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TECHNICAL REPORT

RESULTS OF IPC COPPER FOIL DUCTILITY ROUND ROBIN STUDY

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The reported results are based on the work done by the Copper Foil Ductility Round Robin Task Group, Werner Engelmaier, Chairman, under the auspices of the Metallic Foil Subcommittee of the Base Materials Committee of the Institute for Interconnecting and Packaging Electronic Circuits (IPC).

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1.0 INTRODUCTION

1.1 Objectives and Scope

The Metallic Foil Subcommittee of the Base Materials Committee (formerly the Copper Foil Subcommittee of the Raw Materials Committee) decided in August 1982 to undertake a round robin test program on copper foil ductility. The objectives of this Round Robin Study were set by the Subcommittee to be:

- (1) the determination of typical ductility values for the various types and classes of copper foil*¹ from different foil manufacturers,
- (2) the establishment of minimum ductility requirements for IPC Standard ANSI/IPC-CF-150, Copper Foil for Printed Wiring Applications¹,
- (3) the round robin testing of the fatigue ductility test method for metallic foils² to
 - (a) determine critical and sensitive test method steps, and
 - (b) if necessary, generate the information to emphasize and elucidate any critical test method steps,
- (4) the establishment of the extent to which the relationship underlying the fatigue ductility test method can be utilized to predict the high-cycle fatigue behavior of metallic foils, and
- (5) the determination of the bending fatigue behavior of the copper foils.

Five copper foil manufacturers, designated in this report as I through V, and seven test laboratories, designated A through G, agreed to participate in this Round Robin Study. Of these, one copper foil vendor and one test laboratory participated only during Phase II of the Round Robin.

The Round Robin Study fulfilled its objectives and the results are presented in this report. While the participants in this Round Robin shall remain anonymous for proprietary and competitive reasons, the cooperation of the companies and individuals involved is greatly appreciated. Only Test Lab A, AT&T-Bell Laboratories, is identified since it was utilized as the calibration and standardization laboratory.

* Superior numbers designate references.

1.2 Background

With the widespread use of flexible printed wiring (FPW), it became quickly apparent that FPW flexibility can not be utilized with total impunity³⁻¹³. FPW flexibility has to be an up-front design consideration¹⁴ to avoid conductor fractures during assembly^{9,10} or service¹². However, the most important design information necessary, the ductility of the copper foil, could not be obtained with any of the then existing test methods.

Tensile, bulge and bend tests, in which load is continuously applied until failure occurs, are inherently ill-suited for the determination of the ductility of foil specimens. The thickness of metallic foils has about the same dimension as the grain size, inclusions, surface flaws, etc. contained in the foils. These nonhomogeneities are strain-enhancers which can lead to early failure due to highly localized exhaustion of the available ductility. Furthermore, all of these tests suffer from a lack of definition of the deformation geometries and subject the specimens to stress and strain fields which are not well defined. Additionally, the elongation results are very test parameter sensitive and vastly different results are obtained for the same foil if tests are carried out using different strain rates or gauge lengths. Thus, the best that can be achieved with these tests are comparative results for specific purposes, but the results cannot readily be related to a practical generic ductility parameter.

Any ductility measurement strives to measure the fracture ductility; only the reduction of area measurement, not practical for foil specimens, fully achieves this aim. For bulk samples, elongation measurements yield reasonably close approximations of the material ductility, particularly if the ratio of gauge length to smallest cross-sectional dimension as well as the ratio of specimen width to specimen thickness are no more than 4-to-1 as they are for standard tension test specimens. As these ratios increase, the elongation values deviate more and more from the fracture ductility because (1) large dimensional changes are included from specimen regions not undergoing the large plastic necking deformations between uniform elongation and fracture — for foil specimens, the

gauge length/thickness ratio can exceed 1000-to-1 and the large plastic deformations in the fracture region make only an insignificantly small contribution to the total gauge elongation — and (2) specimen cross-sections substantially deviating from round or square configurations result in complex non-planar stress and strain fields during tensile testing — width-to-thickness ratios of foil specimens can be as large as 1000-to-1. This leads to such curious observations as an elongation dependence on specimen thickness¹³ — clearly an artifact resulting from the test arrangement and not a material characteristic. If the elongation values determined for standard electrodeposited copper foil were indeed measures of the ductility, this foil, with minimum elongation values as low as 2%¹, would not be usable in FPW applications.

