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MILITARY STANDARD

ELECTRICAL CONDUCTIVITY TEST FOR VERIFICATION OF
HEAT TREATMENT OF ALUMINUM ALLOYS,
EDDY CURRENT METHOD



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MIL-STD-1537E

DEPARTMENT OF DEFENSE
Washington, DC 20301

Electrical Conductivity Test for Measurement of Heat Treatment of Aluminum Alloys, Eddy Current Method

MIL-STD-1537E

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MIL-STD-1537B

FOREWARD

An electrical conductivity measurement of an aluminum alloy determines its conductivity in ohm centimeters or in percent of the International Annealed Copper Standard (IACS) by comparison with certified conductivity standards. For a properly identified aluminum alloy, electrical conductivity measurement is a nondestructive method for verifying heat treatment. The electrical conductivity test used in conjunction with hardness testing makes it feasible to verify proper heat treatment.

Electrical conductivity in production part testing is measured by the eddy current method. Direct reading type eddy current instruments indicate conductivity in percent IACS and indirect type eddy current instruments are normally scaled in microamperes. To calibrate either of these types of eddy current instruments, certified non-ferrous conductivity standards are required.

MIL-STD-1537B

CONTENTS

Paragraph		<u>PAGE</u>
1.	SCOPE- - - - -	1
1.1	Scope- - - - -	1
2.	REFERENCED DOCUMENTS - - - - -	2
2.1	Government documents - - - - -	2
2.1.1	Specifications and standards - - - - -	2
2.2	Other publications - - - - -	2
2.3.3	Order of precedence- - - - -	3
3.	DEFINITIONS- - - - -	4
3.1	Volume resistivity - - - - -	4
3.2	Conductivity - - - - -	4
3.3	Percent IACS - - - - -	4
3.4	Eddy current instrument- - - - -	4
3.5	Probe- - - - -	4
3.6	Nonferrous conductivity standards- - - - -	4
3.7	Standard depth of penetration	5
3.8	Lift-off effect- - - - -	5
3.9	Direct reading eddy current instrument - -	5
3.10	Indirect reading eddy current instrument -	5
3.11	Standard depth of penetration- - - - -	6
4.	GENERAL REQUIREMENTS - - - - -	7
4.1	Equipment- - - - -	7
4.1.1	Instruments- - - - -	7
4.1.2	Instrument sensitivity - - - - -	7
4.1.3	Instrument accuracy- - - - -	7
4.2	Standards- - - - -	7
4.2.1	Laboratory conductivity standards- - - - -	7
4.2.2	Instrument conductivity standards- - - - -	7
4.3	Calibration and standardization- - - - -	8
4.3.1	Standardization- - - - -	8
4.3.1.1	Standardization frequency- - - - -	8
4.3.1.2	Lift-off effect- - - - -	8
4.3.2	Laboratory calibration - - - - -	8

MIL-STD-1537B

CONTENTS

		<u>PAGE</u>
Paragraph	4.4	Test article - - - - - 8
	4.4.1	Surface- - - - - 8
	4.4.2	Edge effect- - - - - 9
	4.4.2.1	Curvature correction factor- - - - - 9
	4.4.3	Sample thickness - - - - - 9
	4.4.3.1	Thin specimens - - - - - 10
	4.4.4.	Clad specimens - - - - - 12
	4.4.5	Alclad specimens - - - - - 12
	4.5	Personnel qualification- - - - - 13
	4.5.1	Direct reading instruments - - - - - 13
	4.5.2	Indirect reading instruments - - - - - 13
	5.	DETAIL REQUIREMENTS- - - - - 14
	5.1	Procedure- - - - - 14
	5.1.1	Hardness tests - - - - - 14
	5.1.2	Conductivity tests - - - - - 14
	5.1.2.1	Acceptable mechanical properties - - - - 14
	5.1.3	Correction factors for conductivity readings on round stock - - - - - 14
	5.1.4	Lift-off correction factors- - - - - 14
	5.1.5	Operating precautions- - - - - 15
	5.2	Conductivity requirements- - - - - 15
	6.	NOTES- - - - - 16
	6.1	Intended use - - - - - 16
	6.2	Report of results- - - - - 16

