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Influence of Soft Inclusions on the Strength of Wrought Materials

by D. Pai[1] and M. C. Shaw[2]

Abstract

The three dimensional soft particles (such as sulfides, silicates and voids) present in most materials are modelled by circular voids in sheet metal. Relationships are sought between the shape and orientation of a hole after rolling and testing in tension. Then, the effect of hole shape and size on mechanical properties is considered experimentally. It is found that the presence of voids has a negligible influence on the ultimate tensile stress of ductile materials based on the unperforated area because plastic flow neutralizes the stress intensification present in the elastic region. However, the shape and orientation of the defects are found to play an important role relative to strain at fracture. In certain engineering applications the strain at fracture is more important than the stress at fracture and in this sense the presence of voids may be considered to influence the strength of a ductile material. The critical maximum intensified tensile stress criterion which holds for brittle materials is found to hold as well for ductile materials when the fact that the nominal and intensified tensile stresses are the same for a ductile material is taken into account.

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Introduction

It is well established that defects play an important role regarding the strength of relatively brittle materials. Griffith discussed the importance of sharp hairline cracks in two important papers (1, 2). In the first paper (1), he postulated that a sharp crack will propagate spontaneously leading to gross fracture when the rate of elastic energy release with crack growth is equal to or greater than the rate of energy consumed during crack growth. Since Griffith was concerned with perfectly brittle materials such as glass, the energy absorbed was simply the surface energy associated with the new areas generated. This concept has been extended to cover the quasi-brittle materials (3) and has developed into the discipline of Fracture Mechanics (4) in which a mechanical property known as fracture toughness is used to measure the critical crack length for gross fracture in a specimen subjected to a nominal tensile stress.

In his second paper (2), Griffith took a stress approach and assumed that gross fracture occurs when the intensified stress at the tip of a sharp crack reaches a critical value. This made it possible to explain brittle (tensile) fracture under a purely nominal compressive loading as well as under complex states of biaxial loading. A fracture locus was obtained by the second (stress) approach which predicted the strength in uniaxial compression to be eight times the strength in uniaxial tension.

In a series of tests on tungsten carbide and other brittle materials, Takagi and Shaw (5) found the compressive strength to be closer to three times the uniaxial tensile strength rather than eight times and further showed that Griffith's intensified stress theory could be brought into excellent agreement with experiment if the defect was assumed to be a circular void instead of the hairline crack assumed by Griffith. While the Takagi-Shaw analysis is two dimensional (plane stress) as was that of Griffith, subsequent analysis has revealed little difference between the influence of a two dimensional circular void and a three dimensional spherical void. As in many other problems, a two dimensional model represents a good first approximation to the actual three dimensional situation.

It is also well known that soft inclusions such as sulfides and silicates play an important role relative to the mechanical properties of ductile materials (6-11). For example, Wells and Mehl (6) show a dramatic reduction in ductility with the direction of tensile loading for steel specimens subjected to different forging ratios. (Fig. 1).

The statement is often found in the literature that the transverse strength of a material containing elongated inclusions is lower than the longitudinal strength (the longitudinal property being measured in the direction of the major axis of an elongated inclusion). This statement is or is not true depending on how strength is evaluated. In many engineering applications, strength is taken to mean the stress at which failure occurs. In other applications, such as those in forming, strength is measured in terms of the ability of a material to undergo a certain strain without failure.

Experimental Part

In order to better understand the role that soft inclusions play relative to mechanical behavior of wrought materials, a series of experiments were performed based on the following assumptions:

1. that unfilled voids represent a reasonable approximation to soft inclusions in a harder matrix
2. that cylindrical (two dimensional) defects represent a reasonable approximation to their three dimensional counterparts

Three materials were employed in sheet form (0.125 in = 3.175 mm thick):

1. High purity OFHC copper
2. Aluminum alloy 5052
3. AISI 1018 steel

Specimens were tested in uniaxial tension with and without holes of different shape and orientation relative to the tensile direction. Circular holes of 0.040 in (1mm) diameter were produced by drilling and reaming. Elliptical holes were produced by subsequently rolling the sheet material containing initially circular holes. In some cases a 50% reduction in thickness in 6 passes was used while in others a 35% reduction in thickness in 3 passes was used. Following drilling and rolling, the specimens were annealed for one hour as follows and furnace cooled:

Material	Annealing Temperature °C
OFHC copper	500
5052 Aluminum	340
AISI 1018 steel	875

Two types of tensile specimens (Fig. 2) were employed. One of these (Fig. 2a) was similar to the conventional ASTM sheet material specimen (12) while the other (Fig. 2b) was a shorter, wider plane strain type. Tension tests on specimens with and without single central holes were performed on a model TT-D Instron Universal Testing Machine at a cross head speed of 0.05 in/min (1.24 mm/min) which corresponds to a strain rate of 0.0167/min for the ASTM specimen and 0.100/min for the plane strain specimens.

