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COMPUTERIZED ULTRASONIC TESTING SYSTEM (CUTS) FOR IN-PROCESS THICKNESS DETERMINATION

J. Frankel, M. Doxbeck, S.C Schroeder and A. Abbate

U.S. Army Armament, Munitions, and Chemical Command
Army Research, Development and Engineering Center
Benet Laboratories, Watervliet, N.Y. 12189-4050

ABSTRACT

A Computerized Ultrasonic Testing System (CUTS) was developed to measure, in real-time, the rate of deposition and thickness of chromium plated on the inside of thick steel tubes. The measurements are made from the outside of the tubes with the ultrasonic pulse-echo technique. The resolution of the system is 2.5 µm. (0.0001 in.) and the accuracy is better than 10 µm (0.0004 in.). The thickness is measured using six transducers mounted at different locations on the tube. In addition, two transducers are mounted on two reference standards, thereby allowing the system to be continuously calibrated. The tube temperature varies during the process, thus the input from eight thermocouples, located at the measurement sites, is used to calculate and compensate for the change in return time of the ultrasonic echo due to the temperature dependence of the sound velocity.

CUTS is applicable to any commercial process where real-time change of thickness of a sample has to be known, with the advantage of facilitating increased efficiency and of improving process control.

INTRODUCTION

During processes such as electro-polishing or electro-plating, no real-time information was heretofore available regarding the rate of the process or the thickness of the film. The final thickness was obtained only after the process finished and the specimen cooled, cleaned and dried. For large steel tubes, one or two days are lost before results can be obtained. The choice of proper plating parameters is thus made based only on past experience, usually obtained by means of experimental tests at varying flow and current parameters [1]. This makes the characterization of a plating process cumbersome and extremely expensive, and limits the range of conditions simulated. In the vessel plating technique for large hollow tubes, the bore contains the plating solution, which is pumped in at the bottom at about 85 °C (185 °F) and exits the top at a higher temperature. Currents of the order of 20,000 A are sent through the tube (the cathode), pass through the plating solution and return through the lead-plated anode. [2] (Fig. 1).

A Computerized Ultrasonic Testing System (CUTS) has been designed and developed, which enables the user to evaluate the thickness and the rate of application of chromium films during vessel plating of steel tubes [3]. This system provides continuous information on thickness, rate of deposition and temperature at six different location on the tube, with a thickness resolution of 2.5 µm. (0.0001 in.) and an accuracy of better than 10 µm. (0.0004 in.).

The requirements on thickness accuracy demand extremely stable coupling between the transducer and the tube, and the presence of temperature fluctuations imposes the need for temperature compensation in the equations which calculate the thickness. Due to the high temperatures on the outside surface of the tube, the transducers must be cooled in order to prevent degradation. This will also extend the life span of the transducers. The system incorporates the use of two standards, to provide continuous thickness calibration and drift correction during the measurement.

Computer technology is thus combined with ultrasonics to provide a real time process monitor, automated data gathering, computation and display of the thickness at six transducer locations placed in two

