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COMPUTERIZED ULTRASONIC SYSTEM FOR ON-LINE DETERMINATION OF CHROMIUM THICKNESS DURING PLATING OF TUBES

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A computerized system for ultrasonic thickness determination of plated chromium during vessel plating of large caliber smooth bore tubes has been developed. Temperature compensation is used to minimize apparent thickness changes that are due to temperature fluctuations during plating. Real-time displays of chromium thickness, plating rate, and temperature at six locations on the tube are available.

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INTRODUCTION

This work describes a computerized system to determine the thickness of chromium during the plating process. The thickness (to better than ± 0.0003 inch) and deposition rate of the chromium plated on the bore in the plating process during plating of smooth bore 120-mm tubes is now available.

Electroplating is "blind" in the sense that no information exists of the plate during the actual electrodeposition. The current, flow rate, and temperature, i.e., the plating parameters of the flow-through process presently used are based on the plater's past experience. The technology we have implemented makes chromium thickness information available to the plater during the operation, so that appropriate and timely changes to the process parameters can be made during plating.

The flow-through technique had been adapted to the low contraction (LC) chromium plating process for large caliber tubes. Here the bore of the tube is used to contain the plating solution, which is pumped in at the bottom at about 185°F and exits the top at a higher temperature. Currents of the order of 20,000 amperes are sent through the tube (the cathode), and pass through the plating solution and the lead plated anode.

Ultrasonic pulse-echo techniques can uniquely be adapted to this process, however, special care has to be taken to ensure the stability of the time measurement; a 1-nsec (10^{-9} sec) change in return time signifies approximately a 10^{-4}-inch change in thickness. Our efforts were directed at limiting measured return time fluctuations to this range. We designed and applied transducer holders and fixtures for a special liquid-buffer coupling technique, used a specific couplant, and devised a temperature compensation relationship.

A computer program was written to gather data (return times and temperatures), calculate thicknesses, plating rates, and temperature compensations, and display these in numerical and graphical formats.

TECHNICAL BACKGROUND

Ultrasonics

The basis of a thickness determination using the ultrasonic pulse-echo technique is the measurement of the time delay of a pulse travelling between two parallel surfaces. If the velocity is known, then the thickness can be determined.

We utilize the pulse-echo mode with a liquid buffer. An ultrasonic pulse launched via a transducer traverses the buffer (the coupling medium) and enters from the outside cylindrical surface of the tube (Figure 1). This pulse travels radially in the tube and is reflected back to the transducer from the inside diameter at interface B before plating starts or at interface C when some chromium has accumulated. There is also a reflection from interface A that traverses the coupling medium only. The difference in return times between the reflection from C and from A is processed by the system for the chromium thickness determination. At constant temperature this difference, the travel time, is a measure of the thickness of the steel-chromium combination, the steel thickness being constant and the chromium increasing during plating to an ultimate thickness between 0.005 and 0.010 inch. One may be concerned that the reflection due to the steel-chromium interface B would interfere or dominate the reflection from the chromium-air (or chromium-plating solution) interface C. This is not the case. The ultrasonic reflection from an interface is dependent on the difference in acoustic impedance for the two materials on either side of that interface. Acoustic impedance is the product of the density and velocity of sound. The acoustic impedances of steel and chromium are so close that no reflection can be detected from the steel-chromium interface.

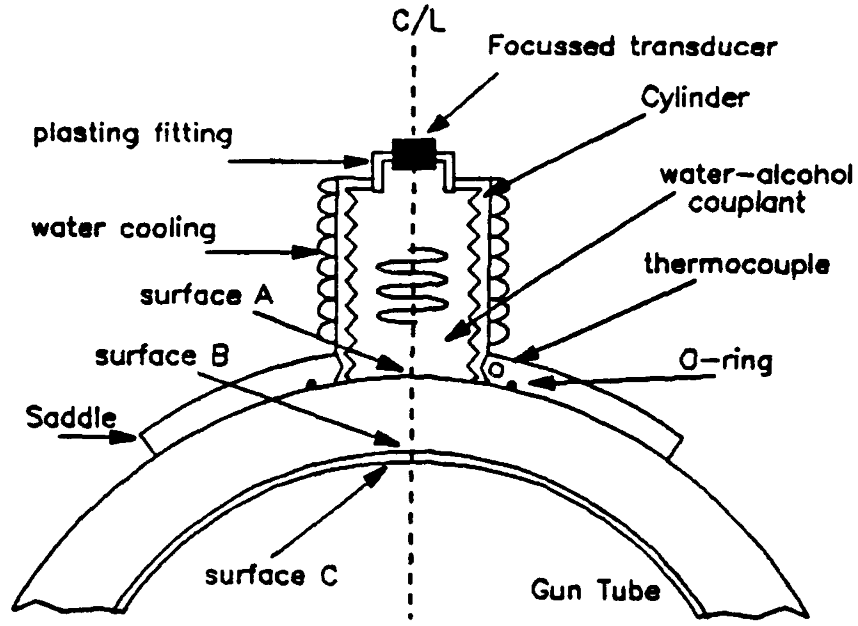

Figure 1. Schematic of fixture using liquid-buffer coupling of transducer.