Results and Discussion

Two types of observation were made which will be considered in the following two subsections.

Shape Change During Rolling

Rolling deformed the initially circular holes into approximately elliptical ones with eccentricity of the ellipse increasing with successive rolling passes (for example, see Fig. 3). The length of the major and minor axes of the holes were measured after each pass. Since it is to be expected that a defect filled with relatively soft material will plastically deform such that its volume remains constant, it is reasonable to assume that the same will hold approximately for a void.

If this is the case

$$\pi r^2 h_o = \pi a b h_1$$

$$ab = \frac{h_o}{h_1} r^2 \qquad (1)$$

where r = initial radius of drilled hole

a, b = major and minor semi-axes of ellipse

h_o = initial sheet thickness

h_1 = thicioness after rolling

Experimental values of a b are shown plotted against values from equation (1) in Figure 4 for a range of reductions for all three materials. The trend is linear with a slope of 45^o except at higher levels of reduction where it appears there may be a small reduction in volume. Thus, equation (1) appears to represent an excellent approximation.

Equation (1) is but one expression for the two variables a and b. Several attempts were made to obtain a second analytical relation without success. However, the observed ratio a/b when plotted against the percent reduction in thickness (R) is reasonably approximated by a single curve (Fig. 5). The ratio a/b is found not to be particularly material sensitive.

When a specimen containing a row of holes (Fig. 6) was rolled, all holes were found to have the same area after a given reduction for aluminum and copper for reductions up to 50% but not for steel. In the case of steel, the holes nearer the center of the specimen showed an increase in area after rolling ($A_1/A_o > 1$) while those closer to the edge showed a decrease ($A_1/A_o < 1$) as shown in Figure 7. This is thought to be due to a significant roll deflection for steel but not for copper or aluminum. Roll deflection would cause the pressure near the center of the specimen to be less than that near the edge. As Van Rooyen and Backofen (;3) have demonstrated, the coefficient of friction will be less where the pressure is high and vice versa. The higher friction near the edge should cause a reduction in hole size with deformation near the edge in accordance with ring compression test results (14). Near the center, the lower friction results in an expansion of the hole with reduction, also in accordance with ring compression results.

It would appear that the behavior of a row of holes offers a very convenient measure of the stiffness of a rolling mill in sheet or plate rolling.

In practice, soft defects are present in groups rather than in isolation and adjacent defects may interact relative to changes in shape and concentration of stress. A few tests were performed to study such interaction effects. In one such test, the specimen shown in Figure 8 was rolled and the shapes of the central (solid black) holes compared after rolling. It was found that whereas hole A was larger than hole B after rolling, holes B and C were the same. This suggests that only immediate neighbors interact which greatly simplifies the problem of studying interaction effects. The hole spacing relative to hole size would of course be an important variable in any interaction study. Since the interaction question was somewhat removed from the main thrust of this study, it was not pursued, the bulk of the experiments being concerned with the behavior of single isolated defects.

Fracture Experiments

Uniaxial tensile tests were performed on a large number of specimens of the three materials (pure copper, aluminum alloy and low carbon steel) with and without single central holes of different shape after rolling and with and without annealing after rolling.

The central defect which may be a circle or ellipse (depending on whether the hole was drilled after or before rolling) with major axis parallel or transverse to the direction of loading, undergoes a substantial change in shape during the tension test. The change is always towards an ellipse with major axis in the loading direction.

The results indicate that the ultimate tensile stress which was calculated based on the sound area at the central crosssection before the tension test, is insensitive to the shape or orientation or size of the hole. This can be explained by the fact that large plastic flow around a void in a ductile material wipes out the effect of hole shape and orientation and reduces the elastic stress concentration effect to a negligible value.

The maximum intensified stress theory of Takagi and Shaw (5) holds good for ductile materials but there is then no difference between the nominal and the intensified normal stresses.

Strain at fracture is found to depend considerably on the orientation of the hole. Of all the defects, an elliptical defect with its major axis aligned with the direction of loading results in the greatest ductility. A round hole (before testing) yields intermediate ductility. Ductility is minimal if the major axis of the elliptical defect is transverse to the loading direction.

Of course, specimens with no holes have the highest ductility. The results on both stress and strain are in keeping qualitatively with the findings in (6-9) which dealt with mechanically fibered inclusions as defects instead of the voids considered here.

At maximum load, the initiation of a small crack is evident at the edges of any hole at points 90° from the load line. This crack grows rapidly with substantial necking with further increase in deformation as the load rapidly falls to zero.

