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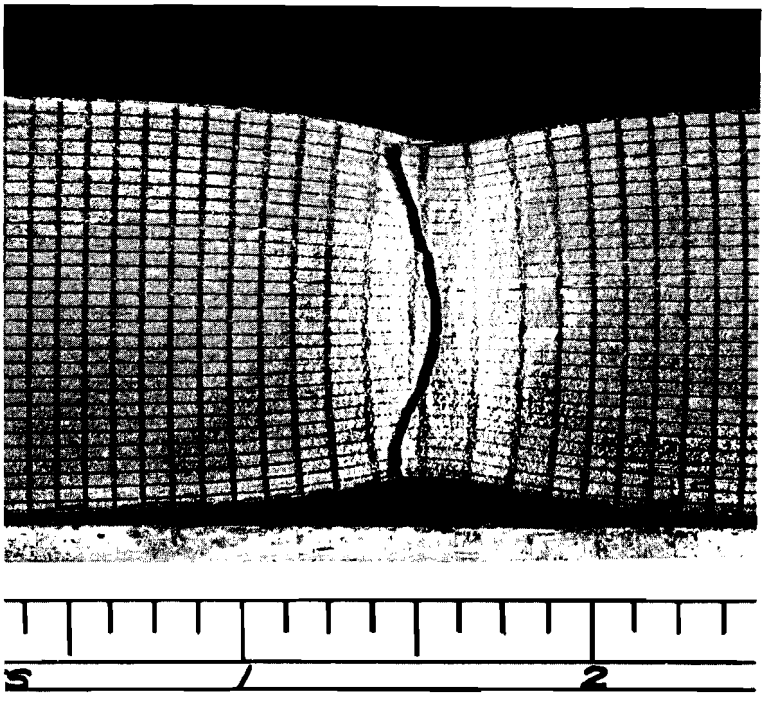
THE EFFECT OF SPECIMEN GEOMETRY ON DETERMINATION OF ELONGATION IN SHEET TENSILE SPECIMENS



FRACTURE APPEARANCE OF GRIDDED SHEET TENSILE SPECIMEN

BY

ERIC B. KULA

and

NORBERT H. FAHEY

18 AUGUST 1960

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INTRODUCTION

The current interest in sheet material has emphasized the need for a more accurate understanding of the significance of ductility of materials. This is especially true of elongation, which is the most common means of assessing the ductility of sheet materials. Unfortunately, elongation values depend on such geometrical factors as specimen thickness and width in addition to gage length and the inherent ductility of the material itself. As a convenience, a constant gage length and specimen width are used as the A.S.T.M. standard sheet tensile specimen[1], but this means that the elongation of specimens of different thicknesses are not strictly comparable. If an interrelationship between elongation, gage length, specimen width, and specimen thickness could be determined, either analytically or empirically, it would be possible to correlate ductility for materials of widely different size and shape.

Recognizing that elongation values can be affected by end restraint, type of fracture, etc., but convinced that elongation is more dependent on specimen size, the primary purpose of this paper is to obtain a greater understanding of elongation as a measure of the ductility of plate and sheet materials as affected by specimen size and gage length. These other variables were studied, together with the influence of specimen geometry on yield and tensile strength, and will be reported at a later date.

LITERATURE REVIEW

There has been considerable interest in the effects of specimen geometry on tensile properties and especially elongation in the past. The older European literature has been reviewed in Handbuch der Werkstoffprüfung[2], whereas much of the American literature is reviewed in a recent DMIC report[3].

Quantitative relations between elongation and gage length and/or cross-section geometry generally take two forms:

a. variation of elongation with gage length for specimens of a given cross-section, and

b. variation of elongation with specimen area in specimens with differing cross-section size and/or geometry but with the same gage length.

Equations relating elongation and gage length have been important because of the great number of gage lengths in common use and the

desirability of comparing elongation values. Throughout the world, the gage lengths used for determining elongation vary from 3.54 to 10 times the specimen diameter for round specimens[2] (4 to 11.3 times the area for flat specimens)[3]. Even inside one country, two or more gage lengths may be used. Some of the equations relating elongation and gage length were reviewed. are:

Martens[4] $$E - E_u = \frac{E_o}{L} \quad (1)$$

Bach[5] $$E - C = \frac{B}{\sqrt{L}} \quad (2)$$

Gallik[2] $$E - E_u = \frac{D_o}{L} \frac{C}{\sqrt{1 + \frac{E_u}{100}}} \left[RA\left(1 + Eu/100\right) - E_u\right] \quad (3)$$

Krisch and Kuntze[6] $$E - E_u = (E_o - E_u)a^{-(L/D_o)^{2n}} \quad (4)$$

Bauschinger[7] $$E - E_u = \frac{Q\sqrt{A}}{L} \quad (5)$$

Bertella[8] $$E - C = \frac{A^{m/2}}{L^m} \quad (6)$$

where

E	=	per cent elongation
E_u	=	per cent elongation measured on an infinitely long gage length
E_o	=	per cent elongation measured on a zero gage length
RA	=	per cent reduction in area
L	=	gage length
D_o	=	original diameter
A	=	original area
$B,C,Q,$ $a,m,n,$	=	constants

In all the equations it is recognized that the elongation decreases to some limiting value as the gage length approaches infinity. This is generally termed the infinite gage length elongation. In some cases the limiting elongation for zero gage length is used. This can be calculated from the reduction in area if constancy of volume is assumed. Between these limiting values the elongation decreases with increasing gage length, in a complex exponential manner according to Krisch and Kuntze, or with an exponential function of the reciprocal of the gage length. This exponent is 1 according to Martens, Gallik, and Bauschinger, 2 according to Bach, and arbitrary according to Bertella. → 10

The dependence of elongation on specimen cross-section area has always been recognized. This can be seen by the designation of gage length as some multiple of specimen diameter. Even for rectangular specimens, gage lengths have been specified as a multiple of the square root of the area. Since the elongation depends on the area and not the dimensions, the cross-section shape is not important. Templin reported similar elongation values for various shaped specimens, in-

cluding tubular[9], of the same area. Some of the equations relating elongation in a fixed gage length and specimen cross-section area are:

Bauschinger[7] $$E = E_u + \frac{Q}{L}\sqrt{A} \quad (5)$$

Bertella[8] $$E = C \frac{1}{L^m} A^{m/2} \quad (6)$$

Templin[9] $$E = C A^n \quad (7)$$

where the terms have the same meaning as before. All three equations show that the elongation increases with some exponential function of the area. Templin's equation does not consider variations in both gage length and area, so the term E_u does not appear.

Malmberg studied the effect of various factors on tensile elongation.[10] By measuring the strain distribution along the length of a bar during straining, he showed that the strain is fairly uniform until just before maximum load, except near the shoulders. When necking occurred, the parts of the bar outside the neck still continued to deform, until just before the fracture load was reached. On round tensile bars varying in size from 5 to 25 mm. diameter, the same variation of elongation with gage length was found for all bars between gage lengths of 2 d to 20 d. This supports the importance of the quantity $\sqrt{A}/L$ in determining elongation. Tensile bars with rectangular cross sections and width-to-thickness ratios varying from 1 to 20 and areas from 25 to 1500 square mm. were studied. In contrast to the results on the round bars, here it was found that the elongation in a certain gage length expressed as a multiple of the square root of the area did depend on area, and tended to decrease with increasing area. Finally, the effect of length of reduced section was studied on round bars. It was found that the shoulders have an effect over a length 1.5 to 3 times the diameter. Beyond this distance from the shoulder, the strain distribution was independent of specimen length.

Miklowitz studied the strain distribution in various size flat tensile bars.[11] He concluded that because of shoulder restraints, straining is non-uniform from the very onset of yielding. In line with this, he maintained a constant ratio of reduced section length to specimen width. He also studied in detail the local strains occurring during necking. Aronofsky also studied necking in flat tensile bars[12]. He studied the effect of width to thickness ratio on the formation of the oblique neck that forms under certain conditions.

Low and Prater studied the effect of various geometries on tensile elongation[13]. They showed that the ratio of reduced section length to specimen width determined the length restrained by the shoulders, and hence the length under simple tension. The influence of lateral restraint in reducing the elongation of bars of width to thickness ratio greater than 6 was pointed out.

PROCEDURE

Since contributions to elongation can ideally be considered to

come from two sources, the uniform elongation and the extension associated with the neck, the effect of specimen geometry on these quantities was to be determined. This was accomplished by photogridding the specimens with a grid spacing of twenty to the inch along the reduced section and analyzing the distribution of strain throughout this region, with particular emphasis placed on the necked region. With this in mind the materials used were selected because of their differences in uniform strain values. The materials used, each of which were individual heats, were hard drawn and annealed copper, AISI 1020 steel, and H 11 tool steel. The copper and steel were obtained as 1/2" thick by 2 1/2" wide bar in random lengths and the H 11 was supplied in 1/8" sheet. After insuring the homogeneity of the material by macroetching and hardness surveys, tensile specimens of various thicknesses and widths were prepared from the 1/2" bar by slicing to the approximate thickness and then careful grinding to size. Specimen thicknesses from 0.010 to 0.500 inches were prepared, with widths ranging from 1/8 to 2 inches, see Figure 1. This resulted in specimen width to thickness ratios of from 1:1 to 200:1 and areas ranging from 0.0013 to 1.00 square inches.

