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TENSILE DEFORMATION AND FRACTURE OF BRAZED JOINTS

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12. Abstract:

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direction was observed. Cleavage facets were detected on fracture surfaces in the case of silver filler and void formation in the case of lead filler, using mild steel as the base material.

ABSTRACT

The tensile deformation of a prototype composite material, the brazed joint, was measured. Highly localized non-uniform straining in the axial direction was observed. Cleavage facets were detected on fracture surfaces in the case of silver filler and void formation in the case of lead filler, using mild steel as the base material.

FOREWORD

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INTRODUCTION

It is well known that a small volume of soft, ductile material, if constrained from deforming, is capable of supporting extremely high stresses as compared with its unconstrained strength. A, by now, classic example of this is a thin transverse brazed or soldered joint in a tensile specimen. It seems apparent that the high load-carrying ability of such joints has its origin in the development of triaxial stresses within the joint due to differences between the yield strengths and the work-hardening rates of the braze material and the parent material. It also seems apparent that the extent to which triaxial stresses are generated must depend upon specimen geometry.

It is the latter which has received much experimental attention in the form of empirical observation of joint strength as a function of joint thickness. Leach and Edelson[(1)] present a curve of joint strength versus joint thickness for Ag-Cu-Zn-Cd joints in stainless steel; the data show increasing joint strength with decreasing joint thickness, reaching a maximum at about 0.0015 inches joint clearance, followed by lower joint strength at smaller joint clearance. It is significant, for purposes of comparison with other data that joint strengths several times that of the bulk filler material could be realized in thin flat tensile specimens only 0.031 inches in thickness, and also that this condition is easily attained with a filler material which does not closely approach the "classic adhesion bond". Case[(2)] presents data for an Ag-Cu-Zn-Ni filler material which shows an increasing joint strength with decreasing joint clearance, reaching a maximum value at several thousandths of an inch clearance, followed by markedly decreased joint strength at smaller joint clearances.

Brooker and Beatson[(3)] conclude from their investigations of the strength of Ag-Cu-Zn-Cd joints in mild steel that the strength of a completely sound joint should be equal to the as-cast strength of the bulk filler material, irrespective of joint clearance (it should be noted, however, that the as-cast filler metal was just about as strong as the mild steel base stock). On the other hand, Coxe and Setapen[4] found, for Ag-Cu-Zn-Cd joints in steel, that strength continually increased with decreasing joint thickness and a similar effect was found when 4140 steel was used as the base material. When the same alloy was used as a filler metal in Armco iron, joint strength was substantially independent of joint clearance, but none of these systems showed a decrease in joint strength at small values of joint clearance.

Bredz[5] presents data for the tensile strength of silver joints in 1020 steel, and in drill rod; this data shows increased joint strength for decreased joint thickness. Bredz and Schwartzbart[6] present additional data for the same two systems, in which the investigation was extended to the range of extremely small joint thickness where a levelling off, or slight decrease, of joint strength was detected.

All of the preceding references dealt with joint clearance as the only geometric variable. Moffatt and Wulff[7], using silver joints in mild steel base stock, varied both specimen diameter and joint thickness; this investigation indicated a linear dependence of joint strength upon the thickness-to-diameter ratio of the joint. Lehrer and Schwartzbart[8] on the other hand, have determined a hyperbolic relationship between joint strength and joint clearance, for the same system, for joints down to about 10^{-4} inches in thickness followed by a very low and constant joint strength at smaller thicknesses. The low strength at small joint thickness is apparently not due to defective joints, and the authors hypothesize that the low strength may represent the brittle fracture strength of the joint in the absence of prior plastic deformation.

There is general agreement that, except in the case of ultra thin joints, fracture strength increases as joint thickness decreases. Moffatt and Wulff[7] found that, in the range of specimen sizes tested, joint strength is the same for two specimens of similar geometry irrespective of joint thickness. A similar conclusion was reached by Meissner and Baldauf[9] with respect to polystyrene bonds in steel. paraffin wax bonds in steel, and eutectic lead-tin solder bonds in brass. This point is not too critical, since plots of joint strength versus joint thickness will not be changed in shape by the operation of dividing joint thickness by the constant diameter used in the series of experiments. Nonetheless, the demonstration that joint strength is a function of thickness-to-diameter ratio opens the possibility of examining the properties of extremely thin joints by the testing of thicker joints of larger diameter.

The disagreement which exists lies in the shape of the thickness versus t/D curves; the curves found in the literature vary from linear, through non-descript, to hyperbolic. In a consideration of the large amount of empirical data which cannot be correlated, it soon becomes evident that the results depend upon factors other than joint geometry. In an effort to resolve some of the many questions which arise, a new attack was made on the problem of the nature of the stress distribution in the brazed joint, and the mechanism by which these joints fail; this took the following form:

(a) A series of different combinations of base stock and filler metal were examined, and strength versus t/D ratio determined.

(b) Silver joints in steel were prepared with rectangular cross-section, comprising a range of ratios of width to depth for constant joint thickness. Some of the thin, flat specimens were loaded almost to failure, and then examined by X-ray for hole or crack formation; in addition, the specimens were periodically removed from the testing machine and current joint thickness determined as a function of applied stress.

(c) Cylindrical joints of silver in steel base stock were stressed to various fractions of the failure stress determined by destructive testing of a single sample from a large block. For the remaining specimens from the same block, joint thickness was determined as a function of applied stress up to a predetermined level and the specimen was then unloaded and the base stock etched away completely to leave only the silver disc. The silver discs were then X-rayed to examine for hole formation, and profile measurements and density measurements were then made on the discs.

(d) Fracture surfaces of silver joints in 1020 steel and in 1075 steel, as well as fracture surfaces of lead joints in copper and 1020 steel, were subjected to detailed examination in an effort to locate the origin of failure.

EXPERIMENTAL WORK AND RESULTS

The procedure employed in producing the joints herein described, is one previously employed by the authors[7], and consists of joining together two large blocks separated by shims at the corners; the filler metal is fed into a reservoir drilled through the center of the upper block. Furnace brazing in a pure hydrogen atmosphere is used for accomplishing the joining, and on melting, the filler metal spreads out radially from the reservoir and completely fills the joint. Upon solidification of the filler metal from the outer periphery toward the center of the joint, dissolved hydrogen is rejected into the riser in the upper block; when the large block is subsequently cut up for preparation of a number of tensile specimens, the center portion containing the riser is discarded. In the case of silver joints in steel, this procedure produces joints of uniform thickness and a number of specimens of the same joint thickness can be prepared from a single block. In the case of other combinations of base stock and filler metal, varying degrees of difficulty were encountered in producing sound joints. In particular, lead joints in steel base stock characteristically showed large non-wetted regions. This problem was cured to some extent by addition of about 0.1% nickel to the lead filler metal; with this modification, the advantageous combination of specimen geometry and very slow cooling rate allowed time for the rejection of dissolved hydrogen into the riser, and most of the joint area was sound. Lehrer and Schwartzbart[8] also found it necessary to make nickel additions to the lead filler metal for the production of sound lead joints in steel.

<u>LEAD JOINTS</u> Lead joints (containing 0.1% nickel) were made in steel, copper, and arc-cast molybdenum. Data are shown in Fig. 1; 0.009" joints in steel were, for the most part, quite sound, but only a single sound specimen was obtained from a

block brazed with no spacers in which the resulting joint thickness was 0.003". Tensile strengths of sound joints in steel lay in the range 6000-9000 psi; the tensile strength of the lead joints in copper were essentially constant and lay in the range 8100-8800 psi irrespective of t/D ratio. Attempts to produce a sound lead joint in molybdenum were not successful; a reasonably sound single specimen containing a few small non-wetted regions exhibited a strength of 13,400 psi. An additional series of lead joints in nickel base stock were attempted, for the purpose of examining the effect of base metal yield strength for two different materials having the same value of Young's Modulus (steel and nickel). These joints were not sucessful on the whole, but a single completely sound tensile specimen removed from one block exhibited a strength of 8500 psi at a t/D ratio of 0.002 (joint thickness: 0.0005", specimen diameter: 0.250". All of the fractured lead joints exhibited a pronounced crater formation on the fracture surface; detailed examination of the fracture surface indicated that a hemispherical cavity existed at corresponding points on both fracture surfaces. Fig. 2 shows matching faces of the fracture surface of a lead joint in steel; the surfaces were photographed with low angle illumination. and the shadows delineate the matching cavities on both faces.

<u>TIN JOINTS</u> A single block of arc-cast molybdenum having essentially zero ductility was made with a tin joint, for the purpose of examining the effect of a high-modulus, low-ductility base stock on a low-modulus, high-ductility filler metal. Fig. 3 shows the data for these specimens.

<u>BISMUTH JOINTS</u> Bismuth joints were made in copper, to examine the properties of thin films of a completely brittle filler in a ductile base stock. Data are shown in Fig. 4.

PROBLEMS IN PRODUCING JOINTS OF LOW-MELTING POINT FILLER METALS In the case of lead joints in steel, it was necessary to go to a temperature considerably above the melting point of the filler in order to reduce the steel interfaces. For the joints of low melting point fillers, the filler metal was not introduced into the riser in the blocks at the time of loading the furnace, but was held in a cool zone of the furnace until after the blocks had been heated up to a temperature sufficient to reduce oxides at the interfaces. After sufficient time for reduction has been allowed, the furnace was shut off and the filler introduced remotely only after the blocks had cooled down to a temperature slightly above the melting point of the filler metal.

JOINT STRAIN MEASUREMENTS For silver joints in cylindrical steel tensile specimens, calculations based on joint thickness and diameter measurements indicated an apparent large volume increase as the specimen was stressed to failure. The calculation of joint volume included the assumption of a meniscus having a diameter equal to the current joint thickness; this approximation is conservative in that if the meniscus diameter is greater than joint thickness, the calculated volume will be too small. Fig. 5 shows a photograph of a specimen under load, in which the meniscus is plainly visible. Recently made interference-fringe measurements of joint contour[10] clearly show that the meniscus is not generally semi-circular in shape, but the extent to which the joint is displaced radially inward is such that the calculated joint volume is conservatively small. Data were obtained by loading the specimen to a predetermined stress level, unloading, removing the specimen from the testing machine and using a filar eyepiece on a metallograph to measure joint thickness. Joint thickness was always measured at the same locations (three in number) around the periphery of the joint; these locations were referenced between a pair of closely spaced axial marks applied with indelible marking ink across the joint. Reference marks were placed on the specimen and on the testing machine grips so that when placed back in the testing machine for stressing to a higher level it would be in the same position it previously occupied. The original joint volume was calculated on the basis of no meniscus, but all subsequent calculations assumed the meniscus.

A very large series of such measurements were made, but not all specimens were tested to destruction: many were sectioned for metallographic examination at various stages in the loading. Figs. 6 and 7 present typical data; Fig. 6 shows mean joint strain, $\frac{\Delta t}{t_o}$, for three specimens tested to destruction and Fig. 7 shows the apparent volume increase, $(\frac{\Delta V}{V_o})_{APP.}$, as a percent of the original volume, It will be noted that apparent mean joint strains are in excess of 0.5 for all three specimens, and that apparent volume increases are in the range of 35-40% for all three specimens. Fig. 8 shows a micrograph of a fractured specimen; although none of the specimens sectioned prior to fracture evidenced holes or cracks, such defects were noted in sections of the fractured joints. In particular, as Fig. 8 shows, although the fracture surface gives evidence of primarily ductile fracture, flat-bottomed pits are often seen, which leads to the suspicion that small patches of brittle fracture have been generated at those points.

In addition to the joint strain measurements on cylindrical test specimens, similar measurements were made on flat, thin tensile specimens. Several series of such specimens were prepared in which various ratios of width-to-depth for constant joint thickness were obtained. Calculations of joint volume were not attempted, but Fig. 9 shows a plot of apparent mean joint strain as a function of applied stress for several of these specimens. Extremely large mean joint strains were observed in the specimens of rectangular cross-section.