Two types of necking were observed. Necking in the width direction was diffuse while that in the thickness direction was localized. In the unannealed specimens with holes, two localized necks form that intersect each other and make an angle of about 35° with the width direction. In some of the unannealed specimens without holes, only one such oblique neck was formed instead of two. This was noticed and reported as early as 1928 by Koerber and Siebel (15). Nadai (16) explains it this way: "It is well known to testing engineers that wide flat bars or strips machined from thin rolled metal sheet when tested in cold worked condition in tension do not break in a surface which is perpendicular to the direction of tension but along an oblique plane perpendicular to the flat sides of the bar inclined at an angle of approximately 55° with respect to the axis of the bar .... the flat bars must have a ratio of width to thickness of the rectangular section larger than 6 or 7 otherwise they neck down symmetrically around a section normal to the bar axis."

The mathematical derivation of the 55° angle as presented by Nadai (16), is based on the observation that the oblique direction with respect to the tensile axis, corresponds to that in which no normal strains are produced under simple extension. Shaw and Avery (17) have followed similar arguments but used Mohr's circle of strain in plane stress to obtain the same result. Nadai suggests that two slip layers symmetrically inclined with respect to the axis form intersecting each other in the weaker region if there is such a region in the interior of the bar. This is certainly true in the case of the specimens with holes and as expected, all the unannealed specimens of all materials with holes form two intersecting slip layers and fracture randomly along one of them.

In contrast, annealed specimens with and without holes necked and fractured along a line perpendicular to the direction of loading (i.e. in a direction perpendicular to the nominal maximum tensile stress direction).

One common feature which was observed in all specimens with holes was that they necked well before the maximum load was reached whereas in a regular tensile specimen without a hole and subjected to uniaxial tension, the theory (18) states that necking instability occurs when the applied load is a maximum.

Concluding Remarks

Experiments on ductile sheet materials (pure copper, aluminum alloy and low carbon steel) have revealed that circular holes (simulating soft inclusions in a harder matrix) change shape upon rolling and also further when subjected to tensile testing. The defects assume an elliptical shape with major axis in the direction of rolling or in the direction of maximum tensile stress in such a way that their volume remains constant. Observation of the relative change in shape of a row of circular holes across a specimen in sheet rolling offers a convenient means for assessing the stiffness of a rolling mill.

The presence of a transverse hole in a ductile tensile specimen of sheet material has a substantial influence on the strain at fracture which depends significantly on the shape and orientation of the hole (soft inclusion). However, the presence of a hole of any shape and orientation has little to do with the ultimate tensile stress based upon the initial sound area of the specimen. One consequence of this is that the maximum intensified tensile stress criterion introduced by Griffith for brittle materials may also be considered to hold for ductile materials when it is recognized that for ductile materials there is no difference between the nominal maximum tensile stress and the maximum intensified tensile stress on the surface of a void.

Acknowledgements

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References

1. A. A. Griffith: Phil Trans. of Royal Soc., 1920, vol22A, p.163.

2. A. A. Griffith: Proc First International Congress of Appl. Mech. Delft, 1924, p 55.

3. E. Orowan: In Proc. of Conference at Mass. Inst. of Technology, 1950, Pub by John Wiley and Sons, NY p 139.

4. G.R.Irwin: J.Appl.Mech 1957, vol 24, p361.

5. J.Takagi and M.C.Shaw: Trans. ASME, Jour of Eng for Industry, 1983 Vol 105, p 141.

6. C.Wells and R. F. Mehl: Trans Am Soc Met, 1949, Vol 41, p 715.

7. A.H.Grobe, C.Wells and R.F.Mehl: Trans Am Soc Met, 1953, vol 45, p 1080.

8. E.A.Loria: Trans Am Soc Met, 1950, Vol 42, p 486.

9. J.Welchner and W.G. Hildorf: Trans Am Soc Met, 1950, vol 42, p 455.

10. W.A.Backofen, A.J.Shaler and B.B.Hundy: Trans.Am Soc. Met, 1954, vol 46, p 655.

11. F.A. McClintock: In "Ductility" pub by Am.Soc.Metals, Metals Park, 1968, p 255.

12. ASTM: "Standard Methods of Tension Testing of Metallic Materials", Ann Book of ASTM Stds, 1980, part 10, E8-79a, p207.

13. G.T. Van Rooyen and W. A. Backofen: Int. J. Mech. Sc., 1960, vol 1, p 1.

14. A.T.Male and M.G.Cockroft: J. Inst. of Metals, 1964-65, vol 93, p 38.

15. F. Koerber and E. Siebel: Naturwissenshaften, 1928, vol 16, p 408.

16. A. Nada : "Theory of Flow and Fracture of Solids", 2nd Ed, vol 1, p. 319, McGraw Hill Book Co., N.Y., 1950.

17. M.C.Shaw and J.P. Avery: in "Vibration Acoustics, Stress and Reliability in Design", 1983, Amer Soc. of Mech. Engrs. N Y, p 247.

