NORTON RESEARCH CORPORATION
70 Memorial Drive
Cambridge, Massachusetts 02142

NRC Project No. 5116-1-1168

SUMMARY REPORT
Contract NASw-1168

A STUDY OF THE ADHESION AND COHESION OF METALS

March 10, 1967 to March 10 1968

by

M J Hordon and M A Wright

Approved by: Norman Beecher
Assistant Director
of Research

Reviewed by: Frank J. Salomone
Contracts Manager

Submitted to:
Headquarters
National Aeronautics and Space Administration
Washington, D C

ATTENTION: Mr. J. Maltz
OART, NASA
Code RRM

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August 1968

Prepared under Contract No. NASw-1168
NORTON RESEARCH CORPORATION
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This Final Summary Report covers the work performed by Norton Research Corporation for the Office of Advanced Research and Technology, National Aeronautics and Space Administration under Contract No NASw-1168, Modification No 4 for the period 10 March 1967 to 10 March 1968

The program is a continuation of a series of investigations on the phenomenon of the adhesion or cohesion of solid metals begun under NASA Contract No NASw-1168, initiated 9 March 1965 Interim Summary reports NASA-CR-76828 and NASA-CR-85864 covering earlier phases of this effort were issued May 1966 and May 1967 respectively

The major contributors to this program were Dr M J Hordon, Program Director and principal investigator, and Dr M A Wright, Senior Metallurgist of the research staff of NRC The program was under the general supervision of Dr N Beecher, Assistant Director of Research for NRC The NASA technical monitor was Mr J Maltz OART, NASA, Code RRM

Some of the results of this program series were published in the technical literature.[1]

A STUDY OF THE ADHESION AND COHESION OF METALS

by M J Hordon and M A Wright

Norton Research Corporation

SUMMARY

Measurements of the interfacial adhesion force produced by the contact under axial loads of copper and nickel surface pairs in high vacuum were related to changes in the electrical resistance across the junction interface and to the plastic strain generated within the specimens In addition, estimates of the extent of the residual bonded zone for welded interfaces were made by metallographic sectioning Under conditions in which contact surfaces were mechanically abraded at vacuum levels below 2 x 10^{-}[illegible] torr to remove adsorbed oxide films, adhesion or tensile rupture forces ranging up to 45 per cent of the bulk maximum tensile load for annealed material were obtained with extensive plastic deformation

The adhesion bond efficiency defined as the ratio of the interfacial bonding force to the bulk maximum tensile load, was found to vary sensitively with plastic strain, measurable bonding forces requiring a minimum level of about 5 x 10^{-}[illegible] in/in residual plastic strain The extent of actual bonded area, determined by metallographic examination of welded surface couples, varied proportionally to the applied compressive load and plastic strain For moderate deforming loads, the bonded area was substantially less than the total available contact area

The junction contact resistance was observed to decrease as W^{-}[illegible] where W was the applied load in the elastic range For axial loads in the plastic range, the electrical resistance became negligible For bonded interfaces, the resistance remained relatively constant with release of compressive load until the asperity contacts were ruptured

INTRODUCTION

The results of previous work carried out at Norton Research Corporation (formerly National Research Corporation) under NASA contracts NASw-734 and NASw-1168 and extensions have indicated many of the general parameters controlling the force of adhesion on a macroscopic scale generated between two compressively bonded materials Detailed information has been obtained concerning the tendency of engineering metals and alloys to adhere under various contact loading conditions, particularly at vacuum levels simulating space environments Information of this nature is of obvious interest in the design of electrical and mechanical devices for space vehicle applications

It has been established that adhesion bonding requires the removal and continued absence of organic and oxide adsorbed films, and that adhesion increases with increasing compressive loading above the yield stress of the metal With proper surface cleaning techniques, including wire abrasion, large adhesion efficiencies (bonding force to compressive yield load ratio) could be observed for ductile metals. Moreover, bonding was found to occur between metals that exhibit little or no mutual solubility

The experimental results of the adhesion experiments described above emphasize that contact bonding may be expected between mating surfaces in the low pressure environment of space provided that sufficient abrasion or deformation occurs to break up the existing oxide layers originally formed in the earth's atmosphere, and that the surfaces flow plastically to broaden the area of contact

At atmospheric pressure, the removal of surface films and the formation of the bond must occur simultaneously since the rate of surface oxidation would be sufficient to insure film reformation with very short exposure times. An exponential retardation in oxide reformation rate occurs at low gas pressures. Thus it is highly likely that a newly formed surface would remain reactive for extended periods of time when surrounded by a typical space environment

For bonding under axial loads, it can be stated that a general description of the adhesion process has been obtained from the experiments performed previously However, the effect of altering many of the normal metallurgical strength controlling factors such as alloy composition, phase distribution, cold work and grain size have only partially been established. Accurate analysis of the results already obtained is limited due to the inherent difficulty in determining the true strength of a pressure bonded joint The force required to separate two materials can be accurately determined using modern strain gage techniques; however precise knowledge of the bonding area is difficult to obtain

In the following report a number of experiments are described which were designed to extend the adhesion data previously obtained The electrical resistance of vacuum formed junctions has been determined which, when combined with metallurgical observations and strain measurements, enables the mean interfacial contour configuration of the contacting asperity areas existing at the interfacial junction to be determined

APPARATUS

The experiments described in this report were carried out on cold welded junctions formed in a vacuum environment The low pressures involved, about 10^{-4} torr were obtained by diffusion pumping a stainless steel vacuum chamber through a liquid nitrogen trap The chamber, shown in Fig 1, was provided with numerous electrical and mechanical inlets and was provided with windows so that the cleaning of the specimen surface by a stainless steel brush could be visually monitored The adhesion apparatus and testing procedures have been described in detail in previous summary reports [2,3]

The wire brush abrasion device consisted of a flattened stainless steel brush which was vibrated through an amplitude of about 3/8 in at 25 c/sec by means of a motor and eccentric cam drive mounted outside the vacuum system The vibration shaft was mounted to a flexible bellows seal so that the brush could be swivelled over the test surfaces and withdrawn

With this design, the motor drive was removed from the vacuum chamber and gas leakage from sealed motor assemblies as well as limitations to the thermal outgassing temperature were avoided

The test specimens were machined from solid bar stock and exhibited a geometry as shown in Fig 2 The flat sides were machined to a dimension large enough to permit the mounting of the strain gages used to measure the total strain generated within a specimen The ceramic adhesive used to bond the gages was unaffected by the outgassing temperatures used in the vacuum tests to remove adsorbed impurities from the vacuum chamber walls

The compression apparatus which was mounted inside the vacuum chamber was designed to allow the application of axial loads to specimens while they were maintained at the required environmental pressure The basic design has been described previously [1]

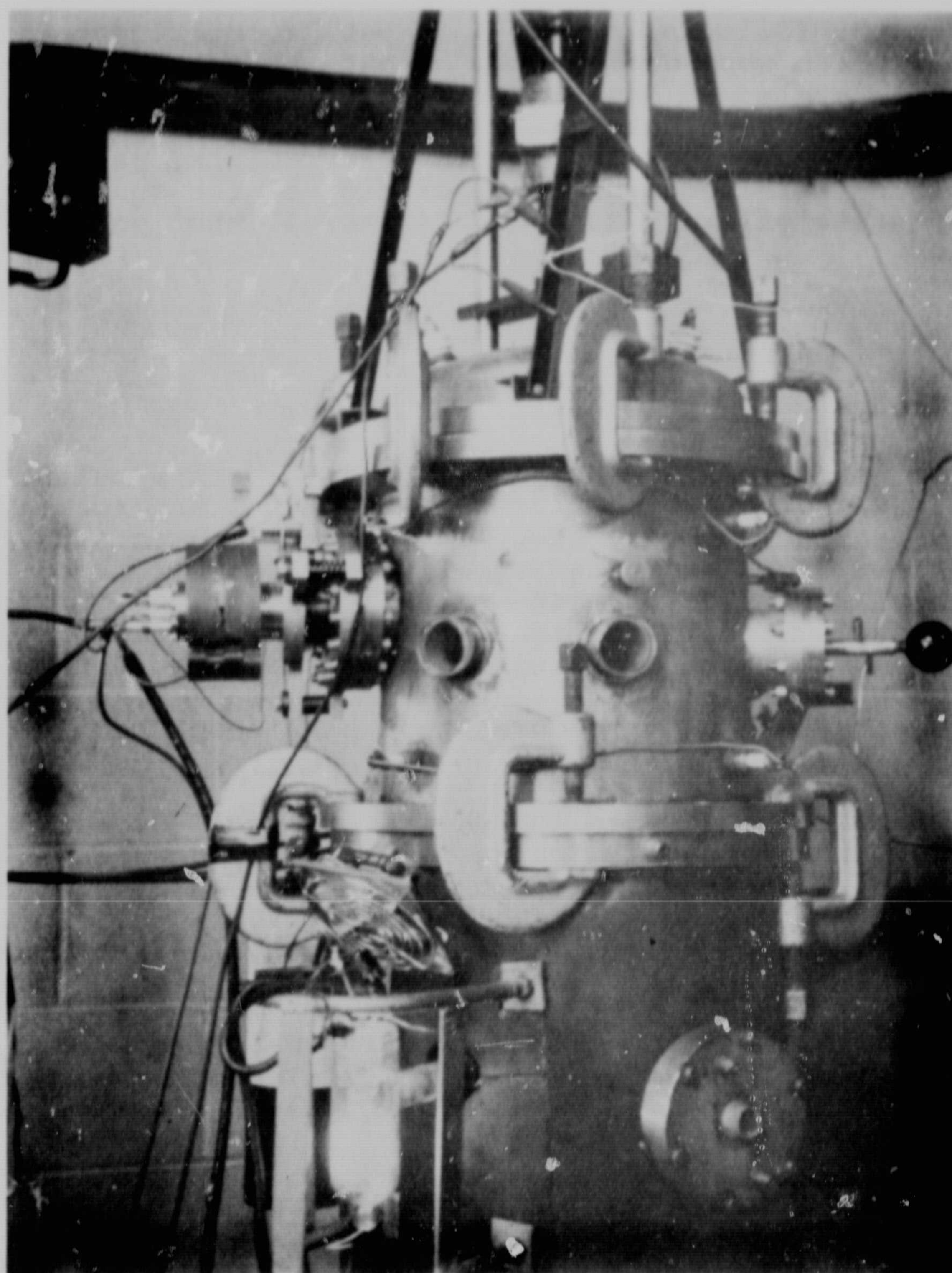

Fig. 1

Adhesion Testing Apparatus

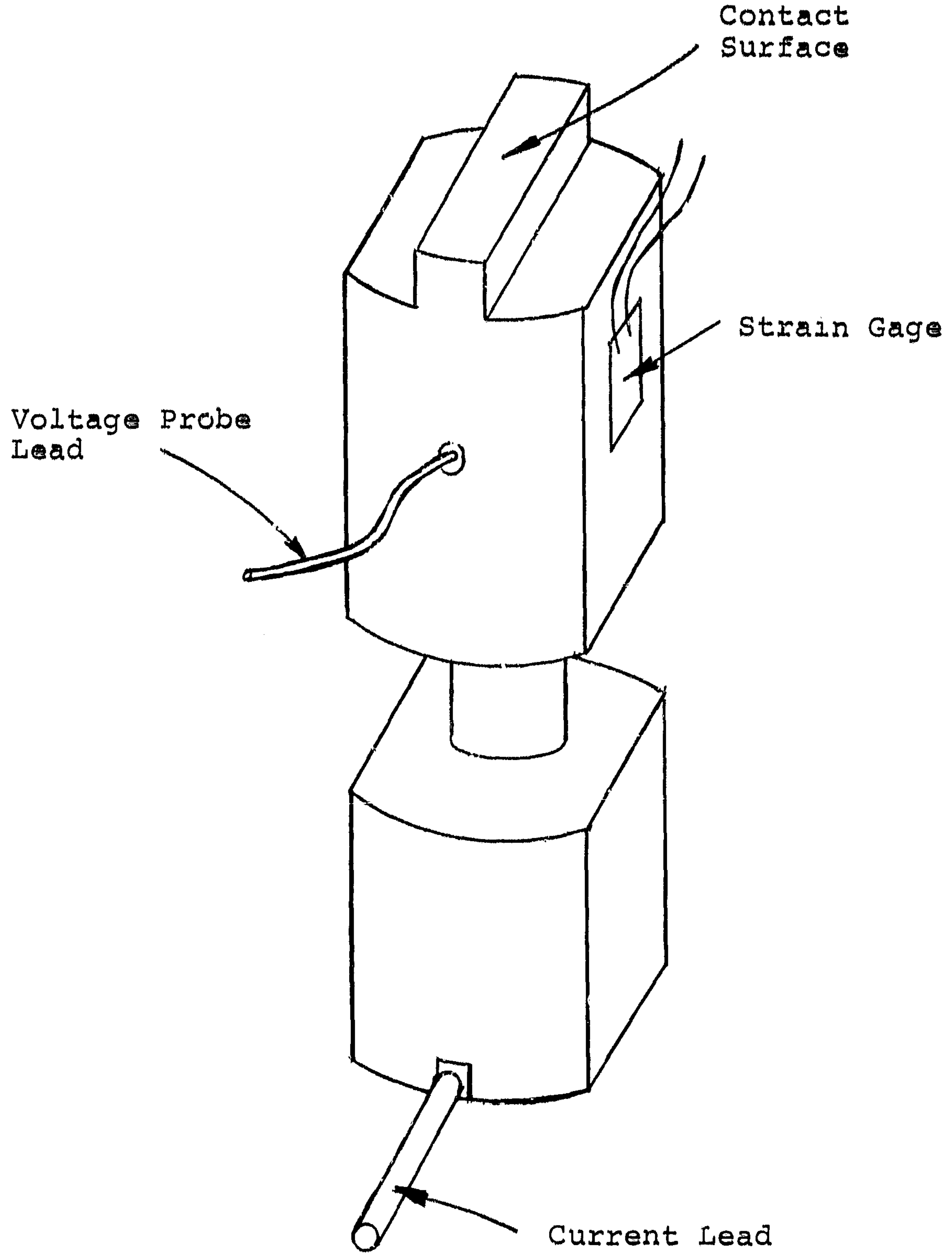

Fig. 2

Illustration of Adhesion Test Specimen

The load was generated by a mechanical ball screw mechanism positioned externally to the vacuum apparatus. The loading shaft passed through the upper flange cover of the chamber and was connected to the upper stainless steel specimen holder through a flexible bellows seal. Each specimen was held in each holder by cover plates rigidly bolted to the holder base. The lower gripping assembly was attached to a massive stainless steel deflection ring. As shown in Fig. 3, the specimen gripping assembly was rigidly fastened to the compression cage suspended from the upper flange cover. The elastically deflecting precalibrated proving ring with 2500 lb capacity permitted the determination of the interfacial load to within ± 1 lb by means of four calibrated resistance strain gages mounted on the ring sides. Force losses in the loading column due to friction and associated effects generated in any contacting seals were therefore avoided. The ceramic foil bonded strain gages were identical to those bonded to the specimen sides and could be used under high vacuum conditions at temperatures to 400°C.