Tensile properties of the various materials used are summarized in Table I.

TABLE I

Material	0.2% Yield Strength psi	Tensile Strength psi	Reduction in Area, %	Elongation, Total, %	Elongation, Uniform %	Specimen Type
Copper, hard drawn	34,800	37,000	69.2	30.0	7.0	.357" D
Copper, Annealed	8,900	31,000	70.4	37.9	26.5	.357" D
1020 Steel	32,300	55,900	63.0	37.1	25.0	.357" D
H 11 Tool Steel	231,000	250,900	----	8.8	5.0	1/2" X 1/8"

The copper was received in the hard drawn condition, and testing was carried out after machining and an anneal of 2 hours at 400°F. The annealed copper was obtained by annealing the as-received material for one hour at 1200°F. It too was given an anneal of 2 hours at 400°F after machining. The AISI 1020 hot rolled steel was normalized at 1700°F prior to machining and annealing at 750°F for 2 hours. The H 11 tool steel was machined to size, austenitized in a salt pot at 1800°F for 20 minutes (after preheating at 1450°F), quenched in still air, and tempered twice, 1 hour each time, at 1050°F.

Since the specimens were of various sizes, a good range in load capacities was necessary and three different tensile testing machines were utilized. The head speed of the machines was regulated so that all specimens were strained at an initial rate of 0.01 inches per inch of gage length up to the yield and then at 0.02 inches per inch of gage length to fracture.

All the specimens had been photogridded prior to testing with the grids spaced at twenty to the inch. Grids were put on the width surface for specimen thicknesses of 1/8" or less and on both the width and thickness surfaces for specimen thicknesses of 1/4" and 1/2", see Figure 2. As shown on this figure, two local strains, namely the width and longitudinal strains, could easily be measured on all specimens and the thickness strain could be measured on the larger specimens. On the thinner specimens the average thickness strains could be measured directly, with a micrometer. Furthermore, any one strain can be calculated from the other two, since because of constancy of volume, the sum of the principal strains is zero.

RESULTS AND DISCUSSION OF RESULTS

Since the distance between grids on a longitudinal line running along the center of the bar was measured, the elongation for any gage length could be determined. Plots of elongation versus various combinations of gage length and area were constructed and observations are made. The idealized picture of tensile deformation is that a test piece contracts uniformly in the transverse directions as it elongates. This uniform deformation continues until a maximum in the load is reached. At this point, further deformation becomes limited solely to a restricted portion of the test piece termed the neck. The size of this necked region depends on the specimen dimensions. The results will be discussed in terms of this simplified picture.

A. Effect of Gage Length on Elongation

Typical results showing the dependence of elongation on gage length for the four materials are shown in Figures 3a to d.

In each case the elongation decreases as the gage length increases, due to the decrease in the fraction of the gage length representing the necked region. There are three features of each curve which are worthy of further discussion. These are the zero gage length elongation, the infinite gage length elongation, and the variation of elongation with gage length between these two values.

The zero gage length elongation does not seem to be a constant value for a given material, but seems to decrease with specimen area. The smallest gage length measured is 0.1 inches however, and closer agreement might have been obtained if the zero gage length elongation had been calculated from measured transverse and thickness strains. It was not possible to obtain accurate values of thickness strain at the fracture however, since the fracture surface often cut through the region of minimum thickness at an oblique angle. Furthermore, all elongation values, measured along the center line of the specimen, include a gap that forms between the two halves of the specimen as the

fracture propagates from the center outward. This gap is normally included in standard elongation values obtained by placing the broken halves of the specimen together and is generally greater the greater the specimen thickness. Finally, there is no indication that bars of different geometries fracture at a constant value of longitudinal strain. Results by Miklowitz[11] suggest that the conditions for fracture are more nearly a constant thickness strain.

The infinite gage length elongation is the elongation that a bar infinitely long would exhibit, and where the contribution of the neck would be effectively zero. This could also be considered to be the maximum uniform extension. This value should be independent of specimen size. The actual results for the longest gage lengths measured do not show this. If infinitely long specimens had been used, no doubt this would have been observed, but the restraining effects of the shoulders tend to reduce the elongation in this region. Of some interest are the very low elongations displayed by the 0.010" specimens, which are even less than the strains at maximum load as determined from true stress-strain tests on round bars. The reason for this must lie in non-uniformity of the original test piece. Even a variation in thickness of 0.0005", which represents 5% variation in area for a 0.010" specimen, would tend to strongly localize deformation from the start of straining, with accompanying low elongation.

The variation of elongation between zero and infinite gage length has been expressed by several of the equations presented earlier. It should be pointed out that in no case is there a sound fundamental reason for deriving any of the equations, beyond recognizing the significance of zero and infinite gage length elongation.

To check some of these equations, elongation has been plotted versus $1/L$ and $1/\sqrt{L}$ in Figures 4 and 5 for each material at one size. The results show that either relationship is valid over short ranges of L, but that neither holds over a large range of gage lengths. In some cases, one or the other relationship does give a reasonably straight line, but for another material or size similar results are not found. It has been noted that extrapolations of the curves to infinite gage lengths do not yield a constant value, and in some cases yield negative values, which points out the inadequacy of the relationships. Plots of the same data on log-log coordinates, Figure 6, do not show a straight line either, showing that Bertella's equation (Eq. 6), is not correct.

After considering the fact that there is no known theoretical basis for expecting a simple relationship, coupled with experimental conditions such as end effects, possible non-homogeneity of material and specimens, and the occurrance of double necks, it is not surprising that no one equation adequately predicts the actual variation of elongation with gage length.

B. Effect of Specimen Area on Elongation in a Fixed Gage Length

The results plotted in Figure 7 show that over a range of sizes, there is a linear relationship between log of elongation in 2" and log of area. There is considerable scatter however, and at low areas

there is a deviation from the linear behavior. These points represent the thinnest specimens, where dimensional variations would have the greatest effect. As discussed earlier, many of the elongation values are lower than the strain at maximum load, which supports the viewpoint of the non-homogeneity of strain because of dimensional variations.

Three equations, Eqs. 5, 6, and 7, mentioned earlier, relate elongation to some power of the area. It must be realized that for a specimen with an area approaching zero, the elongation approaches the uniform elongation, and for very large specimens, the elongation in 2 inches approaches the zero gage length elongation. None of the equations approach these limits at zero or infinite gage length, which emphasizes their empirical nature. Bauschinger's and Bertella's equations do approach a finite value at zero area however. In Figures 8a to d are plotted log ($El - El_u$) versus log area. The uniform elongations were determined from true stress-strain tests. It can readily be seen that a straight line can be drawn here also, although from a practical viewpoint Templin's equation is to be preferred since the amount of scatter for the lower elongations is seemingly reduced.

GENERAL DISCUSSION

There are two questions concerning the observed relationship between elongation and area which are of interest. The first is concerned with the significance of area, rather than width-to-thickness ratio or reduced section length-to-width ratio in determining elongation, and the second with the slope of the straight line portions of the curves in Figure 7.

A. Significance of Specimen Area

Figure 9 shows a plot of the distribution of local elongation, measured over gage lengths of one grid spacing. It can readily be shown that the elongation over a two inch gage length can be represented on such a plot by a horizontal line drawn such that the area under it is the same as the area under the curve. Figure 9 shows a plot of strain distribution for three bars of the same cross-section geometry, but different areas. The shapes of the curves are generally the same, except that as the specimen area gets larger, the curve gets broader which is an indication of the larger extent of the necked region. There is an effect of size on the maximum strain. Here again, the arguments advanced in the earlier discussion are valid, in which it was pointed out that the true zero gage length elongation was not determined. Further the local strain at the extremities of the gage length section is greater for the larger area bar, because of the closer proximity to the neck. All in all however, the greater elongation in 2 inches (area under the curve) for the larger area bars can be attributed to the larger extent of necked region.

Figure 10 shows similar plots of local strain for three bars having the same area. Within experimental accuracy, these bars have the same elongation, and hence the same area under the curve. Notice now that the shapes of the curves are quite different. At a width-to-thickness ratio (w/t) of 1, the local strain decreases uniformly with distance from the fracture. As w/t increases, there is a tendency for

a more rapid decrease of strain with distance in a very narrow range in the vicinity of the fracture, with a change to a more gradual decrease at larger distances from the fracture. The height of the curve for high w/t ratios is such that at intermediate distances from the fracture it lies below, and at large distances from the fracture it lies above the curve for a square specimen, with the net result being the same area under the curve.

Because of the constancy of volume, it is possible to break the longitudinal strains into a component of transverse or width strain and thickness strain. Further insight into the shape of the curves can possibly be found by considering the effect of width-to-thickness ratio separately on width and thickness strains. Some results are plotted in Figure 11, where true strains have been used, since here the sum of the width and thickness strain should equal the longitudinal strain. The width strains were determined over a one grid length (0.05"), whereas the thickness strains were determined over the whole thickness.

The results clearly show the differing behavior for the various w/t's. For a w/t of 1, the width and thickness strains are almost equal. (The hard drawn copper is actually slightly anisotropic, by virtue of having a preferred orientation arising from cold working.) As w/t increases, there is a restraint in the width direction and the ratio of the thickness strain to the width strain increases at the fracture, so that most of the elongation at this point arises from the contribution of the thickness strain.