MIL-STD-1537E

FIGURES

	<u>PAGE</u>
Figure 1. Effective Depth of Penetration as a Function Conductivity and Operating Frequency- - - - -	11
Figure 2. Hardness vs Conductivity for 7075 Aluminum Alloy - - - - -	17

MIL-STD-1537B

1. SCOPE

1.1 Scope. This standard contains procedures for verifying aluminum alloy heat treatment by means of eddy current techniques which measure electrical conductivity. Aluminum alloy heat treatment can be verified when electrical conductivity measurements are used in conjunction with hardness measurements.

MIL-STD-1537B

2. REFERENCED DOCUMENTS

2.1 Government documents.

2.1.1 Specifications and standards. Unless otherwise specified, the following specifications and standards of the issue listed in that issue of the Department of Defense Index of Specifications and Standards (DODISS) specified in the solicitation form a part of this standard to the extent specified herein.

Calibration System Requirements

STANDARD

MILITARY

MIL-STD-410	Non-Destructive Testing Personnel
MIL-STD-45662	Qualification and Certification

(Copies of specifications, standards, drawings and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Other publications. The following documents form a part of this specification to the extent specified herein. The issues of the documents which are indicated as DOD adopted shall be the issue listed in the current DODISS and the supplement thereto, if applicable.

ASTM

ASTM B193	Resistivity of Electrical Conductor Materials
ASTM E10	Brinell Hardness of Metallic Materials
ASTM E 18	Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials

MIL-STD-1537B

(Applications for copies should be addressed to the ASTM, 1916 Race Street, Philadelphia, PA 19103.)

2.3. Order of precedence. In the event of a conflict between the text of this standard and the references cited herein, the text of this standard shall take precedence.

MIL-STD-1537B

3. DEFINITIONS

3.1 Volume resistivity ρ , is a value of resistivity of a known volume of nonferrous metal expressed in ohm (centimeters)² per centimeter or simply ohm centimeters, where the area is of uniform cross-section A in sq cm and the resistance R in ohms is the value for a known length L in cm of the area A, or expressed in equation form

$$\rho = \frac{RA}{L} \text{ (ohm centimeters) @ } 20^{\circ}\text{C (68}^{\circ}\text{F)}$$

3.2 Conductivity. The conductivity, σ , of a material is the reciprocal of volume resistivity or $1/\rho$. It is the relative value of conductivity of any nonferrous metal, to the arbitrary value set for commercially pure copper, and is usually expressed in percent International Annealed Copper Standard or percent IACS, at 20°C by definition, where copper = 100 percent IACS.

3.3 Percent IACS (International Annealed Copper Standard). Percent IACS is the percent value of the conductivity of a material compared to the IACS standard value. The IACS standard is a commercially pure copper rod one meter long with a uniform cross-section of 1 mm² with resistance of 1/58 (0.017241) ohms at 20°C. The conductivity of this standard is considered to be 100 percent IACS.

3.4 Eddy current instrument. An electrical measuring instrument which responds to eddy currents induced in metals by a probe, which induces these currents by means of a time-varying electromagnetic field. Note: Also called an eddy current meter.

3.5 Probe. Many turns of fine wire usually wound on a ferrite or laminated iron core in such a way as to produce a varying electromagnetic field when energized by an alternating current, usually 60 KHz or above for conductivity measurements.

3.6 Nonferrous conductivity standards. Either primary or secondary nonferrous metal conductivity standards which have the following characteristics:

- a. Primary or Reference Nonferrous Conductivity Standards:
Uniformly dimensioned rectangular or round bars of homogeneous nonferrous metal finished to a surface finish which will permit dimensional and resistance measurements such that they can be certified for conductivity values to at least ± 0.2 percent IACS or ± 0.5 percent of stated value, whichever is less at 20°C.
- b. Secondary or Laboratory Nonferrous Conductivity Standards:
Blocks or coupons of nonferrous homogeneous metal of adequate thickness to prevent noticeable effects on the meter readings with

MIL-STD-1537B

the measuring surface finished so as to eliminate lift-off errors and of such an area as to preclude edge effects, calibrated on alternating current by comparison with primary conductivity standards and certified to ± 0.35 percent IACS or 1 percent of stated value, whichever is less at 20°C (68°F).