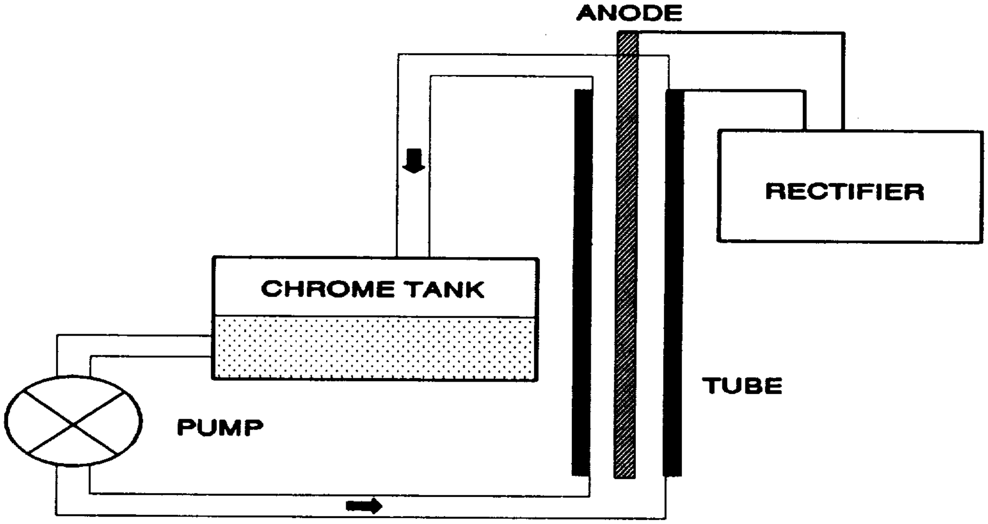


Figure 1 Schematic representation of the flow-through process for large hollow tubes.

rings. [4]

Even though this system was designed for utilization in a vessel plating facility, its principles are general in nature and can be applied to any process in which the thickness of the sample is modified. The fixtures used to couple the sound wave to the sample under study may differ from the one presented here, but the electronics and the software remain essentially the same [3].

PRACTICAL CONSIDERATIONS FOR ACCURATE REAL-TIME ULTRASONIC TESTING

Several concerns were addressed during the design of CUTS and in particular of the transducer assembly: [4]

a. The fixtures used to hold the transducers had to be stable enough not to vibrate in the shop environment so that minute changes in the return time, of the order of nsec., could be associated with changes in chromium thickness;
b. During plating, the temperature at the outside surface of the steel tube can be as high as 95 °C. A cooling system had to be designed, in order not to damage the transducers;
c. In order to measure the distance between parallel surfaces, the ultrasonic beam had to be directed along the radius of the tube;
d. The transducer had to be electrically insulated from the plating circuits.

The most feasible solution to these problems was found in 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. (Fig. 2) Commercially available, 5 MHz longitudinal transducers of 0.75 inches in diameter were utilized. Six transducers were placed 120 degrees apart in two rings at two different locations along the axis of the tube. A water cooling line around the cylinder containing the liquid coupling agent was also used to reduce the temperature at the transducer. The configuration of the six transducers was chosen to optimize the information obtained for an overall description of the plating. By comparing measurements between transducers on the same ring, the wall variation of the chromium film around the section could be evaluated. Furthermore, by comparing results between the two rings, the unevenness of plating along the length of the tube and any possible tapering could be estimated. The set-up time of both rings is roughly 30 min and less time is needed for breakdown.

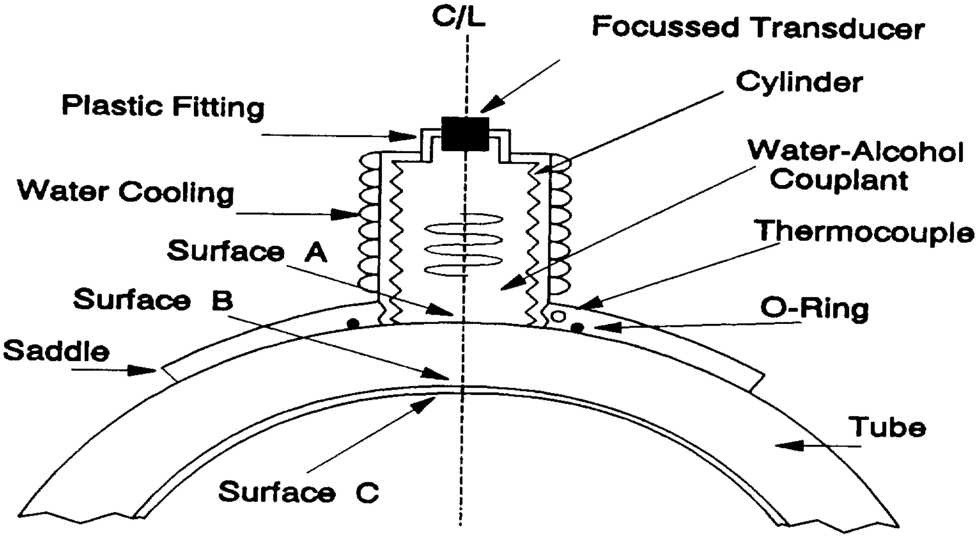


Figure 2 Sketch of the transducer assembly which utilizes liquid-buffer coupling.