The final thickness can also be found by comparing the return times before plating started and after it finished at room temperature. For 120-mm tubes, the wall thickness ranges from approximately one inch near the muzzle to approximately three inches near the breech. There are two long sections in which the inside and outside surfaces are parallel. We utilize these to place our fixtures.

Coupling of the Sound Energy

The following is a discussion of the various coupling techniques used in this investigation, including the reasons for choosing the liquid buffer.

Gluing

The surface of the tube available to the transducer is cylindrical, and the transducer faces are normally flat. Our first attempt at making this measurement for high contraction (HC) chromium, which operates at about 120°F tube temperature, consisted of gluing a transducer to the tube. This method has successfully produced measurements on plating and polishing, and saved the transducer for repeated use. At the higher temperatures of the LC plate, gluing and direct contact between transducer and the hot tube becomes impractical. The commercial transducer and the bond degrade with temperature, and even if the transducer stays glued, the small return time increase due to the actual chromium thickness increase (of the order of nanoseconds) could be overwhelmed by the effect of bonding changes.

Quarter-Wave Plate "Boot"

Our next attempt at solving the problem of high temperature and coupling of a flat transducer to a cylindrical surface, involved the use of a quarter-wave plate "boot" interface between the transducer and the cylindrical tube face. One side was flat for the transducer and the other side was machined to provide a perfect fit for the cylindrical tube surface. The thickness of the boot under the transducer corresponded to a quarter-wavelength of the sound in the steel at 5 MHz. The transducer was glued permanently to the quarter-wave plate, and the boot was glued to the tube. The transducer-quarter-wave plate glue joint was meant to be permanent, and the quarter-wave plate was then glued to the tube whenever a measurement was to be made. To remove the plate from the tube, a sharp shearing blow could be applied to the quarter-wave plate, and the epoxy glue would shatter. The transducer was also water cooled during the run. The technique worked, but when the quarter-wave plate was removed from the tube, not only was that bond shattered, but the bond between the quarter-wave plate and the transducer's faceplate was also shattered. The transducer was also ruined because its faceplate was incapable of withstanding the shearing blow. Because of this and the perceived difficulty of gluing the quarter-wave plate each time and also the need for controlled cooling, this method was abandoned in favor of a liquid path between the transducer and the tube.

Liquid Path Buffer

We had to address several concerns in coupling the sound energy to the tube:

1. The mechanical construction and coupling of the system had to be sufficiently stable so that minute changes in the return time, 1 nsec or less, could be associated with changes in the chromium thickness.

2. The high temperatures of the tube could not damage commercial transducers.

3. The ultrasonic beam had to be directed along the radius of the tube.

4. The transducer should be insulated electrically from the plating circuits.

The solution we found viable was using focussed transducers coupled to the tube through a constant liquid path with constant alignment such that the beam would travel radially to the tube (Figure 1). The transducer is screwed into a plastic fitting that is screwed into a brass cylinder, which in turn is screwed into a saddle-like piece that fits snugly onto the outer diameter of the tube. The brass cylinder is wrapped with a copper cooling coil hooked up to a cold water faucet. The cylinder is threaded on the inside to prevent anomalous reflections of the ultrasonic waves that would arrive at the transducer. Its diameter is about twice the diameter of the transducer. After everything is assembled and mounted on the tube and the transducer is screwed in, the cylinder is filled with an alcohol-water mixture. Here the time measurement consists of obtaining the difference in return time of the signals reflected from A and from B. As the plating run progresses, the cylinder and the liquid couplant in the cylinder tend to reach the temperature of the tube. The cooling coils around the cylinder tend to cool the system. What we noted however, is that if water is in the cylinder, and the cooling coils are activated, anomalous reflections of the ultrasonic pulse are observed on the oscilloscope, making data collection impossible. As the cylinder cools due to the coils, it tends to cool the water from the outer wall in. The temperature of the couplant responds to these heat sources and sinks and tends to stratify. Temperature strongly affects the sound velocity in water, and therefore its acoustic impedance is also affected. Therefore, there are regions of different acoustic impedance, possibly discrete, that anomalously reflect the sound generated by the transducer. In order to avoid this problem, we used mixtures of alcohol and water in the cylinder, where the alcohol to water ratio can be varied to achieve flat velocity-temperature curves over various ranges of temperature. If the velocity is flat with temperature, then the acoustic impedance does not vary as we cross into different temperatures, preventing unwanted scattering. The alcohol-water mixture is varied to adjust the flat portion of the slope of the velocity-temperature curve for various temperature ranges. A 20 percent ethanol-80 percent water (by volume) mixture was used.

