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ULTRASONIC THICKNESS MEASUREMENT
FOR PRECISION CONTROL
OF MACHINE TOOLS

July 1969

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ULTRASONIC THICKNESS MEASUREMENT FOR
PRECISION CONTROL OF MACHINE TOOLS

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ABSTRACT

A prototype ultrasonic micrometer using the pulse interference technique has been developed which gives an accurate, continuous readout. The micrometer has been adapted for control of an electro-spark discharge machine and the system has been used to mill aluminum plates to within ± 0.0001 inch of a constant thickness. Physical principles and electronic circuits for the system are described.

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INTRODUCTION

An accurate thickness measurement technique using ultrasonics has been automated and adapted for measuring the thickness of a part while it is being machined. This report reviews the physical and mathematical principles of the ultrasonic measurement and the electronics for automating the measurement; it describes the electrical discharge milling process and its integration with the ultrasonic measurement; and it reports results of milling an aluminum plate with the prototype system.

The system has two promising possibilities. The first is the precision possible with most materials. The second is that because the part does not have to be removed from the machine for gauging once the machining starts, the time required to produce a finished part may be reduced, and handling, with its possibilities for damage, will be minimized. Damage is also reduced because the thickness measurement requires that only oil touch the part, not a solid material.

Because of its precision and non-contacting features, the ultrasonic gauge may be useful by itself in many instances.

SUMMARY

An ultrasonic thickness gauge and an electrical discharge machine (EDM) have been used to mill an aluminum plate to a constant thickness. The

plate, about 8 x 8 x 1/8 inches, had thickness variations of .5 mils (± 0.005 inches) before machining, but was automatically machined until a constant thickness within ± 0.1 mils was obtained.

The thickness measurement uses the pulsed interference technique, which is a non-contact test requiring access to only one side of the part. The system has a resolution of approximately 0.5% of an ultrasonic wave length in the materials; this is 0.05 to 0.2 mils for most metals at 10 MHz. Because the wavelength depends upon the velocity at which the ultrasonic wave propagates through the material, velocity variations may limit the accuracy of the system in some cases.

Though this report describes work done only on flat aluminum plates, it is not limited to this material or configuration.

ULTRASONIC THEORY

This system's ultrasonic micrometer is based upon our adaption of the pulsed interference technique.⁽¹⁻⁴⁾ Basically, this technique depends upon the interference of a burst of ultrasonic waves reflected from the front surface of the part with the waves which enter the part, reflect off the back surface, and come back into the couplant. (Simplified in Figure 1). When the part is an integral number of half wavelengths thick, the back surface wave will be 180° out of phase with the front surface wave and destructive interference will occur. Each time the wave inside the part bounces back and forth, more of the wave reflected from the front surface is interfered with, causing the null pattern shown on the oscilloscope in Figure 2.

To analyze this waveform quantitatively, we can adapt the method of Brekhovskikh,⁽⁵⁾ who analyzed a wave to show that the total coefficient

FIGURE 1. Beginnings of Null Pattern When Thickness, d , Equals $n \lambda/2$

FIGURE 2. Machining System

of reflection from a layer (medium 2) of thickness d between an incident medium (3) and a backing medium (1) is given by:

$$V = V_{23} + D_{32} D_{23} V_{12} \exp(2ik_2d) \sum_{m=0}^{\infty} \left[V_{32} V_{12} \exp(2ik_2d) \right]^m \quad (1)$$

where

V_{12} = reflection coefficient going from medium (2) to (1)

V_{23} = reflection coefficient going from medium (3) to (2)

V_{32} = reflection coefficient going from medium (2) to (3)

D_{23} = transmission coefficient going from medium (3) to (2)

D_{32} = transmission coefficient going from medium (2) to (3)

ω = angular frequency of wave

C_2 = longitudinal velocity of ultrasound in medium (2)

$k_2 = \omega/C_2$

$\exp(2ik_2d)$ = phase change of wave as it goes back and forth through layer 2.

Also,

$$V_{32} = -V_{23}$$

$$D_{32} = 1 - V_{32} = 1 + V_{23}$$

$$D_{23} = 1 - V_{23}$$

For our case, two modifications need to be made: First, for thicknesses that are multiples of half wavelengths, $\exp(2ik_2d) = +1$. Also, m , the number of transverse of the wave inside the part, does not go to infinity because of the finite length of our pulse. Instead, it is limited to an upper value, m_u , where m_u is the largest integer of the ratio:

$$\frac{\tau}{2t_T}$$

τ = length of pulse burst

t_T = transit time for ultrasound to traverse part.