18. G.E.Dieter: "Mechanical Metallurgy", 2nd Ed, McGraw Hill Book Co. N Y, 1976.

Figure Captions

Fig. 1 Influence of forging ratio on longitudinal and transverse reduction of area (after Wells and Mehl, 6)

Fig. 2 Tensile specimens employed

a) ASTM Rectangular type, dimensions, in. (mm):
$A = 1.50$ (38.1), $B = 1.25$ (31.8), $L = 4.50$ (114)
$G = 1.25$ (31.8), T = variable, $W = 0.25$ (6.4).

b) plane strain type: Dimensions, in. (mm)
$L = 2.20$ (55.9), $G = 0.50$ (12.7), T = variable,
$W = 1.00$ (25.4).

Fig. 3 Change of hole shape during rolling of AISI 1018 specimen

a) before rolling
b) after 2 passes
c) after 4 passes
d) after 6 passes

Fig. 4 Variation of experimental values of (a b) after rolling with values from equation (1).

Fig. 5 Variation of elliptical ratio (a/b) with percent reduction in thickness (R)

Fig. 6 Specimen (4 x 5" = 100 x 125 mm) with row of 0.040 in diameter (1 mm) holes spaced 1.00 in (25.4mm) apart and 0.5 in (12.7 mm) from edge

Fig. 7 Variation of hole size (A_1/A_o) with location of hole across specimen of Fig. 6 (x) for AISI 1018 steel rolled to reduction $R = h_1/h_o = 0.65$ using a Stanat Ex-100, 3 hp (2.24 kW) at 450 rpm rolling mill having a maximum gap of 1.20 in. (30.5 mm).

Fig. 8 Specimen to study defect interaction. All holes 0.040 in (1 mm) diameter with 0.100 in (2.54 mm) spacing. Dimension in inches (mm):
$A = 3.30$ (83.8), $B = 2.70$ (68.6), $C = 1.80$ (45.7), $D = 0.85$ (21.6),
$W = 1.00$ (25.4).

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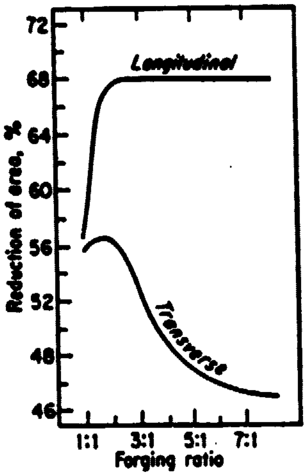
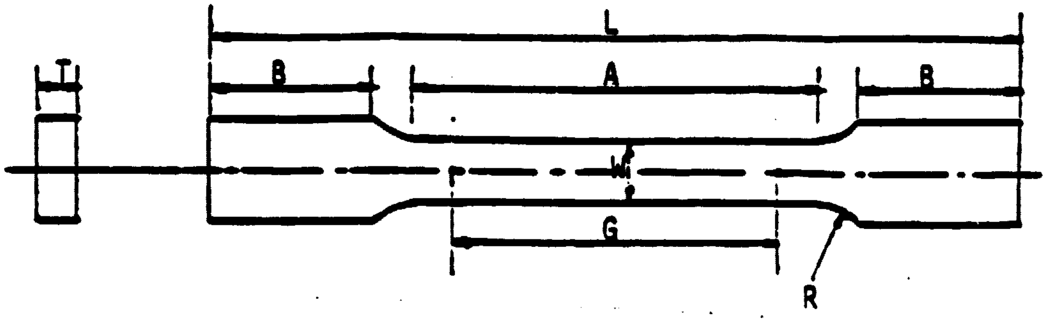
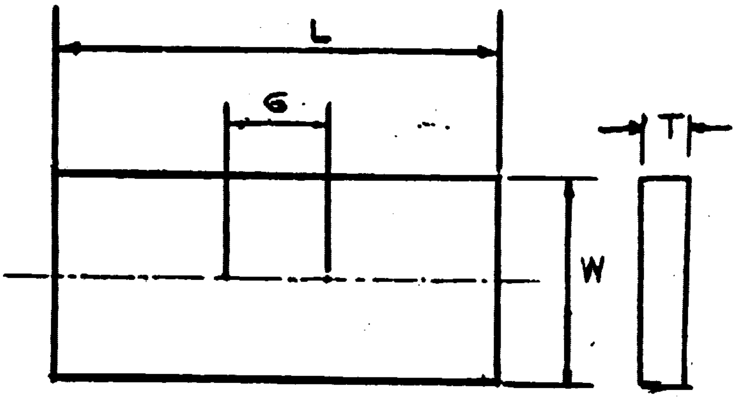


FIG 1.



a)



b)

FIG 2.