The large apparent volume increases in the case of the cylindrical specimens are not consistent with the assumption of constancy of volume during plastic deformation; three possibilities can be considered in searching for an explanation of the apparent volume increase as calculated on the basis of external measurements of joint thickness and diameter:

(a) Numerous large holes generate within the silver disc. This is not consistent with observations of micro-sections, and also the enormous number and large size of holes necessary to explain a 40% volume increase would certainly relax triaxial stresses to the point where one could not generate the high fracture stresses actually encountered.

(b) The disc remains sound, with respect to internal porosity, but cracks generate at the silver-steel interface. An interface crack enclosing a volume equal to 40% of the original joint volume must certainly encompass a large fraction of the joint area, and thus would prevent the generation of the shear stresses which produce the triaxiality leading to high joint strength.

(c) The original, parallel, flat faces of the disc do not remain flat and parallel, but the outer portion of the disc increases in thickness more than the interior portions due to elastic and plastic deformation of the base stock.

RADIOGRAPHS OF FLAT TENSILE SPECIMENS A number of flat tensile specimens were stressed to only a fraction of the anticipated failure stress. They were then securely clamped and ground down to a thickness of about 0.01" and radiographs made of the joint. No porosity was detected, and no cracks detected for those specimens stressed to less than 10,000 psi and joint strains of less than 15%. However, severe cracking was detected for specimens stressed to just over 20,000 psi and joint strain of 30%. The control specimens from the same block failed at 49,000 psi, and the cracking was so severe in a specimen stressed to 23,000 psi that it was concluded the damage was done in the grinding operation and not in the stressing operation. Further attempts at radiography of flat tensile specimens were abandoned in favor of a superior method developed for radiography of cylindrical specimens.

JOINT PROFILE MEASUREMENTS It was concluded that the distortion of the originally flat, parallel faces of the joint was the most likely origin of the large apparent volume increase, and an attempt was made to check on this. A single large brazed block, of silver in steel, was prepared from which four identical tensile specimens were made. One specimen was tested to destruction to obtain a control value for joint strength, and the remaining three specimens were stressed to various fractions of the failure stress of the control. Intended values were 98% 95%, and 90%, but actual values obtained were 97.5%, 92.5%, and 86.2%. Careful measurements of increase in joint thickness and decrease of specimen diameter during testing were made, after the fashion previously described. Fig. 10 shows apparent volume increase in these four specimens during stressing. The silver discs were then removed from the stressed but unbroken specimens, by etching the steel completely away with concentrated hydrochloric acid. This is a tedious procedure, requiring about a week of continuous immersion in acid which must be discarded and replaced several times a day even when the steel is cut off close to the joint (about 1/8" of steel was left on either side of the joint). In addition to the three discs, a sample of the scrap from the large brazed block was also etched to produce a sample of the as-brazed (unstressed) silver joint. Fig. 11 shows the silver discs after removal from the tension specimens, as well as the etched out sample of the as-brazed joint and the fracture surface of the control specimen. The fracture surface clearly shows that the entire joint in that specimen is comprised of parts of only three grains; no grain structure was in evidence on the surfaces of the stressed discs which had been etched out but instead these discs showed a very rough "orange peel" surface. The as-brazed joint, however did show a grain structure; this sample showed a rim of small grains (see Fig. 11) around the outer periphery of the large block, but immediately inside, enormously large grains were visible. After being radiographed, the discs were subjected to density measurements, and then profile measurements were made; however, for the sake of continuity, the latter will be reported on first.

The silver discs from the stressed specimens were noticeably thicker around the periphery than at the center; in fact the thicker rim around the outside could easily be detected by feel. Special 1/16" diameter ball-end adaptors were made for use on a micrometer for measuring local disc thickness. Results of profile measurements are shown in Figs. 12, 13 and 14, which show the "dished" shape of the discs and immediately offer a clue as to the reason for the apparent volume increase of the joint based on exterior measurements. All points shown were measured with the ball-end micrometer except for the extreme outer point, which was measured with the flat-end micrometer; thus the maximum thickness around the periphery is known, but the precise location is not known (i.e., the point of maximum thickness could conceivably occur just inside the surface). A ratchet-type micrometer was used so that all measurements were made at the same small value of applied load, to prevent indentation of the disc. The measurements plotted in Figs. 12, 13 and 14 are for a series of points along a single diameter. Numerous other measurements were made at diameters every 45° around the circumference; results of averaging these measurements are as follows:

Specimen	Mean Thickness, in., Center Portion	Mean Thickness, in., Periphery
As brazed (unstressed)	0.0046	–
86.2% of fracture stress	0.0051	0.0058
92.5% of fracture stress	0.0051	0.0063
97.5% of fracture stress	0.0053	0.0069

As shown in Fig. 12, the measured joint thickness shows a sudden change where the diameter on which the profile was measured crossed a grain boundary. A similar situation occurs in Figs. 13 and 14. This evidence, particularly that of Fig. 12, indicates highly non-uniform deformation from one grain to another, at least in the case where the entire joint consists of parts of only two or three grains. External profile measurements by interference fringe methods made by Bushnell[10], display extreme non-uniformity around the periphery of the joint.

<u>COMPARISON OF OPTICAL JOINT THICKNESS MEASUREMENTS WITH MICROMETER MEASUREMENTS</u> Although reference marks were made around the periphery of the specimen with dry-marking inks so that thickness measurements were always made at the same point, the pronounced distortion occurring after yielding of the steel made optical measurements increasingly more difficult. One might expect that micrometer measurements would tend to be on the low side for two reasons: (a) presumably some small amount of silver is removed during the

week or so that the joint is immersed in acid for removing the steel base stock, and (b) some brinelling must exist when thickness measurements are made with the 1/16" ball-end micrometer. Nonetheless, optical measurements were invariably less than micrometer measurements, as shown in the following table:

Specimen	Thickness at Outer Surface	
	Thickness, in., optical	Thickness, in., Micrometer
As brazed (unstressed)	0.0042	0.0046
86.2% of fracture stress	0.0053	0.0058
92.5% of fracture stress	0.0057	0.0063
97.5% of fracture stress	0.0062	0.0069

Sections of several broken joints were examined and it was found that in cases where the base stock had plastically deformed, the silver disc was indeed thicker just inside the surface of the specimen than at the surface, as shown in Fig. 15. It is on this evidence that the joint contours shown in Figs. 12, 13 and 14 indicate a maximum thickness just inside the specimen surface.

RADIOGRAPHS OF JOINTS Radiographs were made of the three stressed discs and the as-brazed scrap shown in Fig. 11; in this figure a discolored ring, concentric with the perimeter of the discs, can be seen. A similar ring developed on fracture surfaces stored in a dessicator, and thus apparently is not due to the etching process. Prints of the four radiographs are shown in Fig. 16 ; grain boundaries are clearly visible in the radiographs, and show that the joints in the tensile specimen are comprised of parts of only two or three grains, as is also apparent in the fractured specimen shown in Fig. 11. Similarly, some of the grain boundaries visible in Fig. 11 on the unstressed control sample can be seen in the microradiograph of this same piece shown in Fig. 16. Remarkably, the pronounced "orange peel" surface found on the stressed samples after removal from the steel base stock, apparently has registered on the microradiographs. The grain boundaries which show in the microradiographs correlated exactly with the grain boundaries brought out by etching of the discs to remove the "orange peel" surface; examination of opposite faces of the disc showed that the grain boundaries were perpendicular to the plane of the joint. Holes are evidenced in the microradiographs of the stressed discs, but certainly not in sufficient number or size to account for even one percent overall apparent volume increase. It will be noted that the elongated holes appear to have a preferred orientation within each grain. The microradiograph of the unstressed blank exhibits what appears to be a dendritic pattern, but such a pattern is absent in the stressed discs. The light region at the circumference of the discs (i.e., darger region on the negatives) is thought to be due in part to the fact that the x-ray path through the disc at the periphery is shorter than elsewhere because of the meniscus. The extent of the meniscus formed is shown in Fig. 17, which is an oblique view of the edge of one of the discs after having been removed from the steel base stock.

<u>DENSITY DETERMINATIONS</u> Since virtually no holes were observed exposed on the surface of the discs, it appeared that density measurements would provide a quantitative measure of the porosity contained within the disc. However, no great expectations were held that any significant differences would be detected in view of the relatively small amount of holes observed in the radiographs. Density determinations are very difficult on specimens of this size and geometry; i.e. small mass and enormous surface-area-to-volume ratios; none-

theless, arrangements were made to have these determinations made with equipment designed and used for precise density determinations on semi-conductor materials [11]. The results of these determinations are as follows:

Specimen	Density, grams/cc	
	2 mil Wire	0.6 mil Wire
As brazed (unstressed)	10.418	10.404
86.2% of fracture stress	10.474	10.484
92.5% of fracture stress	10.491	10.485
97.5% of fracture stress	10.546	10.481

These data point out the difficulty of such measurements; the diameter of the suspension wire used exerted a small, but noticeable effect on the results. However, it is evident that no significant density changes have occurred, and all of the measured values are lower than the tabulated value of 10.54 g/cc by less than one percent.

FRACTURE SURFACE OBSERVATIONS Small dark streaks were noted on the fracture surface of silver joints while examining them under a binocular microscope; these were at first dismissed as cracks, but the fact that within a single large grain they appear to have a preferred orientation similar to the preferred orientation of the elongated voids discovered in the radiographs, led to a closer examination. The appearance of these markings at low magnification is shown in Fig. 18. It was observed that these dark streaks are almost invariably associated with plugs of silver which have been pulled out. An example of a plug of silver on one fracture surface, and the hole from which it had pulled out of the other surface is shown in Fig. 19; the same region shown in Fig. 19 can be located on the area shown in Fig. 18. At higher magnification, the dark streaks appeared to be quite flat, and so were examined at still higher magnification. It was discovered that they are, in fact, very smooth facets showing evidence of the "river markings" characteristic of brittle fracture; it was never possible to locate both halves of the flat fracture surface for the curious reason that the plugs invariably seemed to be slightly larger than the holes from which they were pulled and the exposed surface of the pulled-out plug was always quite severely distorted. Photos of matching regions from both halves of a fractured joint are shown in Fig. 20; the bottom of the hole shows a flat facet with evidence of "river markings", but the surface of the pulled-out plug is severely distorted and little trace of a flat facet is to be seen. Once having found these flat fracture surfaces at the bottom of holes, an intense hunt for further examples was initiated. Surprisingly (in view of the fact that they had gone unnoticed for a long time), such facets were easy to locate; many previously tested joints were reexamined and the same type of facets found on them. Although many could be found, it was not easy to photograph them at the high magnification necessary because they lay at the bottom of holes. Nonetheless, some prime examples have been recorded and two are shown in Fig. 21; the "river markings" are clearly delineated on these facets, and there is no doubt whatever that they are cleavage facets. However, it is not established that they are cleavage facets in silver; they occur at various depths and thus are not cleavage fracture in the bulk steel or at the steel-silver interface, but it is not known if they are in some second phase within the silver. Silver intrusions well beyond the interface have been found for silver joints in steel, and it is possible that these occur by the leaching out of some low melting non-metallic phase which may become segregated in the joint. The preferred orientation of these facets within a single grain has, associated with it, another puzzling aspect: the facets are invariably much longer than they are wide, and the "river markings" are almost invariably transverse to the length (see Fig. 21). An attempt was made to generate larger fracture facets by increasing constraint beyond that encountered in the silver joints in mild steel. A group of four specimens were made consisting of silver joints in 1075 steel; joint thickness was about 0.004" and the strength of the four joints lay in the range 82,000 to 84,000 psi, in contrast with the 58,700 psi failure strength of the specimens in mild steel. The same type of fracture facets were found on all four specimens; there were many more of them, but unfortunately they were smaller than in the case of the mild steel base stock. They did show the same preferred orientation within an individual grain as was observed in the case of the joints in mild steel.