A ductility test method based on low-cycle fatigue concepts was developed^{15,16} to provide useful ductility information for metallic foil. This method is the basis for both IPC and ASTM foil ductility tests^{2,17} as well as for the IPC product ductility tests for flexible metal-clad dielectrics, flexible printed wiring and flat cable¹⁸⁻²⁰. This method avoids both the troubling gauge length effect and the disproportionate impact of nonhomogeneities by cyclicly exhausting the ductility by fatigue, where the maximum cyclic stresses are far below the ultimate tensile strength, and utilizing an empirical, but for metals universally valid, fatigue relationship correlating fatigue behavior and tensile properties²¹.

2.0 ROUND ROBIN TEST PROGRAM

The Round Robin Tests were governed by the "IPC Test Plan for Copper Foil Ductility Round Robin" (see Appendix A). This test plan includes both the sample plan and the test procedures. The test procedures contain all the instructions in Test Method 2.4.2.1 of IPC-TM-650² (Appendix B) as well as instructions directly related to the round robin test. However, the "Operating Instructions for Fatigue Ductility Flex Tester" (Appendix C) which come with the Fatigue Ductility Flex Testers were neither included nor referred to in the test plan, since investigating the adequacy of Reference 2 as a complete test method was one aim of this Round Robin Study.

The participating copper foil manufacturers submitted to IPC headquarters 24 sheets (8 X 10 inches, see Appendix A) of each foil type, class, and weight sample. Further, they provided for each sample the ultimate tensile strength, s_u , the modulus of elasticity, E , and a representative 500X photo-micrographic cross-section which allowed the determination of the thickness of any surface roughnesses resulting from foil plating tooth, bond enhancement treatments and other causes. The machine or rolled direction was marked on each foil sample sheet (see Appendix A).

The IPC staff provided a sample identification scheme that concealed the identities of both foil manufacturer and test laboratory but allowed grouped analysis of the results. The code-marked samples together with the corresponding photomicrographs and data sheets with the tensile data (see Appendix D) were distributed by the IPC staff to the participating Round Robin test laboratories.

The Round Robin Study includes samples from all foil classes in Standard ANSI/IPC-CF-150E¹, except foil class W6 which does not contain fixed properties but a range of properties intermediate between foil classes W5 and W7. These foil samples were obtained from five vendors and the sample distribution (primarily by different weights/thicknesses) is shown in Table I.

Considering that a minimum of five specimens were tested in both the machine and cross-machine orientation of the 40 different samples, the Round Robin Study is comprised of the results of a minimum of 2800 individual fatigue ductility tests. The test results from each test laboratory were reported on the coded data sheets and forwarded to IPC headquarters. After collecting the data sheets, they were sent to AT&T Bell Laboratories for correlation and analysis.

3.0 ROUND ROBIN RESULTS—PHASE I

Upon correlation and analysis of the combined data, it became quickly apparent that a sizeable number of tests would have to be repeated and some of the test results reevaluated. Because of the extent of these retests/reevaluations it was decided by the Task Force to carry out a Phase II of

Table 1. Copper Foil Sample Distribution For Ductility Round Robin Study

FOIL CLASS	FOIL VENDOR					Σ
	I	II	III	IV	V	
	NUMBER OF SAMPLES					
E1	3	3	3	—	—	9
E2	3	3	—	—	—	6
E3	3	3	—	—	—	6
E4	2	2	—	—	—	4
W5	—	—	—	4	1	5
W6	—	—	—	—	—	—
W7	—	—	—	2	2	4
W8	—	—	—	2	4	6

the Copper Foil Ductility Round Robin. The results of Phase II are discussed in Section 6.0; the results of Phase I, to the extent they are valid or informative, are included in this section.

3.1 Thickness Measurements

An analysis of the thickness measurements reported by the test laboratories revealed three problem areas in the determination of both the specimen micrometer thickness, t , and the core thickness, t_m . These problems were:

- (1) inaccurate thickness measurement instruments at two test laboratories causing biased thickness and ductility results,
- (2) inadequate measuring techniques leading to both crushing of the plating tooth/adhesion treatment surface roughness and to large data imprecisions at three test laboratories, and
- (3) improper evaluation of the photomicrographic cross-sections for the determination of the thickness of the plating tooth/adhesion treatment roughness causing large data spreads and result inaccuracies.

