



Improved Brazing Methods for Tungsten Carbide Tool Bits

Joints of adequate strength can be made between tungsten carbide and steel using copper as a brazing filler metal

BY R. G. GILLILAND AND C. M. ADAMS, JR.

ABSTRACT. The fabrication of tungsten carbide-containing working tools has long relied on brazing as the joining method. This study has addressed itself to developing a better understanding of the more fundamental aspects, both metallurgical and mechanical, of this composite joint. The effort seemed justified since there still existed a significant incidence of field failures, larger tools were becoming more prominent, and mechanical joints have shown attractiveness.

The studies were performed using dissimilar joints of tungsten carbide and 4340 steel. Four filler metals were used to make the joint. Vacuum atmospheres were consistently utilized with heat sources being either electron beam or resistance-furnace. Room temperature mechanical property testing was performed using specially designed specimen holding assembly. Other studies were concerned with substrate wetting, braze joint metallographic and microprobe analysis, and fracture surface analysis.

The results of this study indicated that excellent liquid metal wetting can be accomplished on both tungsten carbide and steel surfaces. This is especially true when using pure (OHFC) copper as the filler metal. Most consistent results are

obtained when resistance heating is used.

Metallographic and electron beam microbeam probe analysis of the composite revealed only minor reactions between the substrates and the liquid metal. Mechanical property tests revealed many interesting facts about the behavior of a brazed joint during plastic deformation. Inhomogeneous strain was observed across the joint, with maximum deformation localized within the filler metal. Maximum shear strengths were found when using copper as a filler metal (30,000 psi), with maximum shear stress of the order of 1000%. Fractographic studies of the failed surfaces exhibited the characteristic features of ductile, simple shear.

Introduction

In the fabrication of rock drill bits and other tools which use tungsten carbide, generally the most satisfactory means for joining the carbide to a suitable back-up material, such as steel, is brazing. The techniques for producing such brazed joints are fairly well established and substantially successful. However, little is known, almost nothing in the fundamental sense, of the properties of such composites, nor of the influences of material and processing variables on these properties. Furthermore, brazed joints between carbide and steel still present some deficiencies. There is a significant incidence of failures in the field, espe-

cially as performance requirements are now becoming more severe, some of which can be associated with the brazed joint. Also, present methods and materials are fairly costly.

Current practices involve the use of an Ag-Cu-Cd-Zn-Ni brazing filler metal which has been selected primarily because:

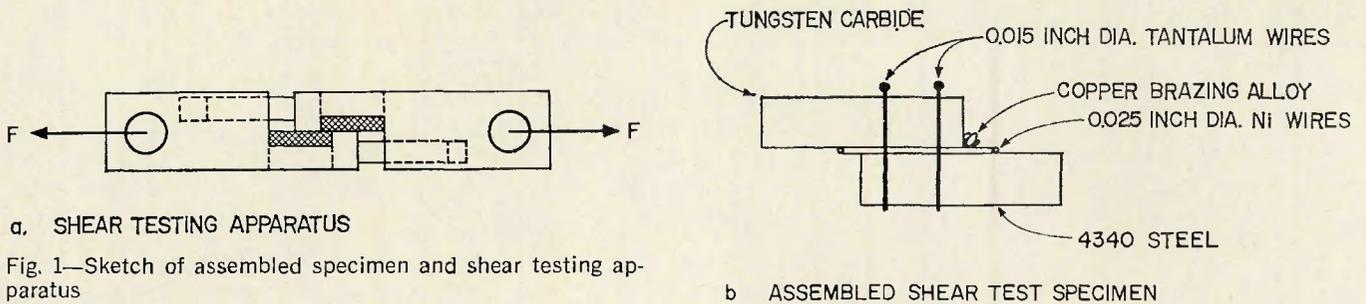
1. It has a conveniently low melting point.
2. It is metallurgically compatible with the materials being joined (in the sense that brittle intermetallic phases are not produced).
3. The small amount of nickel in the filler metal helps promote wetting of carbide.

This filler metal is, as a result, almost universal for brazing tungsten carbide.

A brazed joint between carbide and steel is mechanically very complicated. Three significantly different yield strengths, moduli of elasticity and thermal coefficients of expansion are involved. In an attempt to better understand such a complex assembly, a systematic study of the influences of material and processing variables on the properties of such joints has been conducted. The results of these investigations are outlined below.

