opposite ends of a 200 mm sample. The received signal was sent through the receiver probe of the transducer to the input B port of the phase detector board. The phase difference between the transmitted and received signals is computed by the phase detector and the equivalent voltage value is sent out through the phase-out port. Signal noise from the phase-out value was reduced with a low pass filter. A filter with cut-off frequency of 3.4 Hz was used. Using an NI-9239 analogue input card (National Instruments, Austin, TX, USA), the filtered phase-out values were saved to a PC through NI LabVIEW. Using a TCS140 liquid bath calibrator (E Instruments, Langhorne, PA, USA), the temperature of the steel workpiece was varied in steps of 1 °C and 0.1 °C and the corresponding phase-shift was recorded. The result of this experiment will be discussed in the next section.

4. Discussion

The AD8302 outputs voltage values represent the phase-shift between the transmitted and received signals. The relationship between the phase-shift and phase-out voltage values is given in figures 3 and 4. Figure 3 is the datasheet plot while figure 4 was obtained experimentally using the same parameters as those used for the phase-shift experiments – 2V input, 40 mV received signal with 5.5 MHz signal frequency. 5.5 MHz frequency was used in order to utilize the linear region of the phase output curve; this frequency was chosen experimentally.

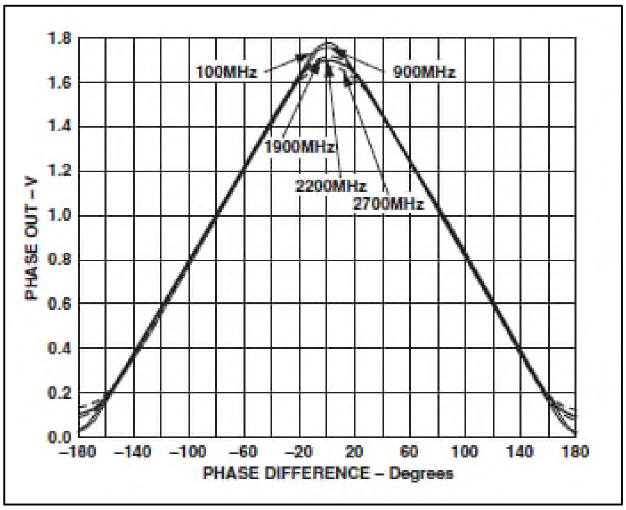

Figure 3. Phase Output vs. Phase Difference [14].

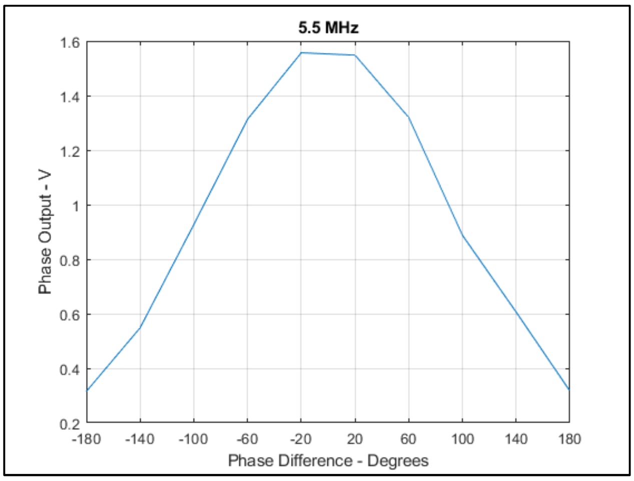

Figure 4. Phase Output vs. Phase Difference for 5 MHz signal.

The first experiment was for a temperature range of 20 to 30 °C in steps of 1 °C. The phase out values which represent the phase-shift between the transmitted and received signals for the temperature range and the micron equivalent values of the residuals of the phase out values are given in the figures 5 and 6 respectively.

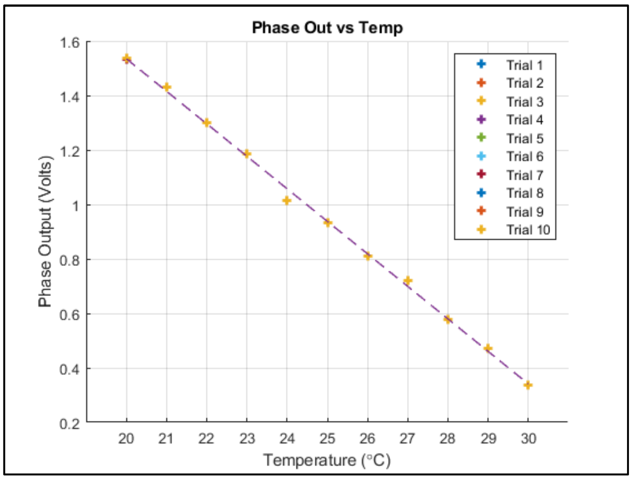

Figure 5. Results of 20 to 30 °C range in steps of 1 °C.