Figures 1 and 2 contain the mean thickness values, the thickness standard deviation ranges and the total measurement ranges from each test laboratory in normalized form. The normalization was carried out by dividing the thickness results by the respective mean thickness results from Test Lab A. Test Lab A became the calibration and standardization laboratory because:

- (1) its thickness measurement instruments are calibrated against both Johansson Gauge Blocks and a Federal Electronic Micrometer, and

- (2) the most extensive experience with copper foil ductility measurements resides there.

In Figure 1 the gauge (micrometer) thickness measurements, t , for both wrought (W) and electrodeposited (E) foils are given. Since W-foil has an adhesion treatment layer that is very thin (about 0.04 to 0.08 mils) and therefore cannot be crushed (see below), the thickness measurements for W-foil reflect the accuracy of the measurement instruments. As can be readily seen from Figure 1, the accuracy and precision of the thickness measurement instruments at test labs A, B, C and D is excellent. However, test labs E and F consistently measured low thickness values; the mean measurement inaccuracy is 0.06 mil for Test Lab E and 0.10 mil for Test Lab F. Examining the data for E-foil in Figure 1 reveals that a measuring technique was employed at Test Lab D which so severely crushed the plating tooth/adhesion treatment roughness that the E-foil thickness measurements from Test Lab D are both the most inaccurate and the most imprecise.

The results from test labs A, B, and C show the same accuracy and precision for both W- and E-foil, while the results from test labs E and F indicate through an increase in both inaccuracy and imprecision that some crushing of the surface roughness layers occurred during the thickness measurements of the E-foil specimens.

In Figure 2 the gauge thickness, t , and the core thickness, t_m , values for E-foil are compared. This comparison gives an indication of the degree to which the surface roughness thicknesses have been properly evaluated from the photomicrographs.

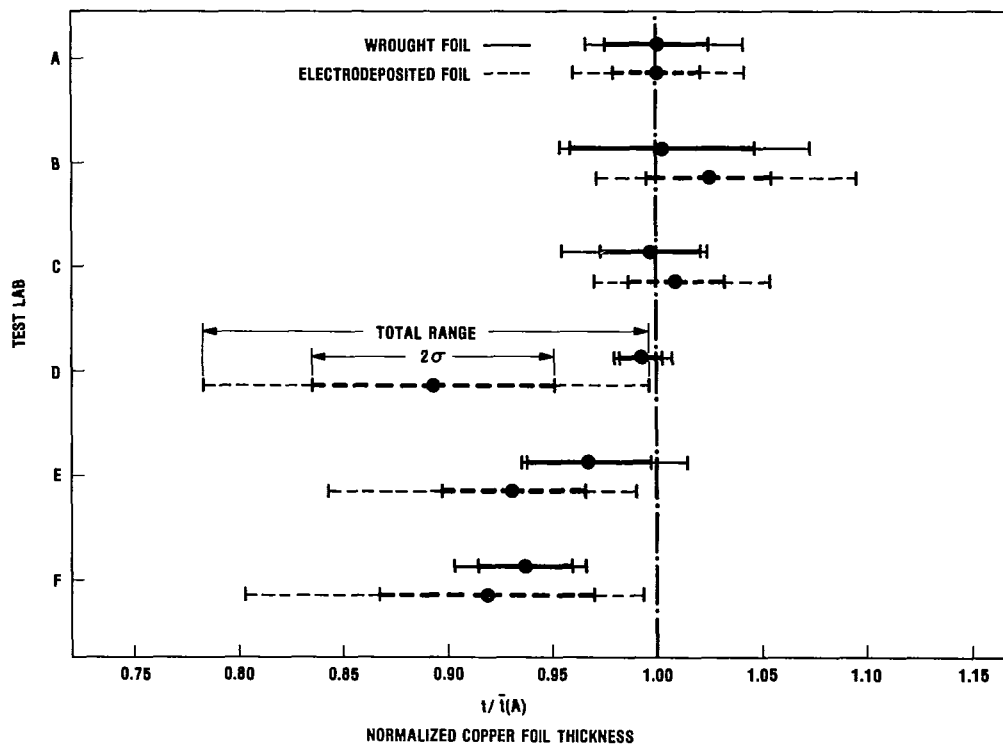


Figure 1. Means, Standard Deviations and Ranges of Measured Gauge Thicknesses of Wrought and Electrodeposited Copper Foil Samples Normalized Relative to Means from Test Lab A.