B. Significance of Exponent "n" in Templin's Equation

Of some importance is the slope of the curves in Figure 7, which is characterized by the exponent "n" in Templin's equation, Eq. 7. The importance of this lies in the fact that it is a measure of the sensitivity of elongation values to thickness changes. It would tell, for example, whether two materials which have the same elongation value at a thickness of 1/8" would also have the same elongation at some other thickness. One is tempted to look upon the exponent "n" as a material property, which can be determined and tabulated. A little reflection on the problem will show the fallacy of such an approach.

Consider the case of the same materials used in this investigation, but fracturing at a lower strain. The curves of percent elongation versus gage length, Figure 3, would then have a different shape. This has in effect been done by pulling various size bars to as constant a strain as possible at the center of the neck, but below the fracture strain, and measuring the strain distribution. These results are plotted in Figures 12a to c together with strain distributions from the fractured bars. It is readily apparent that at small gage lengths the elongations are much lower for the bars not fractured, but that as the gage lengths increase, the elongations for the two cases approach each other, and for an infinite gage length they would presumably be the same. Note further that for some intermediate gage length, say 2 inches, the spread in elongation values between the smallest and largest areas is less for the bars pulled to a strain

less than the fracture strain than for the bars pulled to fracture. If these values of elongation are plotted versus area as formerly, the results such as in Figure 13 are obtained. Allowing for experimental scatter and for the fact that all bars were not pulled to exactly the same strain, it can be seen that a straight line is obtained, but with a lower slope than for the bars pulled to fracture. In fact, in an extreme case, if the bars were all pulled to or fractured at or before the limit of uniform strain the elongation would be the same for all bars over all gage lengths, and the slope would be zero on a log-log plot of elongation versus gage length.

From these considerations, it can be seen that the exponent "n" in Templin's equation is not a general material property which can be tabulated, but rather depends on the ductility of the specific lot of material being tested. For two different materials with the same uniform strain, the one having the higher fracture strain would have the greater value of the exponent "n". Similarly, for a constant fracture strain, the lower the uniform strain the higher the value of this exponent. The quantity, determinable from a single tensile test, which best correlates with Templin's exponent "n" is probably the ratio of the fracture to the uniform strain. Unfortunately, the high strength sheet materials of current interest do have a low value of uniform strain with moderate fracture strains, so that their elongation values are quite sensitive to variations in thickness.

C. Prediction of Per Cent Elongation

In many cases, it would be desirable to be able to predict the elongation for any arbitrary size specimen. Lacking complete data for many specimens which would allow an interpolation to be made, there is a method which suggests itself. This is based on the concept that a constant elongation is obtained if $\sqrt{A}/L$ is maintained constant, as suggested by Bauschinger's equation, Eq. 5. Malmberg found this to be valid for round bars, but not for rectangular bars. The results of this investigation support Malmberg and show that this is not generally true. Nevertheless, under some conditions it is a good approximation. If it is valid, then at a constant value of elongation:

$$\frac{L_1}{\sqrt{A_1}} = \frac{L_2}{\sqrt{A_2}}$$

where L and A are the gage lengths and area of two different bars 1 and 2. To determine the elongation in a length L_2 on a bar with an area A_2 from measurements on a bar with area A_1, simply measure the elongation on bar 1 over a gage length $L_1 = L_2 \sqrt{\frac{A_1}{A_2}}$. From this relation, the elongation in a fixed gage length for any area bar can be calculated from measurements over different gage lengths on one bar.

Some results using this method have been calculated for several size bars of the various materials, and are plotted in Figure 14 with the experimentally determined results from Figure 7. In some cases, the points do not lie on the experimentally determined curve, since the standard 2 inch elongation for the bar used lie off the curve. In general the results are good, and the slopes of the experimental and

calculated curves are the same. Deviations are noted when the elongation must be measured over such a long gage length that either a second necked region or end restraints are encountered.

In a practical sense, this principle could be applied to standard 1/2" wide specimens. Suppose for example one had available and knew the properties of 1/8" sheet. What elongation would be expected in sheet 0.080" thick? From the above relation, one can determine that the elongation measured on $L = 2\sqrt{\frac{.125}{.080}} = 2.5$ of the 1/8" sheet is the same as the elongation in 2 inches on 0.080" sheet. Accurate values should be obtained if the areas do not differ appreciably.

SUMMARY

A study has been made of the effect of specimen gage length, width and thickness on the elongation as determined in a tensile test. Hard-drawn copper, annealed copper, 1020 steel, and H 11 steel were studied.

Although a number of relationships have been proposed to explain the variation of elongation with gage length, the results show that no one relationship adequately describes the course of the curves.

The elongation in 2 inches is found to vary approximately linearly with the specimen area on a log-log plot, showing agreement with Templin's equation. The reason for the dependence of elongation on specimen area rather than width-to-thickness ratio, can be seen from a study of the local width, thickness and longitudinal strains.

The sensitivity of elongation to specimen area or thickness, as measured by the exponent "n" in Templin's equation, $El = CA^n$, is dependent on the fracture strain as well as the uniform strain, and hence varies from heat to heat of material. This exponent is most closely related to the ratio of fracture strain to uniform strain.

If $L/\sqrt{A}$ is maintained constant, the elongation will be approximately constant. Using this relation, it is possible to estimate the elongation for any size bar from measurements made on one bar.

End

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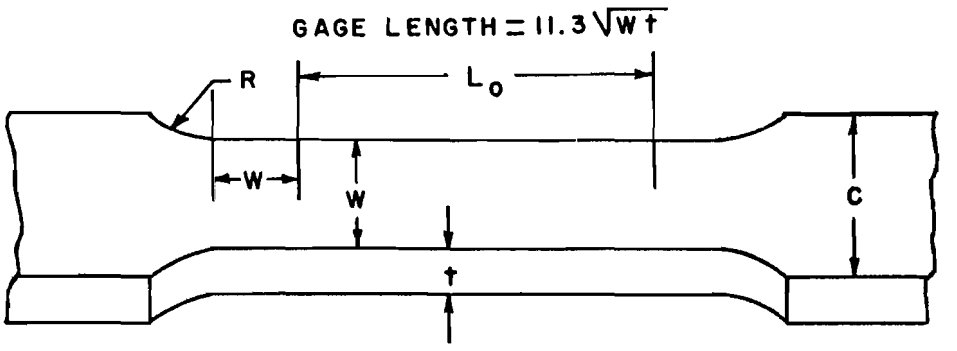


WHERE

W: 1/8", 1/4", 1/2", 1", 1-1/2", AND 2"

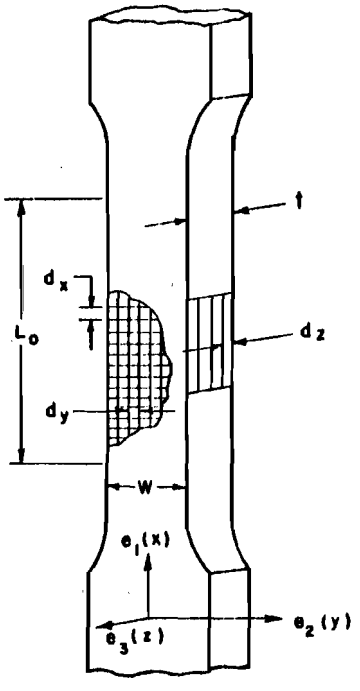
t: 0.010", 0.020", 0.040", 0.080", 0.125", 0.250", AND 0.500"
(IN NO CASE WAS W/t < 1)

C: 1/2" FOR W = 1/8" AND 1/4", 1" FOR W = 1/2", 2" FOR W = 1", AND 2-1/2" FOR W = 1-1/2" AND 2"

R: 1" RADIUS IN ALL CASES

L_o: $11.3\sqrt{Wt}$, BUT MINIMUM 2"

FIGURE 1: FLAT TENSILE SPECIMEN



RELATIONS:

LOCAL STRAINS:

$$e_1 = \frac{d_x' - d_x}{d_x}$$

$$e_2 = \frac{d_y' - d_y}{d_y}$$

$$e_3 = \frac{d_z' - d_z}{d_z}$$

AVERAGE STRAINS:

$$e_1 = \frac{L - L_o}{L_o}$$

$$e_2 = \frac{W - W_o}{W_o}$$

$$e_3 = \frac{t - t_o}{t_o}$$

WHERE:

d_x', d_y', d_z', L, W, and t are the strained values of d_{x_o}, d_{y_o}, d_{z_o}, L_o, W_o, and t_o