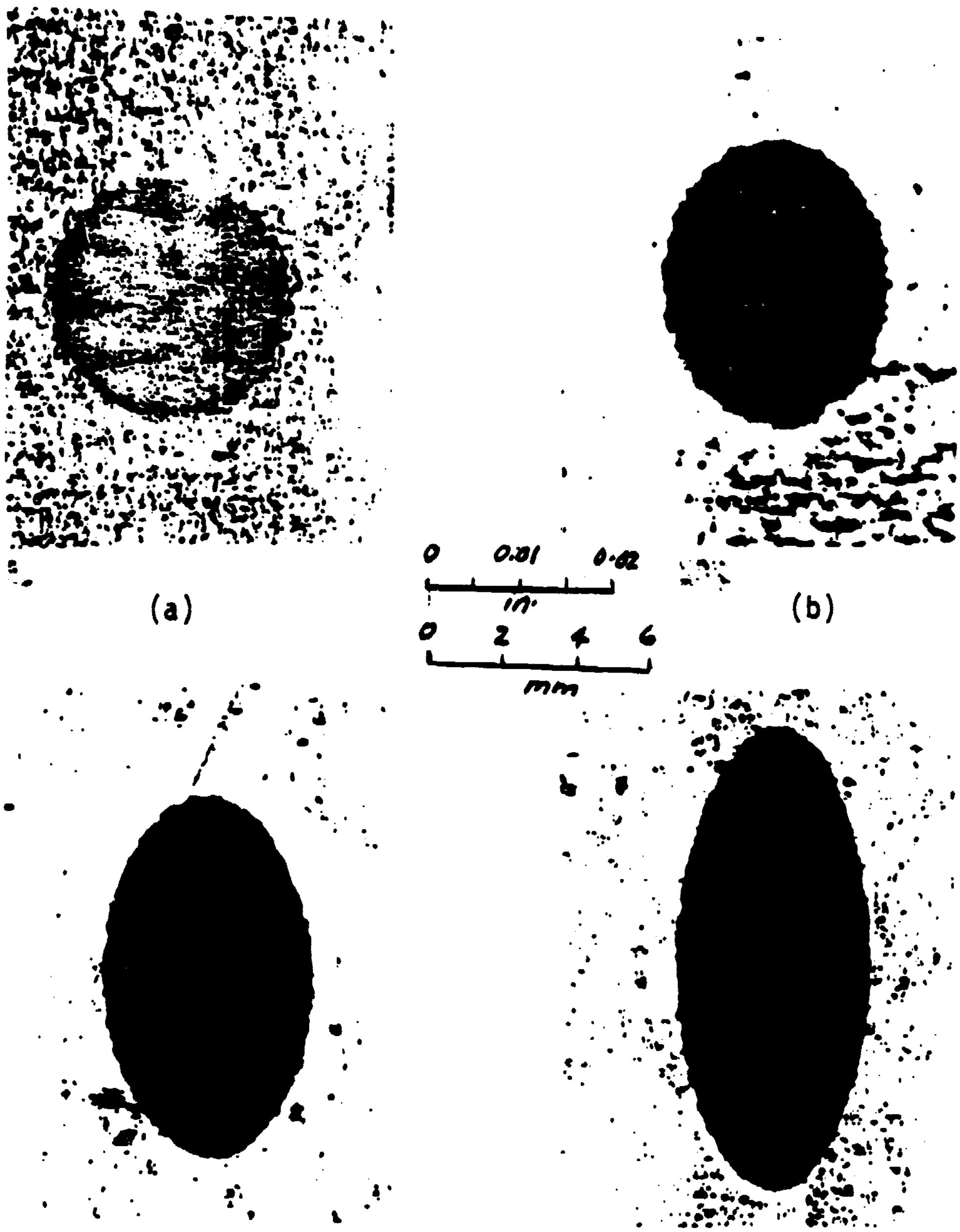


FIG 3

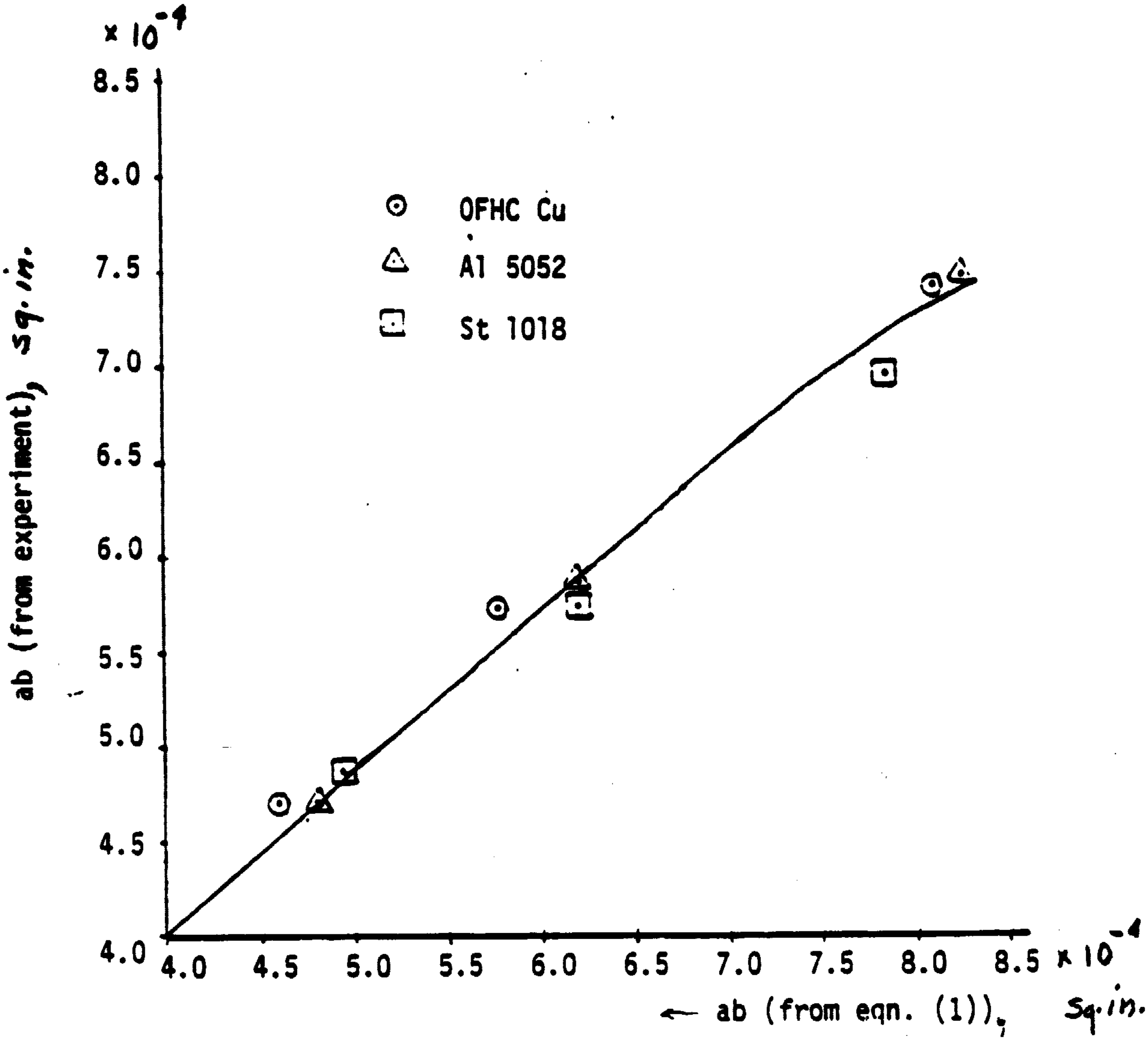

x 10^-4
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
ab (from experiment), sq.in.
OFHC Cu
Al 5052
St 1018
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
x 10^-4
← ab (from eqn. (1)), sq.in.

FIG 4.