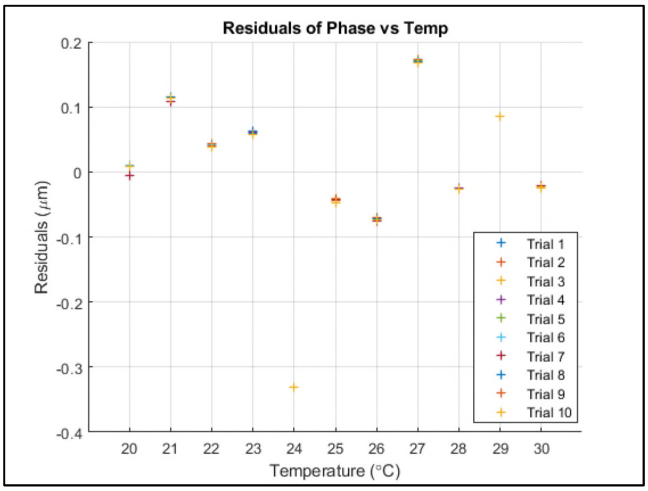

Figure 6. Residual plot of 20 to 30 °C

The second experiment was designed to focus on achieving the required resolution. A range of 20 to 21 °C in steps of 0.1 °C was used. The recorded phase out and the residual plots are given in figures 7 and 8 respectively.

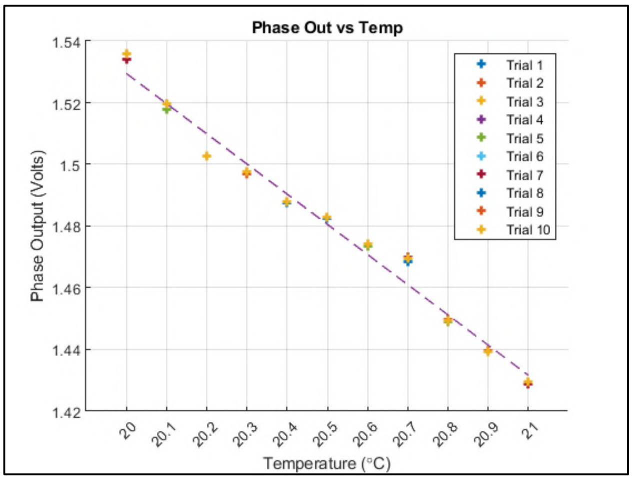

Figure 7. Results of 20 to 21 °C range in steps of 0.1 °C.

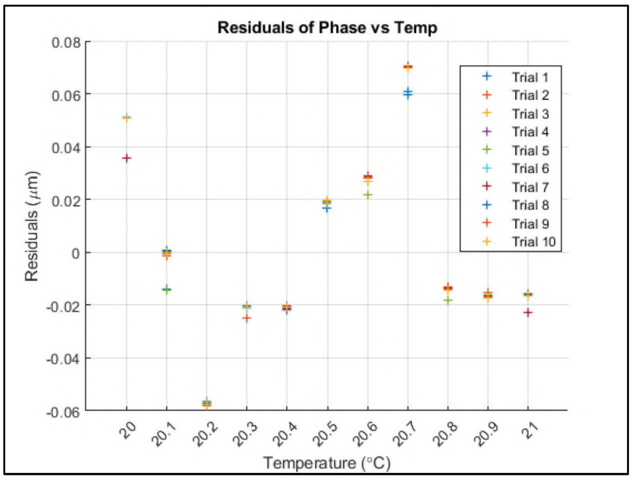

Figure 8. Residual plot of 20 to 21 °C

The results of the simulations as well as the experiments confirm that temperature variation in metals can be measured using the phase-shift technique of ultrasonic thermometry.

5. Conclusions

This study showed that with phase-shift ultrasonic thermometry, core temperature of metals can be measured with a resolution and accuracy of better than 0.5 °C and ±1 °C respectively, even with an attenuated echo signal of 40 mV. For these experiments, a 100 mm steel sample (EN24T) was used. The range of temperature measurement can be increased by combining multiple ultrasonic signals of different frequencies. Two main limitations of the AD8302 board are the nonlinearities at the extremes and at the centre (-180°, 180° and 0°) as seen in figures 3 and 4, and the lack of clarity on the sign of the phase difference from the phase-out value. Choosing a suitable frequency for which phase out values are within the linear region will reduce the possibilities of values falling in the non-linear region as shown in the results of the experiments. The sign of the phase difference is needed for absolute temperature measurement. However, relative temperature variation can be measured without the knowledge of the sign of the phase difference. A possible application of this study would be for temperature monitoring during co-ordinate metrology. As part of future work, more experiments will be carried out in order to deploy this setup in subtractive manufacturing processes. Also, the suitability of the method to different materials as well as the possibility of measuring material temperature at a specific region or point using ultrasound will be studied

6. Acknowledgement

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of the Future Metrology Hub (Grant Ref: EP/P006930/1).

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