DISCUSSION AND CONCLUSIONS

The stresses which exist on a volume element of filler metal in a thin brazed joint subjected to tension consist of a tensile stress in the direction of the applied load and transverse tensions in the radial and circumferential directions. The transverse stresses are generated because the harder, stronger base stock prevents the softer and weaker filler metal disc from contracting radially as much as it would tend to in the absence of constraint. There are several factors which produce differential contraction and generate this constraint. Different values of Young's modulus lead to differential contraction of base metal and filler metal at all values of applied stress, and additional constraint may be generated at higher stress levels due to differences in Yield Point or Yield Strength. Silver joints in steel hold together at stresses far in excess of the Yield Point of low carbon steel, and it would seem that the property which is of paramount importance in generating constraint is a difference in the current yield stress of the silver and the steel.

The local axial stress distribution in the brazed joint is similar (though of opposite sign) to the pressure distribution generated in the compression of a slab of metal between platens where sticking occurs. It is known, in the case of the compression of a cylindrical slab, that the mean pressure at yielding is determined by slab geometry, i.e., the thickness-to-diameter ratio of the slab [12]. In an analogous manner, the strength of silver-brazed joints in cylindrical steel specimens has been demonstrated empirically to be a function of thickness-to-diameter ratio [7]. The solution for the compression of a cylindrical slab in reference (12) indicates a <u>mean</u> pressure at yielding which is about nine times the unconstrained yield strength for a thickness to diameter ratio of 0.04. For a diameter to thickness ratio of 25, the <u>peak</u> stress of the friction hill would be crudely some twenty times the unconstrained yield strength if a continuously rising friction hill is assumed. In the case of brazed joints, the diameter-to-thickness ratio is typically 500 to 5000 rather than 25, and peak stresses of the order 250 to 2500 times the unconstrained yield strength and mean stresses of the order of 100 to 1000 times the unconstrained yield strength would be expected. Stresses of this magnitude cannot occur and in the case of 1020 steel, severe deformation of both base stock and filler metal is observed at stresses below the ultimate tensile strength of the base stock. The indication is that the friction hill does not continue to rise in the classic manner, but must reach a plateau at some short distance in from the periphery. A comparison of a very thin brazed joint with a large D/t ratio and ultimate strength very close to that of the base stock with a second specimen of the same joint thickness but twice the diameter, shows the tensile strength of both specimens identical for all practical purposes. The second specimen should exhibit a mean stress about twice that of the first specimen, if the classic friction hill obtained; however, the existence of a plateau in the local axial stress distribution, extending over most of the joint area, would indicate a mean stress of essentially the same magnitude for the two specimens.

The presence of a stress distribution having a plateau over most of the joint area is consistent with the deformations observed in this investigation. If such a stress distribution actually exists, one can infer that an essentially uniform hydrostatic component of stress exists over all but a thin annular ring around the periphery of the joint. The presence of an essentially uniform hydrostatic component over most of the area of the joint also could serve to explain the appearance of holes over most of the area of the lead joints and the fact that the strength of the lead joints of small t/D ratio were essentially independent of specimen geometry. Hill[13] shows that the stress required to expand a spherical cavity in an infinite medium from zero radius is of the order of three to four times the unconstrained yield strength. In the case of lead, which does not work harden at room temperature, it would appear that the constraint which can be generated in the joint is limited to that value at which micro-defects (such as minute oxide particles or tiny gas holes) will expand; because the deformed metal does not work harden, the expansion of the holes continues until they nearly impinge on each other and the narrow bridges of metal separating the cavities are no longer constrained from necking and extend to failure. In the case of silver, which does work-harden, the required stress for expansion of a spherical cavity is larger. The higher yield strength of silver, as compared with lead, and the larger multiple of yield strength required to expand a hole, means that the applied stress can become large enough to cause serious plastic deformation of the base stock without opening holes in the silver. The stress required to expand a cavity is a multiple of the <u>current yield strength</u> and not of the initial yield strength; thus, the more easily a metal work hardens, the more difficult it becomes to generate holes in the joint. A means of checking on this point would consist of testing lead joints at sub-zero temperatures to see if bubble formation is inhibited or eliminated at temperatures at which the lead exhibits increasing yield strength with increasing strain; conversely, one could test silver joints at elevated temperatures to see if bubble formation is observed in the silver joints at temperatures at which the silver does not work-harden; such a program is currently under way.

It has been found that the originally plane interfaces between the silver and the steel do not remain plane over the entire joint. A large central region, comprising most of the area of the joint, does remain essentially plane, but increases in thickness as the applied load is increased. At the same time, an annular region around the periphery of the joint becomes considerably thicker than the rest of the joint, and a pronounced meniscus is formed. The reduction of area of the steel base stock, plus the generation of the meniscus, provides the reservoir of material from which the joint increases in thickness. It has also been found that some voids are formed in the silver discs at stresses somewhat below the eventual fracture stress of the specimen. These voids, as indicated in microradiographs, are elongated and have a preferred orientation within an individual grain; it is suspected that the X-ray indications are of voids which originated in small patches of brittle fracture and opened up by plastic deformation, rather than of voids which nucleated and grew entirely by plastic deformation. Patches of brittle fracture have been found on the surface of broken silver joints (Figs. 20 and 21), and micrographs of sections through broken silver joints often show flat-bottomed holes which are thought to be sections across these fracture facets (Fig.8). As previously mentioned, it is not established that these fracture facets are fractures of silver; it is known that they are not fractures at the steel-silver interface, and the micrographs of Fig. 8 confirm this, if the flat-bottomed holes are, in fact, sections through the fracture facets.

The generation of a fracture facet within the silver joint would tend to relax the hydrostatic component of stre, at that point, but if the stress distribution consists of a more or less flat plateau over most of the joint area, the loss of load carrying ability of the joint should be approximately proportional to the projected area of the fracture facets. The evidence is that although the facets are numerous, their projected area is only an extremely tiny fraction of the total area of the joint. If the joint is thin, the distance between such facets is ample for the generation of hydrostatic stresses; the data of Leach and Edelson[1] was obtained on brazed joints in strip stock only 0.031 inches in thickness, and yet in that short distance enough constraint could be generated to result in stresses several times the unconstrained strength of the filler metal. In consideration of the presently available information it appears reasonable to assume that the local stress distribution starts increasing from the outer periphery after the fashion of the classic friction hill, but after a distance of four to five times the joint thickness, has stopped increasing and remains essentially uniform over most of the joint and begins dropping off again as the opposite exposed face is approached. Such a stress distribution is almost a necessity in the case of the very thin strip specimens because an impossibly high peak stress would be required if the classic friction hill obtained over the entire joint.

For the case of compression of aluminum discs, local stress distributions of the kind postulated here have been experimentally detected by Van Rooyen and Backofen [14]; pressure sensitive pins embedded in the platens were used for sensing normal and shear stresses at the platen-disc interface, and dome-shaped normal pressure curves have been determined for discs with a diameter-to-thickness ratio as small as 4. This is not too surprising since the complete friction hill is developed only if the disc is plastic but the platens are not; for compression of large diameter, thin discs, both disc and platen remain elastic and for the tensile specimen, both are plastic. For the latter two cases, the complete friction hill is not obtained.

Preliminary results of a mathematical analysis of the normal stress distribution in the brazed joint indicates that the local stress increases from the periphery toward the center but quickly reaches a level which remains constant over most of the joint area[10]. While this analysis is for the elastic case, and presumably does not represent conditions just prior to joint failure when large plastic strains exist in both the braze material and the base stock, it is interesting that the joint deformation predicted by the analysis is of the same kind as actually observed in fractured joints where the base stock has deformed considerably. Perhaps this is due to the fact that although large strains have occurred, the geometry of the disc of braze material has not changed appreciably and it is still essentially a thin disc with a very large ratio of diameter to thickness.

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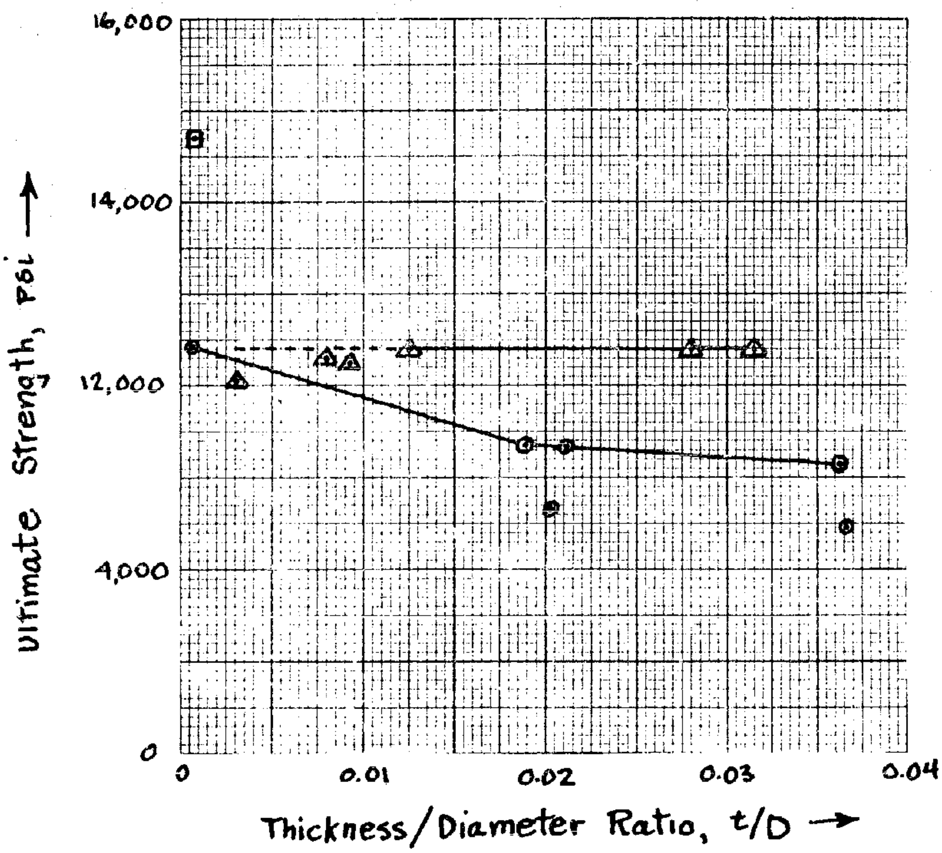
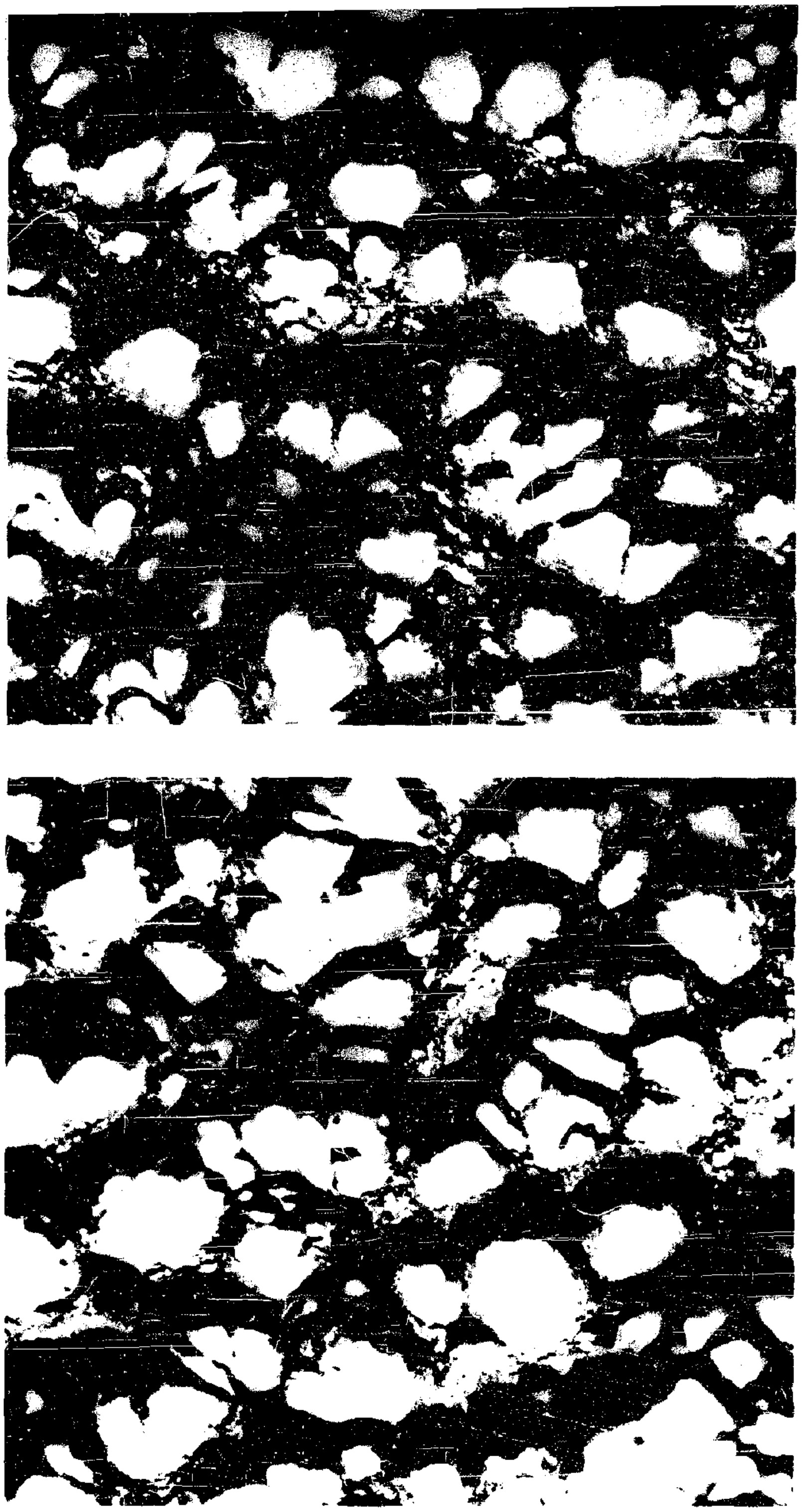