The Temperature Effect

The fractional change in the return time, dt/t of the ultrasonic signal, implicitly a function of temperature through the velocity v, and the thickness s, of the barrel is

$$\frac{dt(T)}{t} = \frac{ds(T)}{s} - \frac{dv(T)}{v} \qquad (1)$$

The effect of the temperature dependence of the sound velocity on the return time is approximately ten times greater than the effect of the change in path length due to the temperature coefficient of expansion.[1]

$$\frac{1}{s}\frac{ds}{dT} = 12 \cdot 10^{-6} / {}^{\circ}C \qquad (2)$$

In our laboratory we measured

$$\frac{1}{v}\frac{dv}{dT} = 15 \cdot 10^{-5} / {}^{\circ}C \qquad (3)$$

To make the temperature compensation, ideally the temperature distribution across the wall where the ultrasonic transducer is placed and where the return time measurement is made should be obtained. This varies according to the current density distribution in the wall, temperature of the incoming plating solution, heat diffusivity in the steel, heat transfer to the bubble-filled plating solution, radiation to the atmosphere, and starting temperature. The temperature at the inside (bore) cannot be measured, and there is not enough information now to obtain the temperature distribution in the wall. During application of the DC current, resistive heating occurs. The incoming plating solution is approximately 185°F, and the outside wall temperature of the tube is from 170° to 220°F, decreasing with increasing distance from the muzzle. The current contacts to the system are at the muzzle position both for the anode and the cathode, so the current density in the tube decreases with distance from the muzzle. This is because the tube wall thickness increases towards the breech and because of the current expended in plating. There can also be some resistive heating through the current clamp to the muzzle, so the muzzle can become the high temperature point on the tube, and the clamp is therefore water cooled. During plating, the operators aim to keep the temperature of the plating solution constant in the tube, and the temperatures and the temperature gradients roughly constant with time, so that we can make temperature compensations to the data. The temperature at the surface of the tube near the transducer is monitored by a thermocouple and recorded by the computer, and for our purposes, we assume that the temperature is constant throughout the wall.

If thickness information were needed at all times, during heat up, cool down, or when the current is turned on or off, i.e., during the complete run, then detailed temperature and temperature gradient information of the tube at the position of the transducer would be more important. This is especially true for a short operation, during which the temperature does not get a chance to stabilize. Electropolishing or reverse etching are much shorter in duration than plating, so the temperature of the tube changes through most of the process, and therefore the determination of removal rates presents a greater challenge.

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[1]This measurement was performed by J.F. Cox and F. Yee of the Physical Sciences Branch, Research Division, Benet Laboratories.

During the run, we manually record the temperature of the plating solution as it enters and leaves the tube so that in the future we can use this data for thermal analysis.

Satisfactory real-time chromium thickness measurements for a plating condition can still be obtained, as long as the temperatures at the outside tube diameter and the incoming and outgoing plating solutions are roughly constant. This means that the effects due to changes in temperature can either be calculated or are small, and then any change in the return time can be associated with the change in thickness of the chromium plate.

Thickness Calculation with Temperature Compensation

The system provides a voltage V proportional to the time between the reflections from A and C (Figure 1). We use a continuous thickness calibration method. This is a measurement of voltages proportional to the return time between two steel standards of known thicknesses. We use these voltages and the known difference in thickness between the standards to convert the voltage readings from the measurement to thicknesses. We also provide a means for temperature compensation of the data. We implicitly assume that the longitudinal sound velocity of the LC chromium and the steel standards are the same.

To calculate x, the change in thickness between two voltage outputs for the measurement as described before, take the specimen and standards at the same temperature T_s (the temperature of the standard).

$$x = \frac{s}{V_{s2} - V_{s1}}[V(T_s) - V_o(T_s)] \tag{4}$$

where s is the difference in thickness between the two standards, V_{s2} and V_{s1} are the voltage output for the standards proportional to their thickness, and $V(T_s)$ and $V_o(T_s)$ are the voltages from the specimen during and at the start of the process, respectively.

We aim to correct this change in thickness x in Eq. (4) for the case when the standards and the specimen are not at the same temperature. We see from Eq. (1) that the velocity in this temperature range decreases linearly with temperature. Therefore, the return time, and hence the voltage, would increase with temperature.

Temperature dependence through the output voltage can be depicted as

$$V(T) = V(T_o)[1 + \beta(T - T_o)] \tag{5}$$

The drift correction

$$\frac{(V_{s2} - V_{o2}) + (V_{s1} - V_{o1})}{2} \tag{6}$$

accounts for any electronic drift of the system. V_{o2} and V_{o1} are the time zero values of V_{s2} and V_{s1} that are defined above.

Finally, the temperature corrected thickness change of the tube referred to T_s is

$$x = \frac{s}{V_{s2}-V_{s1}} \cdot \left[V(T) - V_o(T_o) - \frac{(V_{s2}-V_{o2})-(V_{s1}-V_{o1})}{2} - \beta V_o [T-T_o] \right] \tag{7}$$

where $V(T) - V_o(T_o)$ is the difference in voltage at one transducer between two points in the measurement taken at two temperatures. The last term on the right-hand side is the temperature correction, which is derived analytically using the above considerations.