- c. Instrument Nonferrous Conductivity Standards: Similar or identical to the secondary or laboratory standards in b above except they are fastened securely to an eddy current instrument and certified to ± 0.85 percent IACS at 20°C (68°F) when calibrated against secondary or laboratory standards using the eddy current instrument as the transfer means.

3.7 Standard depth of penetration (English).

$$\delta = 26/\sqrt{f\mu\sigma} \text{ or } 26/(f\mu\sigma)^{1/2}$$

where δ = standard depth of penetration (inches)

f = operating frequency (Hertz)

μ = relative permeability (1.0 for nonmagnetic materials)

σ = conductivity in %IACS

3.8 Lift-off effect. The change in eddy current meter indication when the spacing between the surface probe and the test object changes from an "in contact" position to another position by means of selected nonconducting spacers between the surface probe and the test object.

3.9 Direct reading eddy current instrument. An analog or digital electronic instrument and probe which displays the conductivity of a nonferrous metal under test in percent IACS.

3.10 Indirect reading eddy current instrument. An electronic instrument and probe with variable frequency and gain characteristics requiring graphic interpolation of pointer and scale indication for any probe, frequency and gain combination to obtain values of conductivity of a nonferrous metal under test in percent IACS.

MIL-STD-1537B

3.11 Standard depth of penetration (metric).

$$\delta = 50 \left(\frac{\rho}{f\mu} \right)^{1/2} \text{ or } 50 \sqrt{\frac{\rho}{f\mu}}$$

where δ = standard depth of penetration (millimeters)

ρ = resistivity ($\mu\Omega\text{cm}$) = $\frac{172.41}{\%IACS}$

f = frequency (Hertz)

μ = relative permeability (1.0 for nonmagnetic materials)

MIL-STD-1537B

4. GENERAL REQUIREMENTS

4.1 Equipment.

4.1.1 Instruments. Electrical conductivity of aluminum alloys shall be determined using either a direct or an indirect reading eddy current instrument. Whenever possible, direct reading instruments shall be used for conductivity measurements. Where indirect reading eddy current instruments are required for conductivity measurements, calibration curves are necessary to correlate instrument readings with percent IACS values, since indirect reading instruments typically read in microamperes (μA) and have non-linear characteristics. Indirect reading eddy current instruments require at least three certified standards to verify the calibration curve being used. These standards must be within ± 10 percent IACS of the value being measured, with at least one above and one below the value to be measured.

4.1.2 Instrument sensitivity. Direct and indirect reading instruments shall have a sensitivity such that changes of at least 0.5 percent IACS are clearly distinguishable over the conductivity range of the aluminum alloys under test.

4.1.3 Instrument accuracy. Direct and indirect reading instruments shall be capable of determining the conductivity of aluminum alloys as a percentage of the International Annealed Copper Standard (percent IACS) with an accuracy of ± 1.0 percent IACS or better through electrically non-conductive films and coatings at least 0.003 inch (0.076 mm) thick.
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4.2 Standards.

4.2.1 Laboratory conductivity standards. The contractor or calibrating facility shall maintain three or more certified aluminum alloy laboratory conductivity standards. One laboratory conductivity standard shall be between 25 and 32 percent IACS, another between 32 and 38 percent IACS and the third between 38 and 72 percent IACS. The values of these standards shall be certified to be within ± 0.35 percent IACS or ± 1 percent of their stated value whichever is less, at 20°C (68°F). Calibration intervals shall be based on objective evidence that accuracy as the lesser of ± 0.35 percent IACS or ± 1 percent of value is constantly maintained. Initial calibration shall not exceed 12 months. Calibration will be performed in accordance with ASTM B193 procedure in a system per MIL-STD-45662.