The upper and lower gripping seats for the specimens were provided with mica insulation sheets to electrically insulate the specimen from the compression apparatus. The specimen couples could be removed from the cage in the welded condition by removing the retaining cover plates and sliding the specimens out of the grip slots.

Precise vertical alignment of the specimen surfaces was necessary to ensure accurate bonded area determinations. Thus the compression cage loading assembly was provided with three stainless steel spring-mounted rods, shown in Fig. 4, positioned 120° from each other. Anchored in the compression cage support, the rods maintained axiality of the loading column in compression and tensile deflection.

To measure the electrical junction contact resistance after a specimen pair had been brought into contact, a D.C. current was passed through the mating surfaces by applying a potential to the leads welded into the base of each specimen. The voltage drop across the weldment was measured by a nanovoltmeter with $\pm 1 \times 10^{-9}$ volt resolution sensing through probes placed near to the junction interface.

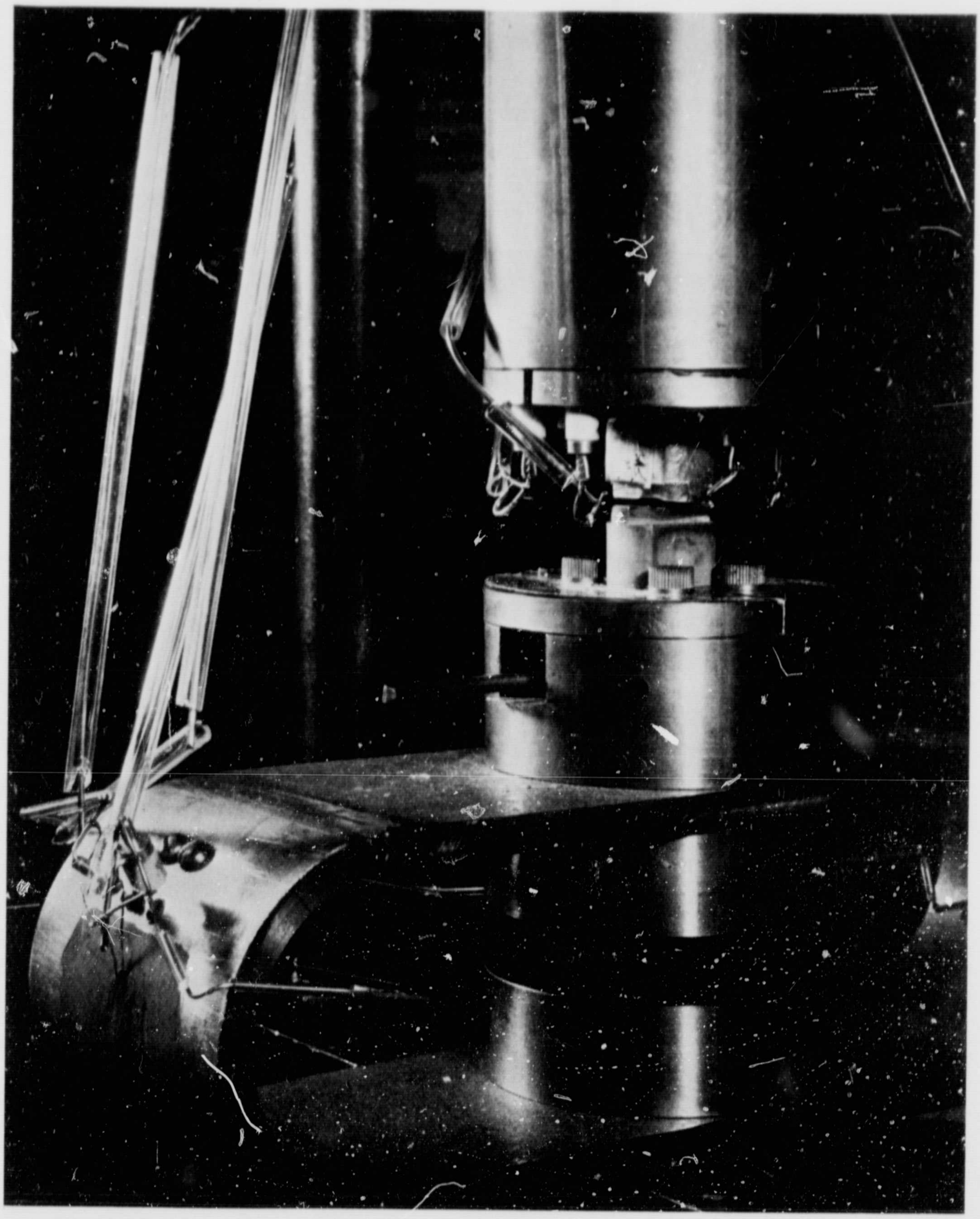

Fig. 3

View of Adhesion Test Specimens and Grip Assembly

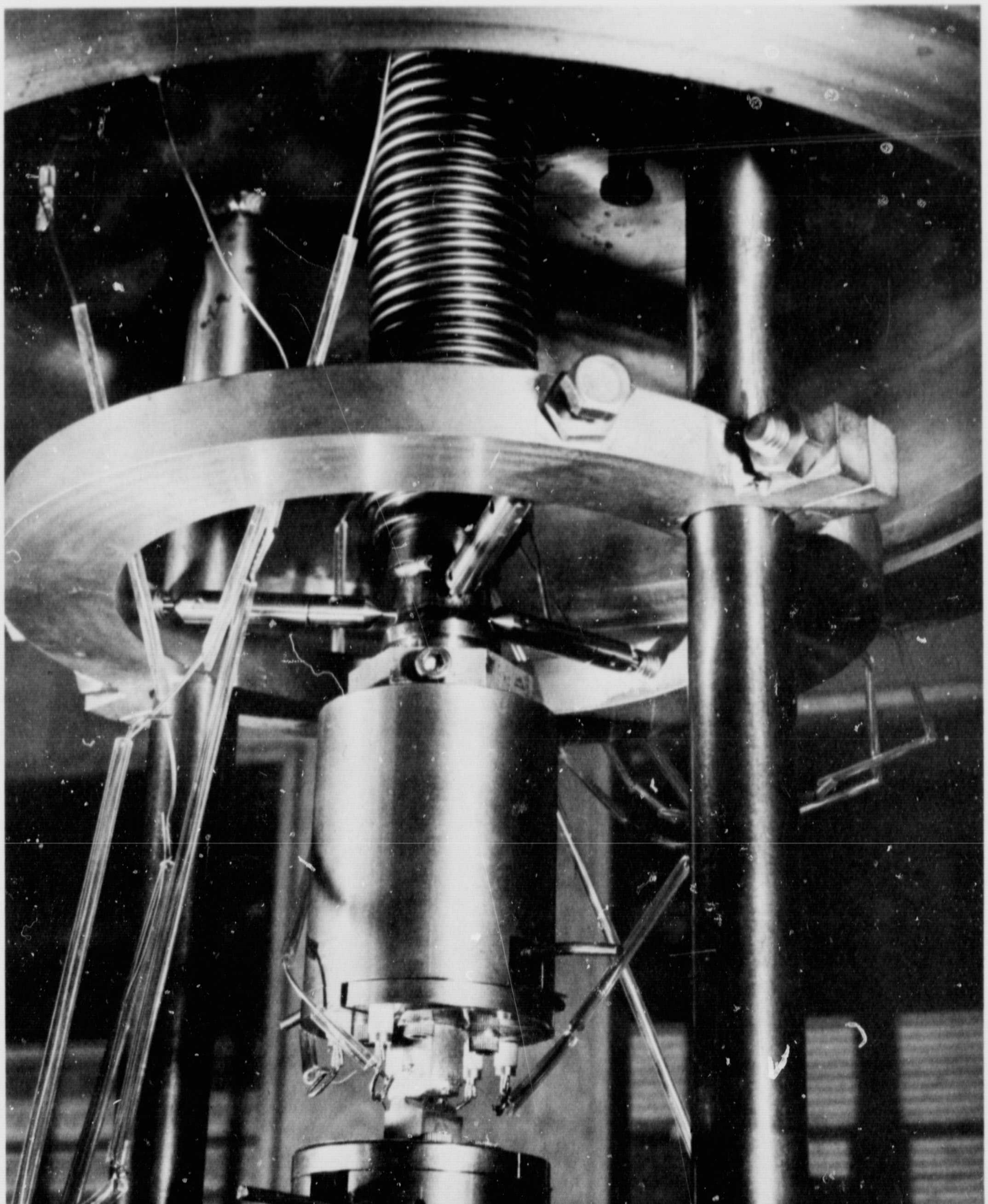

Fig. 4

View of Spring Actuated Axial Load Column Guide Rods

EXPERIMENTAL TECHNIQUE

Adhesion Test Procedure

Specimen pairs fabricated from high purity copper and nickel were annealed for 2 hours in argon gas at 750°C and 800°C respectively

Specimens with smoothly polished contact surfaces were positioned in the adhesion apparatus After initial vacuum evacuation, the vacuum chamber was heated to 200°C to outgas interior surfaces After subsequent cooling, with liquid nitrogen trapping chamber pressures in the range $3 \cdot 7 \times 10^{-9}$ torr were attained

When adequate vacuum conditions were obtained the specimens were abraded with an externally exited vibrating stainless steel brush for 90 to 120 seconds to remove surface oxides and compressed together with nominal contact stresses between 0 8-6 0 times the compressive bulk yield stress The abrasive treatment produced gas bursts up to 2×10^{-7} torr, however the average system pressure was sufficient to preclude surface re-contamination within the experimental contact time

Electrical Resistance Measurements

With the specimen couple maintained in loaded contact, the vacuum chamber was vented to the air and the adhesion apparatus, with the specimens still under load was removed for precise resistance determination Current leads were soldered to the wire extensions protruding from the bottom of the specimen Voltage probes were attached across the junction interface by means of shear connections; however, in some tests voltage measurements were obtained from pointed probes which were mechanically impressed into the surface of the metal Insulating material was placed around the specimen pair and after thermal stability had been achieved the thermo-electric (T E) voltage drop across the contract interface with zero applied current was measured with a nanovoltmeter The T E voltage was then suppressed and the contact voltage determined as a function of an applied constant current The stability of the contact voltage was ensured by the requirement of a linear variation of voltage with current through the zero point

Experimentally, the electrical current was obtained from a model 6265A Hewlett Packard dc power supply which supplied a current constant to within 2.5 x 10^{-4} amp. The instantaneous value of the current was measured with a calibrated ammeter sensitive to within $\pm$ 5 x 10^{-6} amp and adjusted to the required 1 x 10^{-3} amp value. The accuracy of the nanovoltmeter was $\pm$ 1% of the full scale reading. For the usual circuit current of 10^{-3} amp, the voltage measurements were therefore accurate to about $\pm$ 1 x 10^{-9} volts.

The interfacial contact resistance, derived from the impressed voltage/current ratio, was determined with the full compressive load and sequentially with load removal up to the tensile rupture force. Experimentally, the interfacial voltage drop was determined at a constant value of 1 milliamp current at various load reductions.

Strain Measurements

A precise determination of the strain produced within the bulk specimen by the applied force was obtained from the output of strain gages rigidly attached to the specimen sides. These gages formed the active arms of a Wheatstone bridge circuit; thus a voltage imbalance was produced during an adhesion test corresponding to a strain generated within the specimen. Experimentally, the generated potential was amplified and fed into one arm of a Moseley x-y electronic recorder. The output from the strain gages attached to the internal load cell was fed into the remaining arm. Thus the strain produced by small changes of load was continuously recorded. The accuracy of the strain determination was about $\pm$ 1 per cent of the total strain output. For plastic strains up to 10^{-2} in/in, the resolution was about $\pm$ 5 x 10^{-6} in/in.