Figure 1. Strength of Lead Joints in Steel, Copper and Molybdenum

(Legend: ⊡ Lead Joint in Molybdenum
⊙ Lead Joints in Steel
△ Lead joints in Copper)



Direction of Illumination

Figure 2. Matching Fracture Surfaces of a Lead Joint in Steel, showing Cavity Development which leads to Failure. Cavities may be best seen by viewing the Figure obliquely against the arrows indicating the direction of illumination. (X 75)

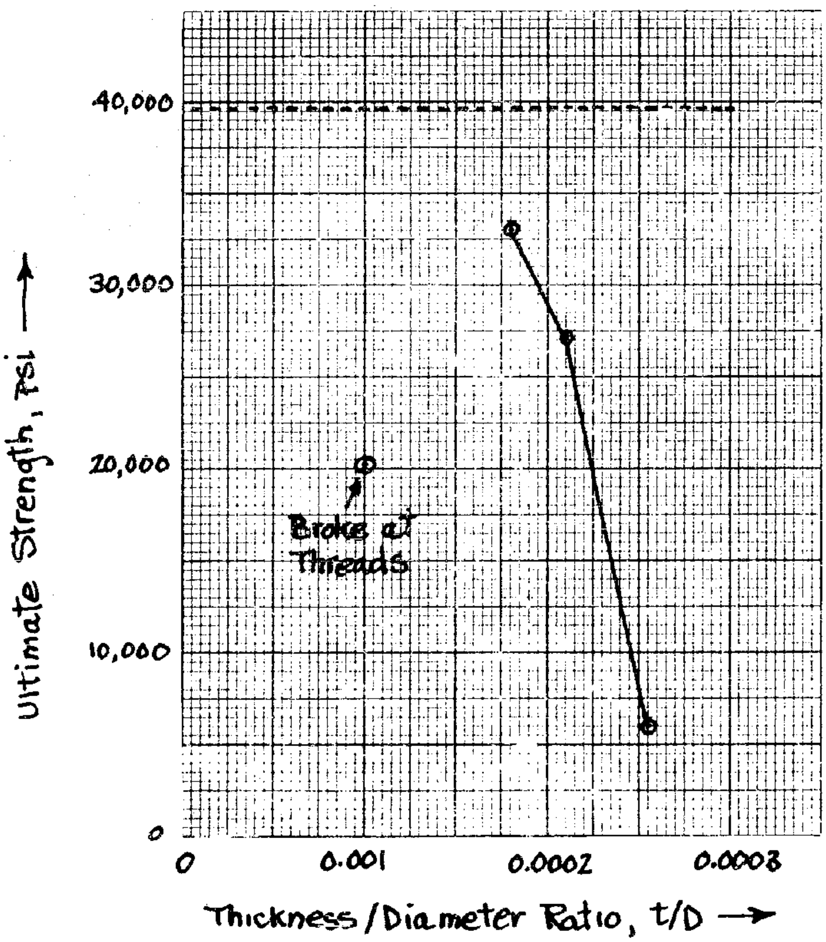


Figure 3. Strength of Tin Joints in Molybdenum: Joint Thickness = 0.0004"

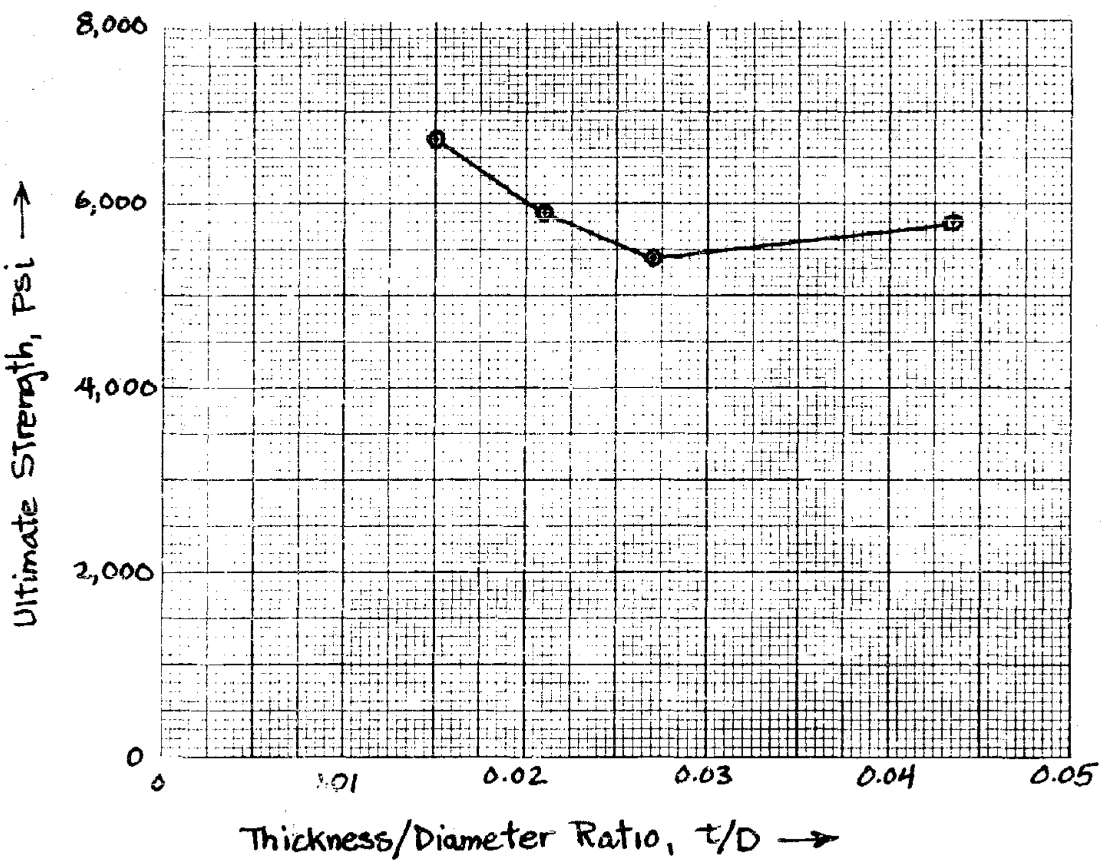


Figure 4. Strength of Bismuth Joints in Copper; Joint Thickness = 0.007"

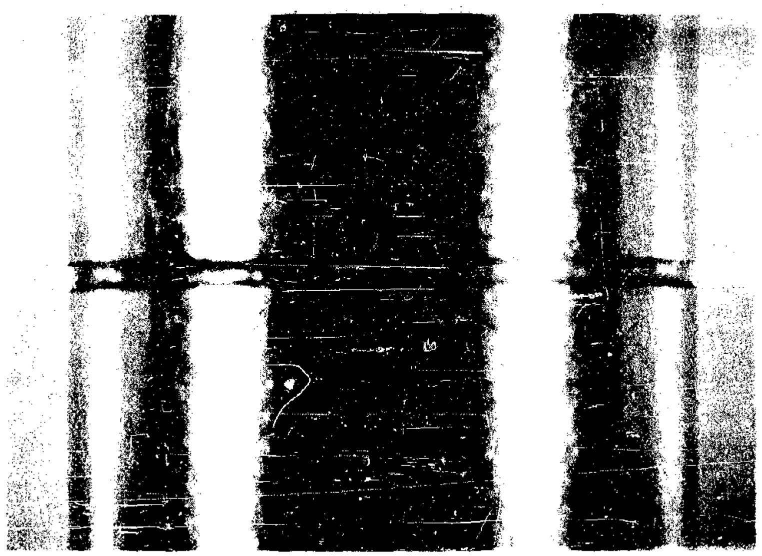


Figure 5. Meniscus Formed in Silver Joint in Steel, under Stress of 47,000 psi. Note that the Deformed Silver on the Left Hand Side is Straight near Joint Center whereas Contour is Essentially Semi-Circular on Right Hand Side.