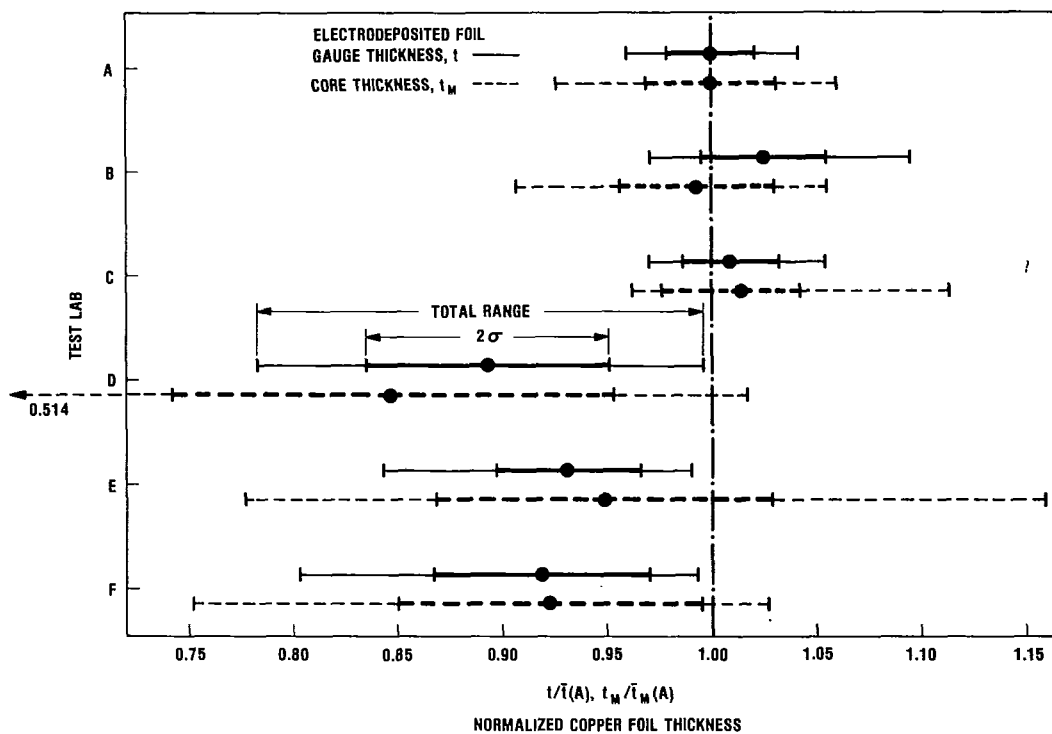


Figure 2. Means, Standard Deviations and Ranges of Measured Gauge and Core Thicknesses of Electrodeposited Copper Foil Samples Normalized Relative to Means from Test Lab A.

cross-sections. As for the thickness measurements, these evaluations are both accurate and precise for test labs A, B and C. Inconsistent evaluation techniques employed by test labs D, E and F are indicated by the large data ranges shown for the core thickness from these test labs.

It is interesting to note that the test labs that consistently produced accurate and precise results are also the labs having the most experience with the measurement of the ductility of foils.

Figure 3 shows a photomicrographic cross-section of 2 oz./ft² E-foil. Also shown in Figure 3 is the proper method to determine the core thickness, t_M . It is most convenient and practical to express t_M as a percentage of t and then use this percentage to determine t_M from the values of t measured for the individual test specimens. Some foil samples exhibited foil roughness on the drum (shiny) side; in those cases the core thickness, t_M , excluded the surface roughness from both foil surfaces.

Figure 4 shows the mean gauge thickness, t , and the mean plating tooth/adhesion treatment thickness, $t-t_M$, at the various foil weights for each vendor. Also given in Figure 4 are the nominal gauge thicknesses and the allowed upper tolerances given in IPC-CF-150¹. All gauge thickness values in Figure 4 exceed these nominal gauge thickness with more than half exceeding even the tolerance values. For the most part, these excess thicknesses can be accounted for by the plating tooth of the electrodeposited foils as well as the addition of