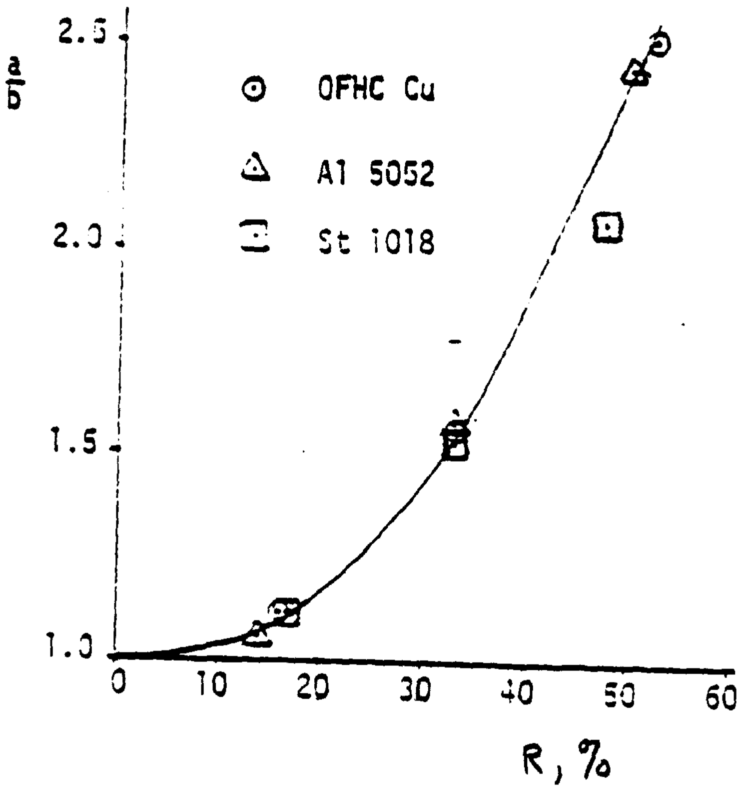


FIG. 5

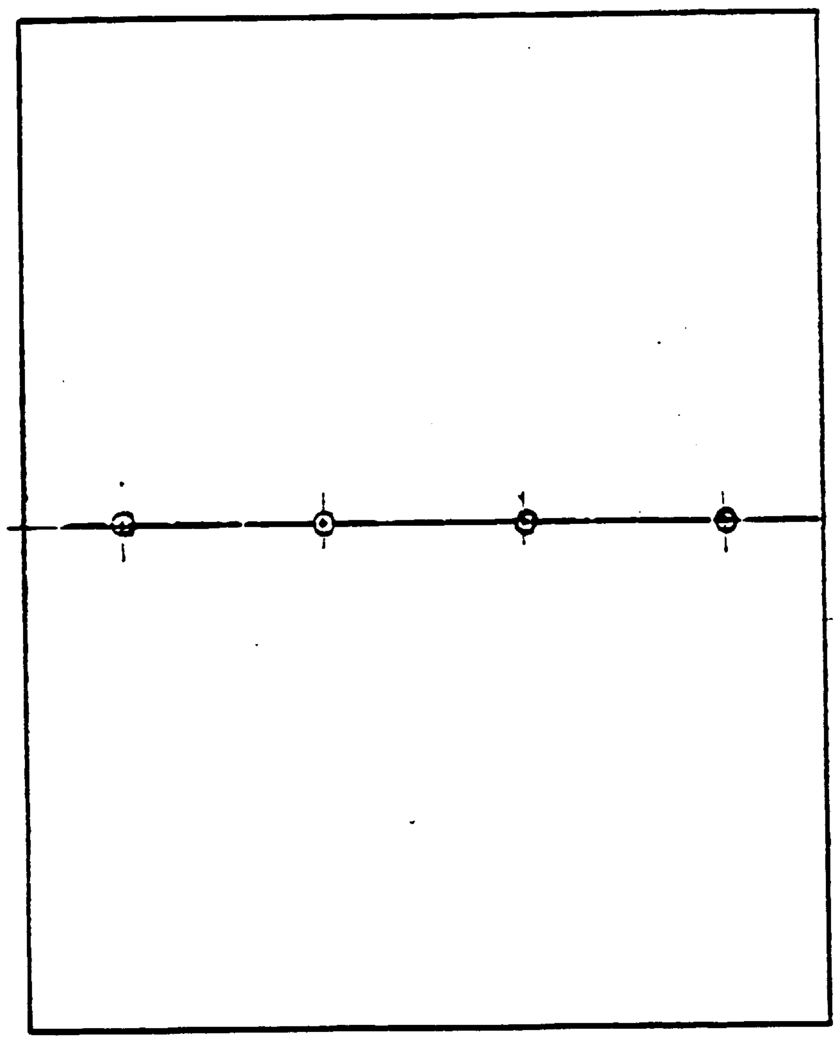


FIG. 6