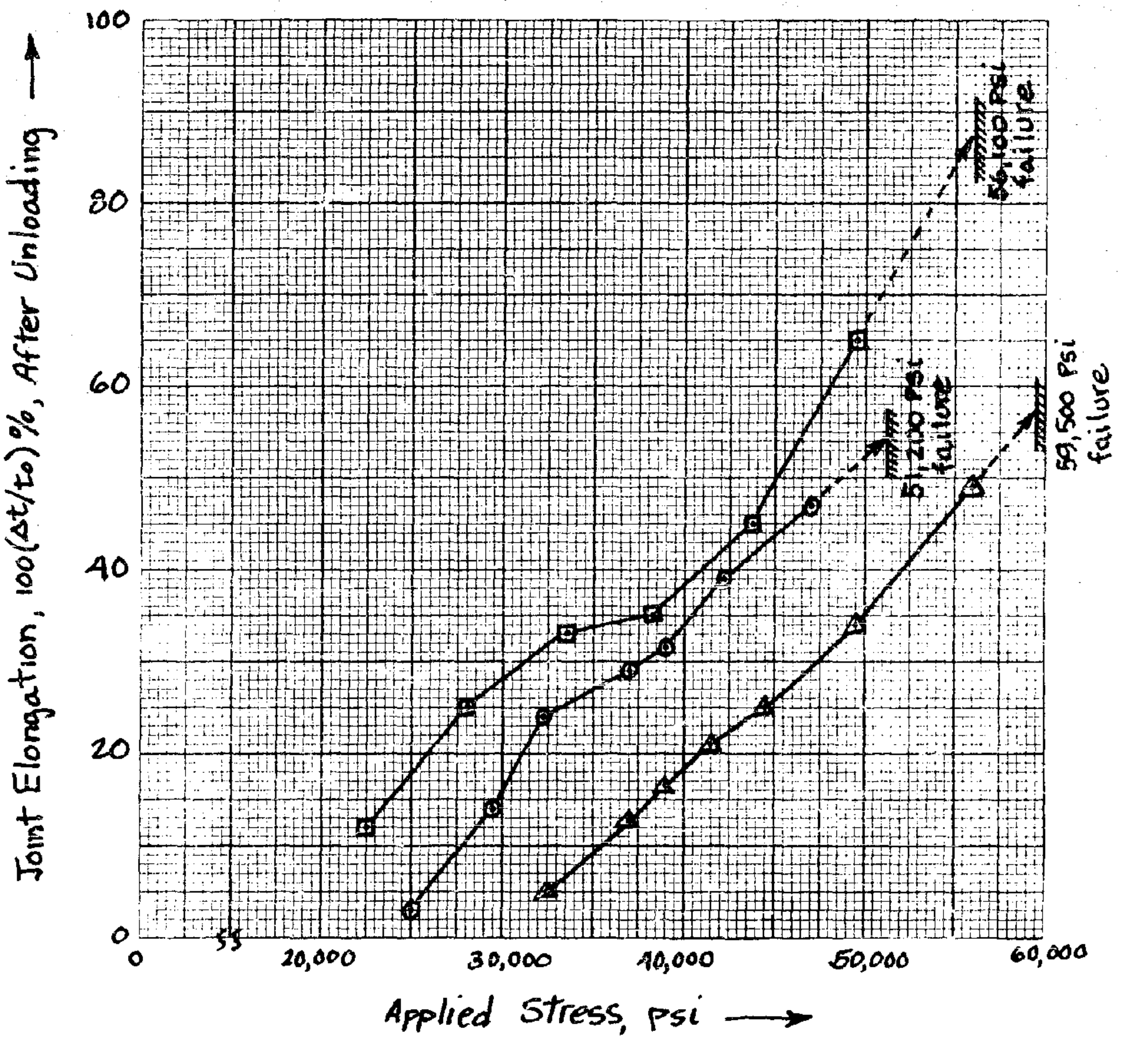


Figure 6. Mean Joint Elongation, $100(\Delta t/t_o)\%$, in Unloaded State, as a Function of Maximum Applied Stress Prior to Unloading; Cylindrical Silver Joints in Steel.

(Legend:

⊡ t_o = 0.0142" ; t/D = 0.0280

⊙ t_o = 0.0162" ; t/D = 0.0322

△ t_o = 0.0047" ; t/D = 0.0094)

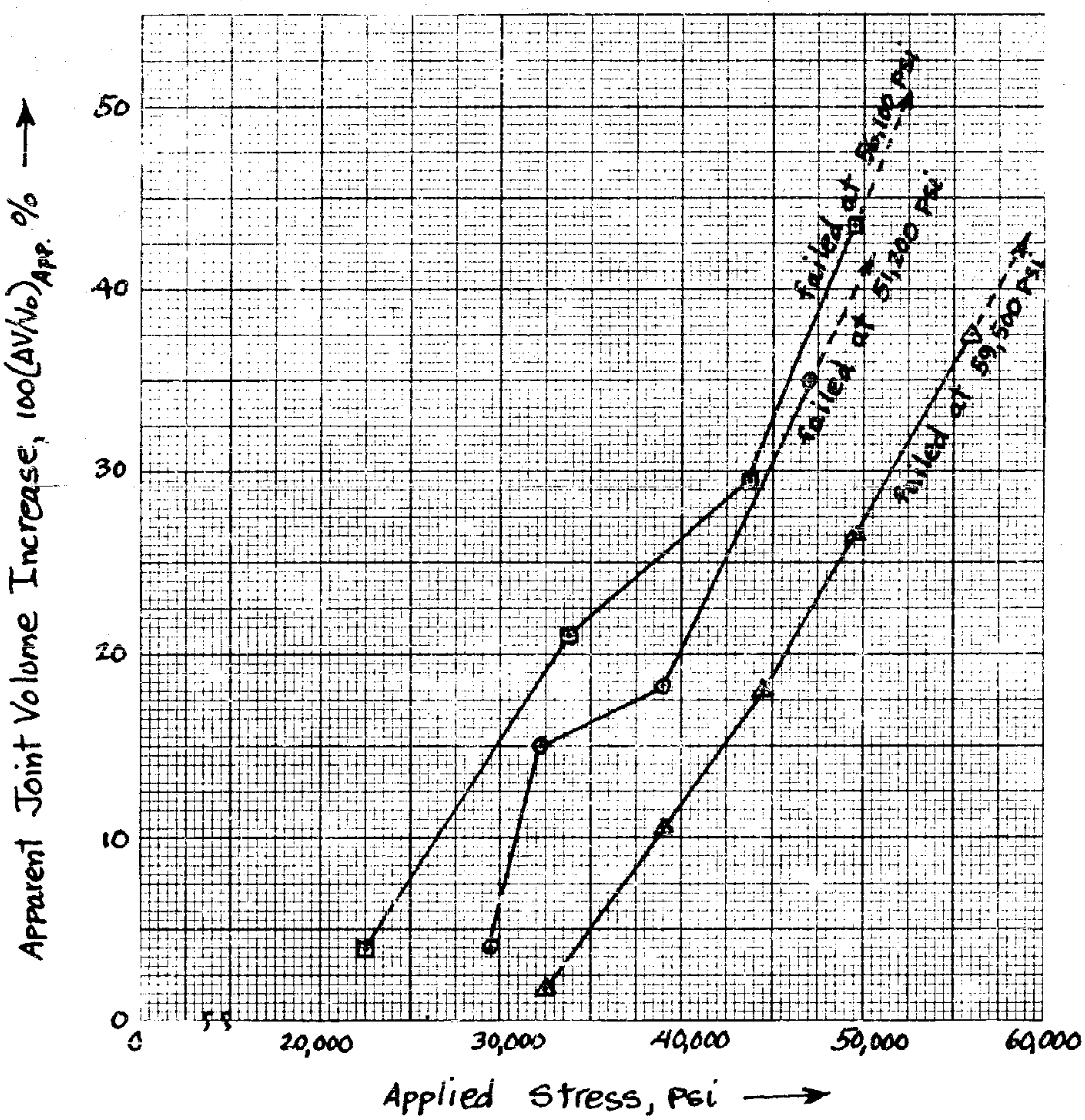


Figure 7. Apparent Joint Volume Increase, $100(\Delta V/V_o)_{App.}$%, in Unloaded State, as a Function of Maximum Applied Stress Prior to Unloading; Cylindrical Joints in Steel.

(Legend:

⊡ t_o = 0.0142" ; t/D = 0.0280

⊙ t_o = 0.0162" ; t/D = 0.0322

△ t_o = 0.0047" ; t/D = 0.0094)

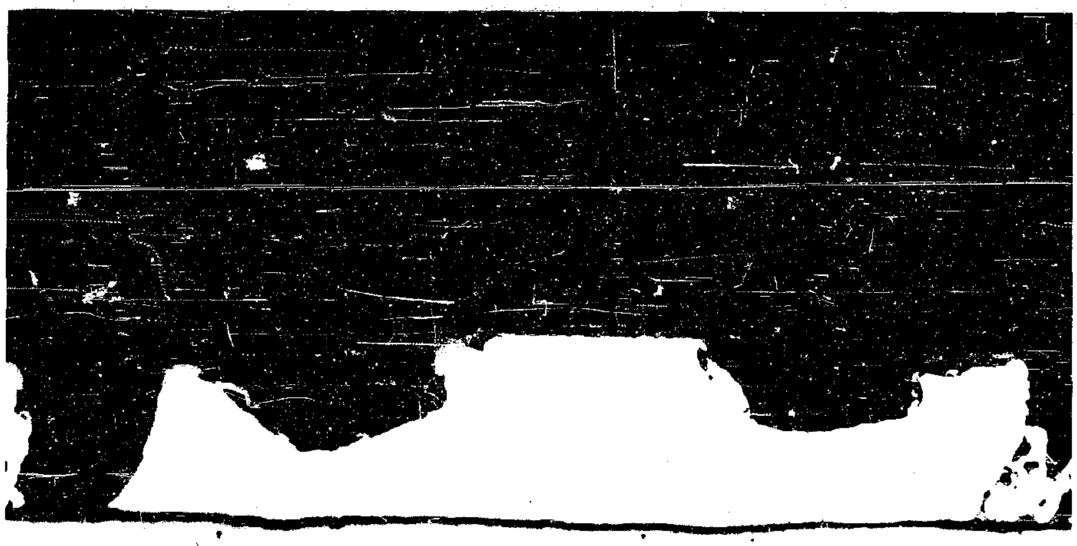


Figure 8. Cross Section of Fractured Joint (Silver in Mild Steel Base Stock) Showing Flat Bottomed Pits in Silver. Initial Joint Thickness: 0.005" (X 200)

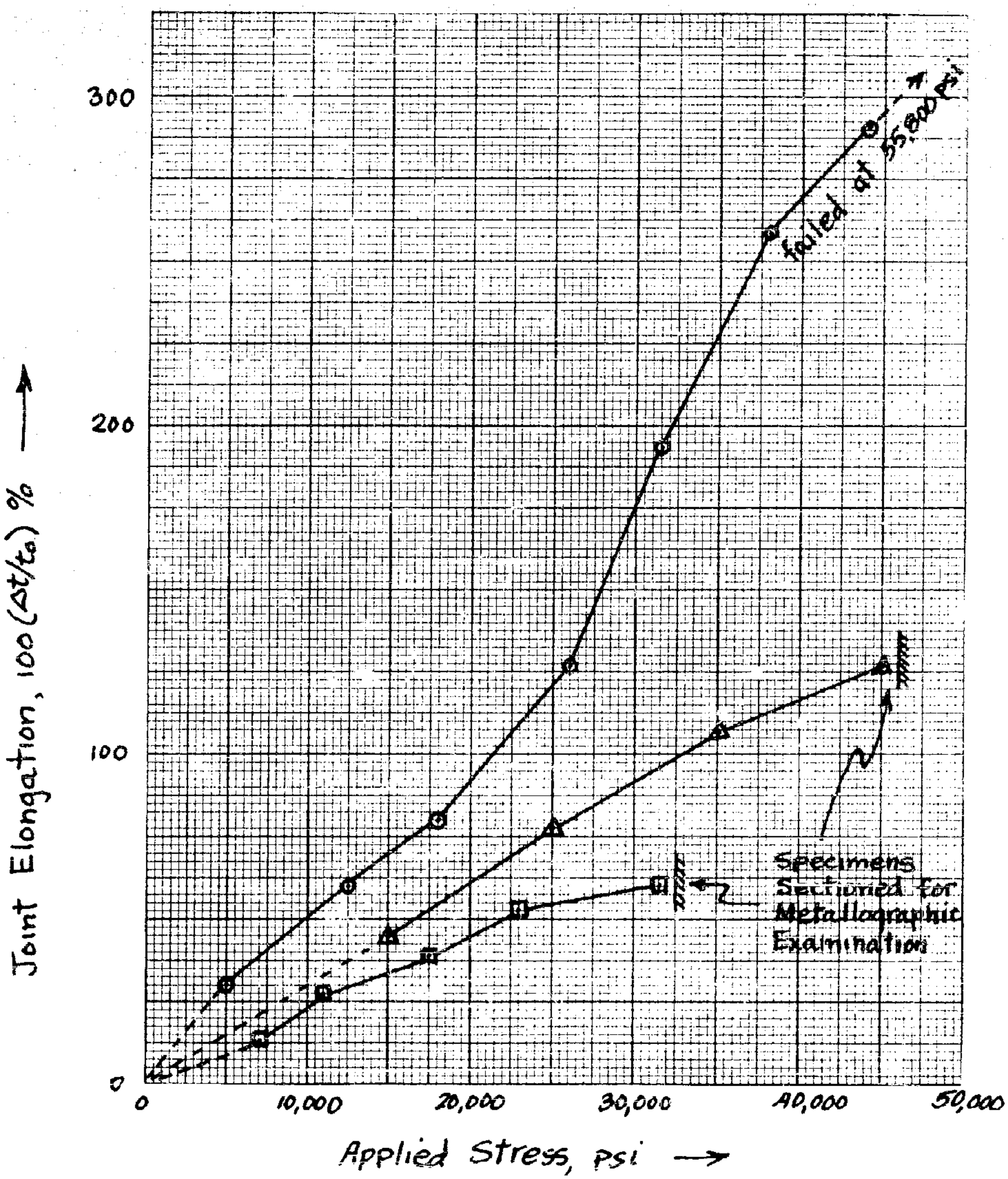


Figure 9. Mean Joint Elongation, $100(\Delta t/t_o)\%$, in Unloaded State, as a Function of Maximum Applied Stress Prior to Unloading; Rectangular Silver Joints in Steel, 0.125" x 0.500" Cross Section.