Metallographic Examination

Selected welded specimen pairs were completely removed intact from the loading apparatus after the applied load had been released and the vacuum environment had been removed. In order to reduce any tendency to alter the character of the formed junction by the subsequent mechanical polishing operation the bonded area was cut from the bulk specimen and mounted in plastic This specimen containing a section of the adhesion interface was constrained within a thick walled cylinder The arrangement, shown diagramatically in Fig 5, insured that uneven polishing or tapering of the specimen did not occur

Accurate measurements of the amount of material removed were made by determining the thickness of the specimen after each polishing operation The original position within the junction of each examined cross-section could therefore be established The specimen was given a final polish with 0 5μ aluminum oxide powder which produced a surface suitable for examination with a Reichert optical microscope In order to remove any "smeared metal" effects produced by the polishing operation and to accentuate the interfacial cold worked layer the specimen was lightly etched in a dilute HNO_3 solution before examination

EXPERIMENTAL RESULTS

Electrical Resistance Measurements

The interfacial resistance between contact surfaces of copper-copper and nickel-nickel junctions under an impressed voltage and constant current was measured after vacuum abrasion and compression to produce residual welding The specific resistance of the interface was continually monitored during the unloading of the compressive force through the zero load point and into the tensile rupture load region Representative load-resistance plots for copper and nickel specimen pairs are shown in Fig. 6 It is evident that upon unloading from the maximum compressive force level, the interfacial resistance remained substantially constant until the final tensile rupture force was approached In the case of nickel, which exhibited much higher strain hardening under plastic compressive loading than the more ductile copper, an increase in resistance was generally detected in the final stages of compressive unloading and subsequent tensile load application, implying an elastic rupture and separation of the contact surfaces

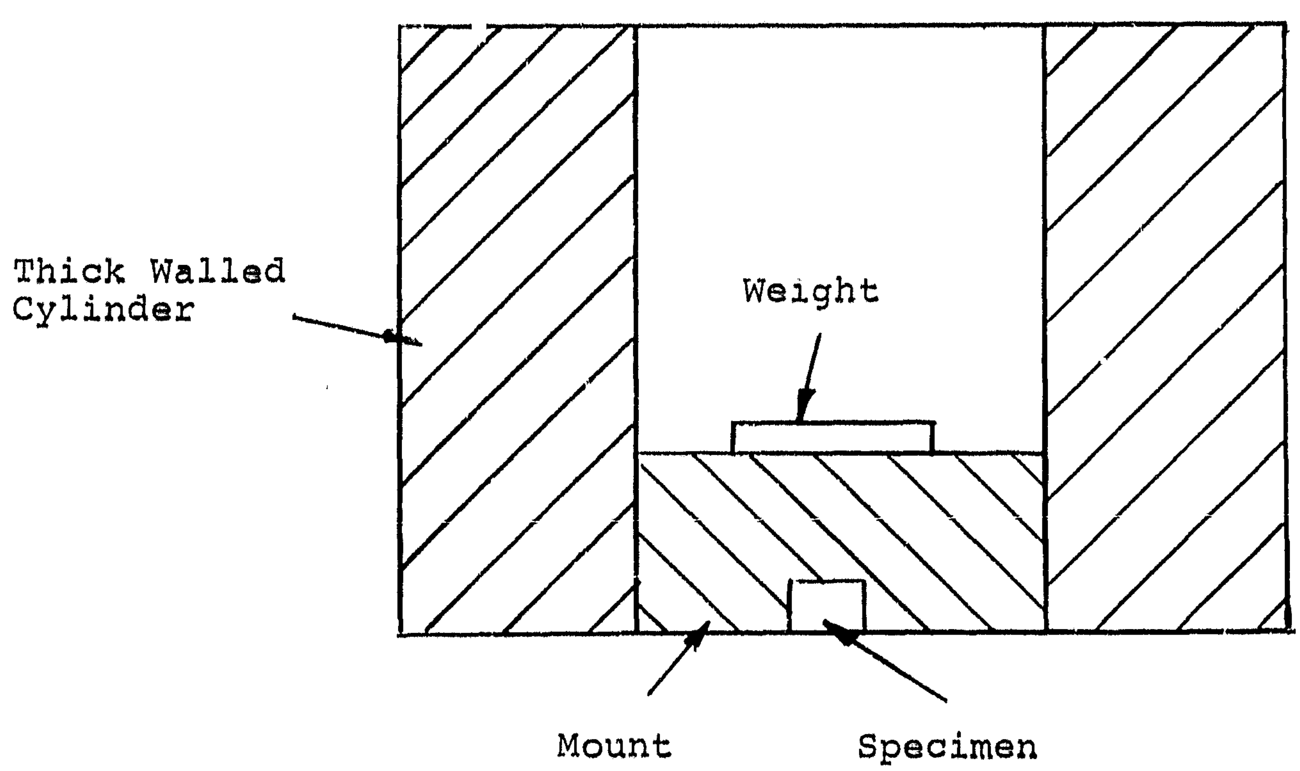

Fig. 5

Apparatus Designed to Ensure the Preparation of Metallurgical Sections of Parallel Spatial Orientation.

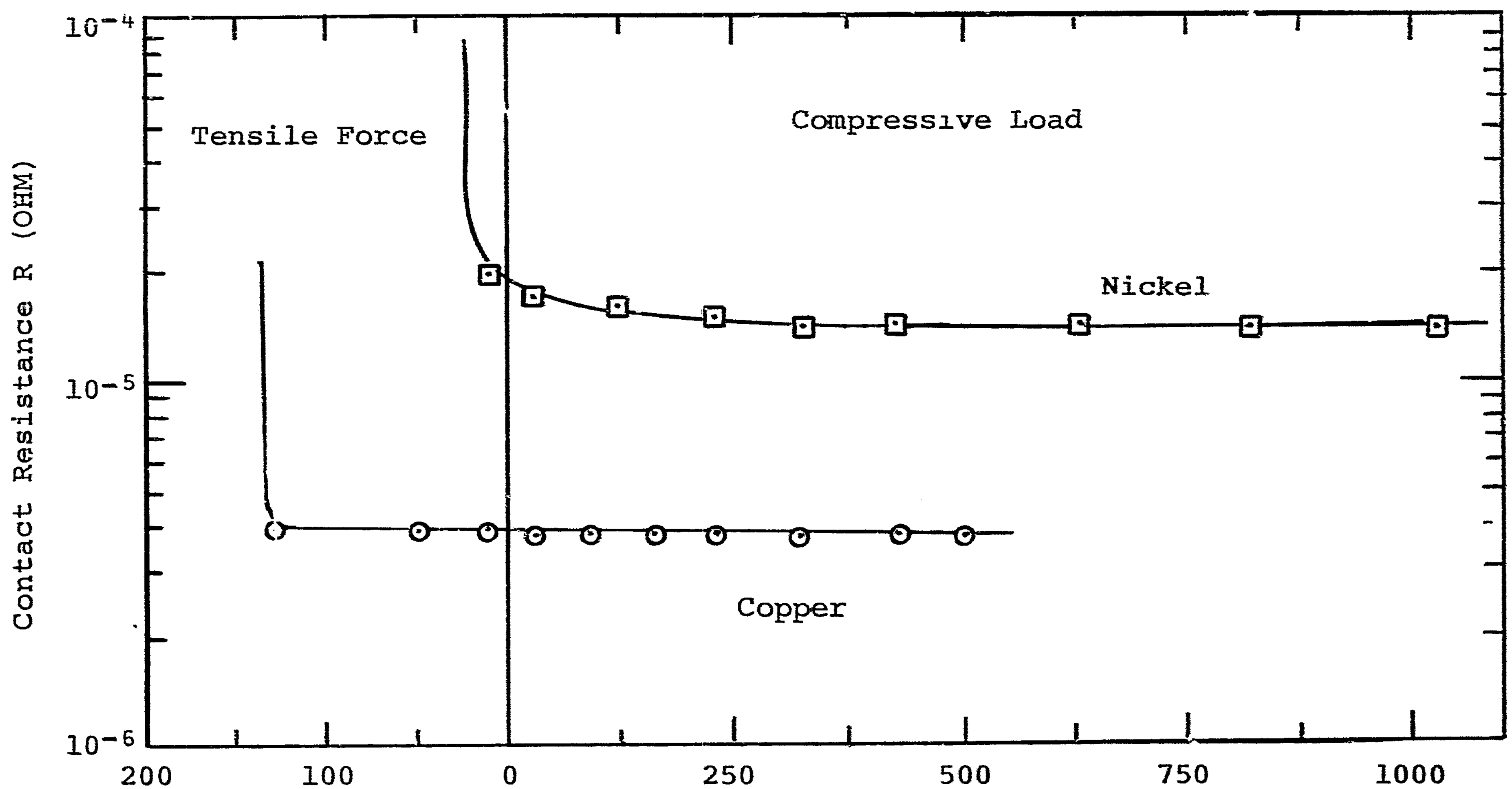

Fig. 6

Variation of Interfacial Resistance with Unloading

In order to compare the specific resistance values observed to bulk resistivity properties, specimens of copper and nickel were prepared in the form of solid rods machined to the configuration of a completely welded pair of adhesion specimens. The resistance of the solid rod was taken as a basis value for a completely bonded interface. Values for the minimum resistance level R_0 at 20°C of $3.8 \times 10^{-[illegible]}$ ohms for copper and 14.0×10^{-6} ohms for nickel were obtained with a minimum cross-sectional area of 0.035 in.^{2} corresponding to the maximum contact interface area used in the present adhesion tests.

The variation of the interfacial contact resistance with applied load in prior compression and subsequent tension is shown in Figs. 7 and 8 for copper and nickel, respectively. In these figures, the compressive load W is plotted as the ratio W/W_y where W_y is the yield load and the adhesion force T is presented as the ratio T/T_f where T_f is the tensile strength of the bulk material. The normalizing parameters W_y and T_f can be derived from known compressive yield stress and ultimate tensile strength data and are listed in Table I.

It is apparent from the curves of Figs. 7 and 8 that the electrical contact resistance decreased markedly as the copper and nickel adhesion specimens were compressed. In the case of copper, essentially complete interfacial conductivity was attained with deformation load ratios above 4. In agreement with previous results, the adhesion force to bulk tensile strength ratio T/T_f, defined as a measure of the adhesion bond efficiency, increased markedly with compression loads in the plastic range, corresponding to load ratios $W/W_y > 1$. It was observed that for compressive load ratios less than unity, corresponding to elastic loading, the residual adhesion was negligible and the interfacial electrical resistance high.

The specific dependence of the adhesion bond efficiency on the degree of plastic compression is illustrated in Fig. 9 for copper and nickel. The sharp decrease in permanent adhesion for surface contacts in the elastic deformation zone was in agreement with previous results. It may be noted that adhesion strengths up to 46 per cent of the ultimate tensile strength of copper were obtained with extensive compression. However, the observed adhesion strength of nickel was considerably lower.

For compressive loads applied within the elastic range, the electrical contact resistance was observed to vary according to the expression $R - R_0 = K/W^n$ where K is a material constant. In

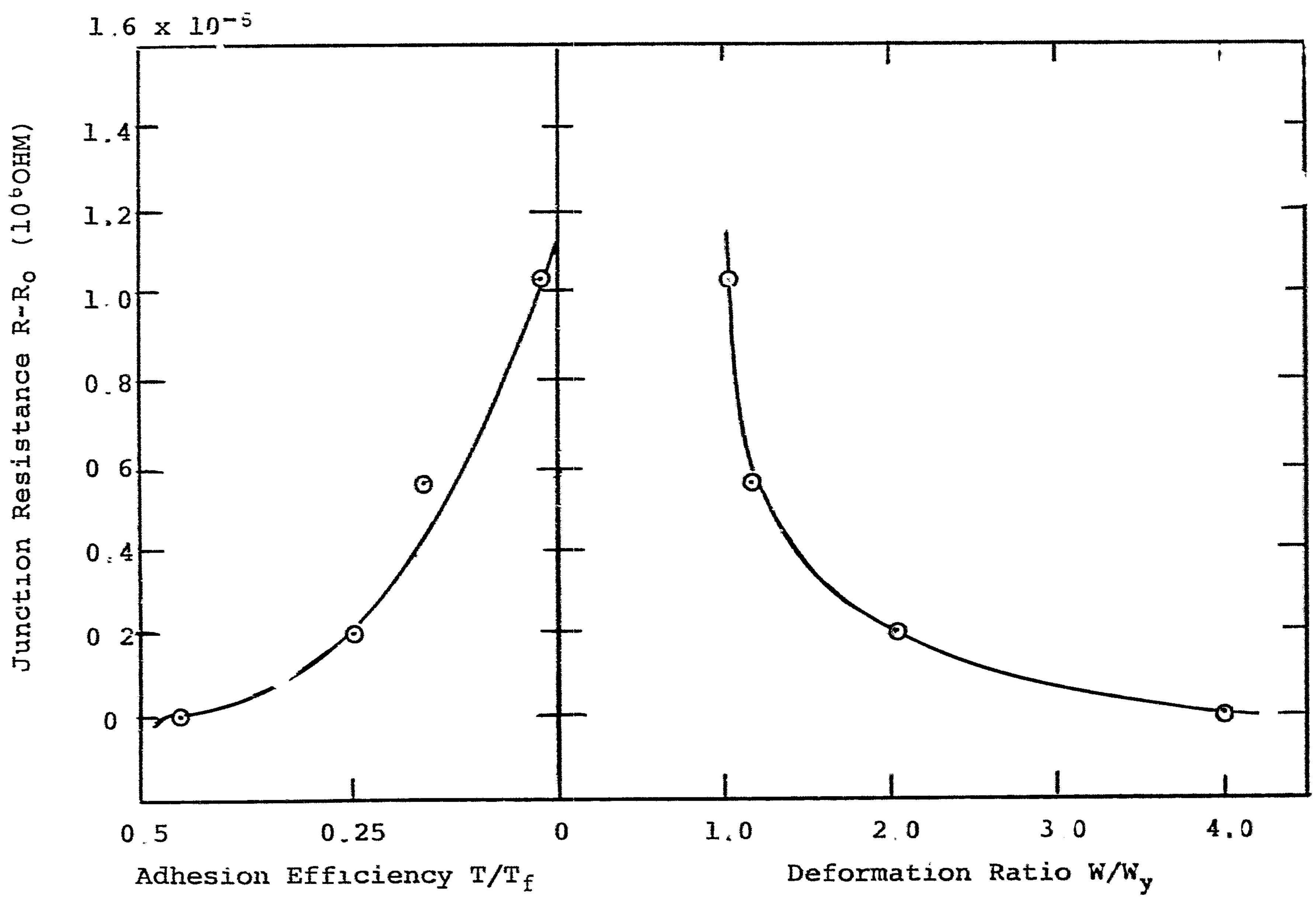

Fig. 7

Dependence of Junction Contact Resistance on the Adhesion Bond Efficiency and Plastic Deformation Ratio for Copper