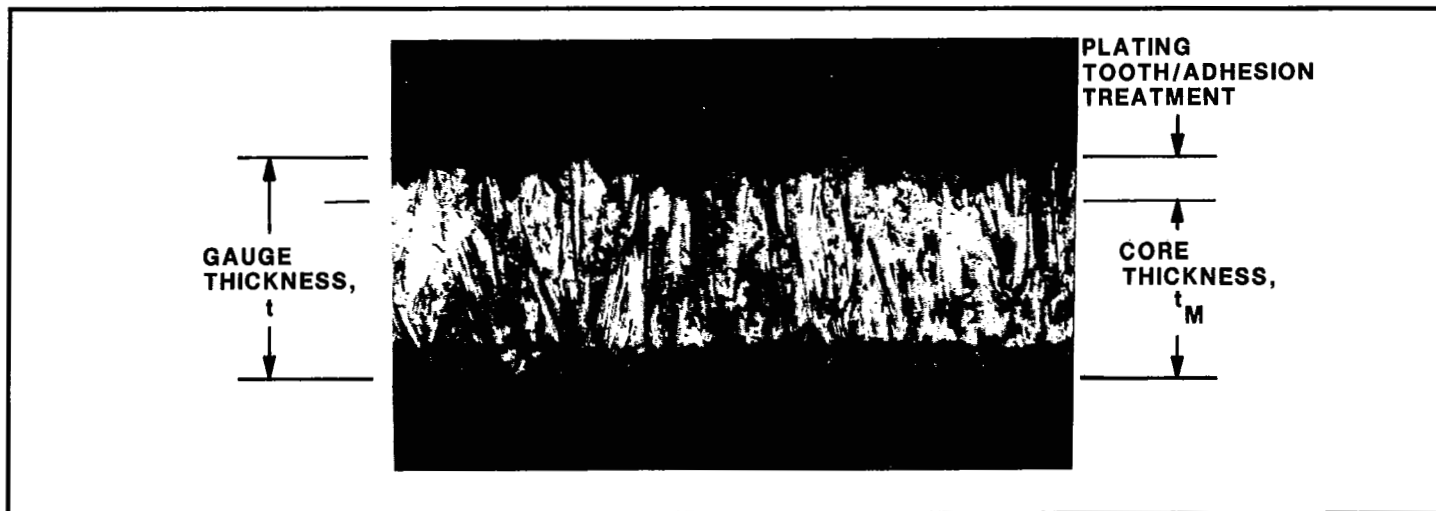


Figure 3. Photomicrographic Cross-Section of 2 oz./ft² Electrodeposited Copper Foil Sample.