(Legend:

⊙ t_o = 0.0012"
△ t_o = 0.0140"
⊡ t_o = 0.0130"

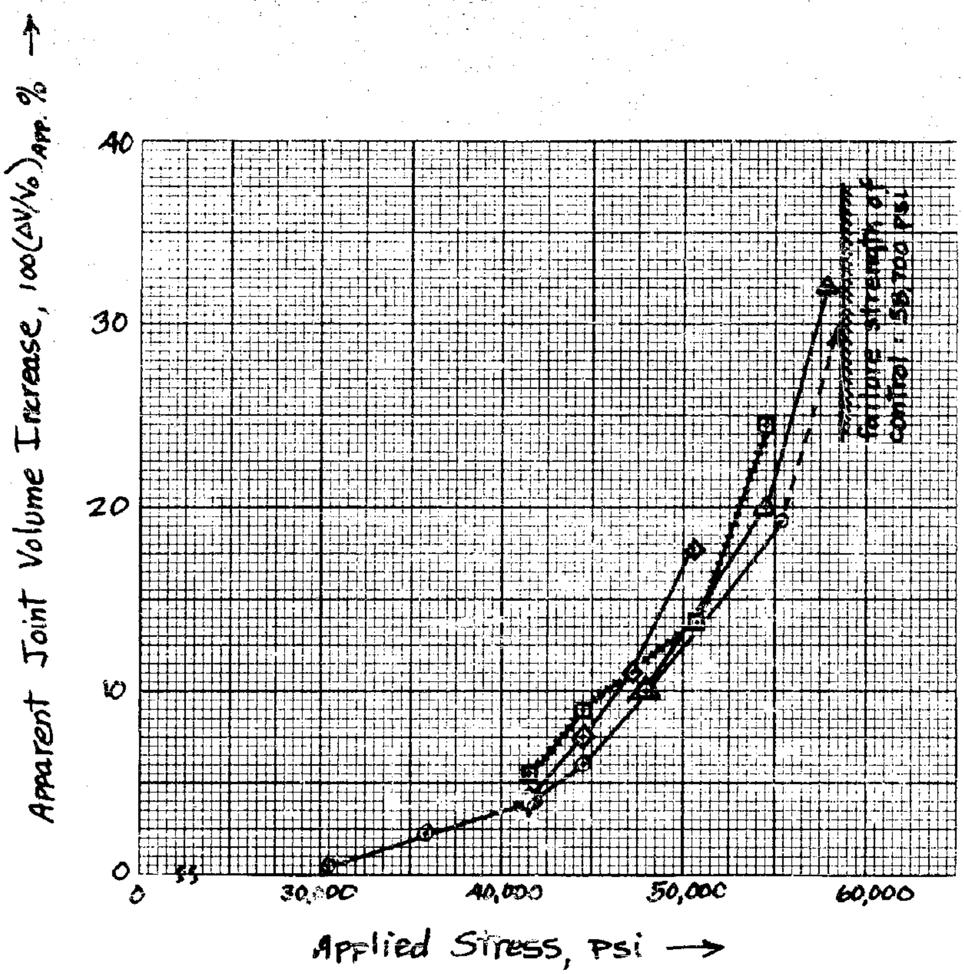


Figure 10. Apparent Joint Volume Increase, $100(\Delta V/V_o)_{App.}$%, in Unloaded State, as a Function of Maximum Applied Stress Prior to Unloading; Cylindrical Joints in Steel; Four specimens removed from Same Large Block; One Specimen Tested to Failure to Obtain Control Value for Failure Strength and Remaining Three Specimens Loaded to Various Fractions of Control Strength and Joints then Removed for Profile Measurements.

(Legend: ⊙ Specimen tested to failure at 58,700 psi
△ Specimen stressed to 57,200 psi
⊡ Specimen stressed to 54,300 psi
◇ Specimen stressed to 50,600 psi)

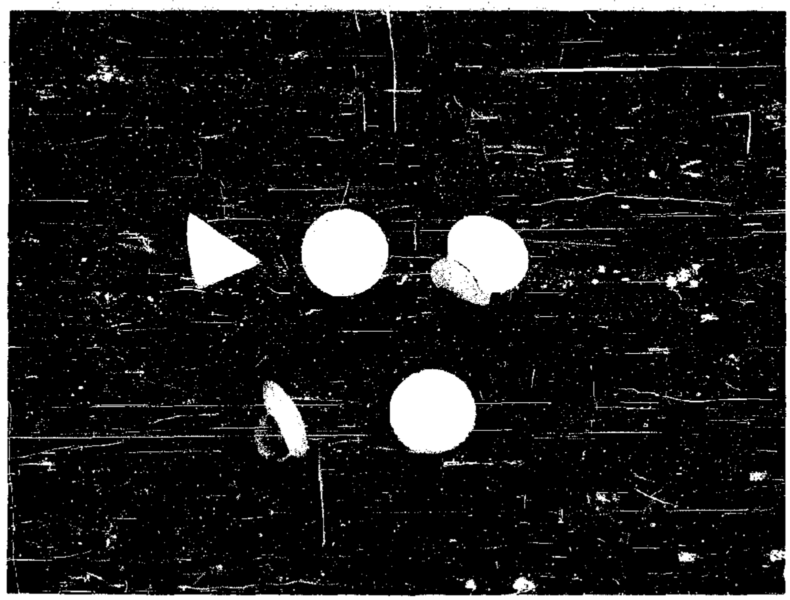


Figure 11. Silver Discs Removed from Stressed Tension Specimens.

(Top Left - control sample of joint removed from scrap remaining from as-brazed block; unstressed.

Top Center, Top Right, Bottom Left - three discs removed from stressed tension specimens.

Bottom Right- fracture surface of control specimen; note portions of only three grains over entire surface.)

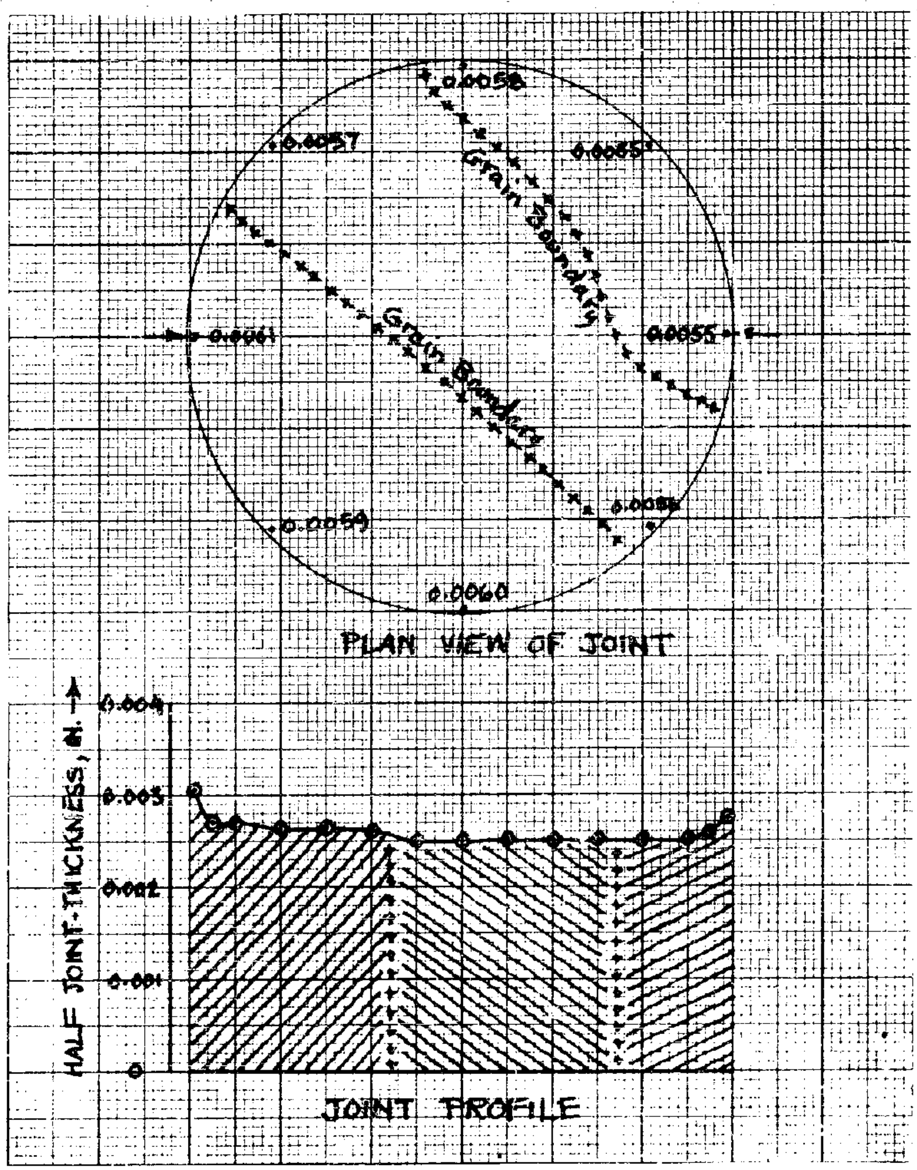


Figure 12. Profile of Silver Disc Stressed to 86.2% of Failure Stress of Control Sample; Original Joint Thickness: 0.0046". Profile was Measured Along Diameter Indicated by Arrows in Plan View of Joint; Plan View Shows Thickness Measurements Around Periphery of Joint.