All of which yields:

$$V = V_{23} + (1 - V_{23}^2) V_{12} \sum_{m=0}^{m_u} (-V_{23} V_{12})^m \quad (2)$$

For a typical system of oil-aluminum-oil, $V_{23} = +0.88$, and $V_{12} = -0.88$. The steps form because the terms in the summation occur one at a time every $2t_T$, with V_{23} alone being the magnitude of the first part of the signal. Our previous analysis was based on having an integral number of half wavelengths inside the part; a fair question would be to find how closely we determine this condition. We can get a feel for this by looking at the nulls of Figure 3. If these waves were in aluminum (ultrasonic longitudinal velocity, $V_L = 244.4$ mils/ μ sec), the difference in wavelength between any two adjoining photographs would be only about 0.02 mils. Of course these wavelengths weren't measured directly; instead, as suggested by the figure, the frequency of the transmitted wave is measured and this in turn is used to calculate the wavelength and thus the thickness.

These calculations are simply:

$$\lambda = \frac{V_L}{f} \quad (3)$$

λ = wavelength of wave in material

V_L = velocity of wave in material

f = frequency within pulse burst

Also,

$$d = \frac{n\lambda}{2} \quad n = 1, 2, 3, \dots \quad (4)$$

A) FREQ: 10133 kHz

B) FREQ: 10143 kHz

C) FREQ: 10153 kHz
(29th MULTIPLE)

D) FREQ: 10163 kHz

E) FREQ: 10173 kHz

FIGURE 3. Null Variations with Frequency Changes

or, using Equation (3)

$$d = \frac{nV_L}{2f} \quad (5)$$

where

d = thickness of part

A plot of this equation for aluminum, with several values of n , is shown in Figure 4. The frequency of the ultrasound can be measured very accurately with a digital frequency counter. The number, n , can be determined without ambiguity by dividing the null frequency, f , by the frequency difference between nulls, Δf . This leaves V_L . V_L has been measured for many materials many times.⁽⁶⁾ Unfortunately, it is not an absolute constant but depends upon impurities, grain orientation, cold working, etc. These characteristics can produce velocity differences up to 5% between parts.

To minimize this error, one or more points on the part are mechanically gauged and the null frequency measured at these points. Equation (5) is then solved for V_L . The important question then becomes how much V_L varies over the part. This variation depends upon the history of the part. The same factors that produce changes between parts may also affect the velocity within a single part, though the variations are usually not as large. If the part is made of a homogeneous, isotropic material there should be no velocity variations. For example, in the results reported later in this report, velocity variations within the aluminum plates milled had to be less than 0.1% for the precision obtained.

Other materials would have to be tested individually to determine their variations. If variations are apparent but predictable, they could be electronically compensated for.

FIGURE 4. Thickness Versus Frequency Curves

Another source of error is thickness variation within the area being gauged. The area being gauged depends upon the size and focusing of the ultrasonic transducer. In this system the area gauged is about 3/16 inch in diameter. The thicknesses within this area will be weighted by the area which they cover.

AUTOMATION OF THE ULTRASONIC THICKNESS MEASUREMENT

From the preceeding section we can see that if we continually vary the frequency so that our signal always remains nulled, we will have a measure of the thickness. The null control electronics do exactly that. They monitor the signal and change the frequency so that a null is always present.

Figure 5 is a block diagram of the control system. Analysis of the system best begins with the oscillator, (Figure 6). This oscillator produces a continuous sine wave. The oscillator is manually tunable over the range of 8 to 20 MHz, and can be voltage controlled over any 500 kHz band within that range. The CW output from the oscillator goes to an Arenberg gated amplifier which gates out a short burst of the signal, amplifies that burst, and attenuates the rest. This burst, about 15 microseconds long, is sent to a well damped PZT ceramic ultrasonic transducer with a resonant frequency of about 12 MHz.

The ultrasound then travels through about 3/4" of couplant to the part and then reflects back to the transducer, which now acts as a receiver. The voltage produced by the action of the ultrasound on the transducer then goes to a gate (Figure 7) which transmits only the null portion of the reflected signal.