4.2.2 Instrument conductivity standards. At least two instrument conductivity standards are required. These standards are similar to the laboratory conductivity standard described in 4.2.1 above except that these standards shall always accompany the eddy current instrument. Also, these

MIL-STD-1537B

standards are calibrated by comparing the eddy current instrument readings with laboratory conductivity standards. Using the comparison method, instrument conductivity standards shall be certified to ± 0.85 percent IACS accuracy. The high and low value instrument standards will have a minimum difference of 10 percent IACS. At least one standard will cover the 25 to 32 percent IACS range and one standard will cover the 38 to 62 percent IACS range. Calibration intervals shall be such that they coincide with the eddy current instrument recalibration cycle (see 4.3.2) or as supported by objective evidence that the required accuracy is consistently maintained.

4.3 Calibration and standardization.

4.3.1 Standardization. Instruments shall be standardized before using as required by following the manufacturer's instructions. Allow approximately 20 minutes warm-up time for all types except solid state which may take up to five minutes. Use the instrument conductivity standards to calibrate the eddy current instrument using the standards nearest to the conductivity range being measured and adjust as required.

4.3.1.1 Standardization frequency. Perform periodic standardization of the conductivity instrument with the instrument conductivity standards at 15 minute intervals during continuous operation.

4.3.1.2 Lift-off effect. Lift-off effect is determined by comparison of readings taken when placing the probe on a bare standard followed by placing a 0.003 inch (0.076mm) thick nonconducting flat shim between the probe and the standard. The difference in the two readings shall not exceed 0.5 percent IACS. If it does exceed 0.5 percent IACS, return the instrument to the calibration facility for repair and recertification. This test shall be performed at least every 60 days or at a frequency based upon objective evidence that the required accuracy is consistently maintained. On indirect reading instruments, lift-off shall be checked daily.

4.3.2 Laboratory calibration. The eddy current instrument shall be returned to the calibration laboratory on a periodic schedule for a complete calibration and certification including scale tracking (if analog type), lift-off, drift and battery replacement (if required). The periodic recalibration of all types of eddy current instruments shall not exceed either 120 days or an interval based upon objective evidence that the required accuracy is consistently maintained.

4.4 Test article.

4.4.1 Surface. The areas to be tested shall be free of dirt, grease, oil or other contaminants. The surface finish of the areas to be tested shall be 150RHP maximum, RMS 165 maximum or less than a maximum established by objective evidence, for the instrument in use, that the required accuracy is maintained. A nonconductive coating up to 0.003 inch (0.076 mm) thick is permissible on parts without determining a lift-off correction factor for eddy current readings.

MIL-STD-1537B

If the nonconductive coating thickness is greater than 0.003 inch (0.076 mm), the effects of the coating on instrument readings shall be determined. Effects of coating thickness shall be established by measuring the conductivity at individual locations before and after removal of the nonconductive coating or by simulating the coating thickness on bare metal by the use of plastic or paper shim stock as outlined in Section 5.1.4. If the difference between the two readings from coated and uncoated aluminum is greater than 0.5 percent IACS, further measurements and instrument recalibration shall be made to further verify the coating thickness and establish the magnitude of the difference in instrument readings. A lift-off correction factor shall be applied as determined from the difference in readings.

4.4.2 Edge effect. To insure readings are not distorted from edge effect, the specimen area to which the eddy current instrument probe is applied shall be at least as large as the outside diameter of the test probe or per manufacturer's specifications. The coil shall be centered on all parts whose dimensions approach this limitation.

4.4.2.1 Curvature correction factor. The limitations on the minimum radius of curvature of concave and convex surfaces on which conductivity measurements can be performed accurately shall preferably be determined by user's tests or shall be in accordance with the instrument manufacturer's specifications. Round stock having a radius of less than the instrument manufacturer's specifications may be tested, provided a fixture is used to insure that the probe is placed in the same position on each piece and a curvature correction factor is used. An acceptable alternate method for round stock with a radius of less than four inches (100 mm) would be to move the probe slowly and gently across the surface at right angles to the length, read the maximum value indicated on the instrument and then apply the appropriate correction factor.

