DEVELOPMENT OF A NONDESTRUCTIVE TEST FOR GLASS-REINFORCED PLASTIC LAMINATES

by

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For a number of years the Bureau of Ships has been sponsoring research for the purpose of developing instrumentation and procedures for nondestructively testing glass-reinforced plastic laminates. Original application of glass-reinforced laminates by the Navy was for construction of small boats. At present, however, the use of these materials has extended to many other structural and semistructural uses. The ever-increasing volume of the materials being procured and the structural requirements involved have necessarily increased the need for improved inspection techniques. Current inspection techniques involve visual inspection with strong white light, and/or tapping of the laminate. It would be highly desirable to furnish the inspector with instrumentation to augment the tests he currently uses.

An "idealized" nondestructive-test instrument for polyester-glass laminate should have as many of the following characteristics as possible:

(1) Portability and ruggedness
(2) Economy and ease of operation
(3) Capability of detection of:

    (a) Delamination
    (b) Porosity
    (c) Dry spot
    (d) Resin segregation
    (e) Incomplete cure

(4) Ability to measure laminate thickness
(5) Ability to measure resin or glass content of laminate
(6) Ability to penetrate at least 1/2 inch of laminate
(7) Must be a "one-side" inspection tool.

Early in the research program, a comprehensive survey was made of existing equipment and procedures, and the various energy forms used by this equipment were reviewed for possible application to laminate inspection.

Samples of laminates containing dry spot, delamination, porosity, and resin segregation were obtained from various manufacturers. In most cases the samples were flat panels 6 inches square, with thicknesses ranging from 0.10 to 0.50 inch. Several samples of glass-reinforced tubing were also obtained for testing. Several laminate panels 1/4 inch thick were made in the laboratory with small cellophane inserts between the two central layers of reinforcement. These panels thus contain typical delamination defects. A group of special panels were fabricated by the Material Laboratory of the New York Naval Shipyard.

The resin employed was modified with styrene to a viscosity of approximately 600 centipoises. The laminates were made in a press with platens heated at 200 F. Polished ferrotype plates were used as the mold, and the curing time was 1/2 hour.

In one group of samples, an attempt was made to hold the resin content of the panels constant, with panel thickness being varied. Table 1 described this group of samples.

In another group of samples, an attempt was made to hold the panel thickness constant at 1/4 inch, while the resin content of the panels was varied. Table 2 describes this group of samples. The maximum deviation of these samples from the 1/4-inch nominal thickness is about 4 per cent.

MISCELLANEOUS TESTS

Inspection with Light

The most effective nondestructive tests currently in use on laminates involve visual inspection by transmitted or reflected white light.

Many tests were made with ultraviolet and infrared light, to determine whether another portion of the light spectrum might prove more efficient than the white range, but white light proved to be superior. The visual inspection of laminates is effective since most serious defects cause discoloration in the material. Obviously the method is limited to translucent material, and some other means must be used where opaque laminates are concerned.

TABLE 1. CONSTANT-RESIN-CONTENT, VARYING-THICKNESS SAMPLES

Panel	Nominal Thickness, inch	Number of Plies	Resin Content, per cent	Specific Gravity
7	1/8	10	38.5	1.79
8	3/16	15	39.1	1.76
9	1/4	20	37.1	1.80
10	5/16	25	39.6	1.77
11	3/8	30	38.9	1.76
12	1/2	40	38.1	1.78

Note: Reinforcement -- Style 1,000 glass cloth.

TABLE 2. CONSTANT-THICKNESS, VARIABLE-RESIN-CONTENT SAMPLES

Panel	Reinforcement	Number of Plies	Resin Content, per cent	Specific Gravity
1	Cloth(1)	21	36.8	1.79
2	Cloth(1)	24	32.1	1.86
3	Cloth(1)	19	41.1	1.71
4	Polyester mat(2)	6	75.4	1.40
5	Polyester mat(2)	9	62.5	1.48
6	Polyester mat(2)	8	67.3	1.45
13	Polyester mat(2)	4	82.3	1.35
14	Polyester mat(2)	10	57.8	1.51
15	Cloth(3)	14	48.8	1.63

(1) Style 1000--114 cloth

(2) 1-1/2 ounce Polyester Mat (Treatment 17)

(3) Equivalent to Style 1000 cloth.