THE MEASUREMENT SYSTEM

Ultrasonics

The ultrasonic equipment consists of a Panametric System 5215 with pulse-echo, multiplexing, and counting capabilities. The least count, or resolution of the display, is 0.0001 inch. The pulse-echo signals are multiplexed between eight transducers.

As the system switches between the eight transducers in sequence, two of these measure the two standards consisting of parallel steel disks. Since the difference in thickness between the standards is known, the system produces a continuous calibration used to convert the time intervals measured by the other transducers to thicknesses. The absolute time measurements by the standards are also used to evaluate any electronic offset. The system is connected to an AT computer that records, stores, computes, and displays data, and an oscilloscope that shows the echo train (Figure 2).

We use an IBM compatible AT/PC with a temperature board and our own program, and obtain a real-time and continuous display of the temperature-compensated thickness of the plate and plating rate at six points in the barrel, along with temperatures at eight positions. The 1-inch diameter focussed transducers have a 5-MHz center frequency and are placed in two rings at different positions along the tube, as shown in Figure 2. Their focal length differs according to the total path length.

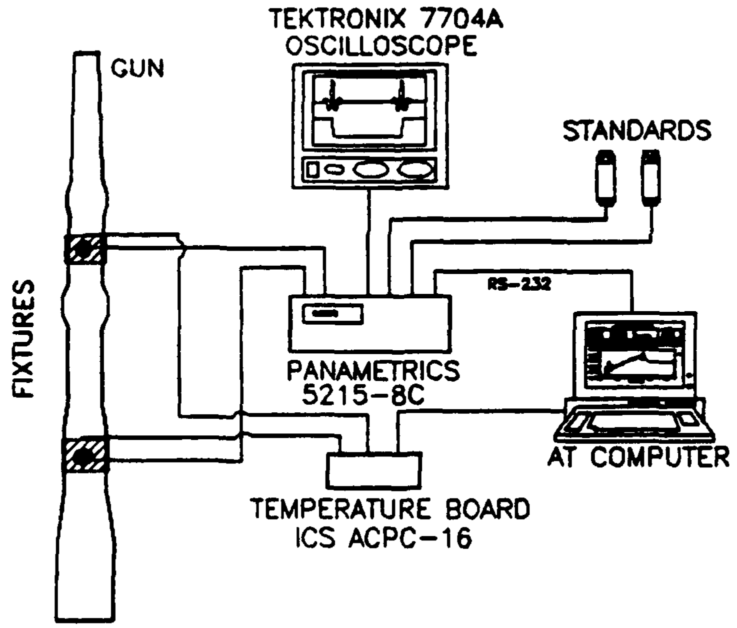

Figure 2. Schematic representation of the ultrasonic measurement.

The transducers in each ring are 120 degrees apart. The multiplexer in the Panametrics switches every four seconds. A complete cycle of measurements involving the eight transducers and eight thermocouples has a duration of 40 seconds.

COMPUTERIZED DATA RECORDING, CALCULATION, AND DISPLAY

As previously mentioned, our measurement system is computer-controlled to achieve a better and more accurate determination of the chromium thickness and the plating rate. A Zenith PC 286 computer is connected to the Panametrics System 5215 via a RS-232 serial communication port, while the temperature sensing equipment is installed internally in the computer. The temperature data are obtained through the Industrial Computer Source (ICS) model ACPC-16 which is an A/D and D/A converter board. When instructed by the computer to read temperatures using the thermocouples, the board automatically calibrates for the zero point. Thickness values from the Panametrics have an accuracy of $\pm 3\times10^{-4}$ inch, while temperature readings have an accuracy of $\pm$ 0.5°C.

The specifics of the system are outlined in Table 1. The program used for the data acquisition and analysis, called CTHICK.EXE, is written in Microsoft Quick Basic v 4.5. Its flow diagram is shown in Figure 3.

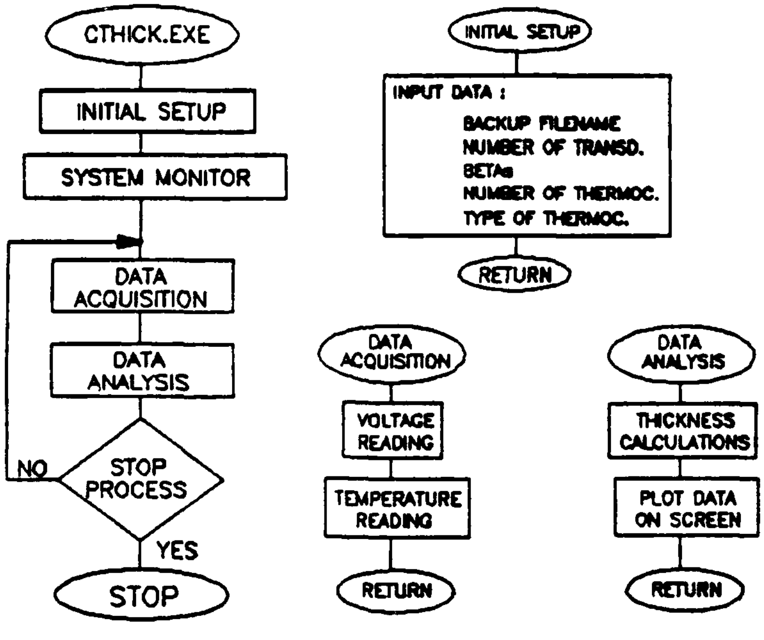

Figure 3. Flow diagram of the software used for the ultrasonic measurement.