4.4.3 Sample thickness. Test articles for which electrical conductivity readings are made without a thickness correction factor shall meet or exceed the minimum thickness shown in Figure 1 for the percent IACS range and frequency being used, except as shown in 4.4.3.1 below. Note: The EDPS determined from Figure 1 graph are 2.66 times the Standard Depth of Penetration determined by equations in paragraphs 3.7 and 3.11.

MIL-STD-1537B

4.4.3.1 Thin specimens. Nonclad aluminum of the same heat treat condition but with a thickness as much as 40 percent below the minimum shown in Figure 1 shall be tested as follows:

- a. For each lot of material, three specimens identified as a, b, and c, shall be tested using stacked material specimens. Measurements of conductivity shall be made with the specimens stacked in the three arrangements shown below.

	ARRANGEMENT		
	(1)	(2)	(3)
Top specimen	a	b	c
Middle specimen	b	c	a
Bottom specimen	c	a	b

- b. Unstacked specimens shall be placed on a nonconductive test surface at least 1/4 inch (6.35 mm) from any electrically conductive material and a measurement of the conductivity of each specimen made.

- c. The average stacked and unstacked conductivity can be calculated.

$$(\text{Average "Stacked"}) = 1/3 (\text{Stacked}_{(1)} + \text{Stacked}_{(2)} + \text{Stacked}_{(3)}).$$

$$(\text{Average "Unstacked"}) = 1/3 (\text{Unstacked}_{(1)} + \text{Unstacked}_{(2)} + \text{Unstacked}_{(3)}).$$

- d. The difference (Average Unstacked) - (Average Stacked) shall be the thickness correction factor to be added to the acceptance limits for the given material and shall be considered the acceptance criterion for measuring the balance of the lot in the unstacked condition in accordance with (b).

(1) If a conductivity measurement determined when specimens are stacked is outside the applicable acceptance range, the specimen in the top position in the measurement shall be rejected. A remeasured new specimen from the lot shall replace the rejected specimen and the stack shall be remeasured. In all measurements with stacked readings outside the acceptance range, the top specimen in the stack shall be rejected and a new specimen chosen as above.

(2) Any lot of parts or material thicker than 0.6 EDP (Figure 1) and with a thickness correction factor between 0 and 2.5 percent IACS may be tested without stacking. Parts or material with a thickness correction factor greater than 2.5 percent IACS shall be stacked before testing.