FIGURE 2: STRAIN DIRECTIONS IN TENSILE SPECIMEN

FIGURES 1 & 2

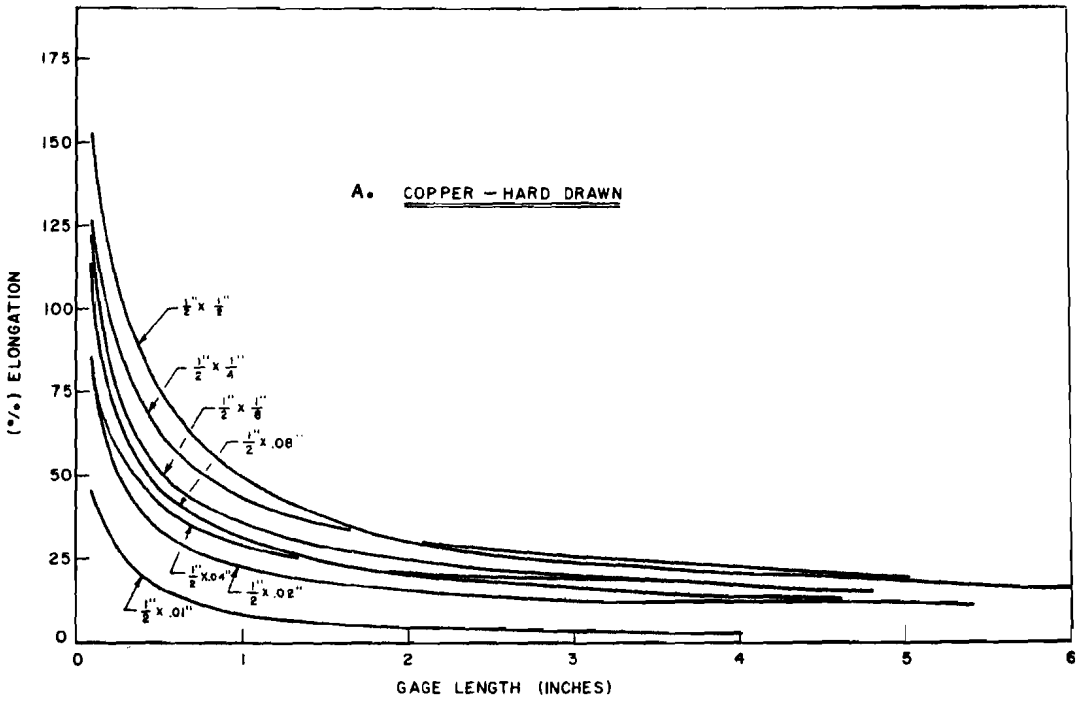


FIGURE 3A

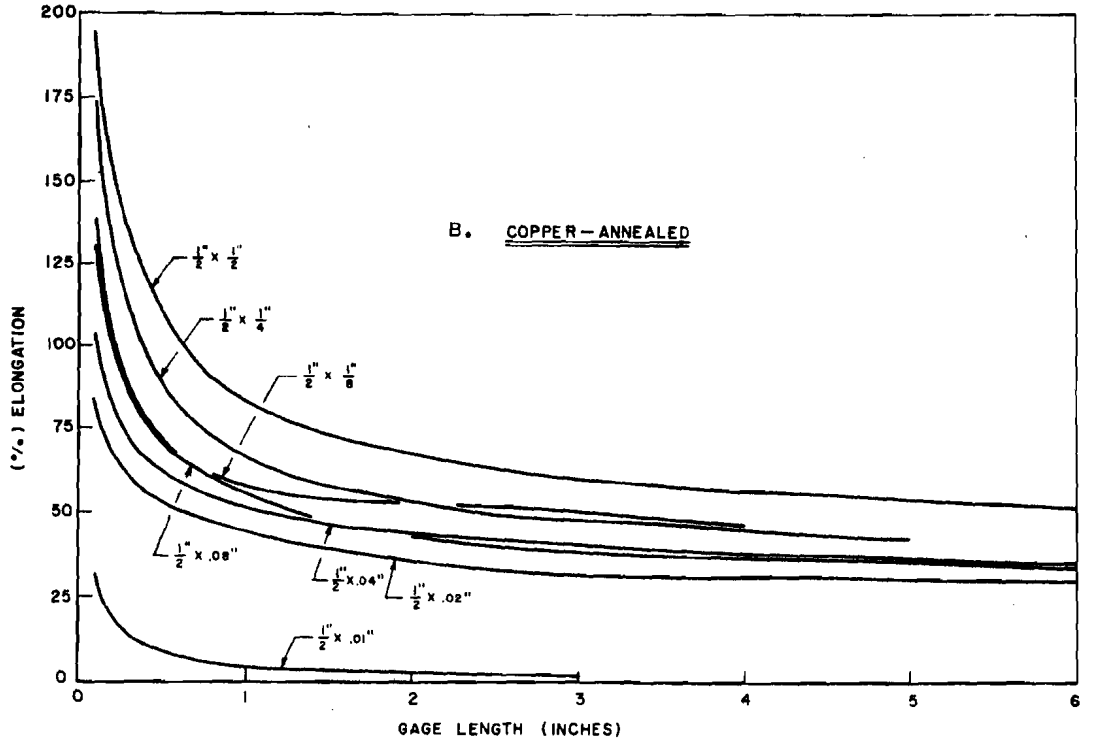


FIGURE 3B

VARIATION OF ELONGATION WITH GAGE LENGTH

FIGURES 3A & 3B

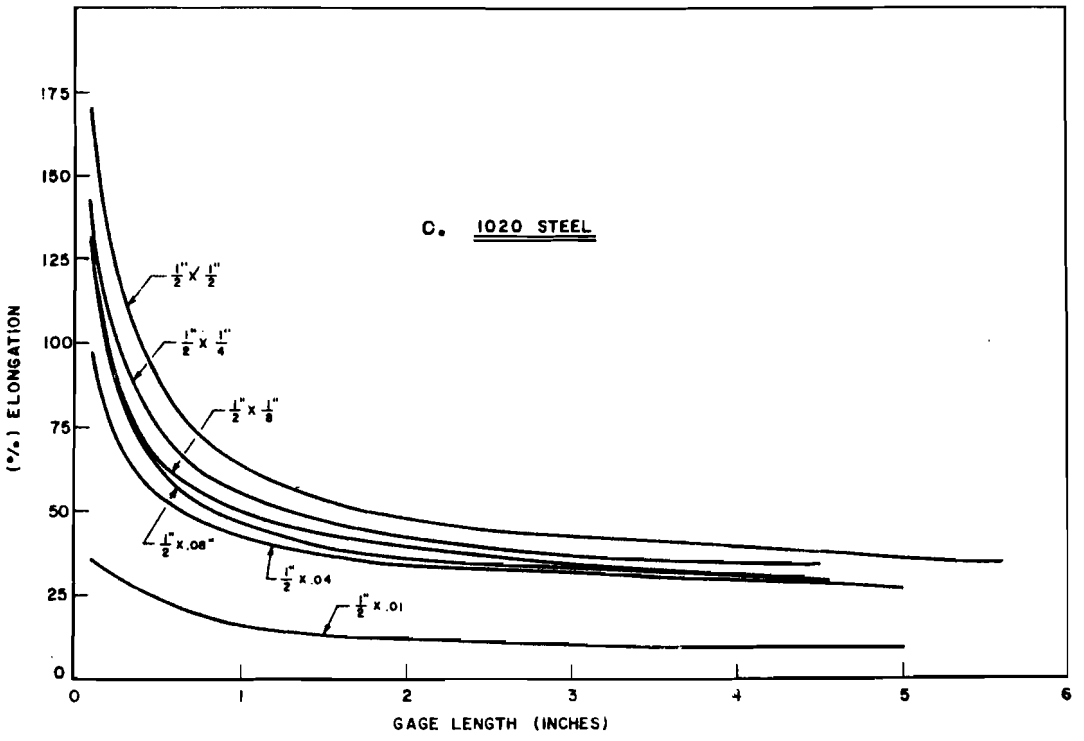


FIGURE 3C