All samples nominally 1/4 inch think.

Tapping Tests

Tapping laminates with a blunt object is often an effective means for locating laminar-type defects, due to the difference in sound generated when the material above a delamination is vibrated. This test method is currently used to evaluate the extent of questionable areas of laminates. Since the results of this test method depend completely upon the skill of the inspector, instrumentation to verify his judgment would be very desirable. Experiments were performed with an electromechanical tapping device, in an attempt to develop such an instrument. The instrument uses a variable-frequency relaxation oscillator to control the tapping rate, and another control allows the force of impact of the tapper to be varied. A crystal detector is used to pick up the vibrations from the laminate. The vibrations can be listened to with earphones, and their waveform may be monitored with an oscilloscope.

The electromechanical tapper used on glass-reinforced laminates did not disclose any more information than routine tapping and listening techniques. However, a device of this type may have a possible application for inspecting "honeycomb" sandwich material, where bonding of the outer skin to the honeycomb reinforcement must be inspected.

Dye-Penetrant Tests

A number of tests were made with liquid dye penetrants, to evaluate the application of the test method to laminate inspection. For a penetrant inspection to be effective, defects must necessarily be open to the surface. Surface crazing and porosity show up very well under penetrant inspection. Where penetrant can be applied to the edge of a panel, delaminations at the edge may be readily located. The method has been very useful for laboratory evaluation of laminate samples.

Radiography Tests

Radiographs were taken of a number of laminate test panels. The panels were 1/4 inch thick, made with Vibrin 112 resin reinforced with 184-114 glass cloth. Exposures were made for 5 minutes at 40 KVP and 8 milliamperes, at a distance of 30 inches. Type M film was used. The radiographs clearly show areas of obvious density variation, such as gross porosity and resin concentrations. Delaminations were not detected. This method is costly and time consuming, and involves a relatively large amount of equipment, so it has been used only for laboratory tests.

ULTRASONIC TESTS

Ultrasonic tests have been used successfully for a number of years to locate internal discontinuities in metals. The method is effective on most metals since they have relatively good ultrasound-propagation qualities. No. Most reinforced plastic materials have poorer acoustic propagation qualities. Therefore, using ultrasonics to inspect reinforced laminates involves much more than a direct "applications" problem.

Pulse Echo

A pulse-echo-type instrument uses a quartz crystal to transmit pulses of ultrasonic energy into the material under test. The time required for a pulse of energy to be reflected back to the crystal from an interface is measured electronically and is displayed as an indication on a cathode-ray screen. This screen may be calibrated so that the thickness of a material, or the distance to a discontinuity in the material, can be determined directly. No.

Laboratory tests with pulse-echo equipment were made at frequencies of 1, 2-1/4, and 5 megacycles per second. No useful results could be obtained.

Through Transmission

Through-transmission inspection is usually accomplished by using an instrument with two crystals, one for transmitting, the other for receiving. The crystals are mounted directly in line with each other, and the work piece is placed between them. An inspection of this type must be conducted in a suitable sound-transmitting fluid such as water or oil. The fluid provides acoustic coupling between the crystals and the work piece. The receiving, or detecting crystal, produces an electrical signal proportional to the amount of ultrasonic energy impinging upon it. The signal is usually amplified and displayed on an oscilloscope screen. Since defects or discontinuities in the work piece attenuate the beam of ultrasound, a sudden decrease in amplitude of the received signal as the work piece is being scanned is indicative of some defect in the material.

While this test method is not a "one-sided" test, it was found to be quite effective for laboratory evaluation of the internal quality of small laminate test panels. Delamination-type defects could readily be located in laminates up to 1/2 inch thick. The extent of the delaminated area could be determined, and the panel surface could be marked accordingly. Dry-spot and gross-porosity defects also could be located. Frequencies of 1, 2-1/4, and 5 megacycles were used for the tests, with the best results obtained at 1 megacycle.