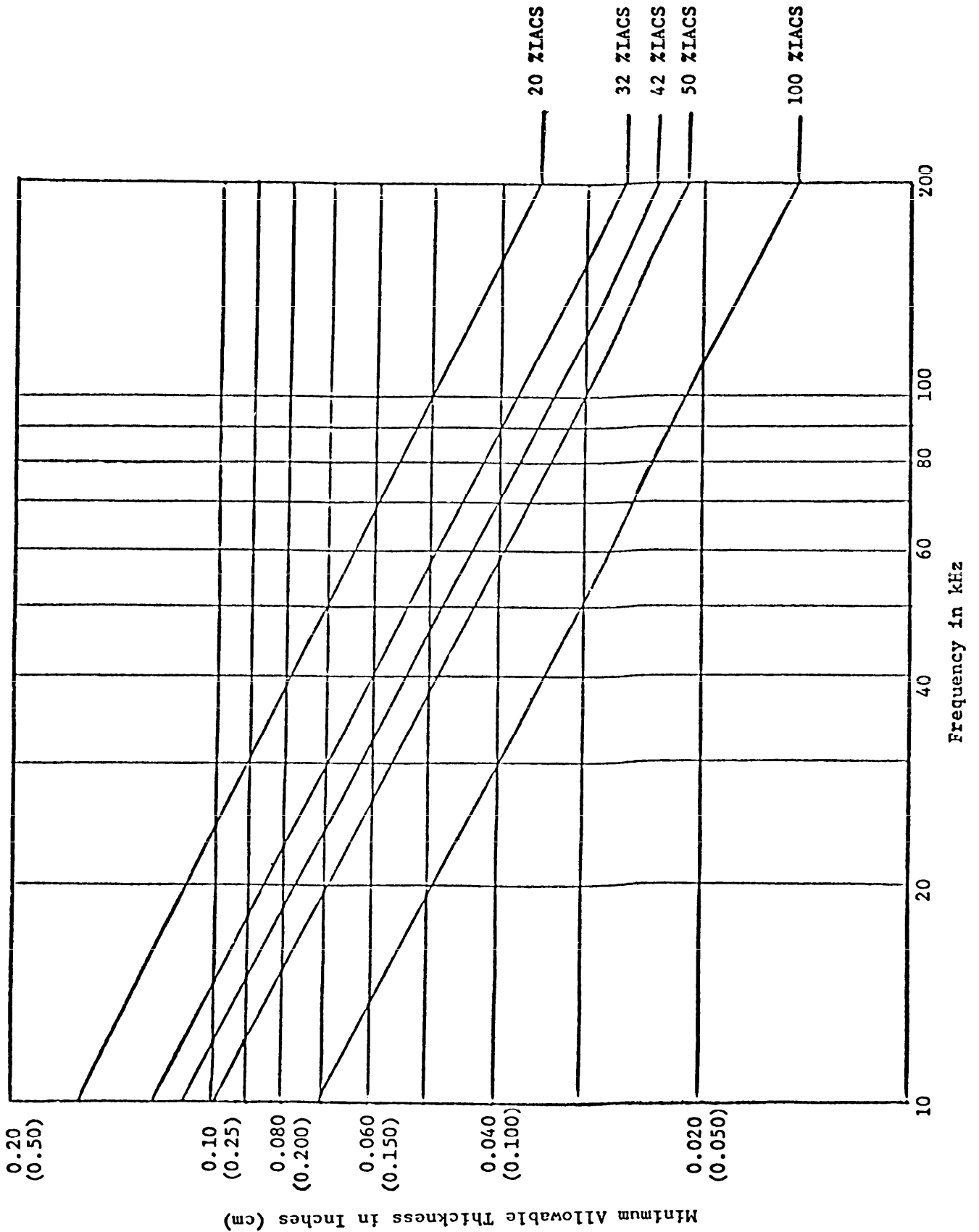


FIGURE 1. Effective Depth of Penetration as a function of Conductivity and Operating Frequency.

111-STD-1537B

- (3) If the thickness correction factor as determined above in (2) is greater than 5 percent IACS, stacking may lead to erroneous results. For correct results a higher eddy current instrument frequency should be used.
- e. Example #1: Suppose a lot of bare 0.040 inch (1.02 mm) 7075-T6 material is to be tested with a 60 kHz instrument and the acceptance range for this material is 30.0 to 34.5 percent IACS. In accordance with Figure 1, at 60 kHz and 32 percent IACS, the minimum thickness is 0.050 inch (1.27 mm). Since $EDP = 0.050 \times 0.6 = 0.030$ inch (0.76 mm), the 0.040 inch (1.02 mm) thick material shall be tested when stacked in accordance with 4.4.3.
- f. Example #2: Suppose three samples taken from the lot and tested while stacked, give readings of 34.0, 34.5 and 34.0 percent IACS. All readings are in the acceptable 30.0 - 34.5 percent IACS range. The average change in conductivity between the "unstacked" and "stacked" readings is +2 percent IACS. This is within the acceptable +2.5 percent IACS range as specified in 4.4.3.1. The new acceptance range for this lot of 0.040 inch (1.02 mm) thick 7075-T6 material, unstacked, is then equal to 30.0 +2 to 34.5 +2 percent IACS or 32.0 to 36.5 percent IACS. The remaining specimens with "Unstacked" conductivity outside the 28.0 to 32.5 percent IACS range are rejected.