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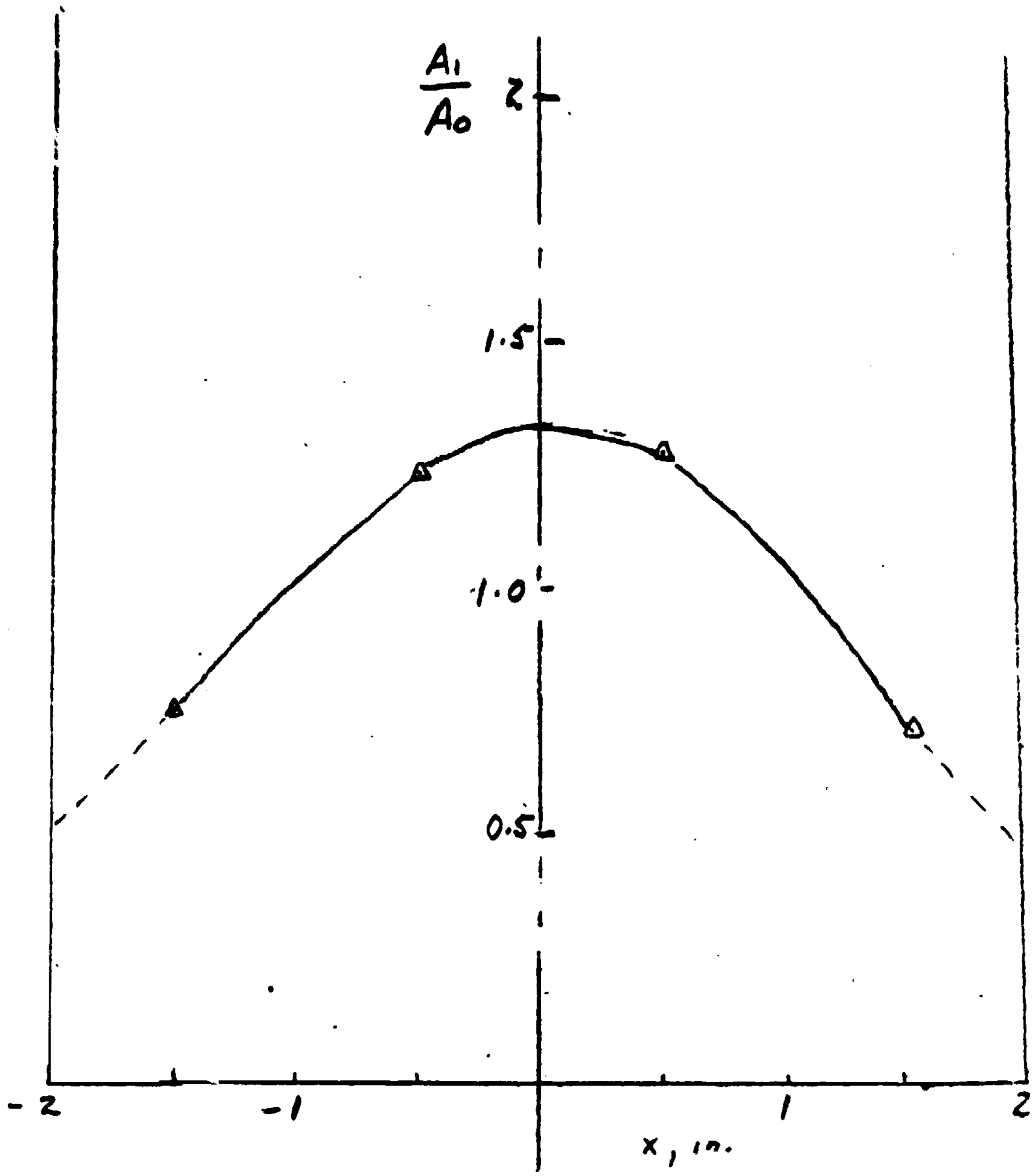