Resonant Frequency

A resonant-frequency ultrasonic instrument uses a transducer to transmit the energy into the work piece. Suitable coupling fluid (water, oil, or glycerin) is necessary between the transducer and the work piece. Electronic circuitry in the instrument is provided to furnish a means of sweeping a prescribed range of frequencies. If the material being tested is in the thickness range corresponding to the frequency range being covered, it will resonate at a frequency characteristic of its thickness. The transducer registers this frequency as a change in the electrical circuit. This change may be detected by means of a change in tone of a signal in earphones, by an increase in the reading of a sensitive meter, or as a "pip" on an oscilloscope trace. The oscilloscope trace may be calibrated so that the location of the "pip" indicates thickness of the work piece directly. If a defect or discontinuity in the work piece presents a large enough reflecting surface to the ultrasonic energy, a "pip" indicating the depth of the defect below the surface will be seen on the oscilloscope screen.

Audigage Tests

A number of commercial resonant-frequency ultrasonic instruments were tested on various laminates. One of these instruments, the Audigage, is manufactured by Branson Instruments, Incorporated, Stamford, Connecticut. The Model FMSS-5 Audigage has a frequency range of 0.65 to 2.00 megacycles. Using a special Type B transducer with this instrument, delaminations could be located in samples 1/4-inch thick. This 1.30 megacycle transducer is made by sandwiching barium titanate between two layers of quartz. Thickness measurements were made on laminates in the thickness range of 1/8 to 1/2 inch, with accuracies within 8 per cent. Thickness measurements could be made within 3 per cent when high-quality laminates were being tested.

Sonizon Tests

Another commercially available resonant-frequency instrument tested on laminates was the Sonizon, manufactured by the Magnaflux Corporation, Chicago, Illinois. The standard Sonizon instrument is equipped with five quartz transducers that cover the frequency range of 0.25 to 5.00 megacycles per second. In operation, a coupling fluid such as oil or glycerin must be placed between the transducer and the work piece. Resonance indications are observed on a cathode-ray screen. The screen can be calibrated to indicate thickness directly.

The instrument is designed primarily for the inspection of metals. The quartz transducers furnished with the equipment will not produce useful resonance indications from glass-laminate materials. Work is currently in progress to adapt barium titanate transducers to the instrument.

Barium titanate is basically an electrostrictive material which, when polarized, assumes properties similar to piezoelectric materials such as quartz. Higher amplitude vibrations can be obtained from barium titanate than from quartz.

If the barium titanate transducers can be used effectively with the instrument, the cathode-ray screen will then produce visual indication of the internal quality of the laminate under test.

DIELECTRIC TESTS

Audio-Frequency Tests

Early evaluation of various energy forms applicable to glass-laminate inspection indicated that dielectric tests might be developed to the point where they could furnish useful information about the material. Initial tests at audio frequencies were performed with probes having planar contact surfaces, applied to flat laminate specimens. An audio-oscillator was used to supply energy to the probes, and a vacuum-tube voltmeter was used to measure voltage changes in the system. These early tests indicated that penetration was achieved to a depth of at least 1/4 inch in laminate, and the method appeared feasible for laminate thickness measurement from one side of the work piece.

Crystal-Oscillator Probe Development

Investigation of existing patents on dielectric-testing equipment disclosed that United States Patent 2,601,649 describes an electronic thickness gage for dielectric materials. This patent is issued to Mr. H. A. Wadman, and is assigned to the Emhart Manufacturing Company, Hartford, Connecticut. It was considered that some modification of this gage might be developed into an inspection instrument for glass-laminate material.