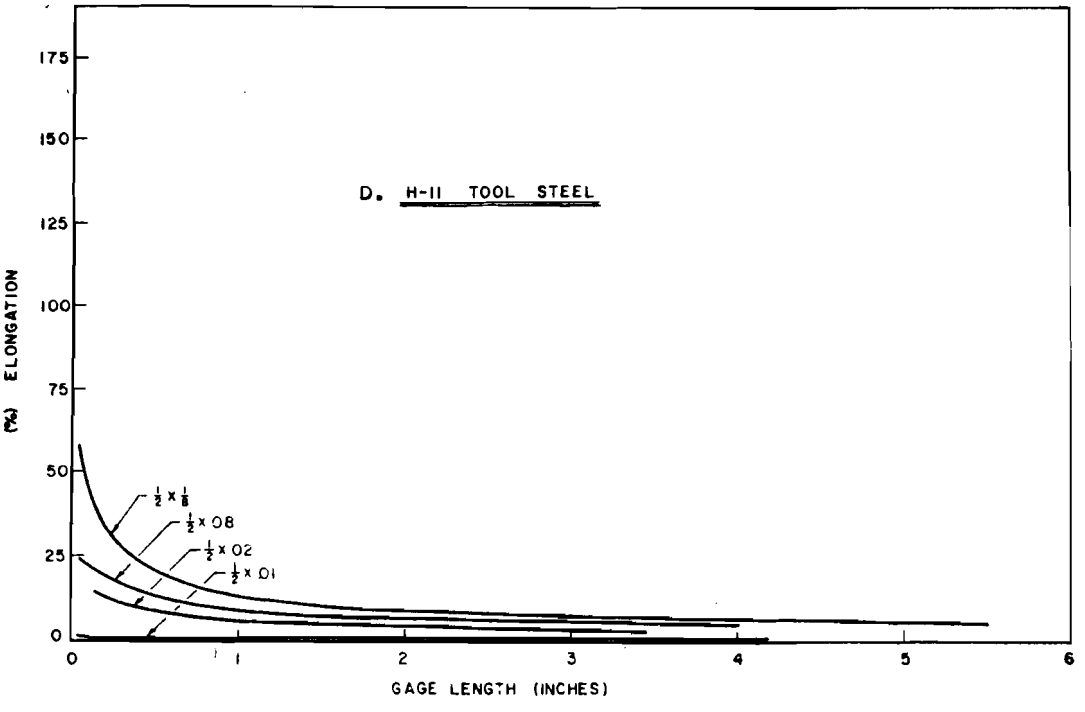


FIGURE 3D

VARIATION OF ELONGATION WITH GAGE LENGTH

FIGURES 3C & 3D

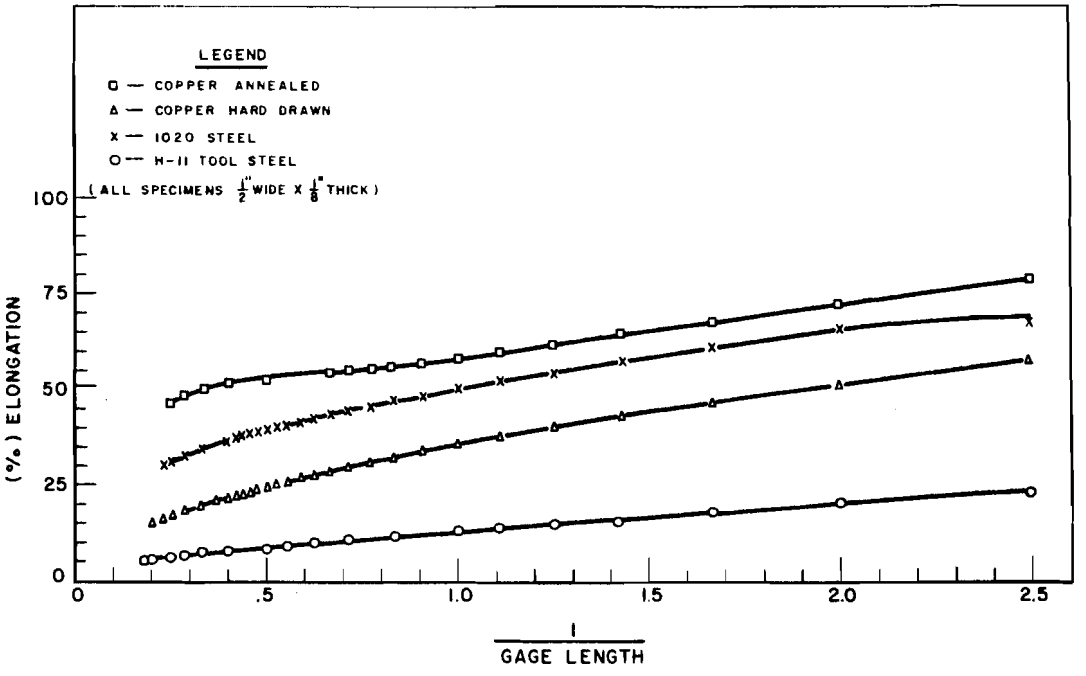


FIGURE 4: VARIATION OF ELONGATION WITH 1/GAGE LENGTH

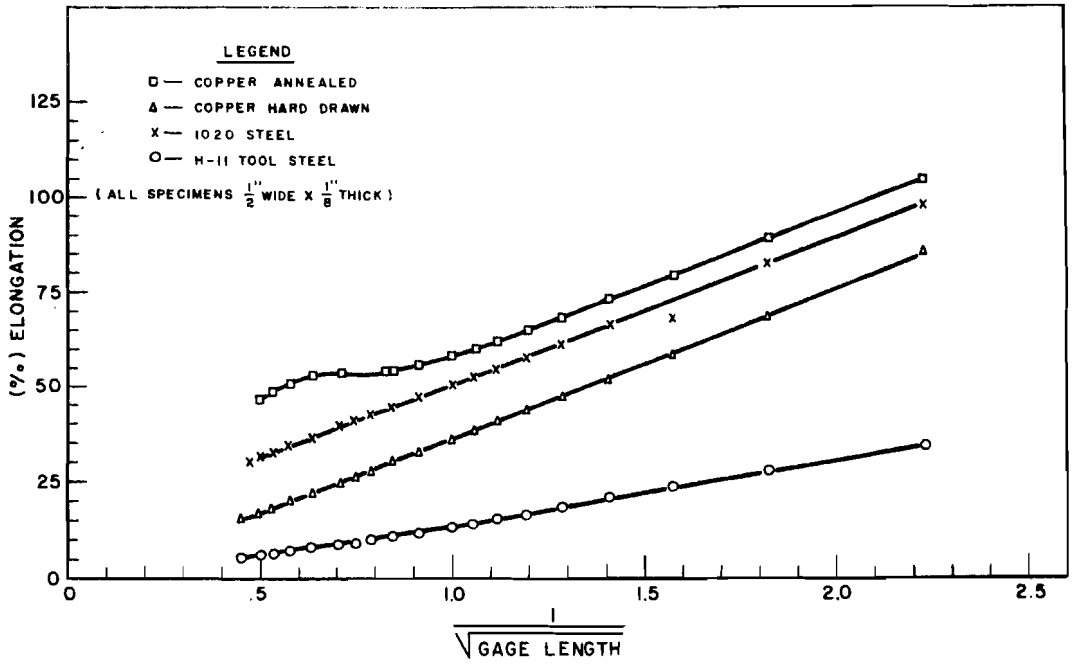


FIGURE 5: VARIATION OF ELONGATION WITH 1/ $\sqrt{\text{GAGE LENGTH}}$