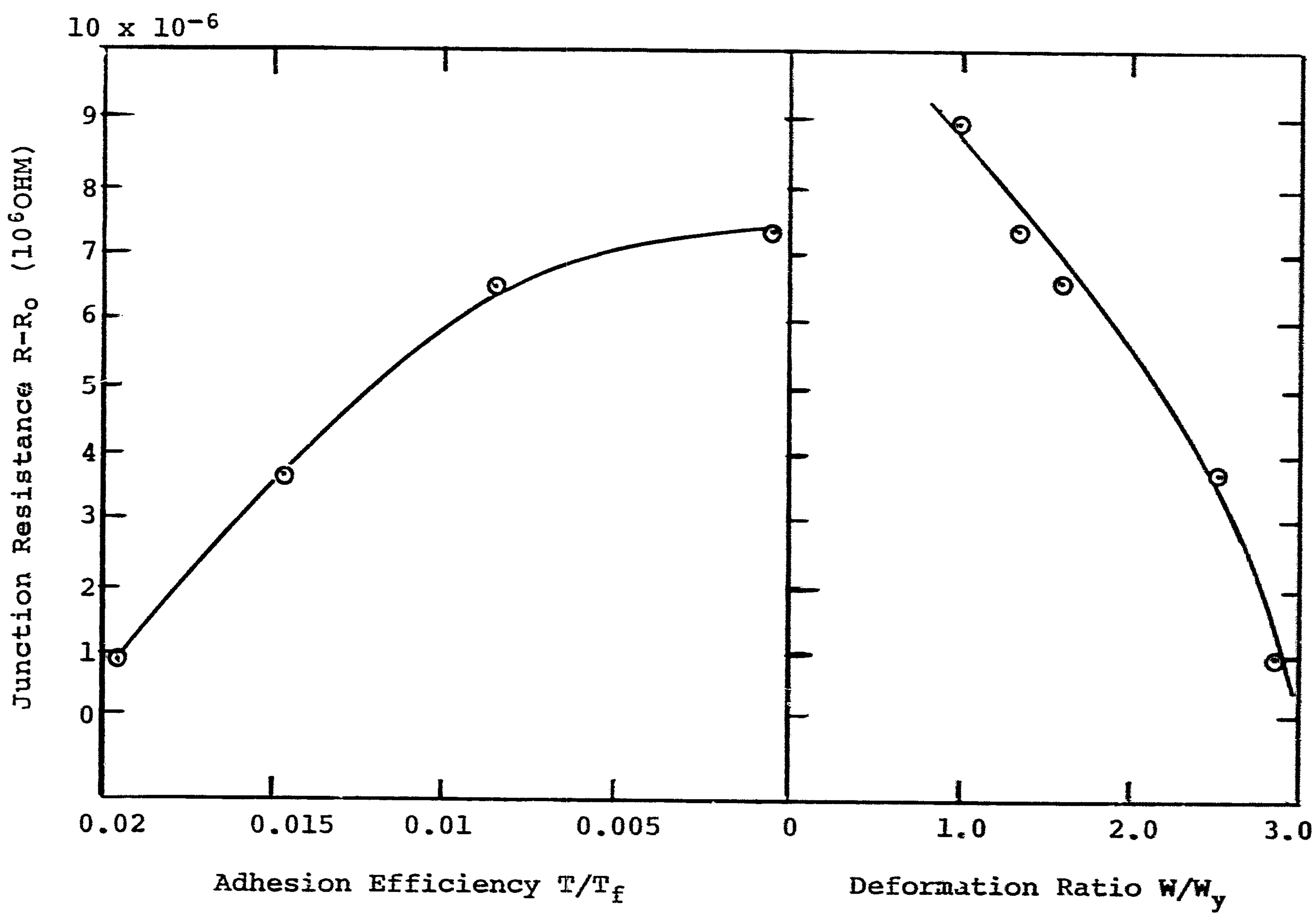

Fig. 8

Dependence of the Adhesion Bond Efficiency and Plastic Deformation Ratio on the Junction contact Resistance for Copper.

TABLE I

MECHANICAL PROPERTIES OF ANNEALED TEST MATERIALS

	Copper	Nickel
Compressive yield stress (psi)	7,000	13 000
Compressive yield load W_y (lb)*	245	475
Maximum tensile stress (psi)	30 000	50,000
Maximum tensile load T_t (lb)*	1 050	1 750
Annealed hardness (Rockwell)	RF-32	RB-18

*Adhesion Specimen pair maximum interfacial area = 0.035 in.^{2}

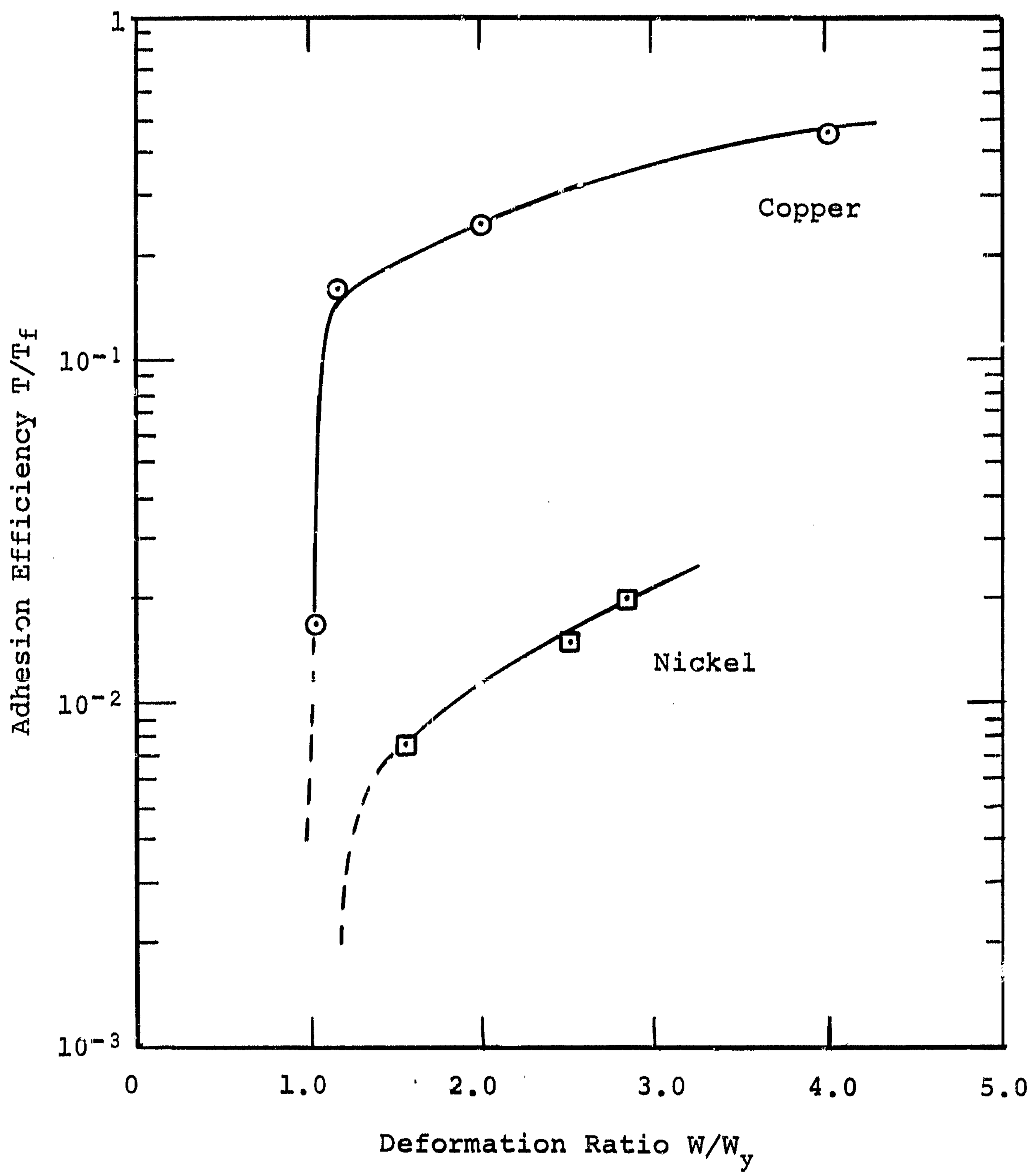

Fig. 9

Variation of the Adhesion Bond Efficiency with Plastic Deformation for Copper and Nickel.

Fig 10 a typical elastic load vs interfacial resistance plot for nickel is shown from which a value of 1/3 can be derived for the exponential constant n from the linear slope Bowden and Tabor[4] have suggested that the linear dependence of R with $W^{-1/3}$ will arise when the surface asperities in contact unload in an elastic manner However, deviations from this value have been observed when the contact interface contains substantial amounts of impurity material It may be deduced, therefore that wire brush abrasion in 5 x 10^{-}[illegible] torr vacuum can produce surfaces with contamination levels below the critical region for a significant time period

Metallographic Examination

The contact junction formed when a compressive force of 1500 lb (W/W = 6) was applied between two copper specimens whose surfaces had been wire brushed in a vacuum of 7 x 10^{-}[illegible] Torr is shown in Fig 11 A detail of the interface at higher magnification is shown in Fig 12 At distances removed from the contact interface area the internal structure was observed to consist of the large undeformed twinned crystals that typify annealed pure copper The structure immediately adjacent to the interface is seen to be heavily deformed and it is evident that much plastic flow has occurred Surface contact was made between the cold worked layers with the position of the contacting boundary perpendicular to the applied stress The extent of the plastic flow observed in these interfacial weldments was surprising since only a minimal amount of surface damage, approximately 5-20μ in depth is caused by the wire brush surface cleaning treatment alone The original "hill and valley" topography produced by the wire brush surface cleaning treatment was therefore altered by the surface flow which occurred during junction formation In contrast the expected sinusoidal variation in height was retained by the boundary between the cold worked layer and the annealed bulk material An example of this is shown in Fig 13

Further examination of Fig 13 reveals that voids were present within the cold worked layer at the specimen interface and at the junction between the cold worked and the annealed material These regions of limited interfacial contact were formed when the lateral flow of the contacting surfaces was insufficient to fill the discontinuities that existed between