Description

The instrument is designed to detect variations in dielectric materials. It does this by using the dielectric properties of the material under test to vary the capacitance of a condenser in a critically tuned resonant circuit. As the dielectric between two plates of a condenser is varied, the capacitance of the condenser is also varied. The contact electrode of the instrument forms one side of this condenser, while the grounded shell of the probe forms the other side. When the contact electrode is placed against a laminate test piece, the capacitance between the electrode and ground is changed. This change in capacitance causes a change in the amount of plate current being drawn by the crystal-controlled oscillator circuit. A vacuum-tube voltmeter is incorporated in the instrument to furnish meter indications proportional to the amount of plate current being drawn by the oscillator. The instrument may be calibrated so that the meter readings indicate laminate thickness (when resin content of the sample is not a variable), or resin content (when thickness is not a variable). A gross defect in the laminate, such as a dry spot or resin concentration, will cause a sudden meter deflection as the probe passes from normal laminate to a position over the defective area.

Three models of the instrument have been built; the first was battery operated, the second used either batteries or regular line voltage, while the Model 3 instrument operates from 110 volts alternating current. The oscillator circuit is contained in the hand-held probe, which is a stainless steel cylinder about 8 inches long and 2-1/4 inches in diameter. The contact electrode, which is placed against the surface to be inspected, consists of a 1-inch-diameter brass roller, mounted on a brass shaft several inches long. The contact electrode is insulated from the stainless steel shell of the probe by a polystyrene bushing.

Thickness Measurements

The Model 3 instrument functions well as a laminate thickness gage. Applying the instrument to the group of samples described in Table 1, a plot of meter reading as a function of laminate thickness was obtained. This plot is shown in Figure 1. Since the samples all contain about 38.5 per cent resin content, thickness of the samples is the critical variable.

To see if the probe would be functional on laminates with considerable curvature, the following experiment was performed. A thickness-measurement test