FIGURES 4 & 5

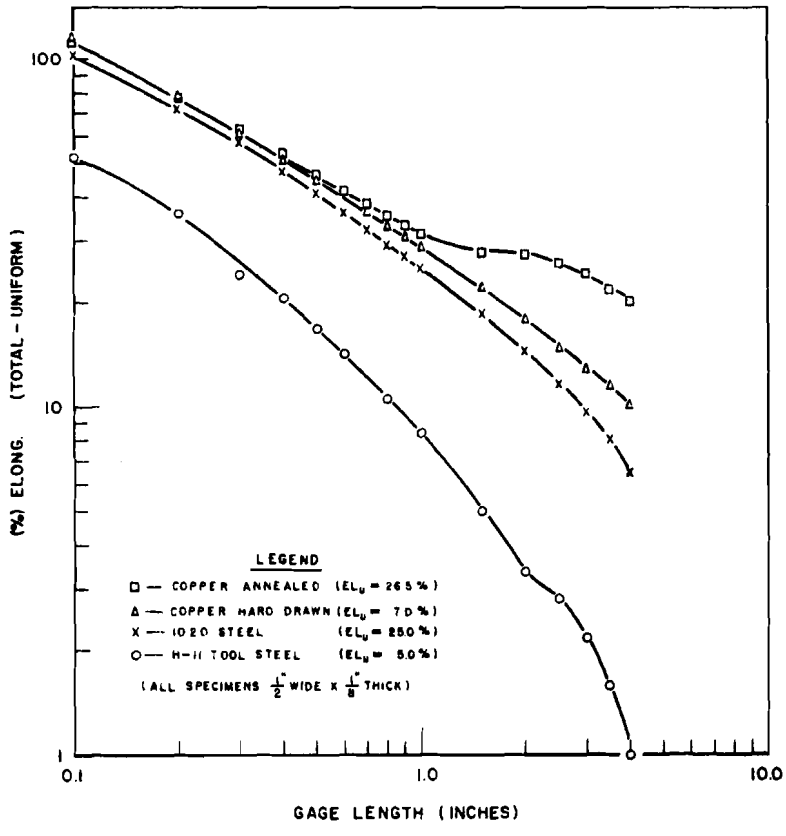


FIGURE 6: VARIATION OF TOTAL-UNIFORM ELONGATION WITH GAGE LENGTH

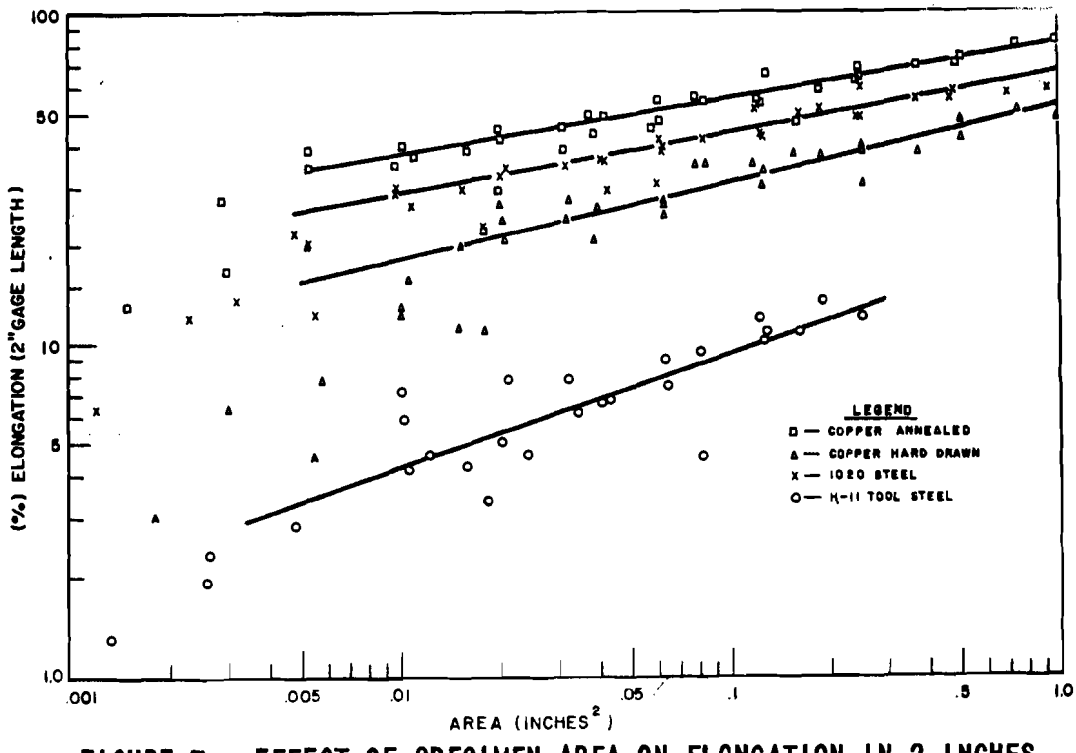


FIGURE 7: EFFECT OF SPECIMEN AREA ON ELONGATION IN 2 INCHES

FIGURES 6 & 7

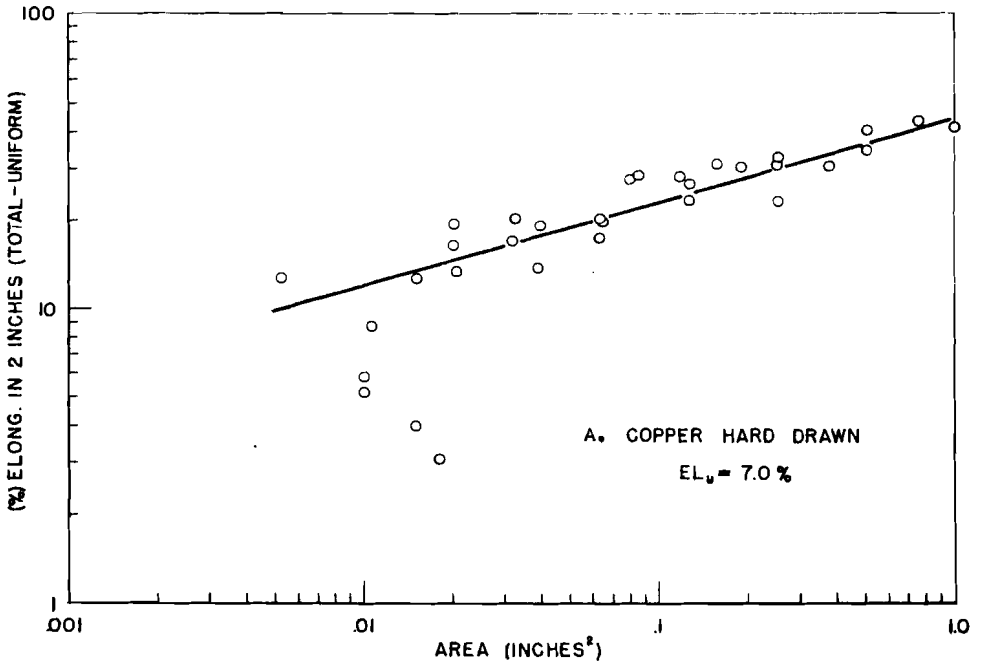