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Materials, Apparatus, and Procedures

Studies were performed utilizing dissimilar brazed joints which consisted of tungsten carbide with a 6 wt-% cobalt binder and 4340 steel. The brazing filler metals used were confined to pure copper and silver, 82 Au-18 Ni (wt), and 74 Ag-28 Cu (wt). The flow points of these filler metals (temperature at which brazing is accomplished) are listed in Table 1.

All brazing operations were conducted in a vacuum atmosphere utilizing either electron beam heating or resistance-furnace heating. Room temperature mechanical property testing was performed using either a hydraulically actuated or a mechanically operated tensile machine capable of testing at a constant strain rate. A specially designed specimen-holding

assembly was fabricated to shear test the brazed specimen. Descriptive drawings are shown in Fig. 1. This part is designed such that little or no rotation of the sample occurs during testing and, thus allows the deformation and fracture modes to approach pure shear.

The procedure for assembly of braze specimens consisted of thoroughly cleaning (acetone) and polishing (8/0 sandpaper) all surfaces to be wet by the brazing filler metals. When required, pure nickel wires of appropriate diameters were used to space the joint prior to brazing. All specimens were wired together using 0.015 in. diameter tantalum, which provided a very tight assembly at brazing temperature. When assembled the brazing specimen was of the lap-joint design with a 1/2 in. overlap; both tungsten carbide and steel parts had a 1/4 in. square cross-section. All brazing cycles were for a duration of 10 min at

brazing temperatures.

After brazing selected joints were submitted to routine metallographic procedures and examination. Other samples were subjected to electron microbeam analysis for microchemical analysis determinations.

Results

The results of the investigations concerned with substrate wetting, various heat sources for brazing, braze joint metallographic and electron microbeam probe analysis, and room-temperature shear strength testing are outlined below.

Wetting Studies

Early in the study it was supposed that an enhancement of the wetting characteristics of tungsten carbide composites would allow the use of a wider variety of brazing filler metal compositions. As a result, since earlier work¹ had shown that enhanced wet-

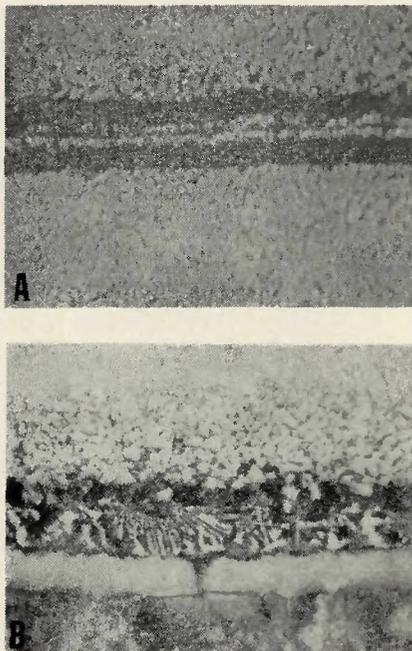


Fig. 2—Electron beam vapor coated tungsten carbide braze joints. A—tungsten carbide to tungsten carbide joint precoated (each surface) with approximately 5 microns of titanium and brazed with pure silver. X500 (reduced 42% on reproduction). B—tungsten carbide (top) to 4340 steel brazed with pure copper. The carbide was precoated with approximately 0.5 microns of titanium. X1000 (reduced 40% on reproduction)