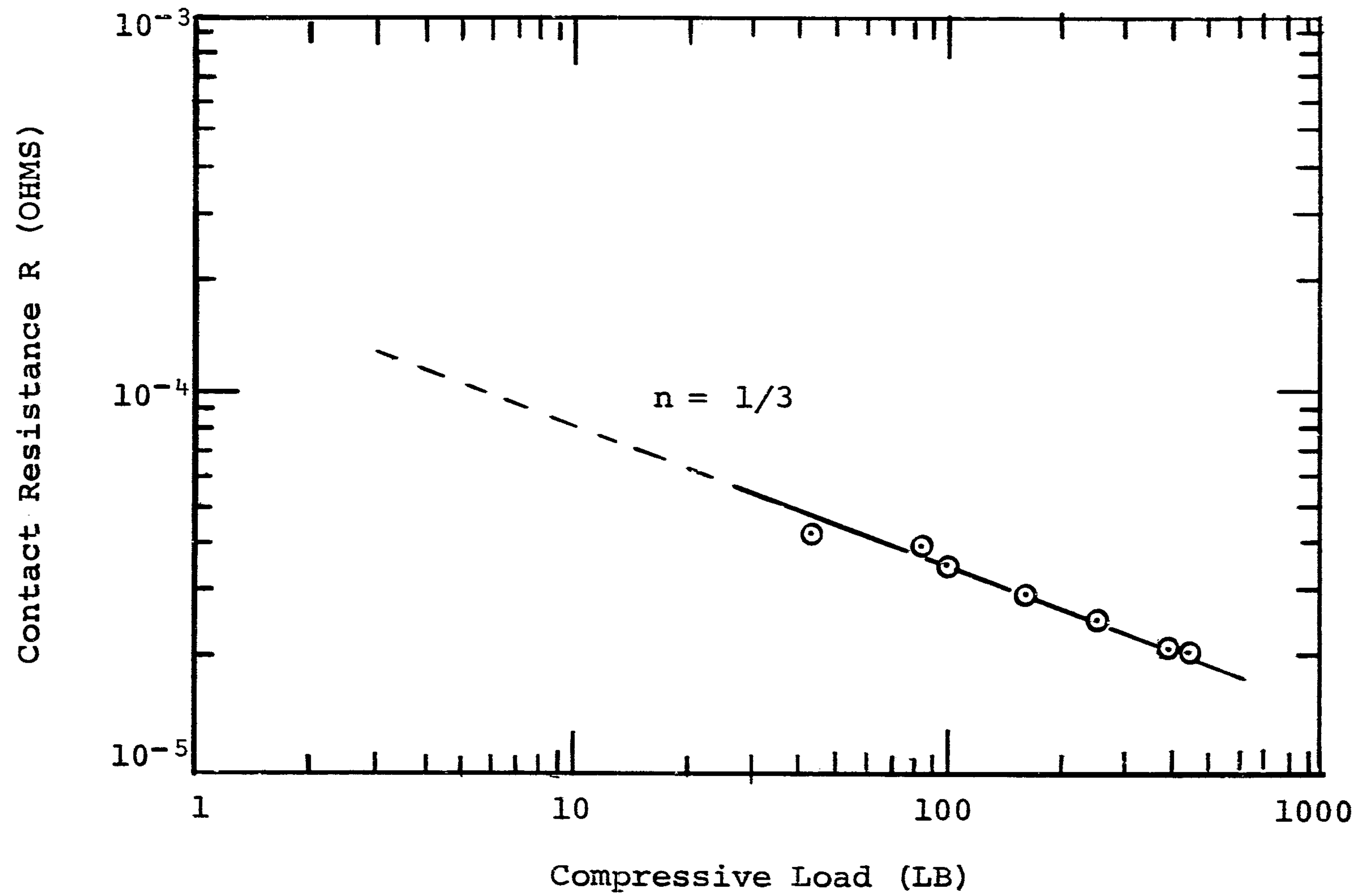

Fig. 10

Variation of the Specific Contact Resistance
with Elastic Compressive Loading for Nickel.

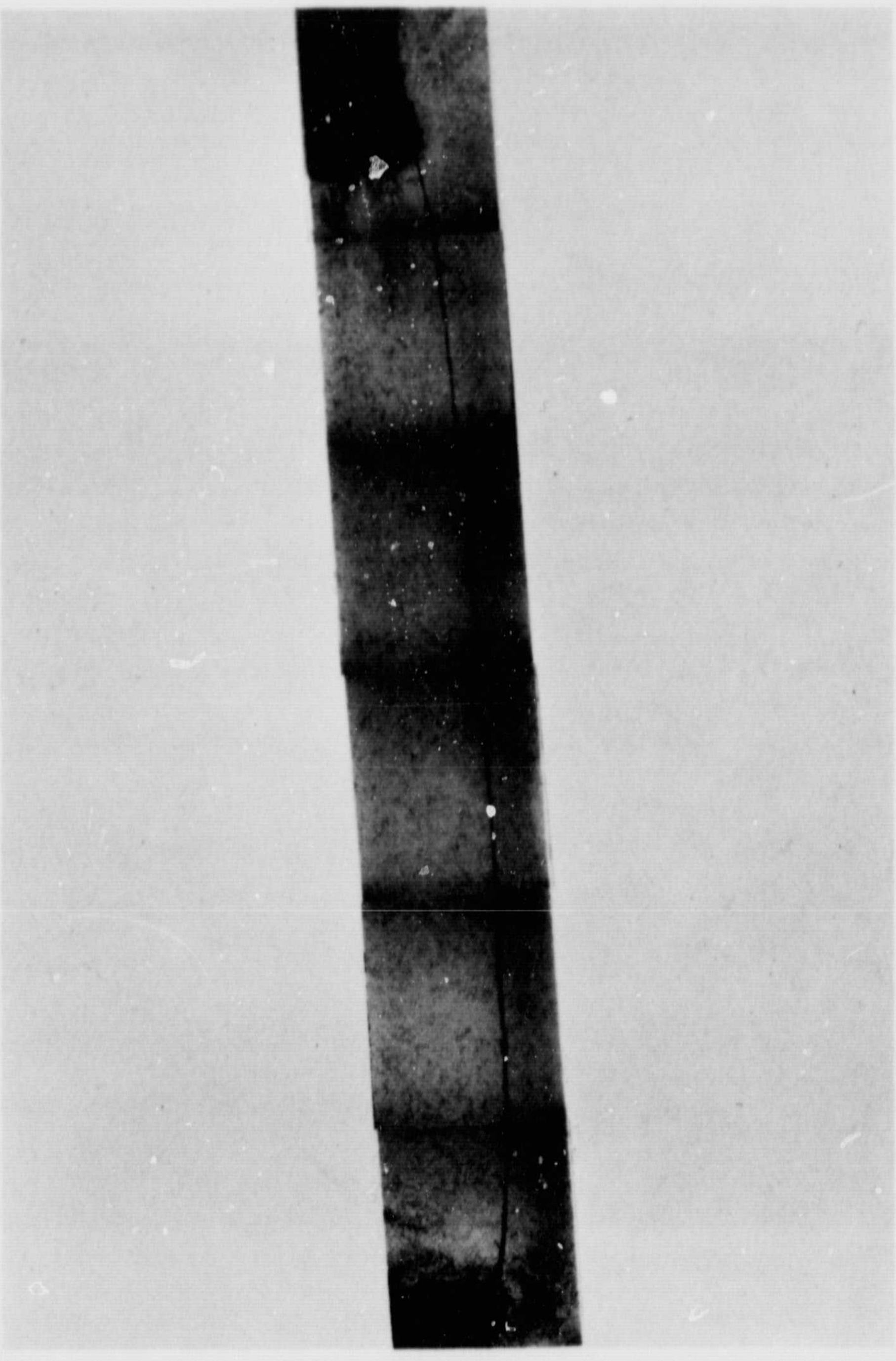

Fig. 11

Composite Photomicrograph of Junction Formed with a Compressive Load of 1500 lb (25X).

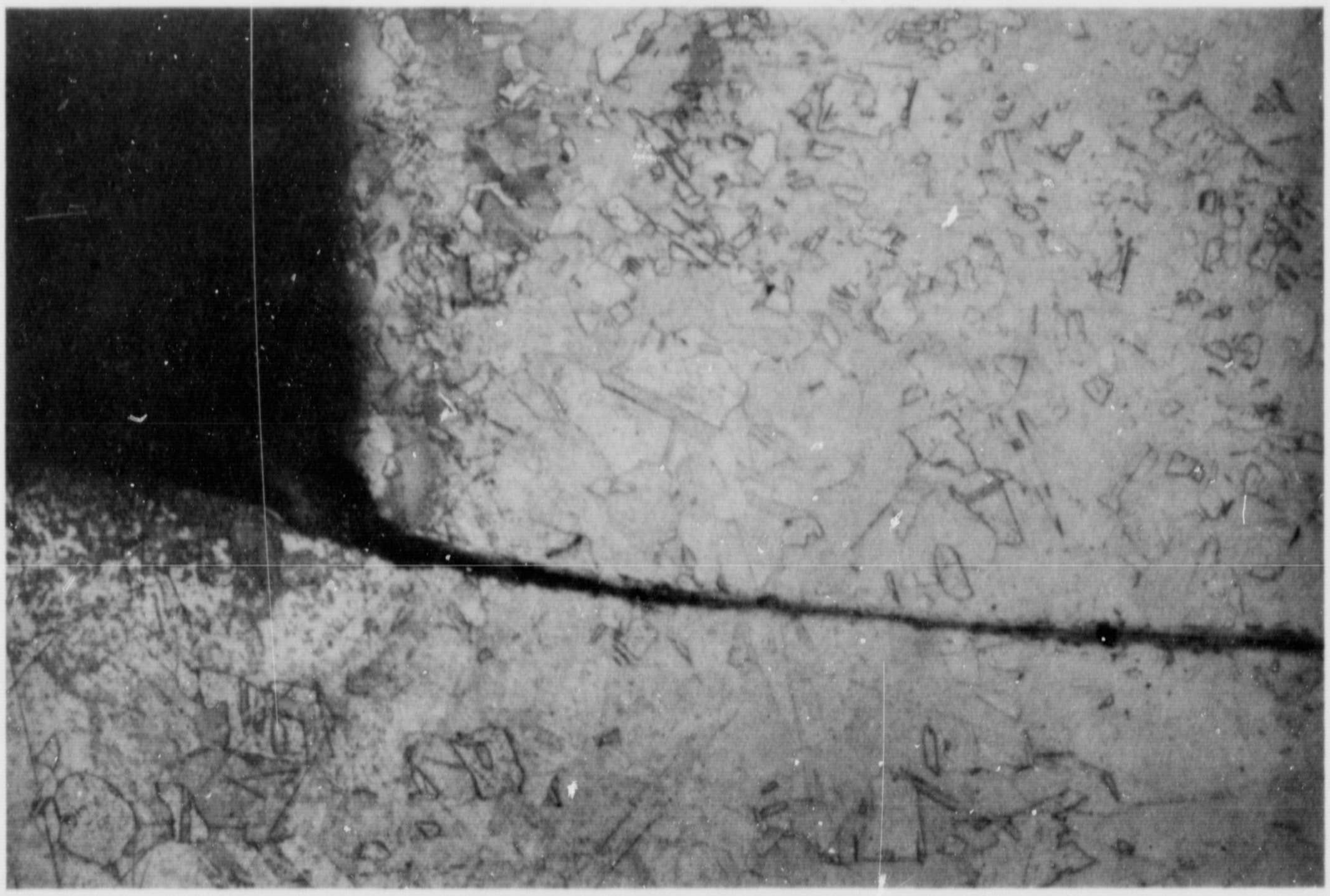

Fig. 12

Detail of Adhesion Interface of Weldment
Shown in Fig. 2. (130X).

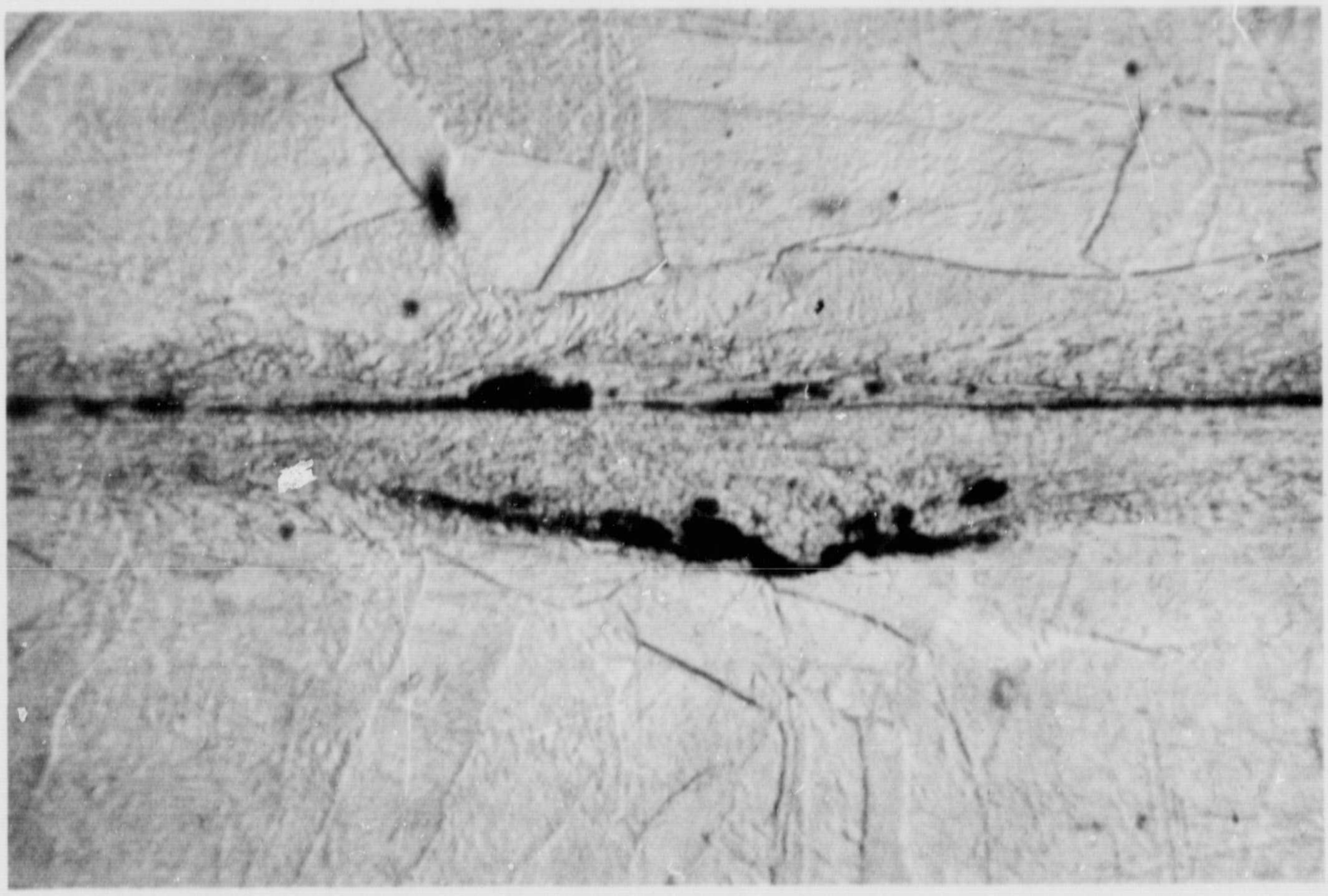

Fig. 13

Voids Present at Interfacial Junction (1300X).

them The major irregularities were scratch marks; however small impurity particles sometimes remained on the surface after the cleaning operation and these prevented close contact at the interface Voids formed by this mechanism shown in Fig. 14 were not commonly observed, for usually the surface layers were found to flow easily around any foreign particles. An example of the effects caused by this extensive lateral flow is shown in Fig 15 A stainless steel particle, broken from the brush used to clean the specimen surfaces, is seen to be perfectly bonded into the copper matrix.