The liquid used for coupling is a water-ethylene glycol mixture. When water was used as the couplant, as the cooling coils started to cool the cylinder, additional ultrasonic echoes appeared between A and C in Fig 2. It is surmised that the cooling of the water caused a layer of cooler temperature near the edge. Since the slope of the velocity-temperature curve for water is steep, this caused its velocity and hence acoustic impedance to increase and act to efficiently scatter sound waves at the layer interface. For these reasons and after trials of several mixtures, the 20 volume % ethylene glycol-water mixture was chosen. This mixture exhibits an almost flat velocity-temperature curve peaking around 60 °C, and its use eliminated the anomalous reflections.

The thickness of the sample is obtained by measuring the time necessary for a sound pulse to travel through the specimen and reflect from surface C (Fig. 2). The sound wave, generated by the transducer, travels through the liquid couplant and is partially reflected from surface A. The portion of sound wave which is transmitted through surface A, reaches surface C and then is reflected back. All reflection are thus detected by the transducer at the other end of the path with different time delays related to the different distances covered. If the velocity of sound in the material is precisely known, then the thickness can be calculated by measuring the difference in time between the two reflections. It has to be pointed out that this approach is valid since the sound wave is not reflected at surface B, (the steel-chromium interface).

The sound velocity in the steel tube is measured using two steel samples of known thickness and the temperature at the surface of the tube near the transducer and at the steel standards is monitored by thermocouples and recorded by the computer in order to compensate for the difference in sound velocity. Since the velocity calibration is continuously performed during the process, these measurements are also used to check and correct for any possible zero or baseline drift of the electronic equipment.

DESCRIPTION OF THE SYSTEM

A schematic representation of the measuring system is given in fig. 3. The system consists of a commercially available ultrasonic thickness gage, an oscilloscope, and an IBM-compatible AT/PC with an A/D temperature board. The Panametrics 5215-1C ultrasonic thickness gage, with a resolution of 2.5 μm (0.0001 in.) and dual Automatic Gain Control, was used to measure the time interval between the interface echo (Surface A) and the first echo from the inside diameter (Surface C). This unit has a multiplexer which can be connected to 8 transducers. Gate adjustments allow the time interval measurement to be made for

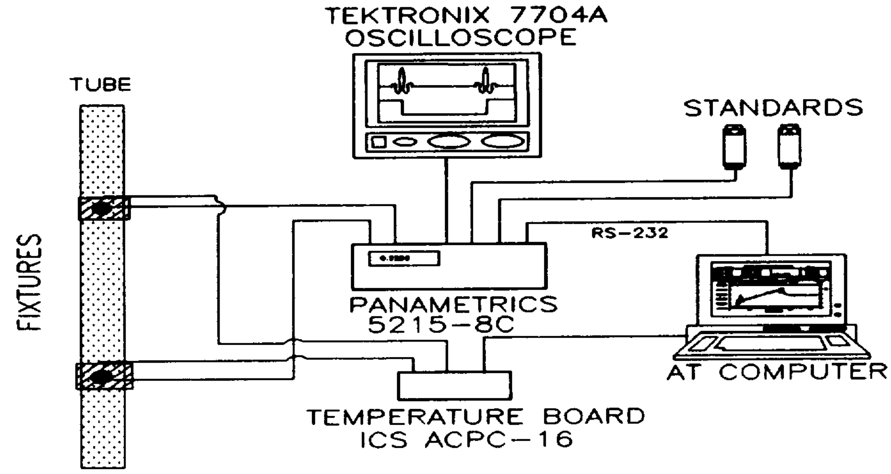


Figure 3 Schematic representation of the ultrasonic thickness measuring system.