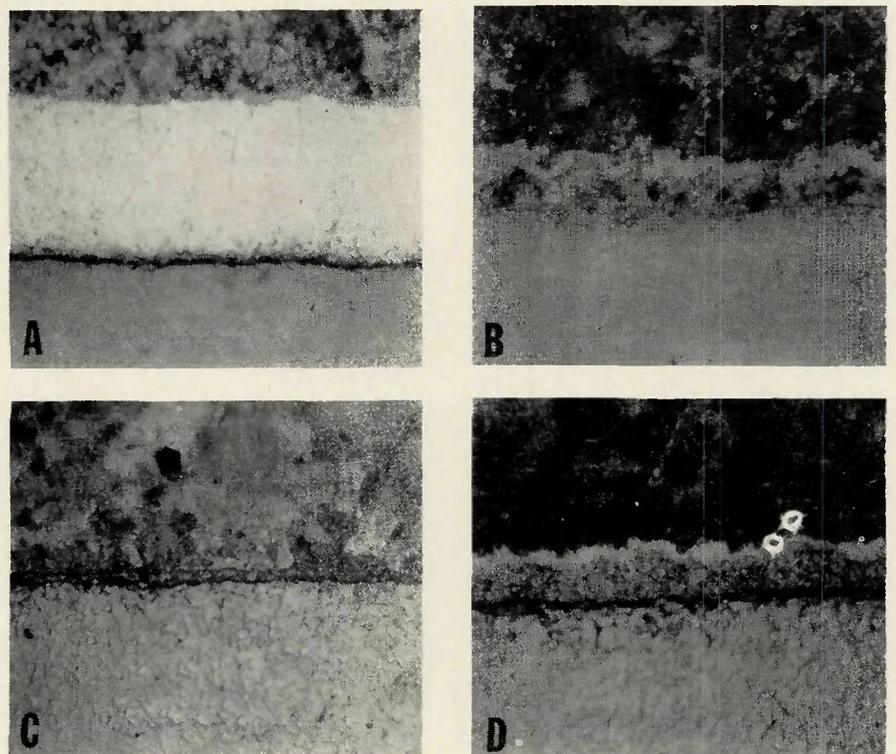


Fig. 3—Electron beam brazed joints between tungsten carbide and 4340 steel (top) without vapor coating using: A—Ag-Cu; B—Au-Ni; C—silver; D—copper filler metals. All joints are "zero clearance" specimens. Etchant: 1% nital. X1000 (reduced 28% on reproduction)

ting behavior was obtained when difficult-to-wet surfaces were pretreated with electron beam vapor coatings of titanium and/or zirconium, this technique was studied and compared with brazing filler metal wetting and flow of uncoated tungsten carbide.

Results of these experiments indicated that all the brazing filler metals incorporated in the study exhibited excellent wetting and flowing properties on this joint combination. It was found that the presence of a titanium coating is not required in order to promote wetting and flow on tungsten carbide, at least when brazing in a vacuum atmosphere. In all cases, wetting and flow was almost instantaneous, whether brazing in a muffle-type, tube furnace or using a diffused electron beam source.

Representative microstructures of titanium vapor coated specimens are presented in cross section in Fig. 2, note the tunnelling of the silver brazing alloy under the vapor coating of Fig. 2A. The microstructures of joint cross-sections of uncoated tungsten carbide to steel joints are shown in Fig. 3, using Ag-Cu, Au-Ni, pure silver and copper as brazing filler metals.

Mechanical Property Study

A major portion of this investigation was addressed to the determination of the room temperature shear strengths of braze joints between tungsten carbide composites and steel. Variables incorporated in this particular phase of the study were the effects of brazing filler metal composition and joint clearance. Initial studies also included the variable of heating source (electron beam resistance heating).

A summary of all mechanical property tests is presented in Table 1. It should be noted that only a limited

Table 1—Summary of Shear Strength Mechanical Property Study

Filler metal	Flow point °C (°F)	Joint clearance, in.	Heating method ^a	Ultimate stress, ^b psi
Au-Ni	980 (1795)	0.000	EB	23,750 (2)
		0.000	Furnace	27,800 (4)
		0.005	Furnace	31,200 (3)
Silver	990 (1815)	0.000	Furnace	5,930 (3)
		0.005	Furnace	17,100 (3)
Ag-Cu	810 (1490)	0.000	EB	9,800 (1)
		0.000	Furnace	14,475 (4)
Copper	1100 (2015)	0.000	EB	20,400 (2)
		0.005	EB	29,990 (4)
		0.000	Furnace	18,960 (6)
		0.005	Furnace	34,570 (5)
		0.010	Furnace	33,625 (2)
		0.015	Furnace	38,770 (6)
		0.020	Furnace	32,870 (6)
		0.025	Furnace	32,250 (4)

^a EB—diffused electron beam heating; Furnace—resistance heated, vacuum muffle furnace.

^b Number of tests indicated in parentheses.

amount of testing was done on joints brazed with filler metals other than pure copper. The primary reason for this was relative expense of gold and silver-bearing filler metals compared with copper, thus inhibiting their ultimate utilization in practical application in the tool bit industry.

The variation of joint clearance was observed to cause only slight differences in the ultimate shear strengths in all joint-filler metal combinations. A plot of joint clearance versus ultimate shear strength is shown in Fig. 4 for copper brazed tungsten carbide to steel joints.