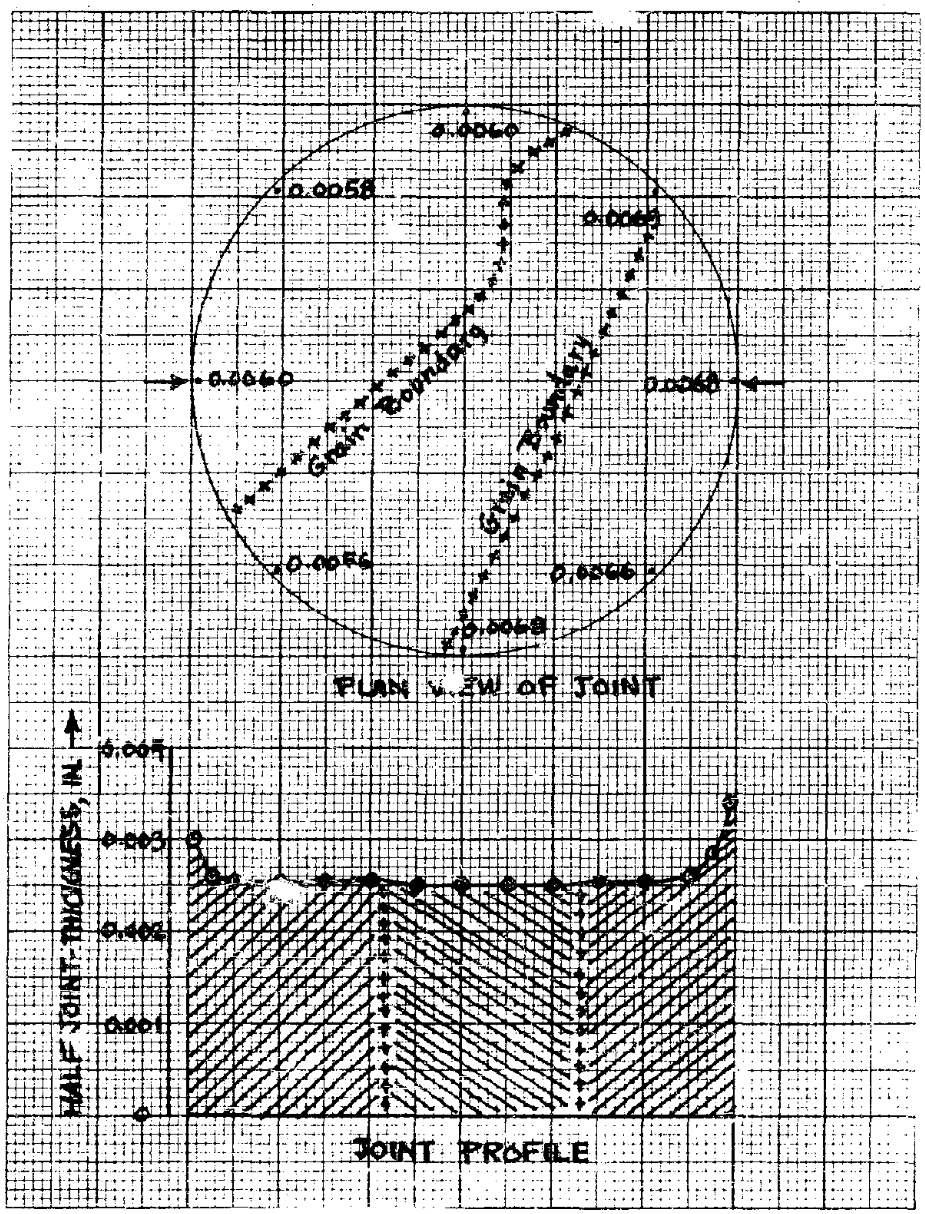


Figure 13. Profile of Silver Disc Stressed to 92.5% of Failure Stress of Control Sample; Original Joint Thickness: 0.0046". Profile was Measured Along Diameter Indicated by Arrows in Plan View of Joint; Plan View Shows Thickness Measurements Around Periphery of Joint.

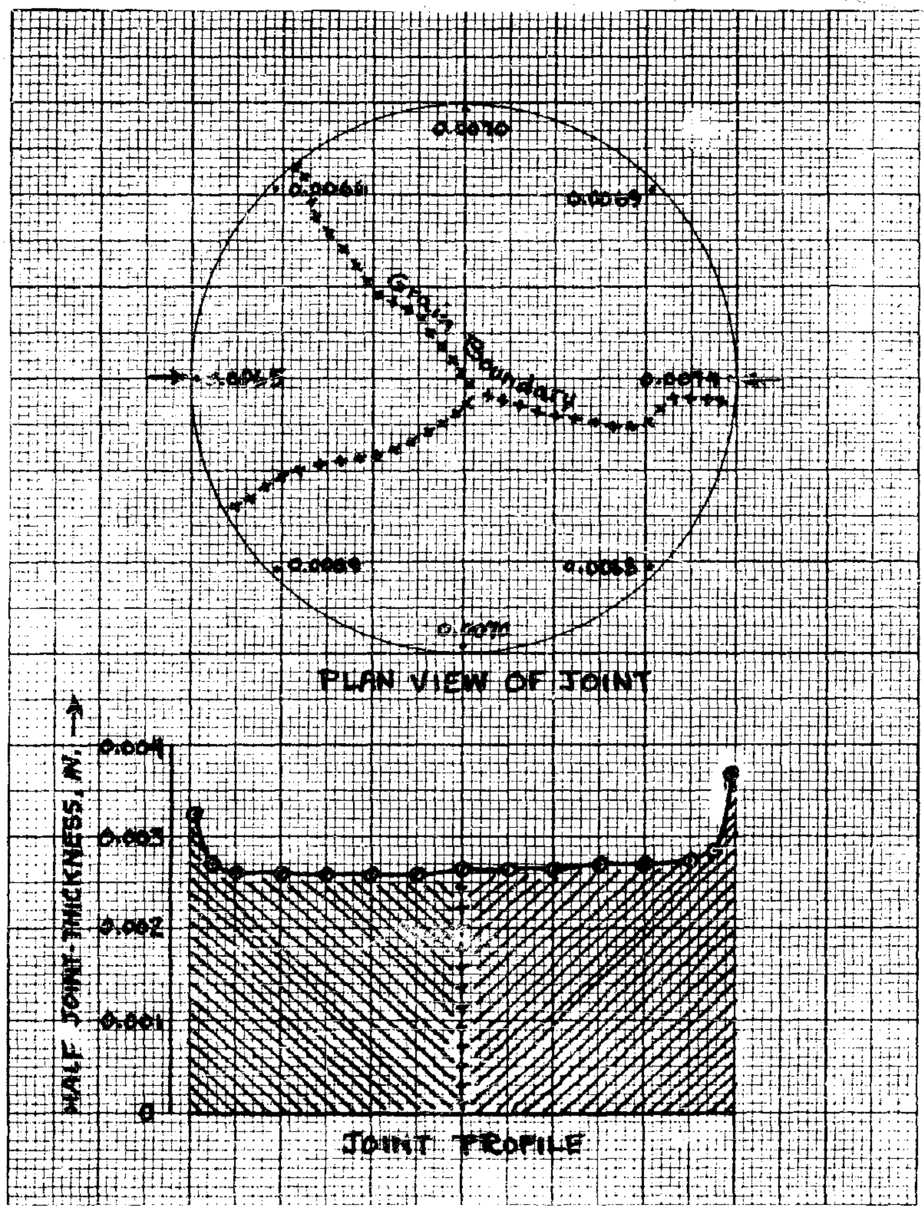


Figure 14. Profile of Silver Disc Stressed to 97.5% of Failure Stress of Control Sample; Original Joint Thickness: 0.0046". Profile was Measured Along Diameter Indicated by Arrows in Plan View of Joint; Plan View Shows Thickness Measurements Around Periphery of Joint.

Figure 15. Localized Deformation of Steel Base Stock at Periphery of Specimen, Illustrating Reason for Optical Joint Thickness Measurements Being Smaller than Micrometer Measurements on Discs Removed from Base Stock. (200 X)

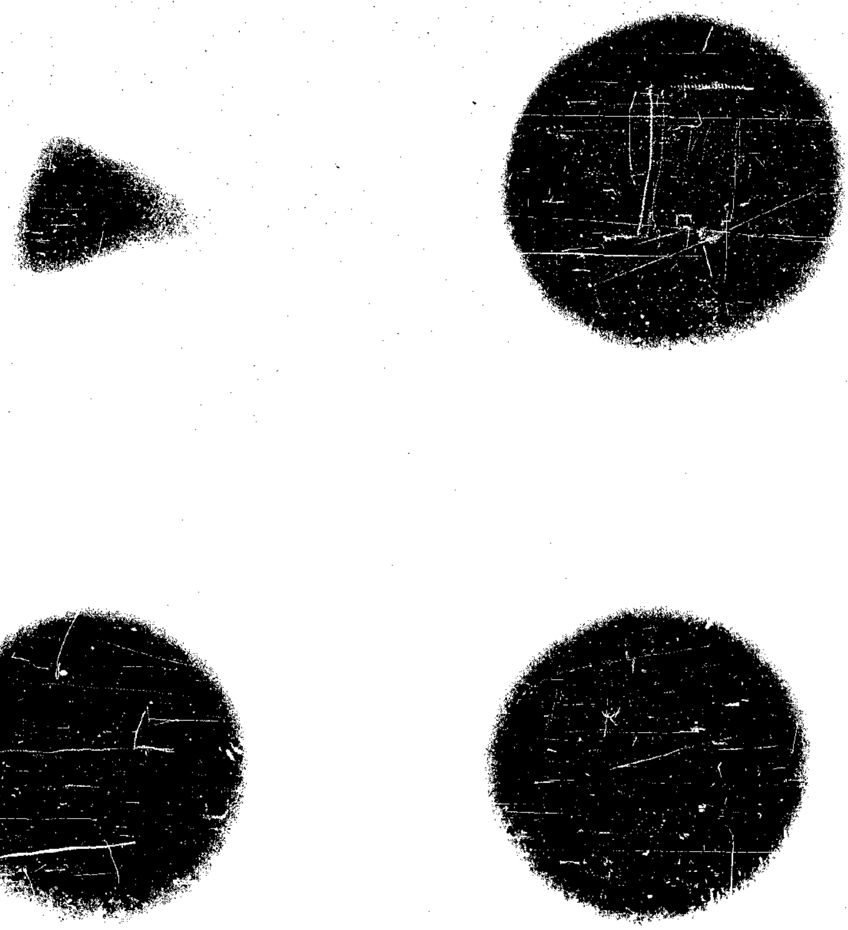


Figure 16. Prints from Microradiographs of As-Brazed Joint and Three Joints Stressed Part Way to Failure (4X)

(Upper Left - As-Brazed Joint, Unstressed
Upper Right - Joint Stressed to 86.2% of Failure Stress
Lower Left - Joint Stressed to 92.5% of Failure Stress
Lower Right - Joint Stressed to 97.5% of Failure Stress)

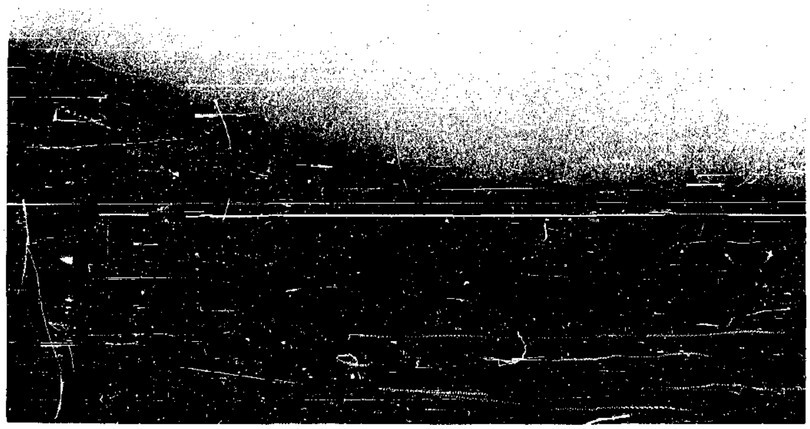


Figure 17. Oblique View of Portion of Periphery of Stressed Silver Disc after Removal of Base Stock; Note Pronounced Meniscus.

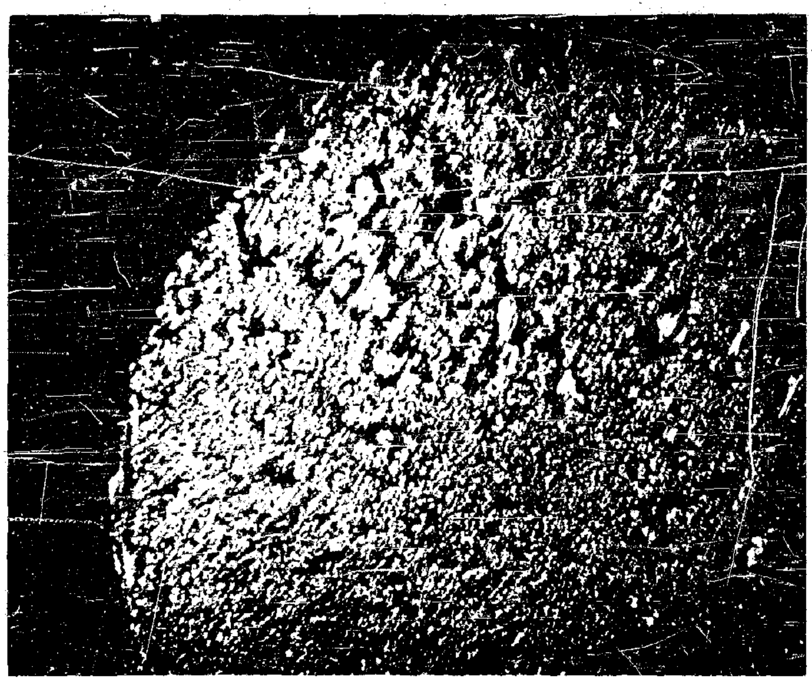


Figure 18. Fracture Surface of Silver Joint in Steel (10X); Note Dark Streaks, Parallel to Each Other, at Upper Center of Photo.