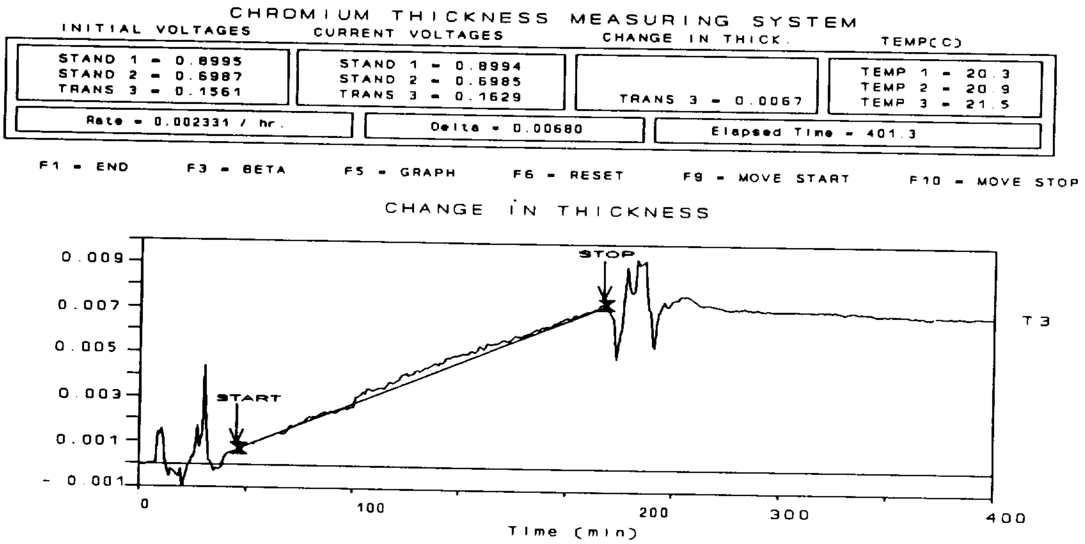
any echo combination. Of the eight transducers, six are located on the tube and two on the standards, and the result of the time measurement are transmitted to the computer in ASCII format via an RS-232 port. The steel standards have thicknesses of 2.28727 cm (0.9005 in.) and 1.77800 cm (0.7000 in.).

A software program was written for the acquisition, analysis and display of the results. The program provides a variety of graphs while plating is in progress. One such screen, from an actual plating run, is displayed in Fig. 4. During the run, eight transducers and eight thermocouples were used, though for simplicity, the numerical display in Fig. 4 shows only three transducers. STAND1 and STAND2 represent the readings on the two steel standards and TRANS3 measures the tube thickness. Two markers, defined as START and STOP, are used to evaluate the plating rate. As shown in Fig. 4, the markers have been positioned at time 45 min., (start of electro-plating) and at time 220 min. (end of electro-plate), so that a straight line joining them fits the actual increase in thickness. Here the plating rate is shown to be 59.2 µm/hr (.002331 in/hr) and the thickness difference between the two markers is 172.7 µm. (0.0068 in.). Mechanical measurements performed by our Quality Assurance (Q/A) technical personnel, showed an increase in thickness of 177.8 ± 18 µm. (0.0070 ± 0.0008 in.). The three thermocouple readings measure the temperature of the standards (TEMP1), of one of the transducers on the tube (TEMP2) and of the steel near the transducer (TEMP3). The computer cycles in a loop of data acquisition/analysis as long as desired. The data are saved in a ASCII file, and can be imported into any program, such as plotting utilities or spreadsheets, for further analysis.

The Panametrics equipment provides a voltage V proportional to the echo return time τ between the reflection of the sound wave from the surfaces A and C in fig. 2. This time τ can be expressed as the sum of various terms:

$$\tau = \frac{2x_s}{v_s} + \frac{2x_c}{v_c} + \tau_x \qquad (1)$$

where x_s, x_c are the thickness of the steel and of the chromium film, respectively; v_s and v_c are the sound velocity in the respective media; τ_x represents any systematic error involved in the measurement. The velocity of sound v_s and the error τ_x are continuously determined using the two steel standards. The difference in temperature between the standards and the sample is also considered in the calculations for v_s. From laboratory testing the velocity of the chromium film was estimated to be approximately 1.13 times the velocity of sound in steel ($v_c = \gamma v_s$), and a similar dependence in temperature is expected for both



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                 CHROMIUM THICKNESS MEASURING SYSTEM
INITIAL VOLTAGES      CURRENT VOLTAGES      CHANGE IN THICK.      TEMP(C)
STAND 1 = 0.8995      STAND 1 = 0.8994                            TEMP 1 = 20.3
STAND 2 = 0.6987      STAND 2 = 0.6985                            TEMP 2 = 20.9
TRANS 3 = 0.1561      TRANS 3 = 0.1629      TRANS 3 = 0.0067      TEMP 3 = 21.5
Rate = 0.002331 / hr.       Delta = 0.00680       Elapsed Time = 401.3
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Figure 4 Computer display during the plating run. The straight line is a fit used to obtain the plating rate.

materials.