In the initial setup shown in Figure 3, information about the system is given to the computer. At this point, we inform the computer of the number of transducers and thermocouples used and also the values of β from Eq. (7) to be used for each transducer.

From gun steel specimens in our laboratory, we have evaluated $\beta = 15 \times 10^{-15} \pm 10$ percent (/°C). Also, the type of thermocouple used has to be specified in order for the ICS board to convert voltage data from the thermocouples into temperature values.

Once the initial setup has been completed, the program allows the plater to monitor the system. In this phase, shown in Figure 3, the program continuously displays on screen the voltages obtained from

Table 1. Ultrasonic Measurement System Specifics

Zenith PC 286 Computer

Microprocessor	:	Intel 80286/287
Working at	:	8 MHz
Operating system	:	DOS 3.20
Memory	:	3 Mb
Graphic display	:	EGA
Communication ports	:	RS-232 Centronics
Hard disk drive	:	40 Mb
Floppy disk drive	:	360 Kb

Panametrics 5215-8C Thickness Gauge

Measurement mode	:	Interface echo and first back echo
Number of channels	:	8
Range	:	1 ÷ 4 inches
Resolution	:	0.0001 inch
Accuracy	:	± 0.0001 inch
Display	:	Four digits
Display update rate	:	One per second
Communication ports	:	Parallel/analog RS-232
Settings for RS-232	:	ID #01 Parity even Baud rate 4800 Stop bits 1

High Accuracy Analog Connection PC Model ACPC-16

Thermocouple types	:	J, K, E, T, S, R, B, G, D, C
Used in our system	:	J, K

Type	Range (°C)	Resolution (°C)	Accuracy (°C)
J	-100 to 100	0.02	± 0.7
	100 to 880	0.01	± 0.5
K	-50 to 1260	0.02	± 0.7

Cold junction compensation: internal

Compensation error at terminal temperature of:

Type	25°C	15-35°C
J	0	<0.25°C
K	0	<0.3°C

the Panametrics and the temperature read from the ICS board. These values obtained are not saved; this is merely a stage in which the plater can check if everything is working properly or make the necessary changes.

Once the system has been checked, the plater can start the real data acquisition and analysis. From this point on, the data are saved in a file and displayed on the screen as a function of time. The program provides the user with a variety of plots to be viewed:

- Voltages
- Temperatures
- Thickness calculated using Eq. (7) and assuming $\beta = 0$. This is equivalent to neglecting the temperature effects.
- Thickness calculated using the complete Eq. (7).

Any time base and range can be specified by the user.

All these values are plotted on screen versus time either as absolute values or as relative to a starting value defined by the user. For example, the time when the plating starts can be defined by the plater as the "reset" or starting point. Thereafter, thickness values can be plotted relative to the absolute thickness at reset. The thickness of the chromium plated at time t is obtained as the difference between the values of the thickness evaluated at time t and at the start of plating. The computer display is shown in Figure 4. The plater defines the starting and final point with two markers and the line connecting those two points is used to compute the thickness of the chromium plated and the rate of plating. In Figure 4, those values are 2.153 thousandths inch per hour and 7.0 x 10^{-3} inches for the rate and the total thickness of chromium, respectively. This plot was obtained during actual plating on 28 June 1990.

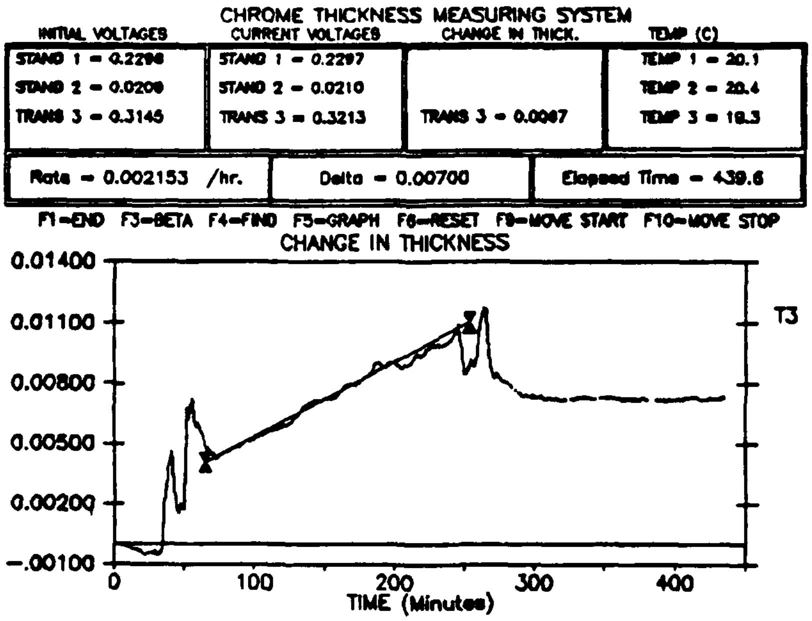

Figure 4. Computer display during the plating run. The straight line is a fit used to obtain the plating rate. The beginning and end points of the line are set visually by the operator and are used to determine the change in thickness, delta.