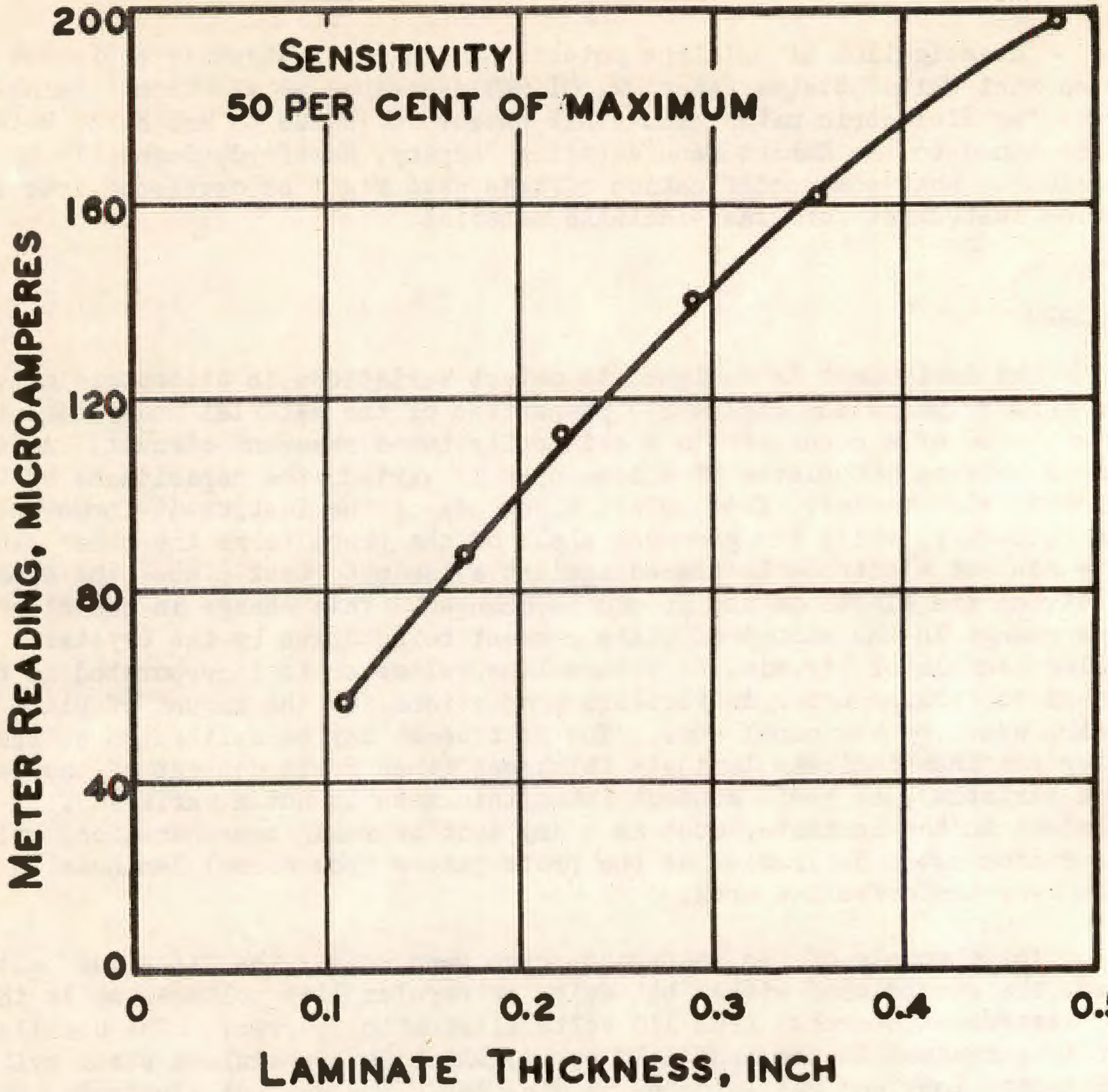

FIGURE 1. METER READING AS A FUNCTION OF LAMINATE THICKNESS

was made on a section of glass-reinforced plastic oil-well tubing. The 3-1/2-inch-OD tubing is made with glass-mat reinforcement and is centrifugally cast. The roller electrode was placed against the outer surface of the tubing, and readings were taken at 45-degree intervals around the circumference. A tubing micrometer was used to obtain actual thickness readings for correlation with the meter values. This relationship is shown in Figure 2. The maximum wall thickness variation is about 0.025 inch, and is readily indicated by the probe.

Resin-Content Measurements

Resin content as well as thickness of laminates affect the plate current readings of the Model 3 probe. Although thickness appears to have the greater effect, it is possible to use the instrument as a resin-content gage.

For resin-content measurement tests, panels of the same thickness (1/4 inch) were chosen. Table 2 describes these samples. The resin-content range covered by these samples extends from about 30 to 80 per cent. Mat and cloth type reinforcement is used in the samples, although no sample contains both types. The curves in Figure 3 show plate current plotted as a function of the resin content of the samples. Note that the curve from the cloth-reinforced samples differs distinctly from the mat-samples curve. Evidently the type of reinforcement affects the measurements.

CONCLUSIONS

(1) Visual inspection is still the best nondestructive test for laminate quality, when the materials concerned are not opaque.

(2) A skilled inspector, using "tapping" tests, can locate suspicious areas in opaque laminates by noting the duller sound obtained when tapping these areas. An electromechanical tapping device may be effective for checking the bond of the outer skin to honeycomb reinforcement.

(3) Dye penetrants will detect laminar defects occuring at the edges of a panel, and will also show surface porosity and crazing.

(4) Radiography will detect internal density variations, porosity, and cloth folds, but is usually ineffective for locating delaminations.

(5) At present, pulse-echo ultrasonic techniques are ineffective for laminate inspection.

(6) Through-transmission ultrasonic tests are quite effective for locating internal defects such as delaminations, dry spots, and gross porosity, in small laminate panels. One megacycle operation is superior to 5 megacycles.