The change in thickness is evaluated by subtracting the initial value measured before the process tarted from the absolute measurement of the thickness. In the case of electro-plating, at time zero $x_c = 0$, and the thickness of the chromium film is evaluated by the following relationship:

$$x_C = \gamma \cdot \left[v_S(T) \, \frac{\tau - \tau_x}{2} - x_s \right] \tag{2}$$

ANALYSIS OF THE SYSTEM

In order to optimize the accuracy of the measurements, an error analysis was performed on experimental data obtained during plating. The standard deviations and thus the errors involved in the evaluation of the chromium thickness x_C are shown in Table I. The total error in the estimation of x_C is 9.41 µm. (0.00037 inches). The largest contribution is given by the uncertainty of the value of the sound velocity in chromium. From eq. 2 it is clear that the effect of γ on the value of x_C is proportional, hence an error of γ of 3%, corresponds to a 3% error in x_C. The film thicknesses measured with this technique vary from 10 to 250 µm (0.5 to 10 mils), resulting in an error ranging from 0.4 to 7.6 µm. (0.015 to 0.30 mils). We expect to reduce the total error by more extensive testing on electrodeposited chromium to evaluate v_C. The main problem lies in the non-uniform composition of the film, as well as the presence of inclusions and other kind of defects.

The temperature coefficient of sound velocity, β, was assumed the same for steel and chromium. The error in the estimated thickness due to this approximation can be expressed by the product of the uncertainty in the estimation of β ($\Delta\beta$), and in the difference in temperature between the standards and the tube. Even if this difference is 100 °C and $\Delta\beta$ is assumed to be as high as 10^{-4}, the error is less than 1%, thus it can neglected in view of the larger error introduced by the uncertainty given by γ.

A comparison between thickness measurements performed during plating by our system and values

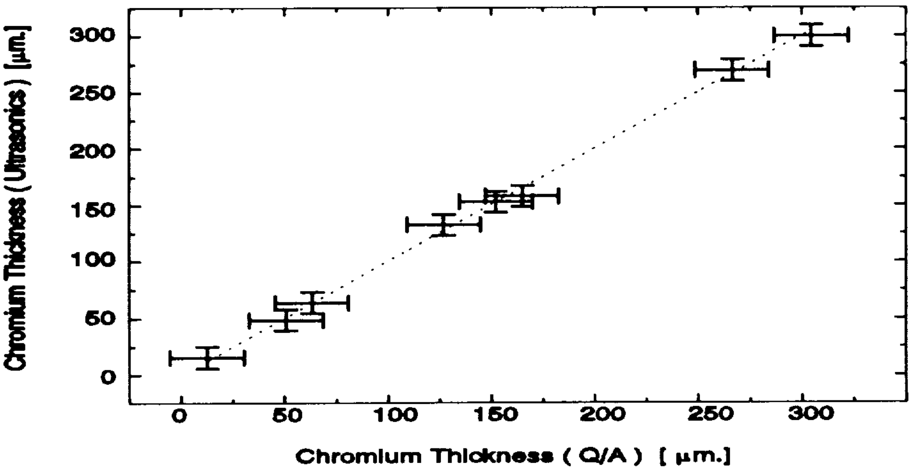

Figure 5 Error analysis.

later obtained by Quality Assurance (Q/A) personnel, was performed for an extensive number of shop plating runs. Results are shown in Fig. 5, where the thickness data obtained using our ultrasonic system is plotted as a function of the Q/A findings. The dotted line represents the one-to-one correspondence and the error bars represent the accuracy associated with each measurement. In the case of mechanical measurements performed by Q/A, this value is estimated to be 17.78 µm (0.0007 in.). It has to be pointed out that this is the accuracy required by process engineering. Good agreement between results can be found, even for higher values of chromium film thickness.