The computer continues in this loop of data acquisition/analysis until the plater instructs it otherwise, stating that the process is over.

RESULTS

Comparison of Thickness Measurement Methods

We have compared our ultrasonic results with stargage data obtained by Quality Assurance (Watervliet Arsenal, Watervliet, NY) personnel. Final plate thickness is inferred from stargage data by subtracting "after" from "before" plating, bore diameter data, and making appropriate corrections for electropolishing.

The limit of error of the stargage is divided into three parts:

1. The round-off error. Diameter readings are rounded off to the nearest thousandth inch, so the contribution to the error is ± 0.5 mil (1 mil = 0.001 inch).

2. Circular approximation error. The stargage gets its reading by matching three points on a circle to the inside diameter, therefore, the reading is dependent on the angular position of the stargage.

3. Concentricity error. Even when the above errors are considered, the stargage still does not determine how even the chromium coating thickness is around the circumference.

We estimate the limit of error for all these conservatively to be ± 0.7 mil on the chromium thickness. The resolution of the ultrasonic measurement during plating is 0.0001 inch, and most of the time the accuracy is better than 0.0003 inch. This refers to every location measured, so that if three locations are measured around the tube, we infer how evenly the chromium is applied around the tube during plating. Uneven plating around the diameter of the tube can not be detected quantitatively with the stargage.

Plating Runs

This report encompasses several, but not all, generations of the system. A summary of results obtained in some of the most representative plating runs is outlined in Table 2. Each of the runs is the result of actual shop plating on a gun tube conducted by the Advanced Technology Branch, Research Division, Benet Laboratories. A brief description of these runs is discussed below.

In the 2 March 1989 run, the quarter-wave plate boot with solid bond was used. Also, the equipment used for the ultrasonic return time measurement was different. In this case, a Sonic Mark I with a Sonic 120 Thickness Adapter was used, and the results were very encouraging. As seen in Table 2, the ultrasonic equipment measured a final value of deposited chromium of 4.6 ± 0.4 thousandths inch, while the Quality Assurance stargage measured 5.0 ± 0.7 thousandths inch.

The main problem was removing the fixture from the tube without damaging the transducer. As already mentioned, this method was abandoned in favor of a liquid-buffer coupling.

The 14 August 1989 run was the first one made using a water path between the transducer and the tube. The cylinder was held onto the tube by a harness. Cooling took place by radiation from the cylinder's outer surface that was painted black.

Table 2. Summary of Chromium Plating Results
(thousandths of an inch)
(temperature corrections are included in results)

		Plating Run: 2 March 1989		
	Measured			Q/A
	4.6±0.4			5.0±0.7
		Plating Run: 14 August 1989		
	Electropolish	Plating	Total	Q/A
	-2.7±0.4	4.8±0.4	2.1±0.6	2.3±0.7
		Plating Run: 14 February 1990		
	Measured			Q/A
TR #3	1.3±0.3			1.5±0.7
TR #4	1.2±0.3			1.5±0.7
TR #5	1.4±0.3			1.5±0.7
		Plating Run: 31 May 1990		
	Measured			Q/A
TR #3	7.2±0.3			7.5±0.7
TR #4	7.3±0.3			7.5±0.7
TR #5	6.9±0.3			7.5±0.7
		Plating Run: 22 June 1990		
	Electropolish	Plating	Total	Q/A
Bottom:				
TR #3	-1.6±0.3	5.5±0.3	3.9±0.4	3.5±0.7
TR #5	-1.6±0.3	4.3±0.3	2.7±0.4	3.0±0.7
Top:				
TR #7	-1.6±0.3	4.3±0.3	2.7±0.4	3.0±0.7
		Plating Run: 28 June 1990		
	Final-Initial	Plating		Q/A
Bottom:				
TR #3	7.1±0.3	6.4±0.3		6.5±0.7
TR #5	6.5±0.3	6.2±0.3		6.5±0.7
Top:				
TR #7	+0.2±0.3	-3.3±0.3		-0.5±0.7
TR #8	-0.2±0.3	-0.1±0.3		-0.5±0.7
		Plating Run: 22 February 1991		
	Final-Initial	Plating		Q/A
Top:				
TR #3	6.6±0.3	7.8±0.3		4.5±0.7
TR #5	3.0±0.3	4.5±0.3		4.5±0.7
Bottom:				
TR #6	6.9±0.3	6.9±0.3		6.0±0.7
TR #7	3.8±0.3	4.3±0.3		6.0±0.7

We were able to make a quantitative determination of an interruption in deposition after a small interruption in plating (Figure 5). The change in thickness data show an initial plating rate of 0.003 inch/hour, then a level region, and then a plating rate of 0.002 inch/hour. The flat portion started just after a one-minute interruption in current due to a failed rectifier that was quickly switched. Even though the interruption in current was very short (one minute), we monitored an interruption in plating of approximately fifty minutes. Again, our results were satisfactory, since as seen in Table 2, they match quite well with the value obtained by Quality Assurance.