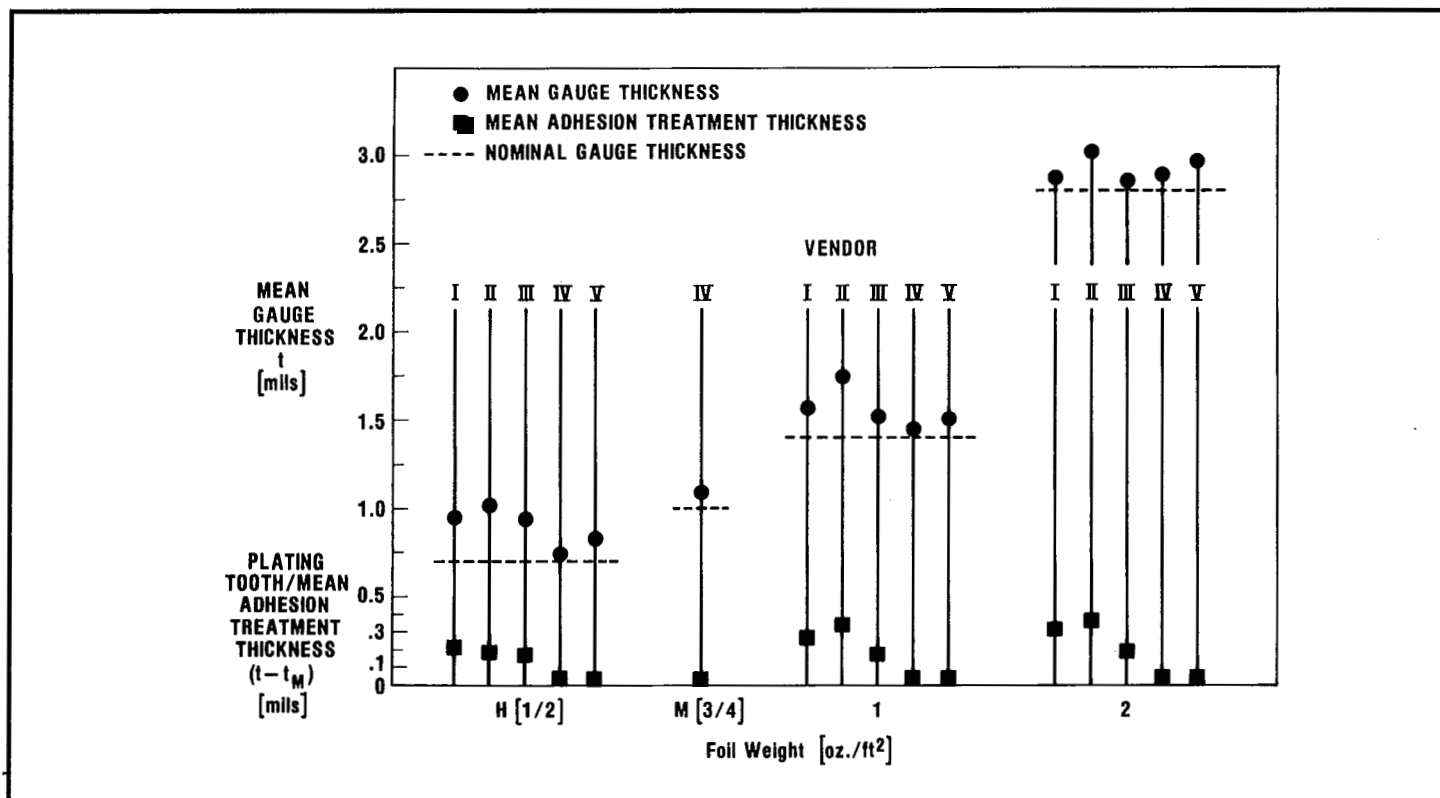


Figure 4. Means of Measured Gauge and Plating Tooth/ Adhesion Treatment Thicknesses Differentiated by Foil Weight and Vendor.

the adhesion treatment layer to foils meeting the thickness requirements¹. The data in Figure 4 suggest that the total gauge thickness for all foil vendors and the plating tooth profiles for the E-foil vendors are vendor/process characteristic.

Inaccuracies in the measurements of the gauge thickness, t , and the core thickness, t_m , result in an almost one-for-one inaccuracy in the obtained ductility values¹⁶. Therefore, it was essential that the ductility determinations from test labs D, E and F be reevaluated using correct thickness values. Since the thickness values of test labs A, B and C are in close correspondence, this reevaluation was carried out using the corresponding mean values of the respective thicknesses from test labs A, B and C. Test lab G, added for Phase II, also used these thickness means to evaluate the fatigue test results.

3.2 Test Mandrel Selection

Analyzing the results from the fatigue tests revealed that not any of the test labs completely followed (or was able to follow) the recommendation that the test mandrel diameter should be selected to give fatigue lives in the range of 30 to 500 cycles-to-failure^{14,16} (Appendix C). Four reasons for this noncompliance were apparent: (1) foil

ductilities have improved sufficiently (Ref.1) that the originally prescribed nominal 79-mil-diameter mandrels (Ref.2) are no longer adequate to produce failures in less than 500 cycles for some of the thinner foils, (2) some foil samples have ductility/thickness combinations that result in fatigue lives slightly below 30 cycles for the 79-mil mandrels and slightly above 500 cycles for the 250-mil mandrels (in cases like this the 250-mil mandrels are preferred, see below), (3) for some foil samples different mandrels are required for the machine (M)- and cross-machine (XM)-orientations to obtain flex lives in the 30-to-500 cycle range and the test personnel did not use different mandrels for the M- and XM-orientations, and (4) the testing personnel was ignorant of the recommended fatigue life range and used the 79-mil mandrels exclusively.

The choice of the test mandrel diameter has no effect on the fatigue ductility value, provided the obtained fatigue lives, N_f , fall within $30 \leq N_f \leq 500$ cycles. Fatigue life results outside this range give fatigue ductilities which can increasingly deviate from the proper value^{14,16}. Of the deviations from the recommended range, the deviations from the lower limit have the more severe consequences. At extremely low-cycle fatigue ($N_f < 20$ cycles-to-failure) de-

viations (indicated by the dashed curve in Figures 5 and 6) from the Manson-Coffin relationship²¹, which is the basis for the fatigue ductility test method^{15,16}, occur due to the increasingly more significant effects of strain hardening, susceptibility to crack initiation at non-homogeneities, neutral (zero strain) surface shifts, and prestraining caused by the initial bend¹⁴. The primary cause appears to be cyclic strain hardening where the strength cyclicly increases and the ductility correspondingly decreases. At cyclic strains $\Delta\epsilon > 10\%$ the foil embrittlement is rapid enough to result in early low-cycle fatigue failures.