The use of electron beam heating does not greatly affect the ultimate strength of copper brazed joints, although some reduction in strengths are observed when brazing with the other filler metals (Table 1) or when the joint clearance is greater than zero. (A "zero joint clearance" is produced by using no joint spacers.) The plot of Fig. 4 indicates that highest

strengths are obtained when a 0.015 in. joint clearance is used for copper brazes; although, with the exception of the zero clearance tests, the variation in strength is less than 7,000 psi for joint spacings between 0.005 in. and 0.025 in. These tests were performed using variable strain rates.

During the course of the shear testing program very large amounts of plastic strain were observed before failure occurred; some linear elongations were as high as $\frac{3}{16}$ in. An indication of the amounts of shear strain involved with such large linear elongations is exhibited in Fig. 5. This shear test sample was copper brazed and stressed to greater than 90% of its ultimate shear strength, at which point the specimen was unloaded. These observations prompted the use of a more accurate test and samples of varying joint clearance were prepared for testing at a constant strain rate on an automatically recording testing machine. Higher magnification pictures of the homogeneous strain shown macroscopically in Fig. 5 are shown in Fig. 6. These views are from polished specimens which have

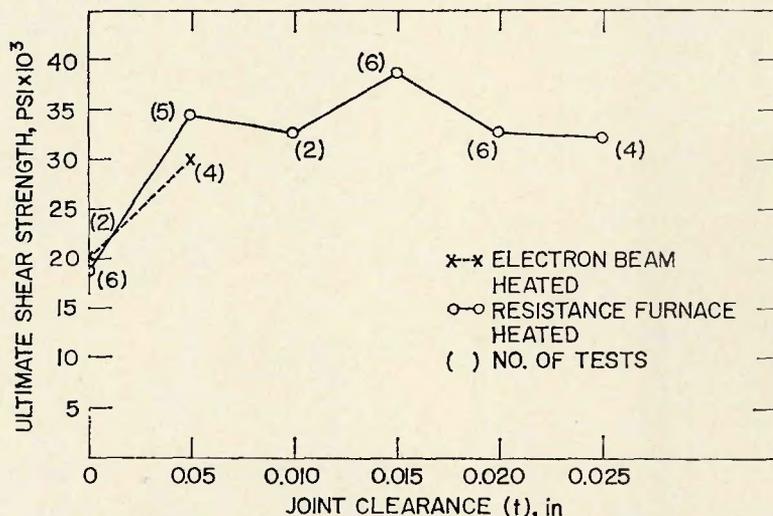


Fig. 4—Ultimate shear strength vs. joint clearance for copper brazed steel-WC joints (tested at room temperature with variable strain rates)

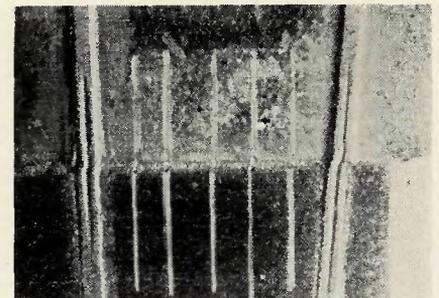


Fig. 5—View of tungsten carbide (top) to 4340 steel brazed with pure copper with a 0.005 in. clearance and stressed to approximately 90% of the joint ultimate before unloading. X6 (reduced 41% on reproduction)

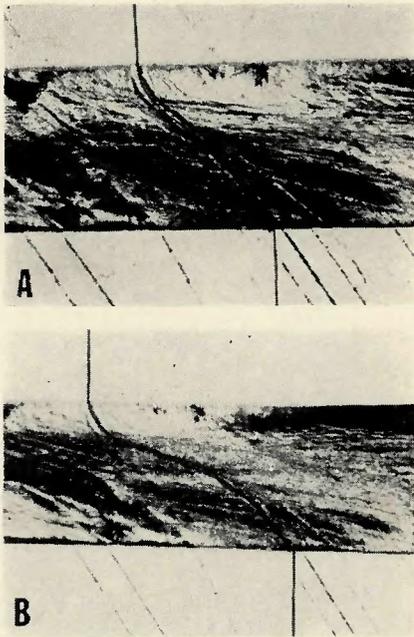


Fig. 6—Microscopic views of the progressive deformation of a copper brazed 4340 steel/tungsten carbide joint, as exhibited by the displacement of a scribed line across the joint. The width of the joint is 0.010 in. Note the inhomogeneous strain across the joint in both A— $\gamma = 0.73$ in./in.; B— $\gamma = 1.28$ in./in.

been progressively strained to failure after a line has been scribed across the joint.