FIGURE 8A

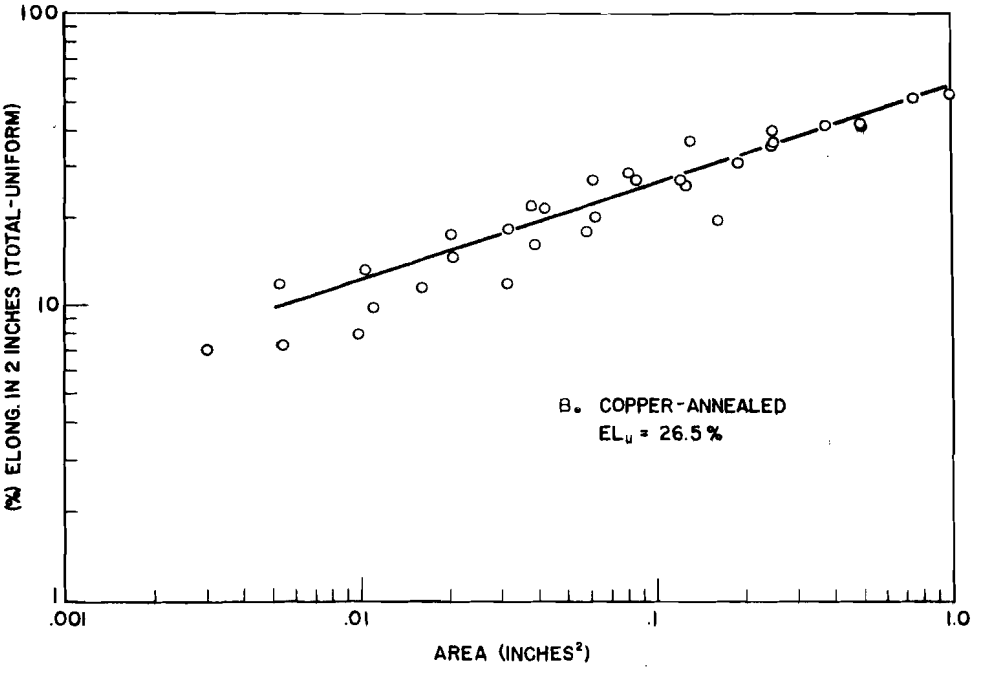


FIGURE 8B
EFFECT OF SPECIMEN AREA ON TOTAL-UNIFORM ELONGATION

FIGURES 8A & 8B

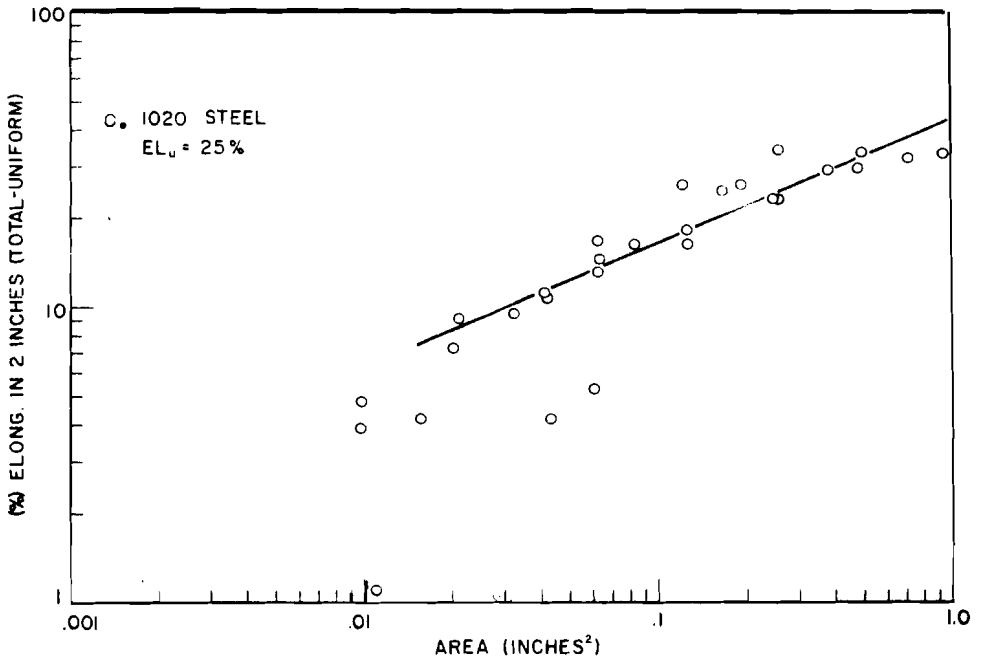


FIGURE 8C

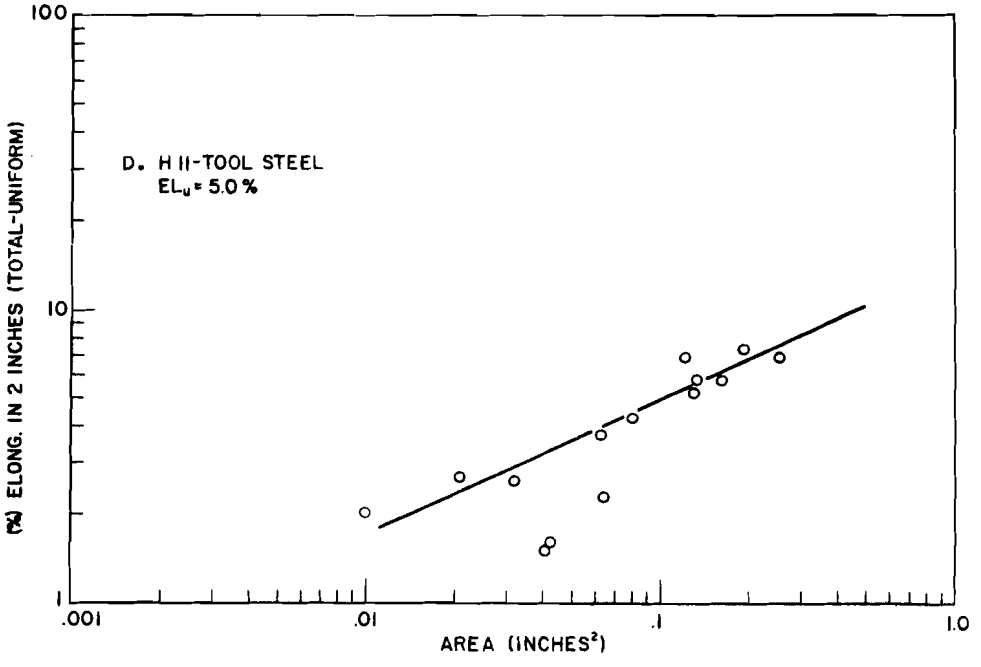
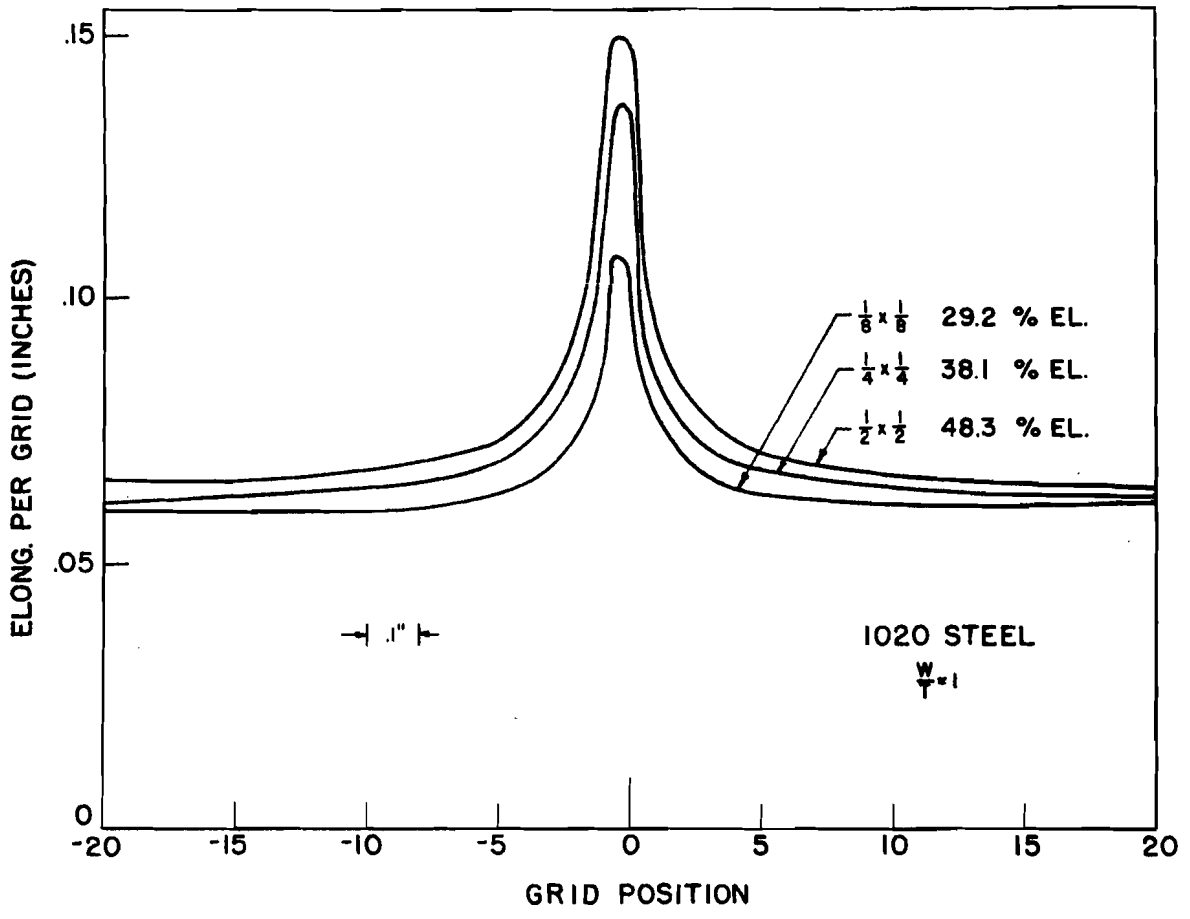