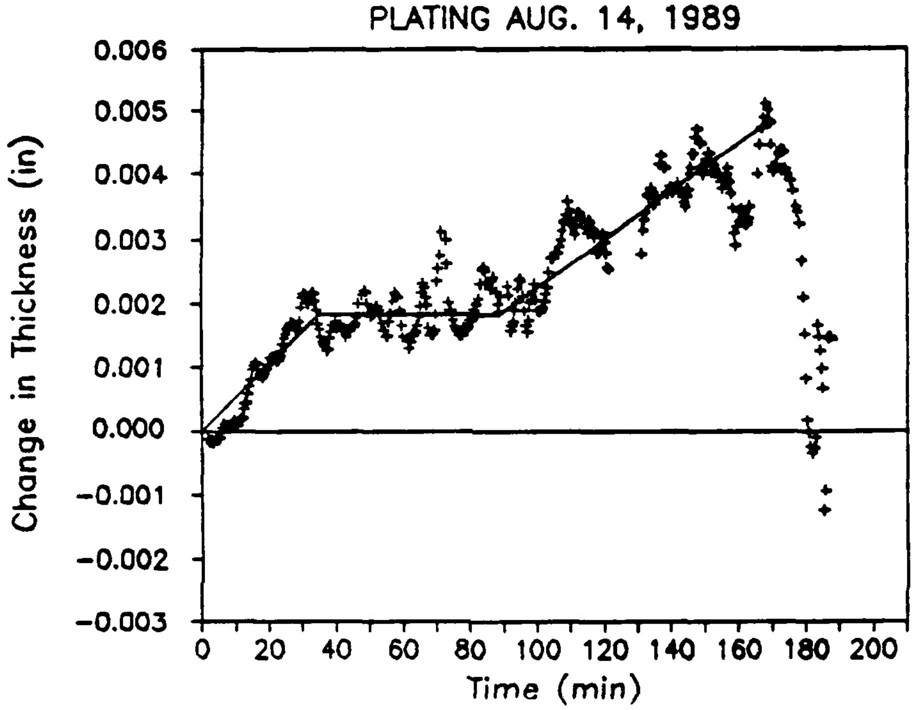

Figure 5. Change in thickness measured during plating. The three lines were plotted to indicate the regions with different plating rates, as described in the text.

Starting with the 22 June 1990 run, we were using the final configuration of two rings with three transducers each at different distances from the muzzle. Data were obtained from two transducers on the top ring (near the muzzle) and from one transducer on the bottom ring. Here we observed an anomaly we had not detected before. Once plating started, there was a large change in apparent thickness. We ascribe most of this effect to the large increase in temperature (from room temperature to ~ 65°C) when the hot plating solution starts flowing in the tube and the high plating current is applied. At the beginning of the plating, the change was an apparent increase, and at the end it was an apparent drop. Although the temperature correction was effective for smaller fluctuations during the course of plating, it could not correct for the much larger and sudden temperature changes at the start and termination of plating. This is probably due to a relative change in acoustic impedance between the liquid and the gun tube which changes the phase and amplitude of the reflected echo from the first interface. By picking the plating starting point and ending point on the voltage or thickness display and extrapolating the linear plating curve both forwards and backwards, we were able to evaluate the actual chromium thickness (Figure 4).

In the following run on 28 June 1990, the gun was a 120-mm with a longer tube than usual. The anode had to be extended via a screwed on section. On the top section, the lead was sputtered on, and at the bottom it was electroplated on. Of the six transducers mounted, data were obtained from four: two at the top and two at the bottom. The top transducers which were mounted above the new anode, recorded a slight loss in chromium thickness during plating, while the lower ones recorded an increase in chromium thickness. We were able to detect this anomaly in deposition along the tube during plating.

The last run presented was made on 22 February 1991. A plot of some of the data obtained in this case is shown in Figures 6 and 7. In Figure 6, the temperature of the fixture, and therefore by approximation of the gun at that level, is plotted as a solid line, while the temperature of the transducer is plotted as the dashed line. Figure 7 shows the change in thickness measured by one of the transducers (TR #6).

The two arrows labeled START and STOP represent the start and stop times of plating, respectively. It can be easily seen that the temperature of the gun increases rapidly as plating starts, and then remains practically constant. The change in thickness, on the other hand, increases linearly during plating with a constant rate of 2.3 thousandths inch per hour.

As noted in Table 2, in the top ring the two working transducers measured two different thicknesses. The bottom ring showed the same anomaly. TR #3 and TR #6 are almost on top of each other--at the same angle but at different heights on the tube. This is equivalent to saying that the two transducers have the same angle ϕ but different heights z, relative to a cylindrical coordinate system centered in the tube. The ϕ dependence of the deposition rate seems to correlate for the two ring positions on the tube.