The results of these limited tests permitted the calculation of true shear stress-true shear strain curves. The shear strain, γ , was calculated, as shown in Fig. 7, by recognizing that the shear strain equals the tangent of the angle of shear, θ , or the linear elongation, Σ , divided by the joint clearance, t . The instantaneous area of shear was calculated by first assuming no change in joint width during the test and determining the varying joint length by subtracting the recorded elongation, Σ , from the original length of the shearing surface. A tabulation of the results for shear strength tests on copper brazed speci-

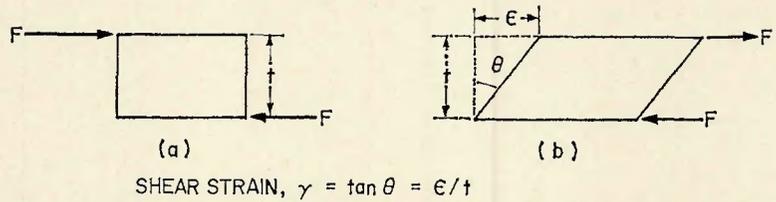


Fig. 7—Diagram of copper in joint illustrating deformation behavior and true shear strain calculation

Table 2—Summary of Shear Test Data on Copper Brazed Steel—WC Joints with a Constant Strain Rate of 0.01 ipm

Joint clearance, in.	Ultimate engineering shear strength, psi ^a	Fracture engineering shear strength, psi	Fracture shear elongation-in. (total)	Fracture shear strain-in./in. (total)
0.000	26,700 (1)	26,700	0.010	6.67
0.005	28,800 (1)	25,750	0.021	4.20
0.010	33,625 (2)	22,800	0.049	4.90
0.015	31,300 (1)	23,500	0.050	4.00
0.020	33,200 (2)	19,400	0.066	3.30
0.025	29,700 (2)	18,450	0.082	3.28

^a Number of tests indicated in parentheses.

mens strained at a rate of 0.01 ipm is presented in Table 2.

The load vs. elongation curves, presented in Fig. 8, are illustrations of the data shown in Table 2. Using the technique described above, true shear stress-true shear strain curves were calculated and are presented in Fig. 9 for the various joint clearances. The data reported here have been corrected for machine and testing apparatus straining. These curves indicate that maximum fracture stress and strain was observed with "zero clearance" joints (the spacing of "zero clearance" joints was determined metallographically to be approximately 0.0015 in.).

A close examination of Table 2 and the curves of Fig. 9 will reveal that fracture elongations of 0.082 in. and percent strains of greater than 660% were observed in these tests. A representation of these shear parameters is shown in Fig. 10. These curves of shear strain and elongation versus joint clearance graphically illustrate

the large amounts of deformation observed in these tests.

These observations of large inhomogeneous shears are and have been the subject of considerable research interest.²

For comparative purposes, the microstructures of joint cross sections of copper brazed specimens at the different clearances are shown in Fig. 11. These microstructures are typical and are analyzed in the section to follow.

Electron Micro-Probe Examination

Two copper brazed specimens were prepared and submitted for electron microbeam probe examination. Local concentrations and concentration distributions of Cu, Co, Ti, W, and Fe have been examined in one or the other of the samples. The results are graphically represented in Fig. 16–18. The trace shown in Fig. 12 is noted on the micrograph of analyzed area in Fig. 13. All intensities reported have not been corrected for fluorescence,

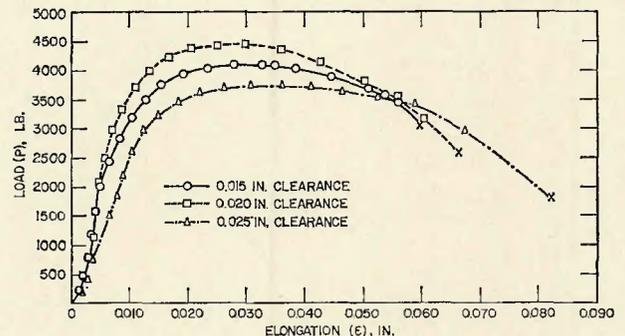
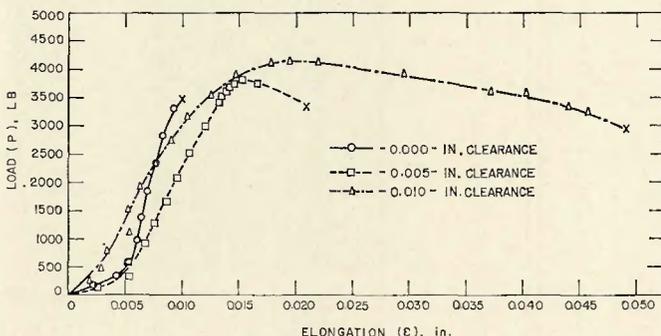