FIGURE 8D

EFFECT OF SPECIMEN AREA ON TOTAL-UNIFORM ELONGATION

FIGURES 8C & 8D



LONGITUDINAL STRAIN DISTRIBUTION IN GAGE LENGTH SECTION FOR BARS OF DIFFERENT AREA

FIGURE 9

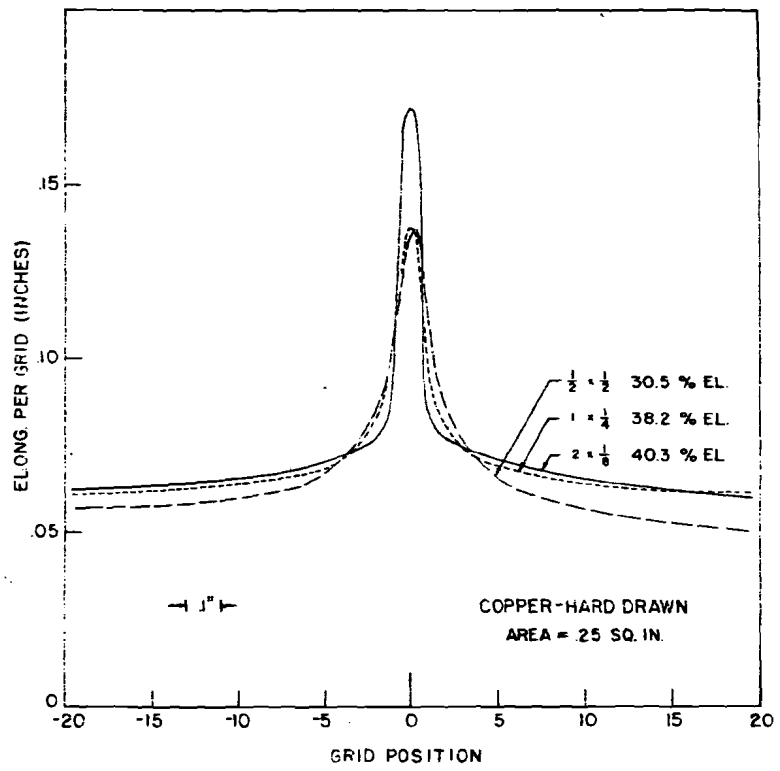


FIGURE 10: LONGITUDINAL STRAIN DISTRIBUTION IN GAGE LENGTH SECTION FOR BARS OF SAME AREA BUT DIFFERENT GEOMETRY

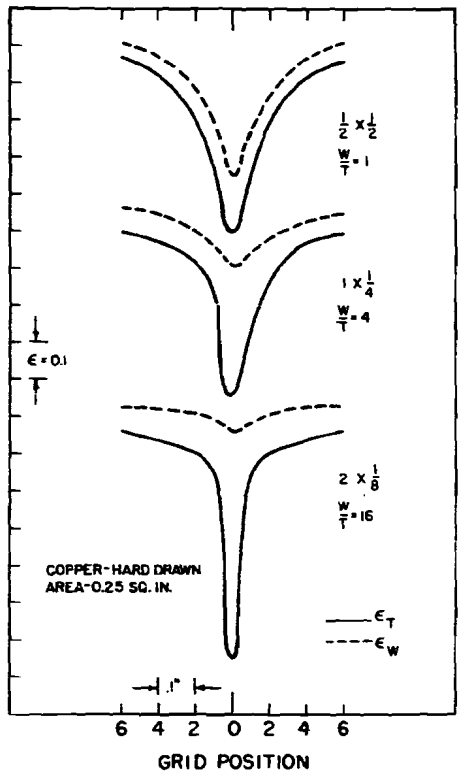


FIGURE 11: WIDTH AND THICKNESS STRAIN DISTRIBUTION IN GAGE LENGTH SECTION FOR BARS OF SAME AREA BUT DIFFERENT GEOMETRY

FIGURES 10 & 11

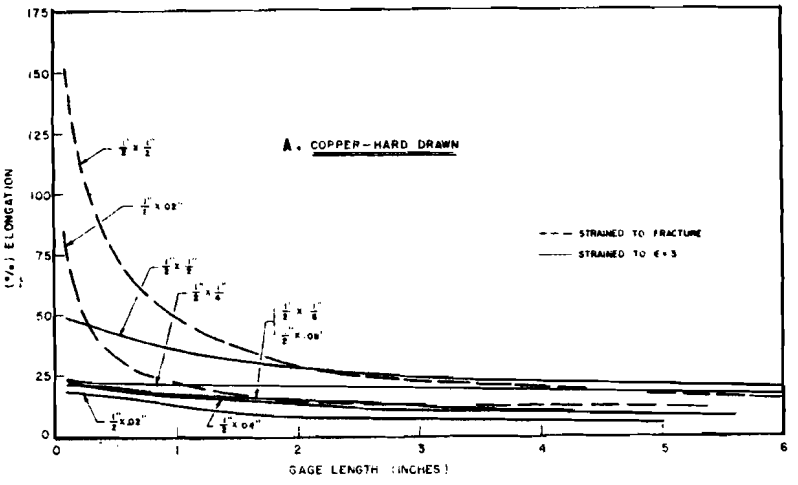


FIGURE 12A

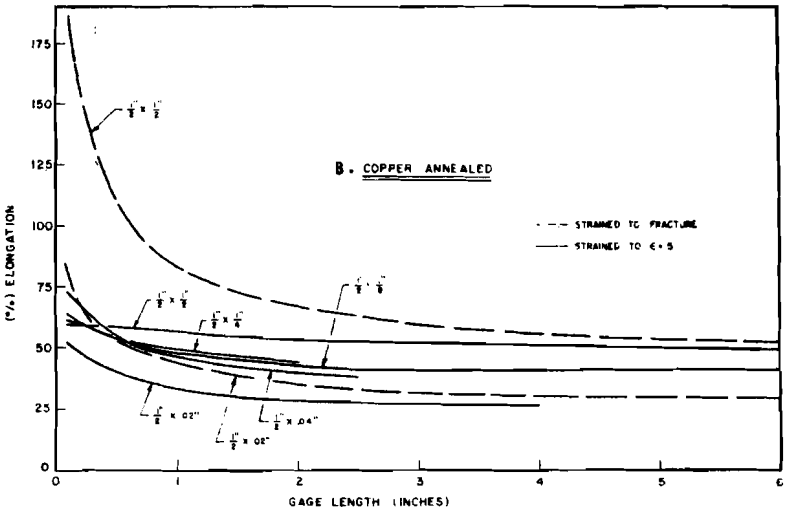


FIGURE 12B

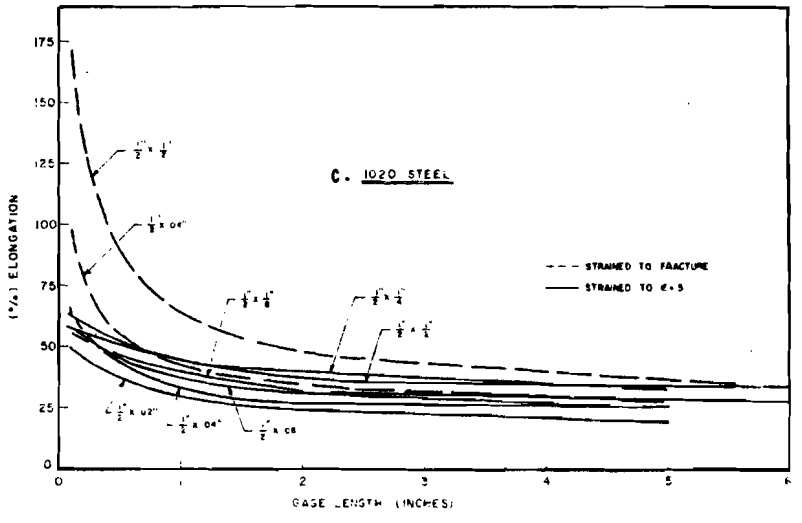


FIGURE 12C
VARIATION OF ELONGATION WITH GAGE LENGTH

FIGURES 12A, 12B & 12C

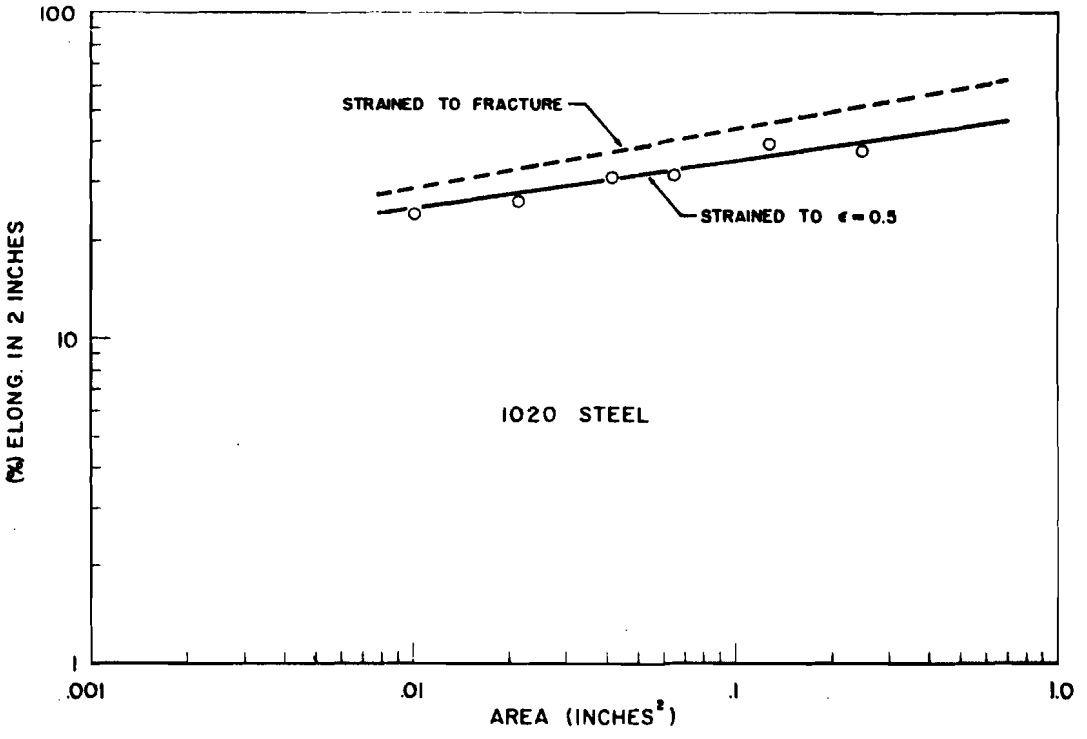


FIGURE 13: VARIATION OF ELONGATION IN 2 INCHES WITH SPECIMEN AREA

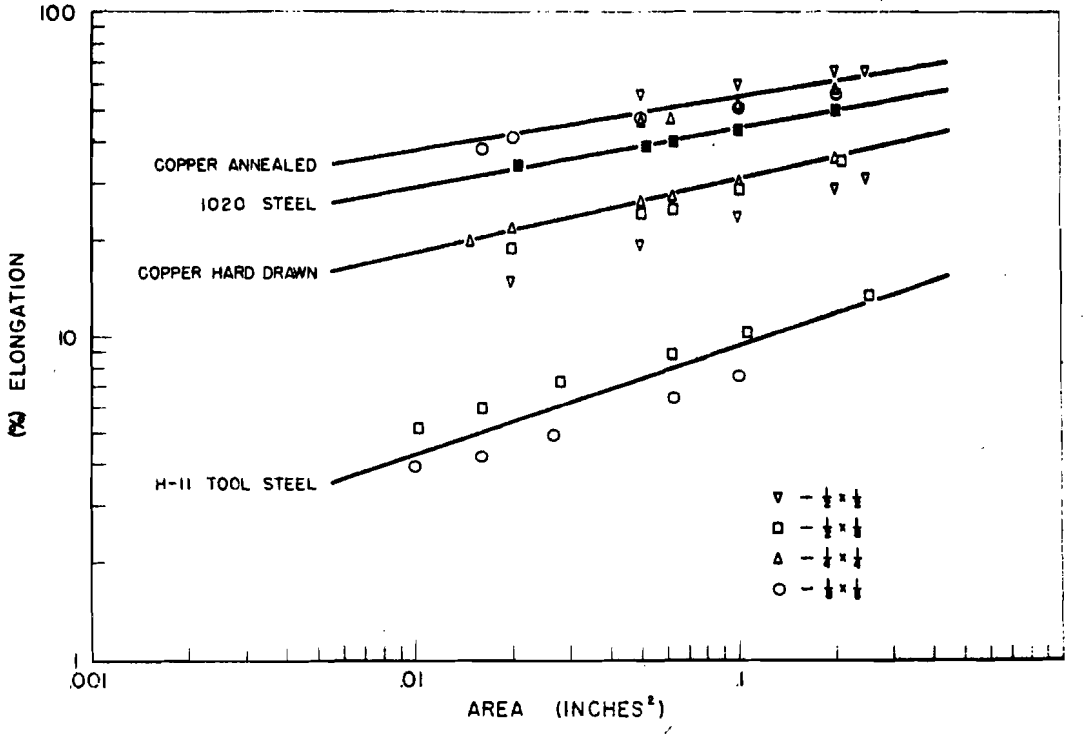


FIGURE 14: CALCULATED VARIATION OF ELONGATION IN 2 INCHES WITH SPECIMEN AREA

FIGURES 13 & 14