The total length of voids observed in each cross-section profile was accurately noted. The accumulated observations could then be arranged to clearly show the variation in the bonded area at various points through the specimen. From the results shown in Fig 16, it can be observed that the area of contact, a maximum at the center of the specimen, diminished progressively at locations near to the specimen edges, regardless of the value of the junction formation pressure. Calculations from these curves indicated that 67 per cent of the geometric area of the specimens was in optical contact when a compressive force of 1500 lb was used to form the junction. In contrast, only about 24 per cent of the interfacial area was in contact in the junction formed with a 600 lb load. These results are to be compared with the bonded area values of 48 per cent and 20 per cent estimated from a knowledge of the forces required to break the bond between two additional specimens formed under identical conditions.

In addition to measurements designed to indicate the total void content associated with a given interfacial cross-section, further observations were made designed to indicate the size and the position of each individual void. Multiple observations obtained from cross-sections taken at 0.010 in. intervals across the junction were combined and a two dimensional representation or contact contour view of a typical area within the junction region was obtained. The schematic result shown in Fig. 17 reveals the nature of part of the welded junction and indicates the position of the numerous void areas.

Strain Measurement

The total strain produced within a bulk specimen of copper with variations in the applied load is shown in Fig. 18. Initially,

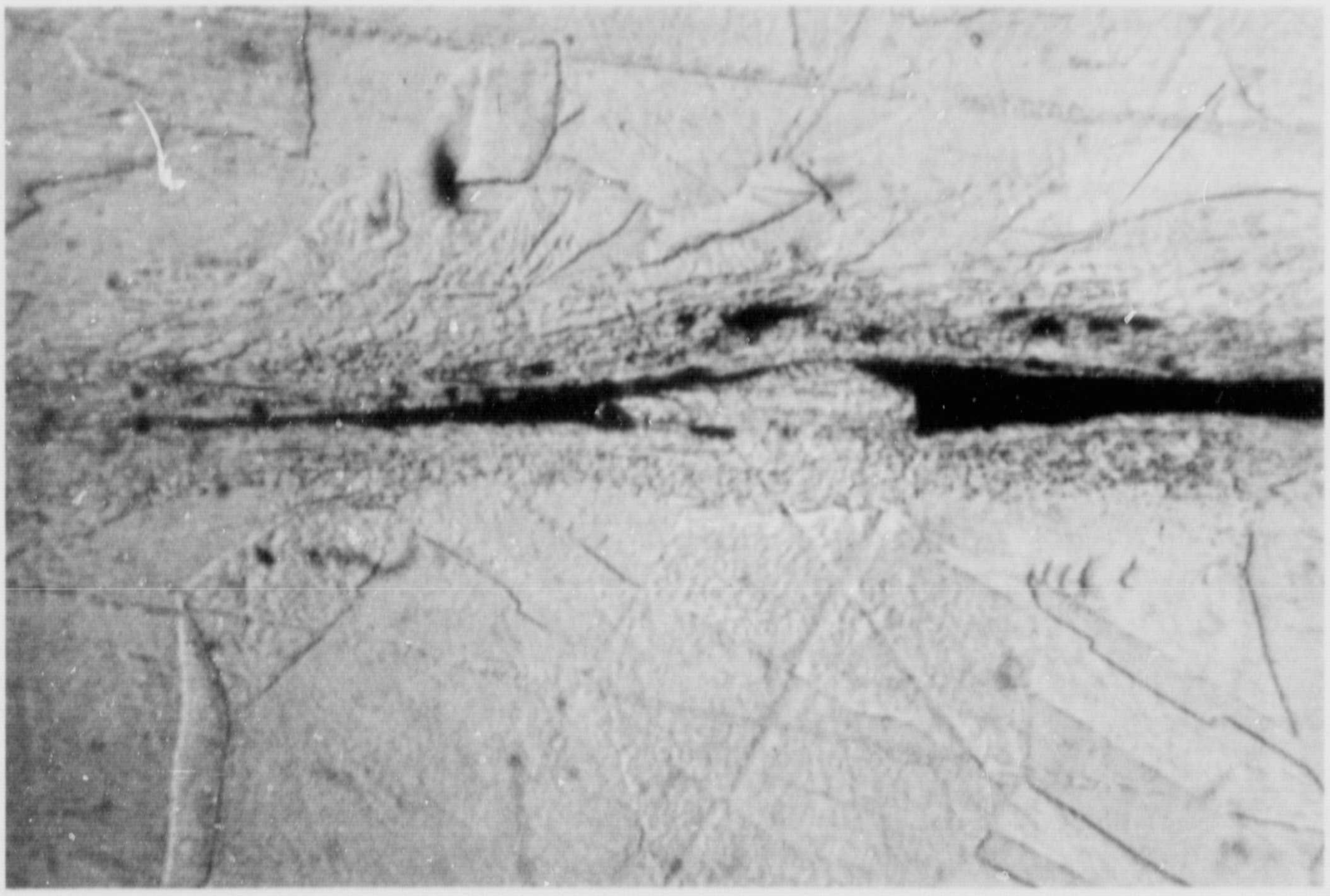

Fig. 14

Impurity Particle at Interface (1300X).

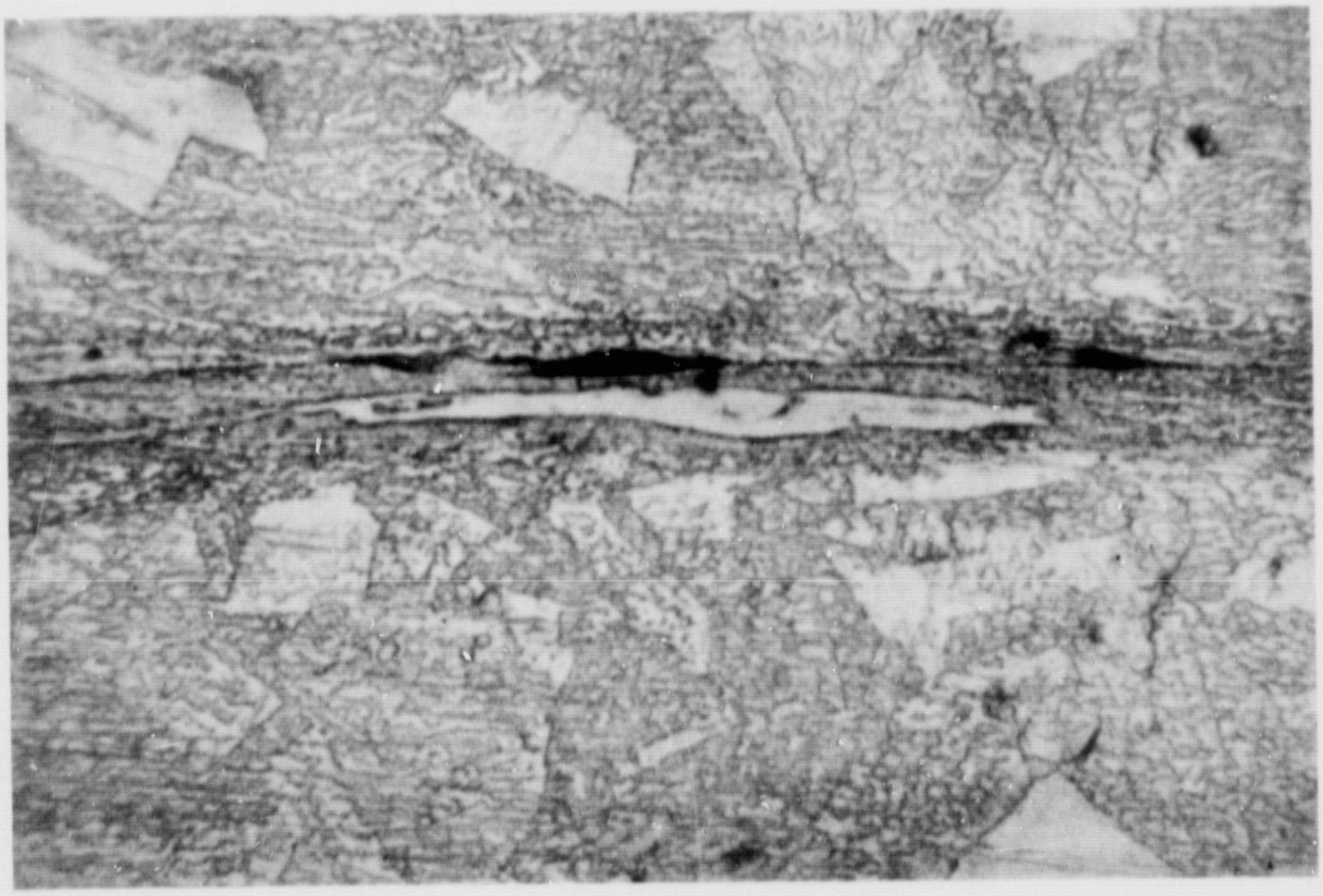

Fig. 15

Stainless Steel Impurity Cold Welded into the Contact Surface of a Copper Specimen (1300X).