FIGURE 5. Ultrasonic Micrometer and Controller

FIGURE 6. Oscillator

This gated portion of the signal then goes to a peak-reading circuit (Figure 8) where the maximum r-f amplitude is converted to a dc voltage. This dc signal is then compared with a reference signal in an operational amplifier. The difference is amplified and sent to the voltage controlled oscillator through the logic-sweep circuit. In practice, the reference voltage is adjusted so that the signal is not right on the null, but is instead roughly 10 kHz to one side, as was shown in Figure 3. If the part then gets thinner the signal at the null will tend to get smaller, but this is noted by the peak-reader and the voltage to the oscillator is increased, increasing the frequency and increasing the null signal again. The gain in this feedback loop is kept very high so that only a 4 millivolt change in null signal can drive the oscillator through its entire 500 kHz range.

If something happens to the signal momentarily, the voltage to the oscillator will tend to go very high and "hang up" at a high frequency. To avoid this, a logic circuit and sweep generator are used to sweep the voltage down until the system is stable again.

Electrical Discharge Machining

The cutting action of the EDM is based on the vaporization of metal from the part surface due to an arc between the electrode and part, which have a high frequency pulsed dc voltage applied to them. To initiate cutting the electrode is lowered until the voltage breaks down the oil dielectric and arcs are formed. The oil is forced down a hole in the center of the electrode so that it is evenly distributed between the electrode and part. (See Figure 1. Various electrode configurations have been designed for better dielectric distribution.)

FIGURE 8. Peak Reader, Amplifiers, and Logic-Sweep Circuits

Because a moving solid object on the part opposite the ultrasonic transducer would interfere with the thickness measurement (by rapidly changing the reflection coefficient there) the transducer measures the thickness within the area of the hole in the electrode. Since the electrode does not cut at the point of measurement, the part must be kept in motion while being cut. For the same reason, as shown (greatly exaggerated) in Figure 9, the depth of metal removed after the measurement, d , must be less than the desired tolerance when the desired thickness is approached.

Referring again to Figure 9, we see that material is removed from the electrode as well as the part. To keep the desired shape on the electrode, the part is moved beneath the electrode with a quasi-random motion in two directions. This motion is provided by a pair of stepping motors capable of being controlled manually or by a computer-generated magnetic tape.

Integration of the EDM and the Ultrasonic Micrometer

The two preceeding sections have described the automation of the ultrasonic thickness measurement and the method of electrical discharge machining. The EDM and the ultrasonic micrometer were integrated to show that the system is feasible, capable of high precision and requires a minimum of part handling.

We have shown that the null control electronics continuously hold the signal at one of the nulls. The frequency producing this null is read on the frequency counter, as was shown in Figure 3. Three digits of this reading, usually the units, tens, and hundreds of kilohertz, are converted to an analog voltage. This is then compared with a reference voltage (which we could think of as a reference frequency or thickness) and that difference

FIGURE 9. Tool Erosion and Measurement Error

signal is used to control the vertical position of the EDM tool (Figure 10). This is controlled by a servo valve in the EDM's hydraulic head. If the measured frequency is lower than the reference (implying a thick point), then the EDM is in a normal operating mode, but if higher, the electrode is retracted about 0.02 inches from the work piece. An override signal from the logic circuit keeps the EDM retracted if the signal is not nulled. All of the ultrasonic control can be switched out for using the EDM alone.

Results

The system has been used to mill an aluminum plate to a constant thickness and the ultrasonic micrometer was used alone before and after machining to gauge the part. A typical mechanical gauging of the plate before and after machining is shown in Figure 11. The plate was 2S aluminum about 8 x 8 inches. As shown in the figure, the plate tapered by about 10 mils before machining and by only 0.2 mils afterwards.

Before machining the plate was gauged at 34 points in a mechanical gauge which had a resolution of 0.1 mils. The null frequency was then found at one of the points and the velocity calculated. This velocity was used in determining the thickness at the rest of the points ultrasonically. The gaugings were then compared; they differed by a maximum of 0.3 mils with an average error of 0.13 mils. Because of the final results obtained on the aluminum plate, we feel that later improvements in the electronics and plate surface finish have reduced these differences.

FIGURE 10. Frequency Reference and Control Relays

FIGURE 11. Before and After Gagings

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