Fig. 8—Load vs. elongation curves for: A (left)—0.000 in., 0.005 in., and 0.010 in. clearance joint in copper brazed tungsten carbide-4340 steel lap joint specimens; B (right)—0.015 in., 0.020 in., and 0.025 in. clearance joint in copper brazed tungsten carbide-4340 steel lap joint specimens

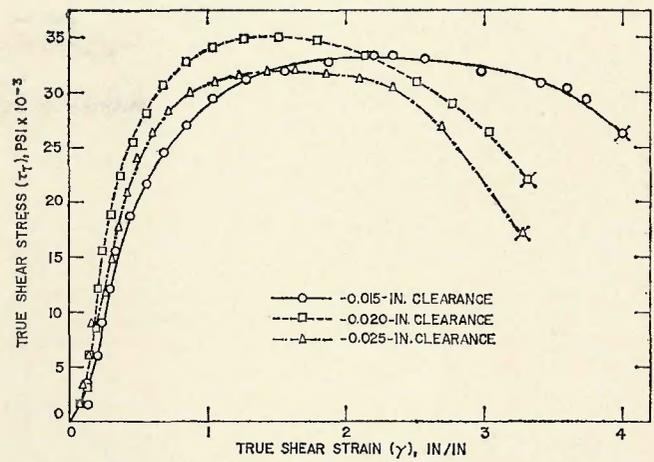
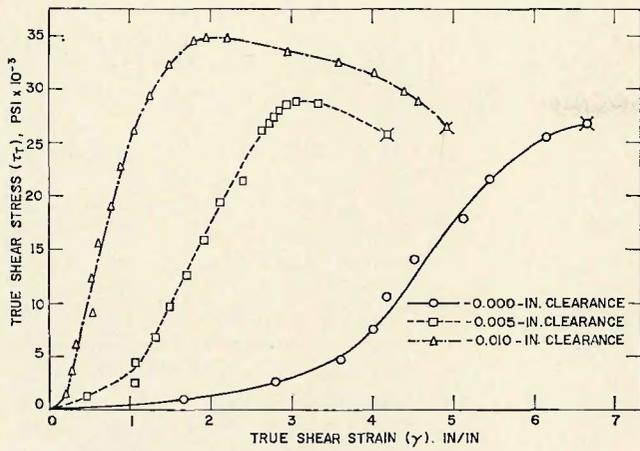


Fig. 9—True shear stress-true shear strain curves for: A (left)—0.000 in, 0.005 in and 0.010 in. joint clearances in copper brazed tungsten carbide-4340 steel lap joint specimens; B (right)—0.015 in., 0.020 in., and 0.025 in. joint clearances in copper brazed tungsten carbide-4340 steel lap joint specimens

absorption, or machine alignment errors.

As seen in Figs. 12 and 13, the titanium coating was not observed in the analysis of the interface (sample number IR-11). Also, in this sample the copper brazing alloy was virtually excluded from the joint and could only be found in the fillet area shown in Fig. 15. The joint area was observed, in Fig. 13 and 16, to contain a ternary alloy of Fe, Co, and W in approximate ratios of 2 parts, 1 part, and 1 part, respectively. In the uncoated sample (No. IR-14), a zone is observed at the tungsten carbide filler metal interface (Figs. 14, 17, and 18) which is iron-base, containing Co and Cu with a small amount of tungsten. These reactions are not

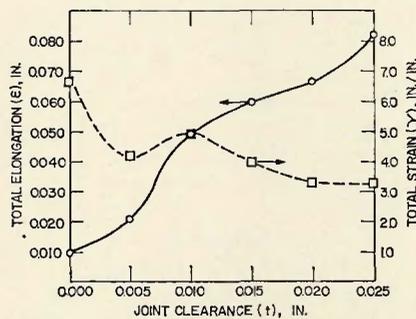


Fig. 10—Total elongation and total strain vs. joint clearance for copper brazed steel-WC joints (tested at room temperature using a constant strain rate of 0.01 ipm)

deleterious effects to the joint strength and deformation (at least in the uncoated specimens).