PRESENT AND FUTURE APPLICATIONS OF THE SYSTEM

The main advantage of our system over more conventional means utilized by Q/A personnel resides in the possibility of measuring the thickness of the chromium film as it is being plated as well as its greater accuracy. The system described has been implemented for many months in our vessel plating facility. In these cases, it has been possible to terminate the plating once the desired thickness of the chromium film had been reached, resulting in cost savings. Due to the strict tolerances of some plating processes, machining is required if too much chromium has been deposited. On the other hand, if the film is not thick enough, complete stripping of the chromium is required and the plating has to be performed a second time.

Furthermore, there were instances in which the measuring system was able to inform the plating operators of possible problems in the plating process. For example, in one case it was possible to make a quantitative determination of an interruption in deposition after a short interruption in current. Also the difference in plating rate before and after the interruption was measured, with the final thickness result again validated by Q/A personnel.

A problem that might be encountered in the plating of long tubes is straightness. Any curvature of the anode causes a different spacing between the anode and the inside diameter of the tube, resulting in different amounts of chromium deposited across the section. The system is able to detect the occurrence of this problem by comparing the thickness values obtained by the three transducer on the same ring.

All the measurements discussed here were obtained from test runs during the development of the ultrasonic thickness measuring system. Now, with the system fully developed and in use, plating is stopped or remedial action is taken as soon as any of the problems mentioned are detected. In the future, we envision a computerized system, in which the information about the thickness of the chromium film is processed along with other information such as plating current or velocity of the liquid solution, to control and optimize the plating process. Further improvements of the system, from the point of view of process control and of increased accuracy is planned but not developed at this time.

SUMMARY AND CONCLUSIONS

Ultrasonics and computer technology have been integrated to obtain the means for "seeing" during plating. The thickness of a chromium film can be measured in real time with resolution and accuracy much better than that of the mechanical measurements which can be performed only after the plating process is finished. The advantages of this are many. Among those the possibility of intervention for remedial action in the case of problems. A detailed description of the system was given, starting from the theory of the measurement to the experimental details. The system is now being incorporated into process control so to stop plating as soon as the desired thickness is reached, or to monitor any unpredictable or irregular behavior of the process.

TABLE I. Results from Error Analysis

Parameter	Standard Deviation	Error [μm]
Thickness of Standards [μm]	0.25	1.27
Velocity Ratio ($\gamma = v_C/v_S$)	0.03	6.42
Temperature Dependance β [°C^{-1}]	10^{-5}	2.00
Time delay Meas. on Standards	.0001	6.22
Time Delay Meas. on Sample	.0001	1.39
Temperature Meas. [°C]	1	0.75
	TOTAL [μm]	9.41

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MICROWAVE SENSOR FOR ICE DETECTION

BY

G.D. ARNDT*, A. CHU*

L.G. STOLARCZYK** AND G. L. STOLARCZYK**

ABSTRACT

A microwave technique has been developed for detecting ice build-up on the wing surfaces of commercial airliners and highway bridges. A microstrip patch antenna serves as the sensor, with changes in the resonant frequency and impedance being dependent upon the overlying layers of ice, water and glycol mixtures. The antenna sensor is conformably mounted on the wing. The depth and dielectric constants of the layers are measured by comparing the complex resonant admittance with a calibrated standard. An initial breadboard unit has been built and tested. Additional development is now underway.

Another commercial application is in the robotics field of remote sensing of coal seam thickness.

1.0 INTRODUCTION

Ice build-up on the orbiter low temperature fuel tanks, airfoil surfaces and highway structures can create hazardous transportation conditions. Ice build-up on the orbiter's low temperature fuel tanks is a safety concern in NASA'S Space Shuttle Program. After filling insulated fuel tanks on the booster rocket, the count down time period can continue until ice build-up reaches 1/16 inch. During the insertion phase of flight, the ice layer could fragment and damage heat shield tile and windows of the shuttle. Presently, ice depth measurements are made manually by scratching away the ice layer and determining its thickness. Because of the large physical size of the fuel tanks, the number of measurements is limited.

* NASA Johnson Space Flight Center

** Raton Technology Research, Inc.