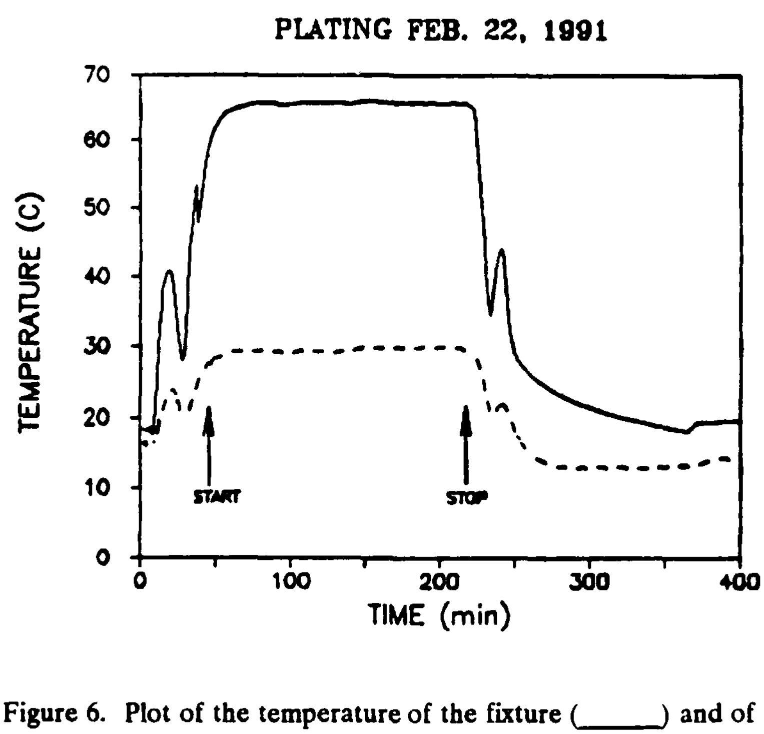

Figure 6. Plot of the temperature of the fixture (______) and of the transducer (------) during plating.

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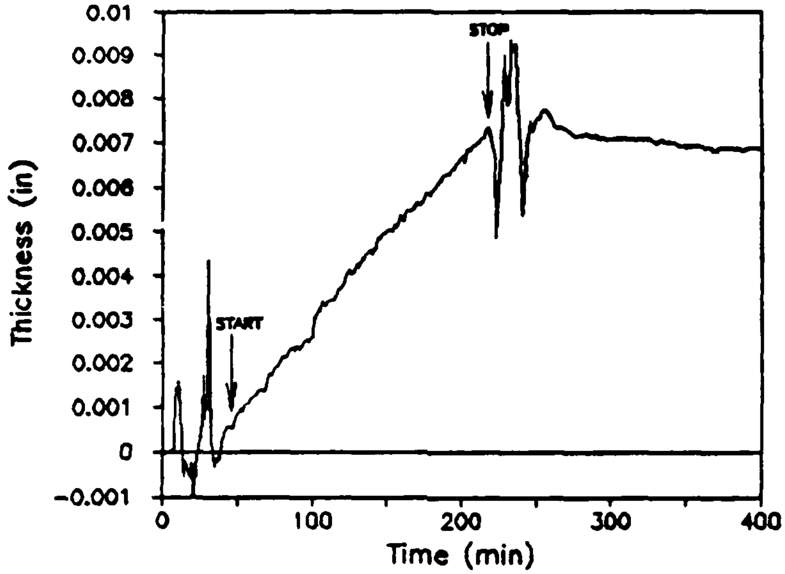

Figure 7. Change in thickness measured using the ultrasonic measurement during plating.

CONCLUSIONS

We have added ultrasonics and computer technology as the means for "seeing" during plating. Now we can evaluate the evenness of the plate--its thickness and plating rate at six specific locations both around and along the tube while the tube is being plated. We have continuous calibration and temperature compensation. The resolution of our measurement is much better than the stargage measurements. The accuracy is better than ± 0.0003 inch, while the accuracy of the stargage is estimated as ± 0.0007 inch for reasons mentioned in the text. With this system, it is also possible to do research and development in plating; we measured effects which were heretofore unpredictable or irregular, e.g., interrupted plating or inadequate treatment of anode or cathode in the shop or uneven plating around the tube. It is also possible to observe different rates of plating at different levels in the tube.

The most important result is that the plater can intervene during plating by changing the flow rate or other plating parameters for remedial action. Previously, none of this could be done either in the laboratory or in the shop. Now quantitative observations are available in the shop.

Further studies should be conducted for process control, temperature compensation, current density distribution in the tube, and complete system description of the process. The equipment is currently being used in the flow-through facility.

REFERENCES

1. John C. Askew, "Effects of Varying Plating Parameters on the Longitudinal Distribution of Low Contraction Chromium in Long Gun Tubes," ARCCB-TR-89021, Benet Laboratories, Watervliet, NY, August 1989.

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