The area scans of Figs. 16–18 are accompanied by light micrographs representative of the area of analysis which indicate the path of the element traces of Fig. 12–14. These area scans lend further support to the element distributions observed in the traces and aid in the identification and analysis of the composition of the various phases present in the microstructures.

Fractographic Analysis

Selected samples were fractured and submitted for replication and electron microscopic analysis of the fractured surface. A representative

uncommon in dissimilar brazed joints and apparently have not caused

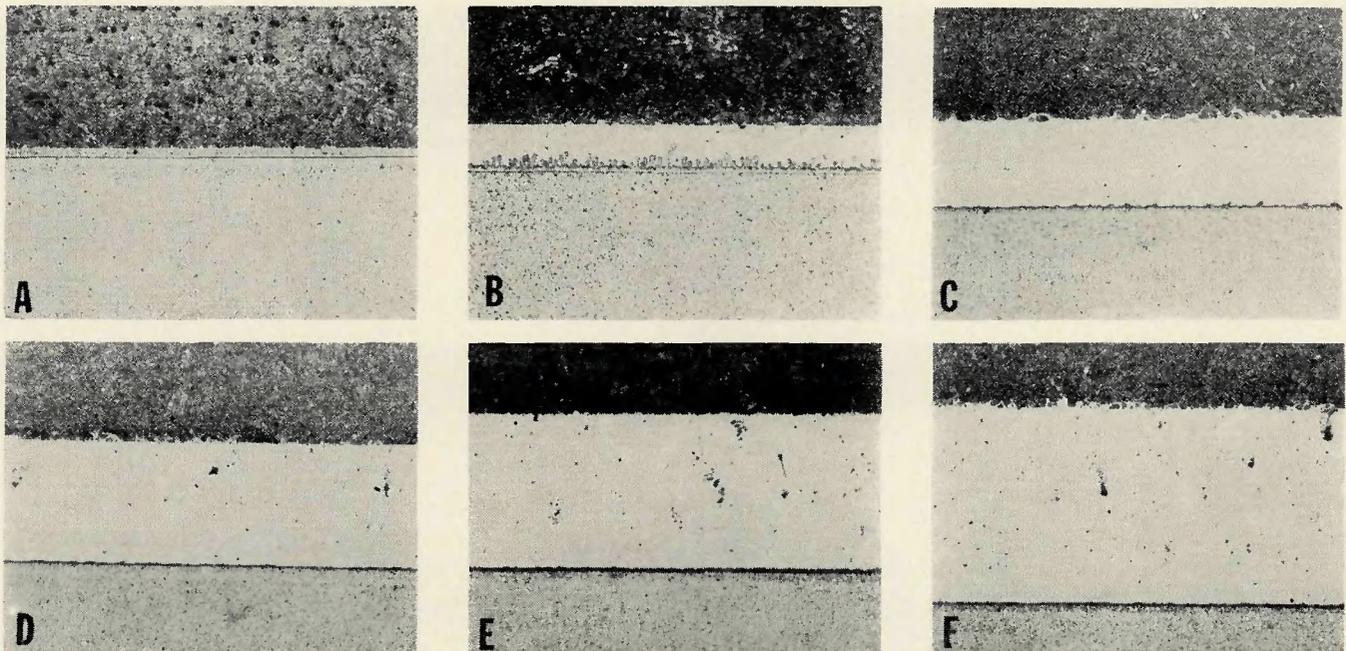


Fig. 11—Microstructure of copper brazed tungsten carbide (bottom) to 4340 steel joints at various clearances. Brazed in vacuum at 1100° C using resistance heating. A—0.000 in.; B—0.005 in.; C—0.010 in.; D—0.015 in.; E—0.020 in.; F—0.025 in. Etchant: 1% nital. X75 (reduced 28% on reproduction)