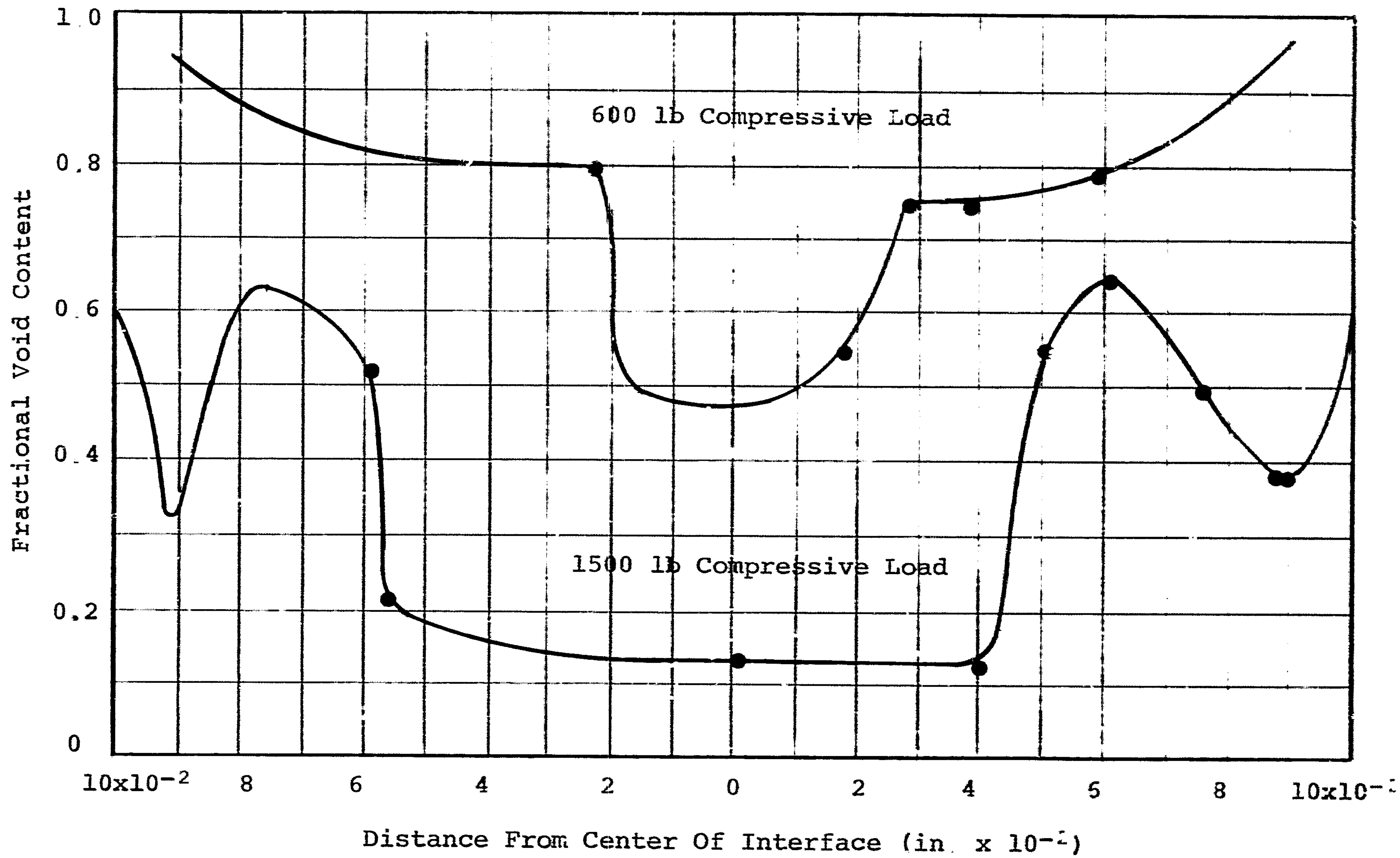

Fig. 16

The Variation of Void Content Across the Interfacial Junction Profile

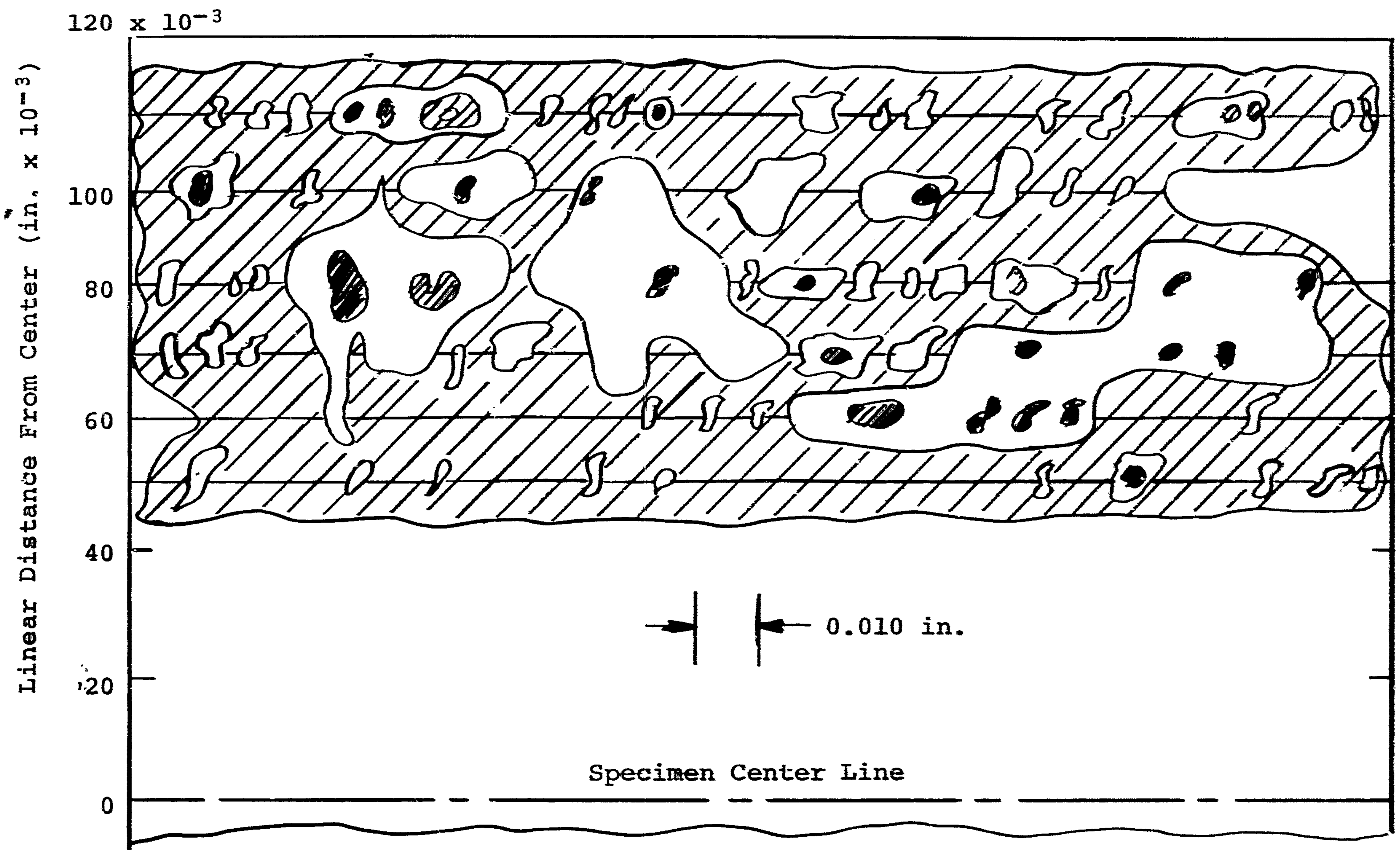

Fig. 17

Schematic Representation of Section of Junction Interface Showing Interfacial Bonding Area Contour and Void Distribution.

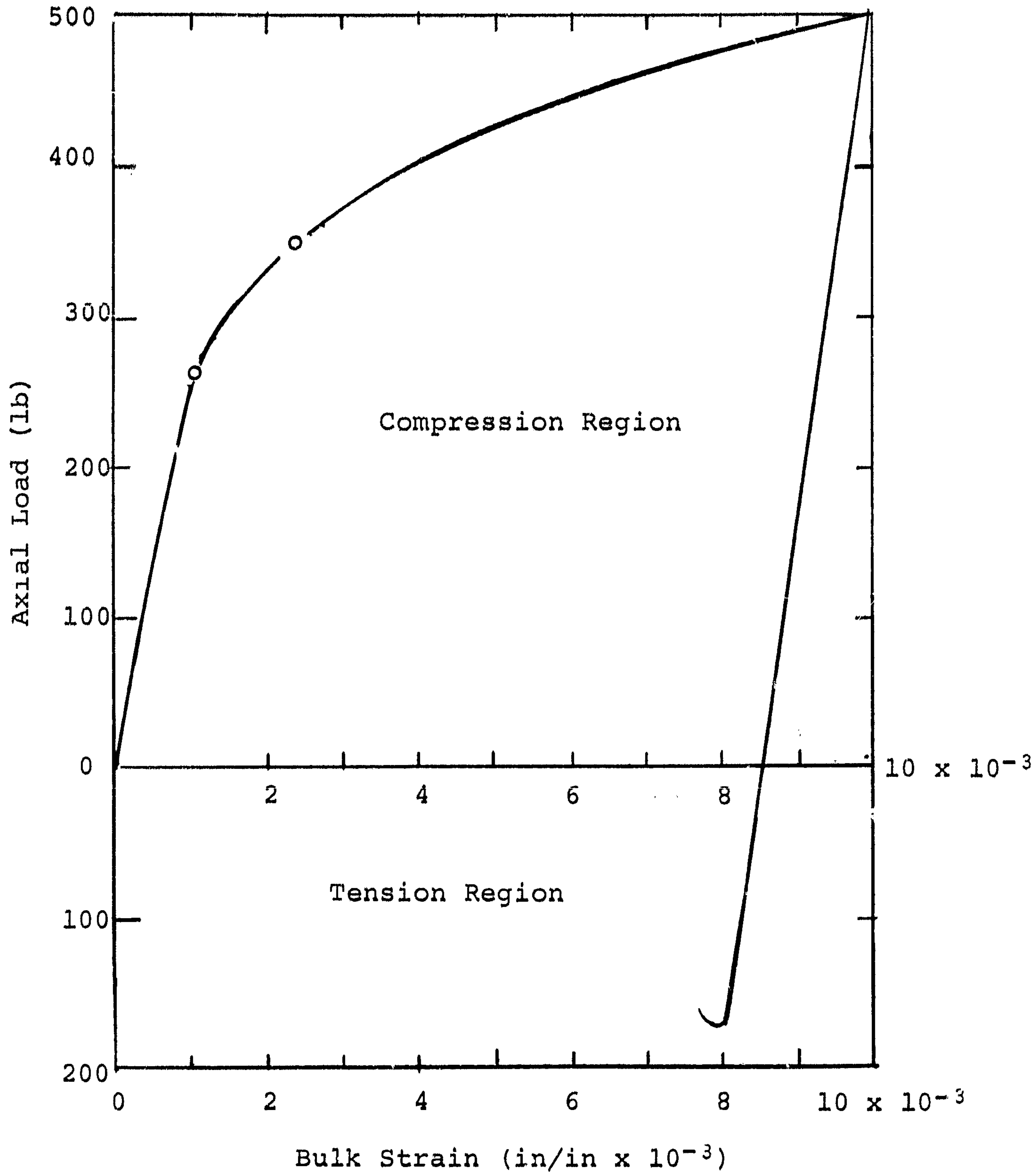

Fig. 18

Effect of Load on the Strain Produced in the Bulk Specimen.

small increases in the load were observed to cause the strain to increase in an essentially linear manner. In this region the strain was elastic and the specimen recovered when the load was removed. Junction formation with the associated cold welding could not be detected in specimens compressed in this region of the curve. With copper specimens, when the load was increased above 250 lb corresponding to the bulk yield stress at the junction of 7000 psi for copper, increasing amounts of plastic strain were introduced into the interfacial region. The strain gage attached to the bulk specimen was sensitive to this plastic displacement and a change of slope was produced on an X-Y chart recording monitoring the load-deflection variations. When the compressive load was released, the specimens recovered elastically until the zero load condition was reached. Subsequent tensile loading produced further elastic tensile deformation. If the junction bond strength was high, some plastic flow occurred prior to the fracture of the interfacial bonds.

The tensile force necessary to separate junctions formed at various applied plastic strain levels is shown in Fig. 19. The amount of plastic strain produced within the specimen bulk sensitively controlled the adhesion strength of vacuum formed weldments. Interfacial bonds could not be detected until gross plastic strain was generated within the test samples.

Additional observations indicated that the physical state of the specimen surface also determined the strength of vacuum formed joints. Only very weak adhesive bonds were formed between pre-compressed specimens even though very large plastic strains were generated during the deformation process. Specifically, an applied load of about 325 lb sufficient to cause a plastic strain of 10^{-4} was applied between a copper specimen pair. It was then released and the specimens were separated with 5 lb of tensile load. After rebrushing the specimen surfaces and applying a compressive load sufficient to generate a further 1.5×10^{-4} strain increment, a bond requiring 62 lb of separating force was produced. However, an additional 4.0×10^{-4} strain increment only 34 lb of adhesion force. Further larger strain increments produced welds, none of which exhibited a tensile fracture load greater than 88 lb. It was apparent that work hardening of the contact surface severely limited the extent of surface displacement, although macroscopic yielding of the underlying bulk material occurred. Reproducable interfacial bond strengths were only observed when the specimens were fully annealed.

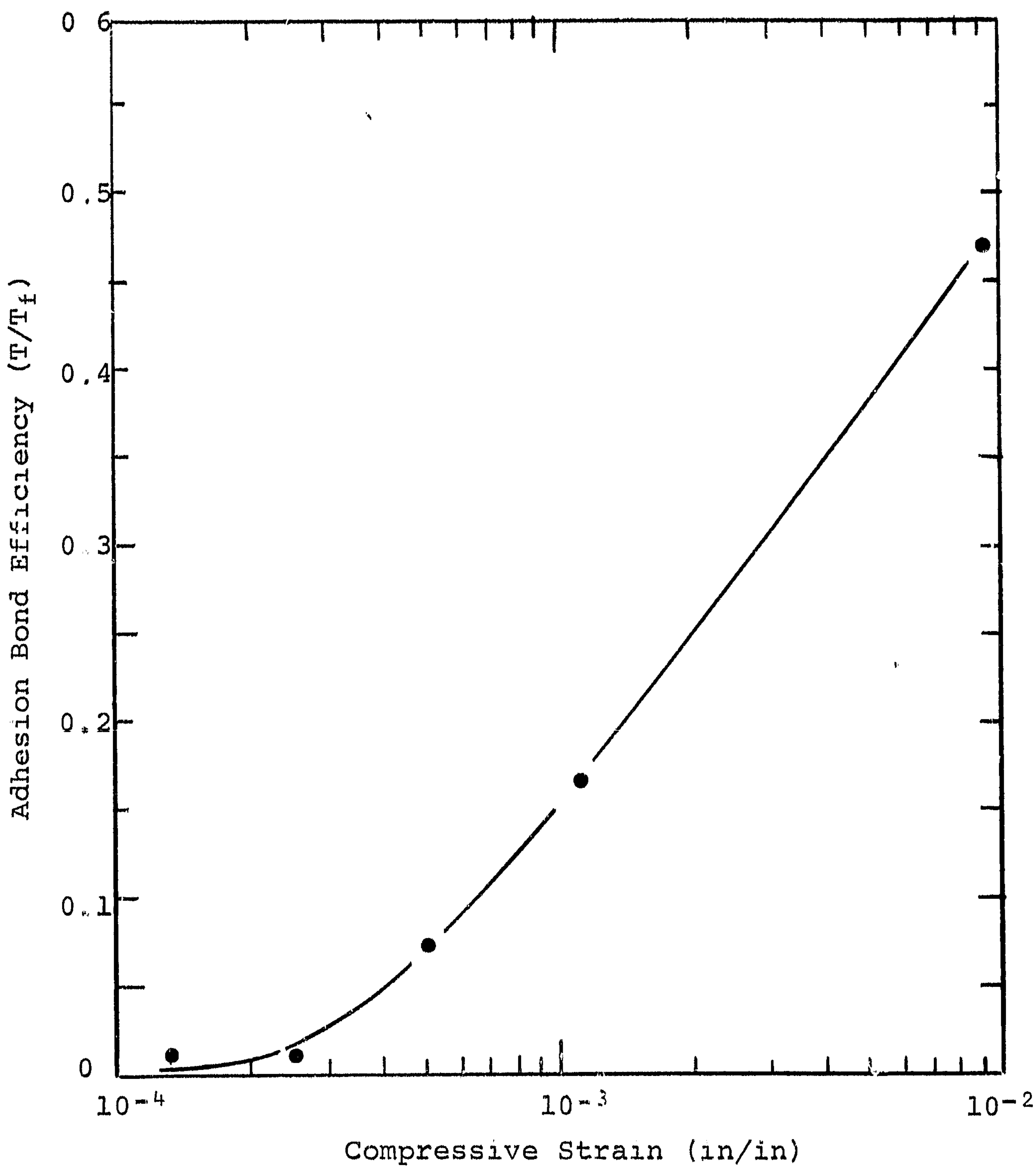

Fig. 19

Variation of the Adhesion Bond Efficiency with Compressive Strain for Copper.