Figure 5 (taken from Reference 14) shows a plot (Manson-Coffin plot) of cyclic strain range, $\Delta\epsilon$ vs. fatigue life, N_f , with the independent fatigue contributions of the elastic and plastic strain ranges given also. The graph includes also the deviations (dashed curve) that typically occur from the $\Delta\epsilon$ vs. N_f -plot in the range of extremely low-cycle fatigue. These deviations show that ductility calculations from extremely low-cycle fatigue data result in ductility values that are too low. For fatigue lives of $N_f > 500$ cycles-to-failure the deviations depend on the accuracy of the tensile-strength/modulus-of-elasticity ratio, s_u/E , since it is this ratio that defines the elastic strain range, $\Delta\epsilon_{\text{Elastic}}$, vs. fatigue life, N_f , relationship.

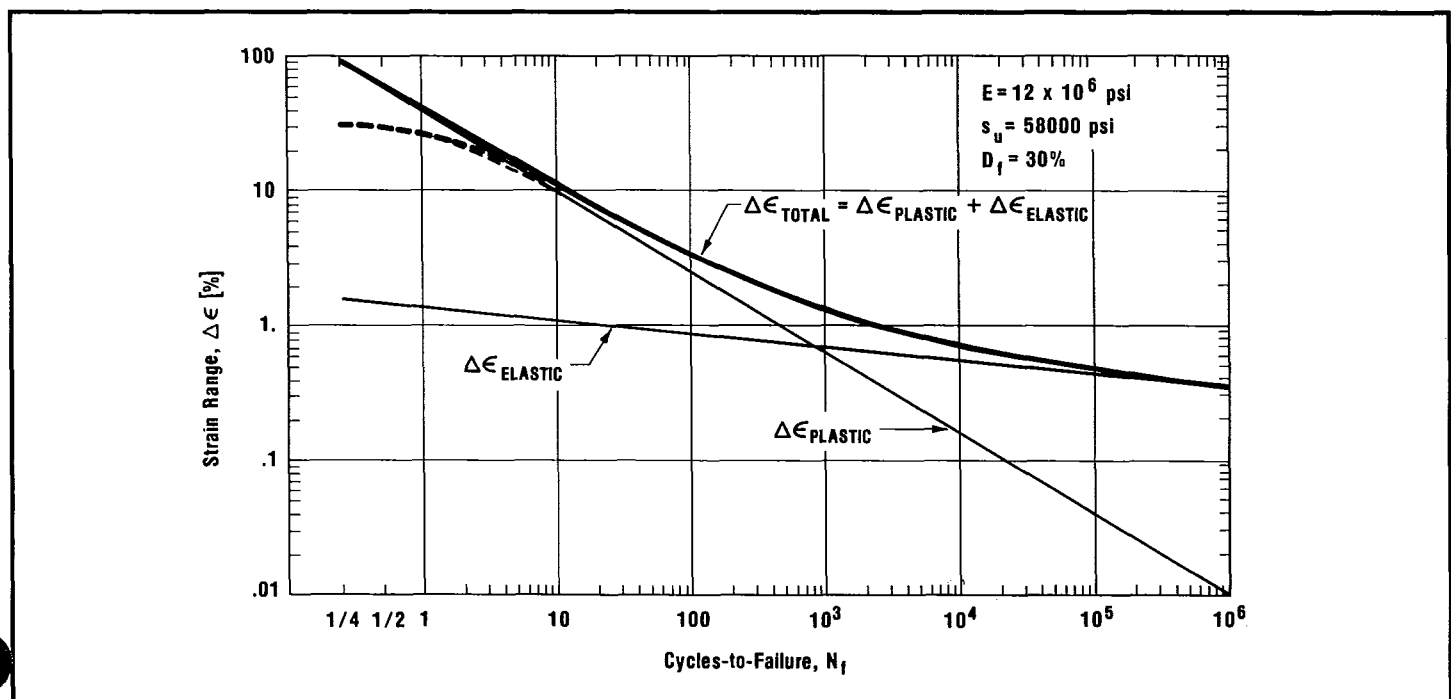


Figure 5. Manson-Coffin Plot (Cyclic Strain Range vs. Fatigue Life) Showing Contributions of Elastic and Plastic Strains and Deviation at Extremely Low-Cycle Fatigue.