4.4.4 Clad Specimens. Electrical conductivity measurement of clad specimens shall be permitted only when correlation has been established between the conductivity readings and the acceptable range of heat treat response for the clad specimens. Correlation shall take into account the possible range of cladding allowed by the applicable material specification and limitations of the instrument operating frequency and specimen thickness. All procedures for conductivity measurements of clad aluminum alloys must be supported by documented evidence of correlation with heat treat response and hardness measurements over the allowable range of cladding thickness and shall be subject to review by the procuring agency.

4.4.5 Alclad specimens. Alclad materials shall be inspected at 50 to 75 kHz. When testing alclad parts thicker than 0.091 inch (2.3 mm) the cladding shall be partially removed on at least one part per inspection lot by spot-facing. If the value obtained in the spot-faced area is acceptable, a second reading shall be taken on the alclad surface of the same part. The difference in conductivity between the two readings shall be used as a cladding correction factor when inspecting the remaining parts in the lot. In case of doubtful or marginal values, a second part from the same lot shall be spot-faced, and the average difference shall be used for the cladding correction factor. The above procedure shall be performed on each lot of material.

MIL-STD-1537B

4.5 Personnel qualification.

4.5.1 Direct reading instruments. Personnel performing tests using direct reading instruments shall receive sufficient instruction for proper performance of the test and utilization of the equipment. Proper performance includes the capability to demonstrate operation and standardization of the equipment in accordance with the requirements of this standard.

4.5.2 Indirect reading instruments. Personnel performing conductivity tests using indirect reading eddy current instruments shall be qualified to level II requirements of MIL-STD-410.

MIL-STD-1537B

5. DETAIL REQUIREMENTS

5.1 Procedure.

5.1.1 Hardness tests. Measure the hardness of the first part in the lot to be tested to determine if the parts are in proper heat treated condition or the as quenched condition. Perform Rockwell hardness in accordance with either ASTM E10 or ASTM E18.

5.1.2 Conductivity tests. Maintain the temperature of the test probe, the standards and the test material within 3°C (5.4°F) of each other. Operate the electrical conductivity instrument in accordance with this specification and the manufacturer's recommendations. When tests are being made, the probe must be firmly pressed against the surface of the material or part. The condition of the part or material being tested shall meet the requirements of 4.4. Readings of unsatisfactory or questionable conductivity must always be verified by a recheck of the instrument calibration standards and then a hardness measurement must be performed on the material before making a disposition.

5.1.2.1 Acceptable mechanical properties. Acceptable hardness or conductivity, or both, of aluminum alloy materials do not guarantee acceptable mechanical properties. Inspection shall be based upon evidence of specified heat treatment or cold working on the accompanying fabrication outline or written certification, as well as on acceptable hardness and conductivity readings.

5.1.3 Correction factors for conductivity readings on round stock. A suggested procedure for establishing a curvature correction factor for round stock as specified in 4.4 is by using flat stock of the same material and temper as the round stock to be tested or material having conductivity within 5 percent of the stock to be tested. Measure the conductivity of the flat stock with an eddy current instrument (reading "a"). Then machine the flat stock to a radius within the tolerance of the radius on the round stock to be tested. Again measure the conductivity (reading "b") using a fixture to hold the probe in the same position as is to be used on the round stock to be tested. The correction factor to be added to the readings on the round stock is reading "a" minus reading "b". Repeat for 3 specimens and take the average. CAUTIONS: (a) Prior to machining curved surfaces on flat stock, establish that the conductivity of the flat stock does not vary appreciably throughout the depths to be exposed. (b) Do not over heat the part during machining since this will appreciably change the conductivity.