DISCUSSION

The apparent areas of contact that existed between copper specimens forced into contact by various compressive loads can be obtained from calculations based on the metallographic observations and are shown in Fig 20 Increases in the applied load were observed to produce a corresponding increase in the contact area in agreement with the linear dependence predicted by the analysis of Greenwood and Williamson [5]

If it is assumed that no stress concentrations or plastic constraints exist in the interfacial junction region, the area actually bonded between the specimens can be estimated from the measurements of adhesive force and a knowledge of the ultimate tensile strength of bulk copper The computed values are also shown in Fig 20

The contact curves illustrate quite clearly that only a fraction of the total geometric area was actually in contact at any specific load level The bonded area was essentially zero for compressively applied loads less than the bulk yield strength of the material Increasing the load applied to the specimens above the yield resulted in a proportional increase in the contact area, thus the overall contact stress remained constant at about 60,000 psi

The results obtained from the electrical resistance measurements, although not sensitive to the actual degree of interfacial contact under plastic loads, showed quite clearly the presence of residual adhesion As the specimens are unloaded and recover elastically, the contact area will decrease, and the resistance will rise The rate of increase of resistance is sensitive to the area of contact and to the degree of cleanliness of the contacting junction For clean interfacial junctions and elastic compressive loads the junction resistance R_J obeys the relationship:

$$R_J = KW^{-1/3} \qquad (1)$$

where K is a constant and W is the compressive load.

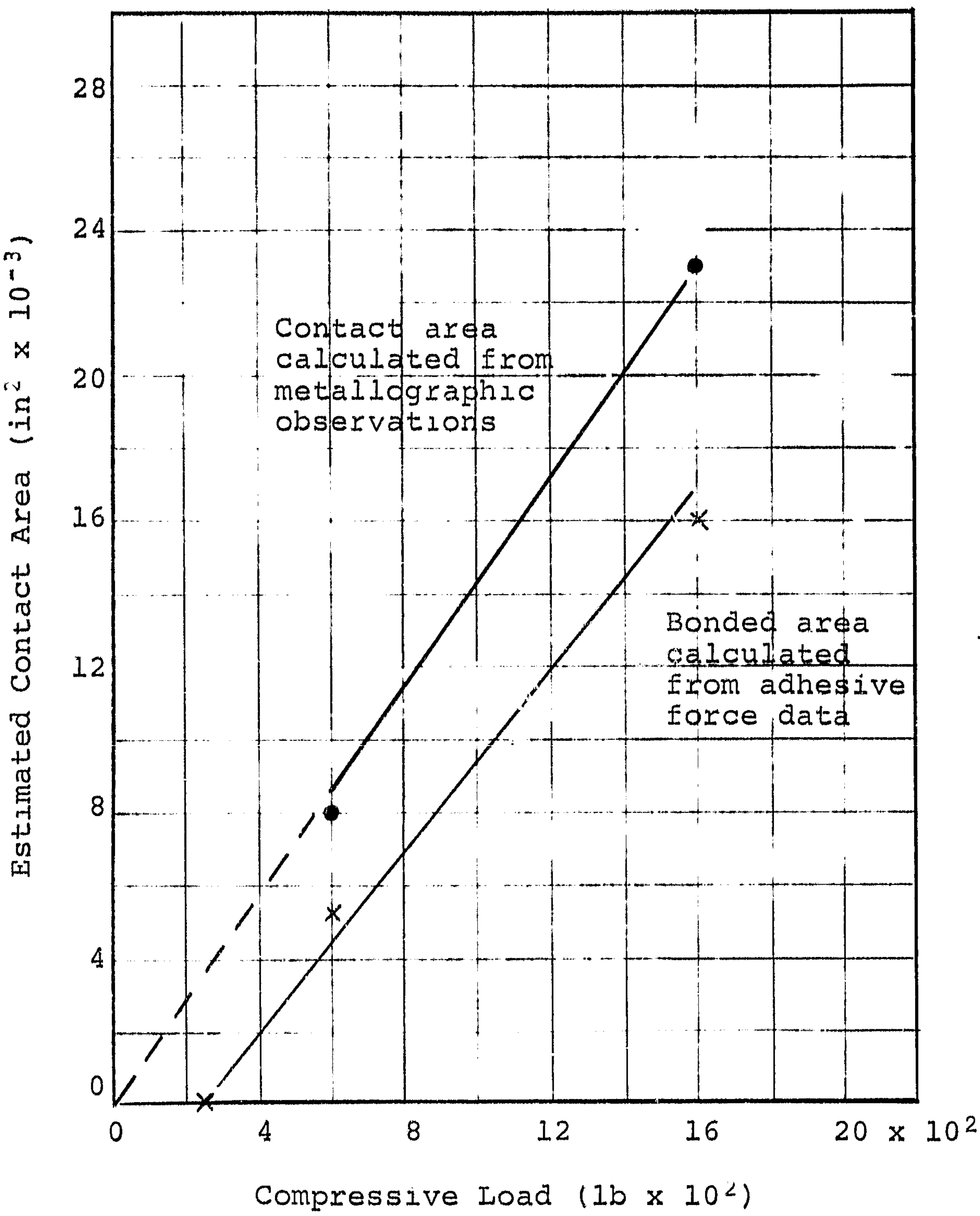

Fig 20

Interfacial Contact Areas Determined as a Function of the Applied Compressive Load.

If interfacial bonds have been formed then the resistance will remain essentially constant as large amounts of the compressive load are removed For copper, the weldment resistance remained constant until a tensile load sufficient to separate the specimens was applied The resistance of bonded nickel specimens, however, began to increase prior to fracture even though a compressive load was still applied between the specimens This feature is probably influenced by the extent of the elastic energy stored by the material which is large for nickel.

It is tempting to describe the resistance offered to the passage of the electrical current by the interface as a constriction resistance Assuming the radii of the multiple contacting spots show a gaussian distribution, the constriction resistance R_C can be estimated:

$$R_C = \frac{\rho}{2an} \qquad (2)$$

where ρ is the bulk resistivity of the material, n is the number of contacting asperities and a is a mean value for the asperity radius

The total contact area A_J, assuming generally circular asperity cross-sections, can also be estimated:

$$A_J = n\pi a^2 \qquad (3)$$

Values of A_J can be obtained from the metallurgical observations shown in Fig 20

Proper combination of the above equations enables both n and a to be calculated for specimens compressed to given load. Fig 21 shows the number and size of the contacting asperities computed using the typical data shown in Table II. It can be seen that at very low loads the contacting area consists of a small number of junctions having a relatively large radius; a number of small isolated areas within these spots are bonded. At larger loads, many additional asperities start to make contact and thus the average contact radius is reduced.

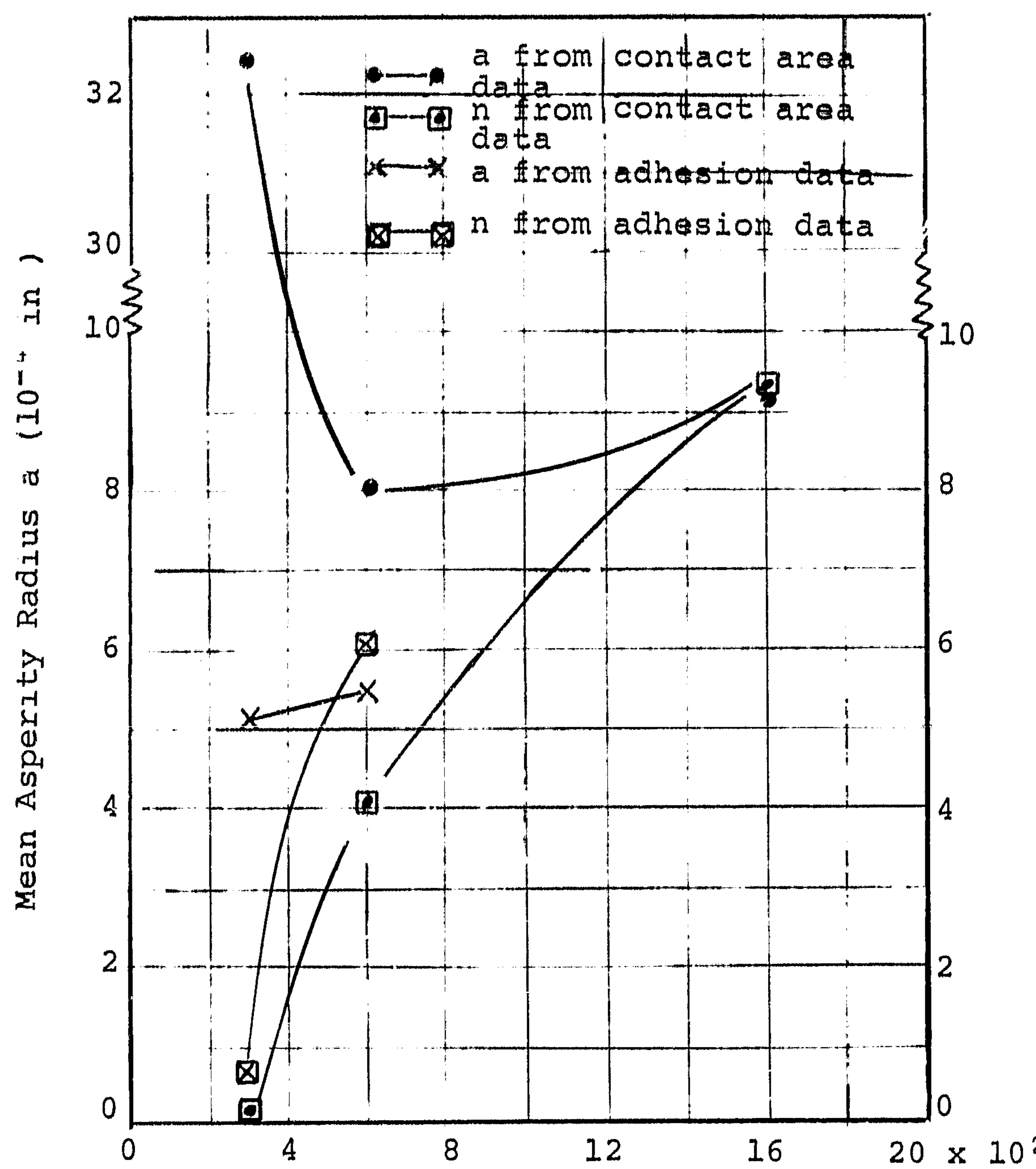

Fig. 21

The Dependence of the Number of Contact Asperities (n) and their Mean Radius (a) on the Applied Compressive Load.

TABLE II

ESTIMATES OF BONDED AREA FOR COPPER ADHESION SPECIMENS

Applied Load (lb)	Electrical Resistance* (OHMS x 10[illegible])	Contact Area (in^2 x 10^{-3})	Bonded Area (in^2 x 10^{-3})
250	1	3 4	-
600	0 1	8 4	5 7
1500	-	23 4	16 0

*An applied load of 1500 lb produced a junction where contact resistance was essentially zero The mean contact asperity radius of 9 x 10^{-4} in was calculated from the metallurgical observations

Further, detailed analysis of this data is not warranted at the present time since the contact junctions produced between two abraded surfaces are most certainly directional and the assumed gaussian distribution of the contact radii is not substantiated by metallographic observations These results do indicate however, that an approximate analysis of the geometry of the junction region is possible using the results of rigorously controlled experiments combining metallographic observation with electrical resistance measurements

Strain gage techniques to detect the start of a nonlinearity in the strain produced by the applied contact load indicated quite clearly that plastic strain had to be produced in the bulk specimen if the strength of the cold welded joint were to be measured by the proving ring assembly. The minimum amount of bulk plastic strain which had to be applied varied from about 2 x 10^{-5} in/in for copper to about 2 x 10^{-4} in/in for nickel

The difference in applied strain level necessary to produce residual adhesion may be attributed to the greater amount of elastic strain energy stored in deformed asperities of nickel than in copper during the compressive portion of the adhesion test. Upon release of the compressive load, a larger release of strain energy in nickel would act to rupture local bonded areas, thus lowering the residual permanent adhesion.

FUTURE WORK

Based on the experimental results of the present program and its forerunners, it is evident that aside from surface oxide contamination, the adhesion efficiency or capacity to bond of various metals is largely governed by metallic ductility and plastic flow Accordingly, it would be extremely fruitful to measure bonding efficiencies for a variety of metals as a function of plastic strain generated below the contact surface. On a normalized basis, such comparative data would not only indicate the relative ease of bonding of different metals, but would also serve as an engineering guideline in estimating the extent of adhesion likely to occur in a given contact stress condition. The plastic strain criterion would also be useful in permitting the effect of secondary parameters such as lattice structure, interatomic distance and chemical valency on adhesion to be distinguished.

A second major parameter which should be studied in further detail is the actual residual bonded area. As shown in the present work, the contact area increases proportionally to load and plastic flow Correlation of contact area estimates by metallographical techniques with adhesion force measurements can yield estimates of the actual adhesion strength

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