FIG 7

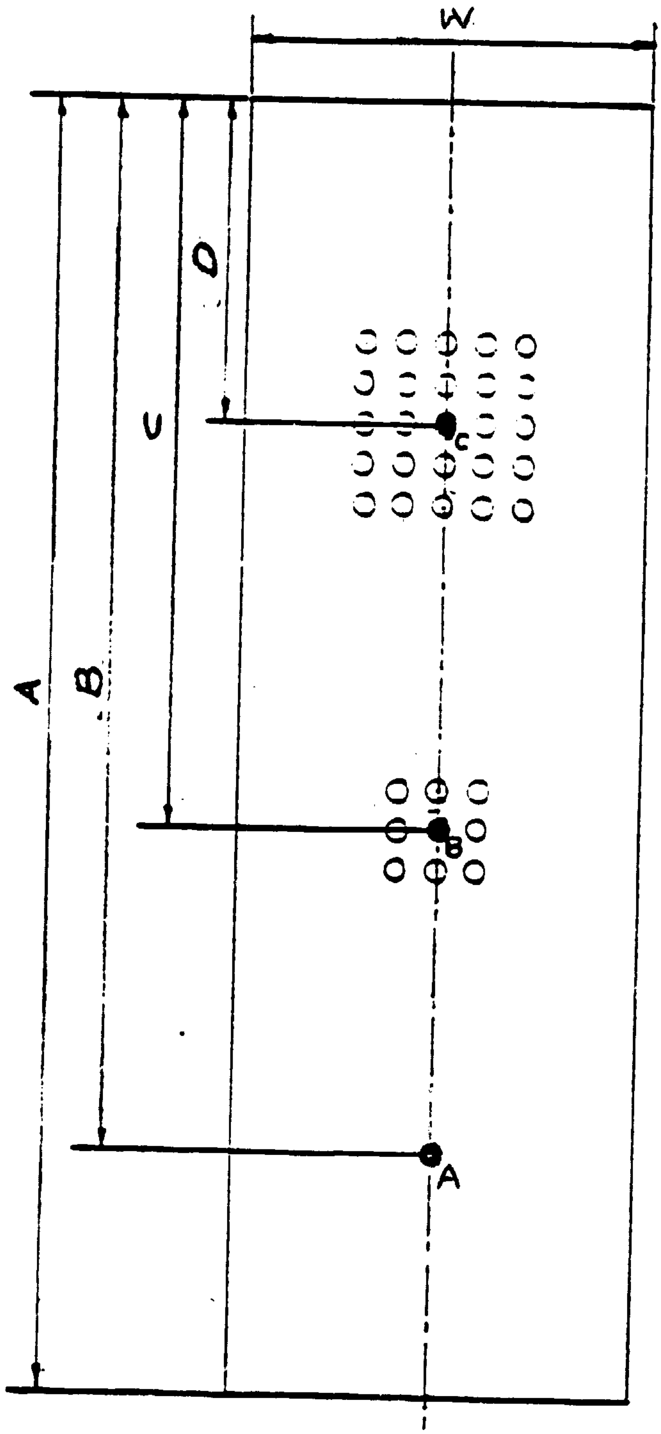

FIG. 8