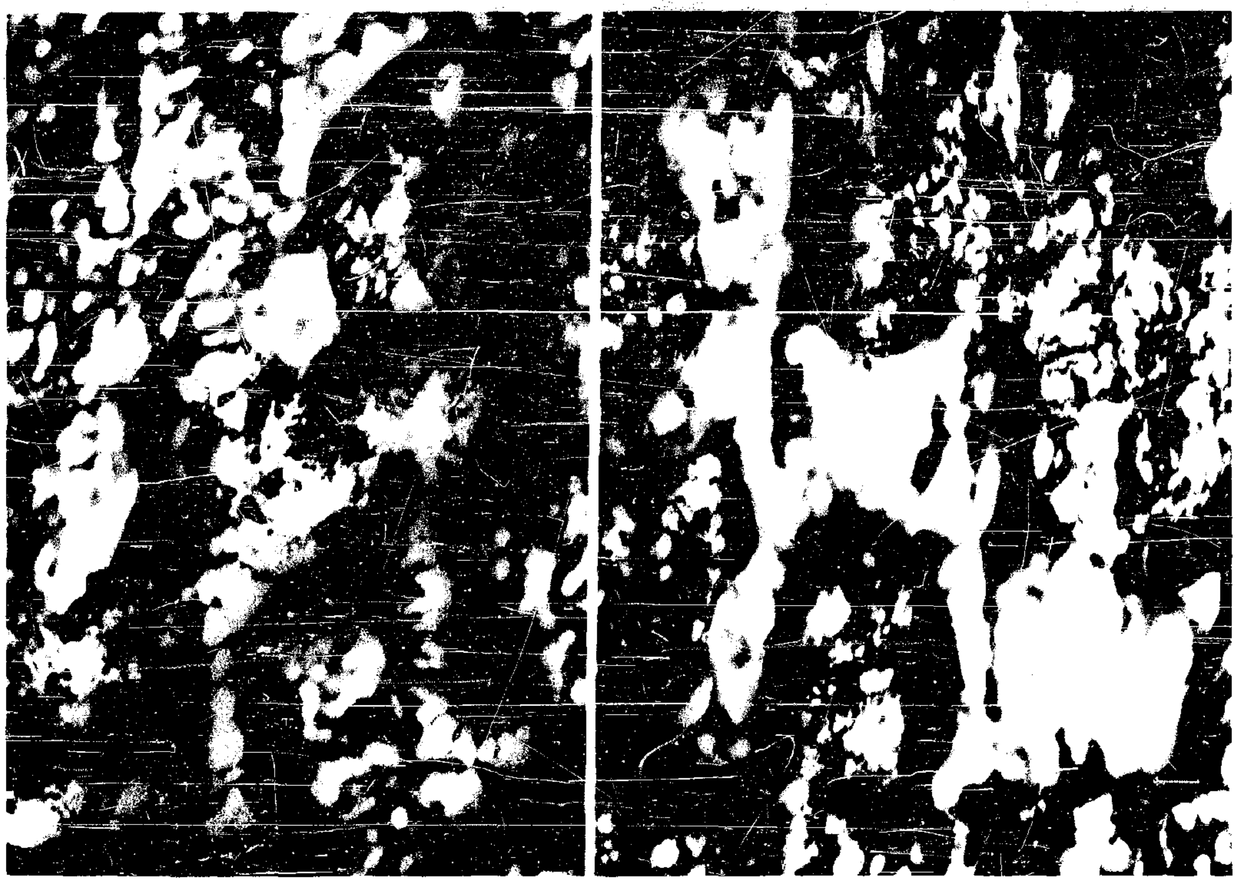


Figure 19. Matching Regions from Both Halves of Fracture of Silver Joint in Steel (X50)

Left Photo: Focussed at Top Surface of Plug of Silver Pulled out of Opposite Face.

Right Photo: Hole from which Plug has been Pulled; Focussed to show Hole Outline.

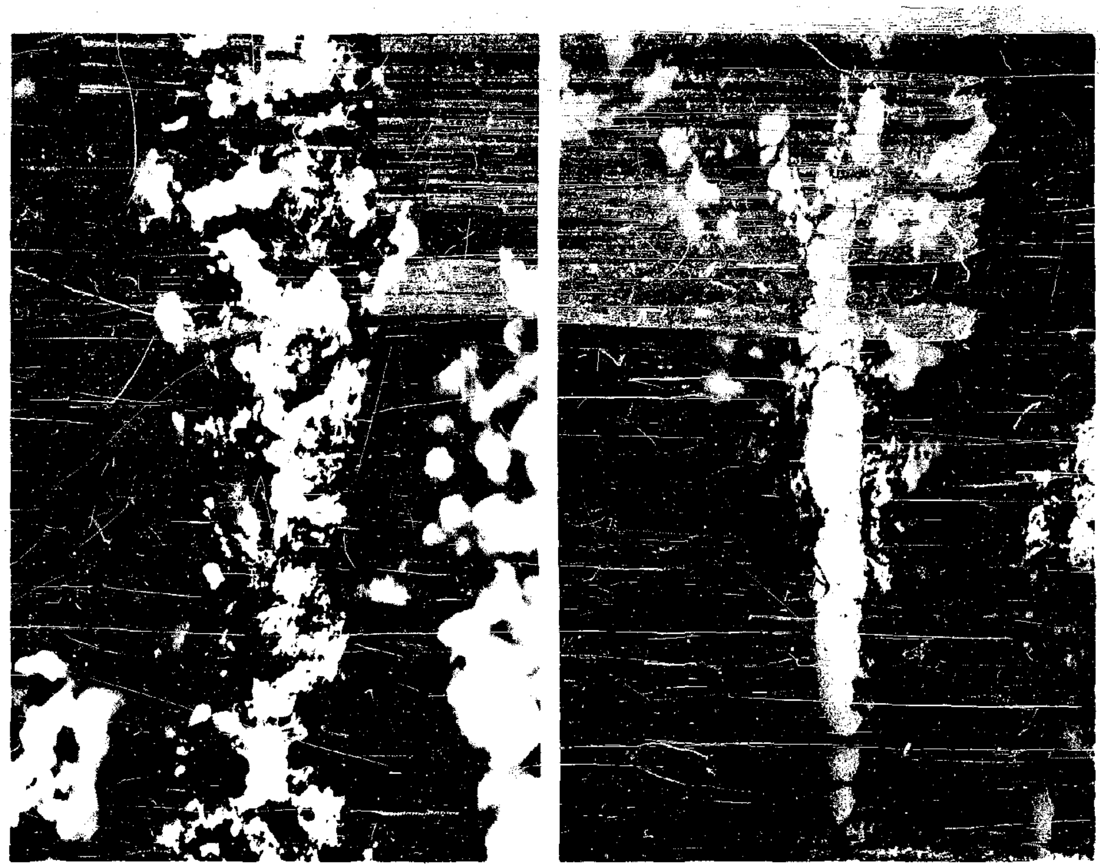


Figure 20. Matching Regions from Both Sides of Fracture of Silver Joint in Steel (X200)

Right Photo: Fracture facet at bottom of hole; note evidence of "river markings."

Left Photo: Highly distorted surface of plug pulled from hole; note that only fragmentary traces of fracture facet remain.

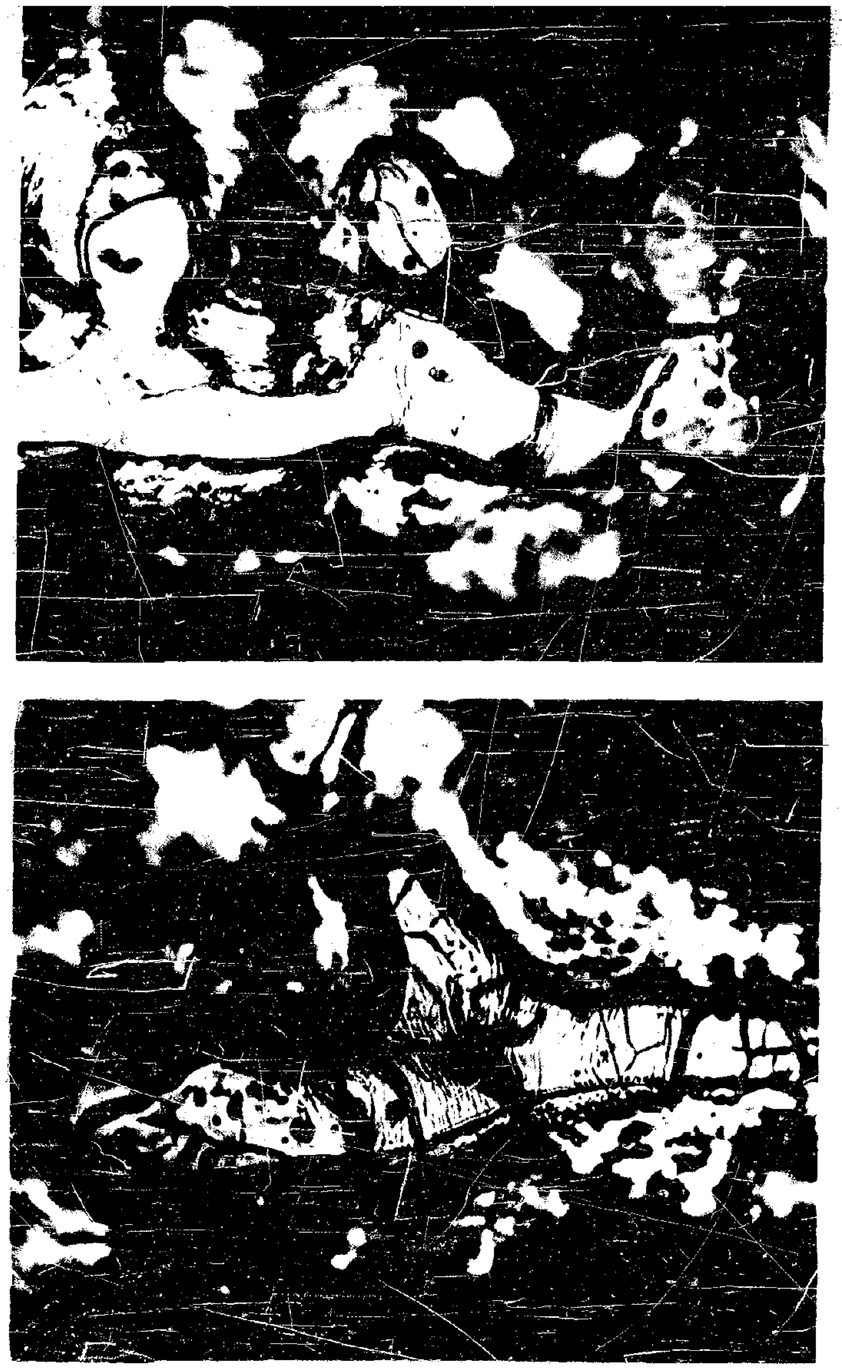


Figure 21. Two Examples of Fracture Facets Found at Bottom of Holes from which Plugs had Pulled out During Fracture of Silver Joint in Steel (both X400). Note Clearly Defined "River Markings" Indicative of Cleavage.

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