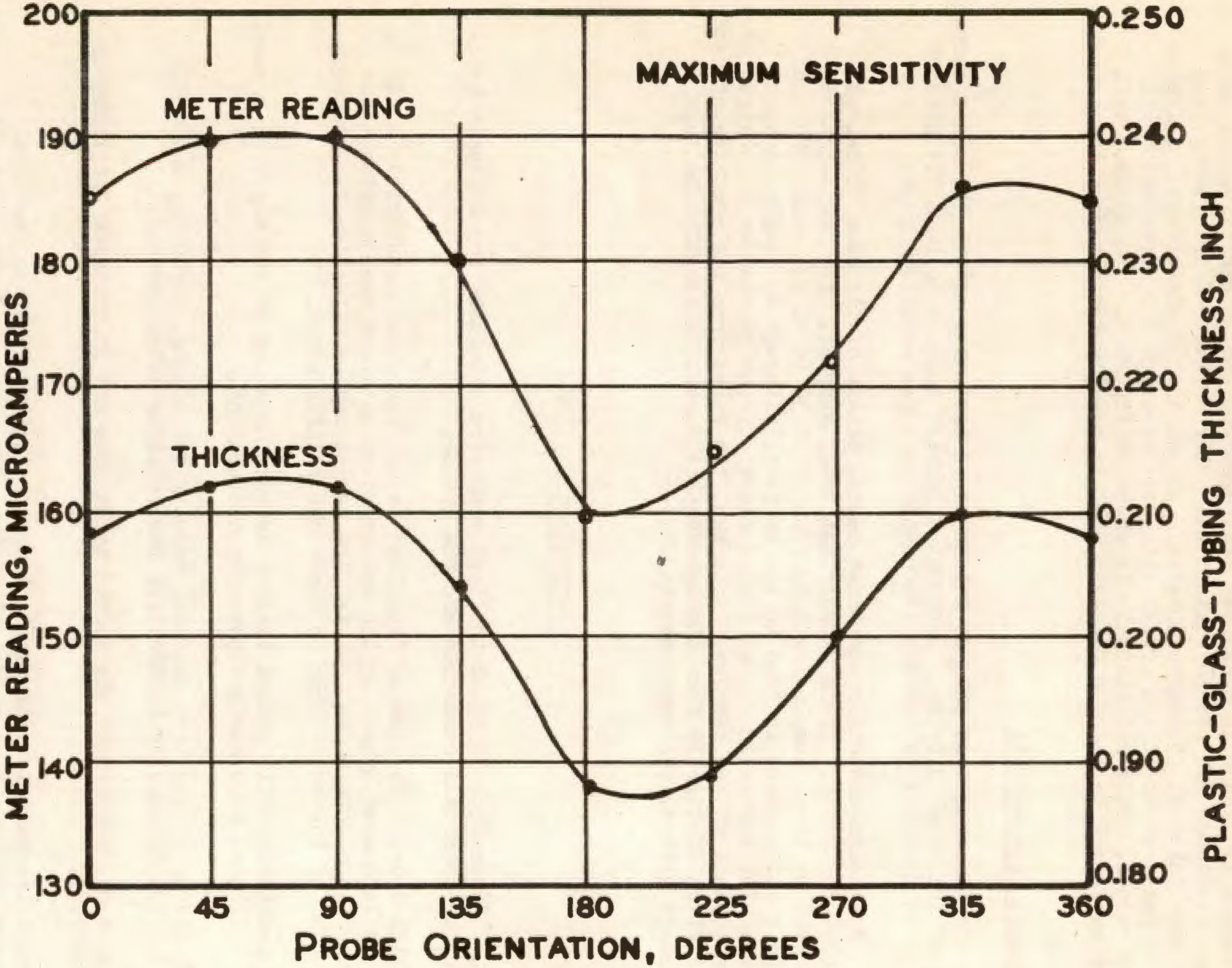

FIGURE 2. COMPARISON OF METER-READING AND THICKNESS CURVES

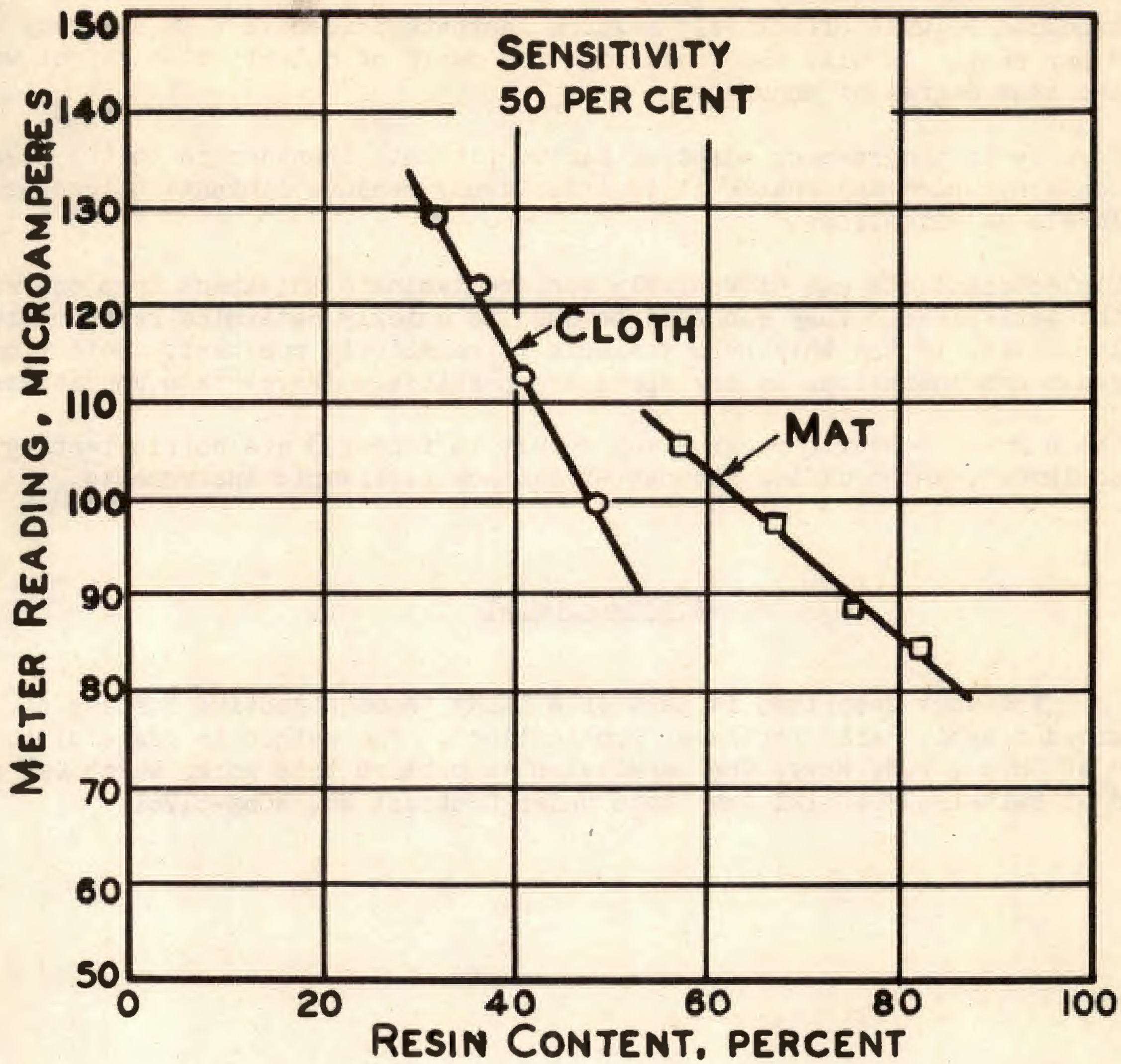

FIGURE 3. METER READING AS A FUNCTION OF RESIN CONTENT

(7) One resonant-frequency instrument, the FMSS-5 Audigage, used with a Type B transducer, will effectively measure laminate thickness with accuracy within 8 per cent. It will also determine the depth of delamination defect with the same degree of accuracy.

(8) Work is in progress on adapting barium titanate transducers to the Magnaflux Sonizon, which may enable it to effectively measure laminate thickness and locate delaminations.

(9) Dielectric tests can effectively measure laminate thickness from one side of the work piece. They can also be used to quickly determine resin content of laminates, if the thickness variable is relatively constant. Detection of resin concentrations or dry spots are possible under certain conditions.

(10) The current research program may result in improved dielectric-testing equipment, and modified resonant-frequency ultrasonic instruments.

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