5.1.4 Lift-off correction factors.

- a. Establish lift-off correction factors for material or parts having a nonconductive coating exceeding 0.003 inches (0.076 mm) as follows:

MIL-STD-1537B

- b. Obtain plastic shim stock or paper of the same thickness as the nonconductive layer on the parts to be tested. Where paint thickness is not known, it will be necessary to remove or measure the paint thickness, for example, nonuniform coatings.
- c. Place the shim or paper on a bare specimen of the same nominal conductivity as the parts to be tested.
- d. Note the difference in readings of conductivity between tests run when the probe is placed directly on the surface of the bare specimen and when the probe is placed on the paper or plastic shim stock on top of the specimen. Use this difference as the lift-off correction factor for readings on the parts to be tested.

5.1.5 Operating precautions.

- a. When necessary to rub or slide probe tip against a surface, do it gently to save wear on the probe surface.
- b. Do not bang probe tip against surface being measured.
- c. A firm consistent probe pressure is desirable.
- d. Clean the surface of the material to be measured, if required.
- e. Keep the probe tip clean by wiping often with a clean lint-free cloth or a suitable commercial wiper.

5.2 Conductivity requirements. The conductivity measurements for acceptance of heat treated aluminum alloys shall be within the conductivity range for the specific alloy and type of heat treatment condition defined by the applicable contracting agency materials specifications.

IIL-STD-1537B

6. NOTES

6.1 Intended use. Hardness must be known for the conductivity test to be meaningful in measuring heat treatment. Figure 2 shows a typical variation of hardness and conductivity of an aluminum alloy with heat treat condition. Note that both hardness and conductivity values are required to define a given heat treat condition.

6.2 Report of results. Results shall be reported in a manner acceptable to both the contractor and the procuring agency.

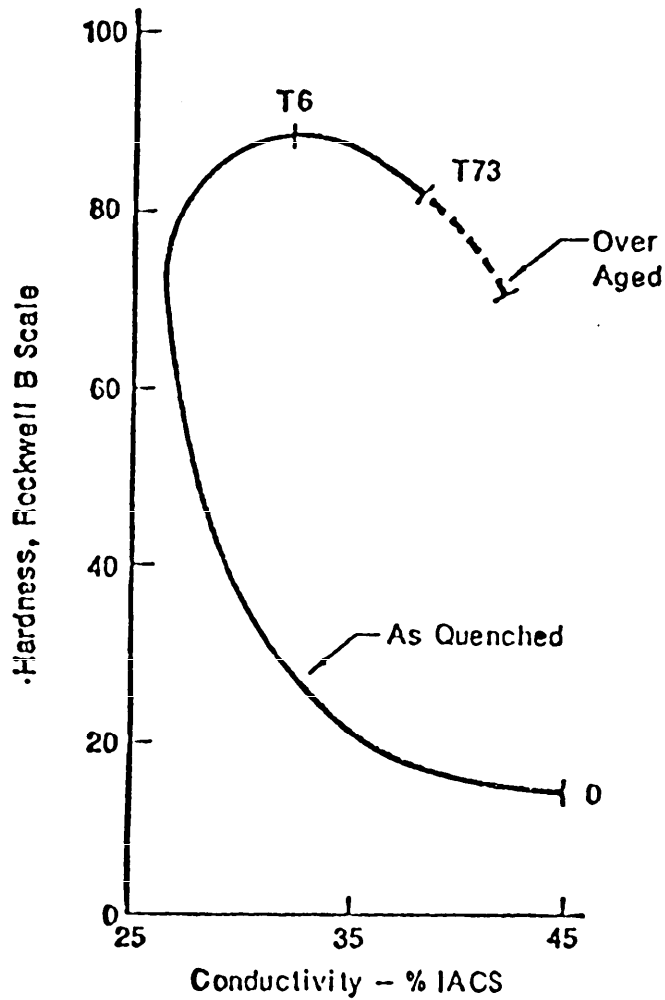
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MIL-STD-1537B



NOTE: Two different hardness conditions can provide the same conductivity reading in %IACS. Use hardness to verify condition.

NOTE: Figure 2 is a typical curve for information purposes only and shall not be used for acceptance or rejection.

FIGURE 2. Hardness vs. Conductivity for 7075 Aluminum Alloy.

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