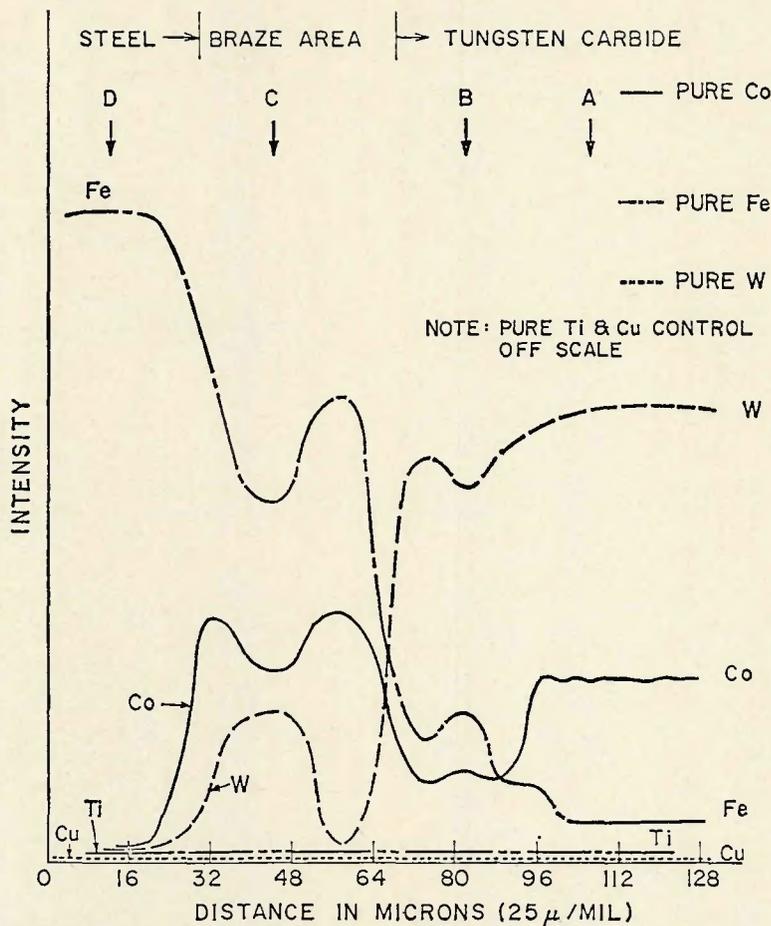


Fig. 12—Electron microprobe traces across sample No. IR-11 (Ti coated surface) shown in Fig. 15. The indicated positions are points of intensity read-outs

micrographic from this study is shown in Fig. 20. Note the classical simple shear features, as exhibited by coalescence of voids generated at the sites shown.

Discussion of Results

As stated above, the use of electron beam vapor coatings was not found necessary to provide capillary flow in braze joints of this combination. The electron beam heated sample, No. IR-

11, which was coated with approximately a 0.5 micron thickness of titanium, exhibited a unique microstructure (Fig. 16a). A comparison of Fig. 2B and Fig. 19 will reveal that the eutectic-like structure is exhibited in only the titanium vapor coated sample. The duplex, two-phase structure is difficult to explain using the microprobe data obtained. The presence of a higher percentage of tungsten in the coated sample, relative

to the uncoated sample (No. IR-14), suggests that this duplex structure might be representative of one of the two-phase regions found in the Fe-W system.

In addition, the initial presence of titanium at the tungsten carbide interface could have resulted in increased reaction with carbon by the carbide forming elements present (Fe, Ti, and W). In any event, it is obvious that the initial presence of titanium has caused more interfacial reaction to occur, resulting in a more complicated microstructure than when no vapor coating was performed. Unfortunately, carbon cannot be detected with the microprobe equipment available and the amount of titanium present was below analysis accuracy.

The zone metallographically observed at the filler metal-tungsten carbide interface of uncoated, copper-brazed samples (Fig. 17a) can more easily be understood. At 1100° C, copper will dissolve about 3 wt% iron or about 4 wt% cobalt. On solidification, a copper-base ternary alloy will contain small amounts of iron and cobalt. This inversion of the copper-rich liquid alloy to an iron-cobalt rich solid alloy is caused by the large solid-liquid region existing almost the entire length of the phase diagram in both the Fe-Cu and Co-Cu binary alloys. The position of this solidified zone is explained by the much higher coefficient of thermal conductivity possessed by the tungsten carbide. The thermal conductivity of tungsten carbide plus 6% cobalt is about 42.5 BTU/ft-hr-° F, which is twice as high as plain carbon steel.

It was observed early in the testing program that using the electron beam as a heat source produced joints exhibiting fluctuating strength data. The observation that numerous voids and inadequate brazing filler metal flow

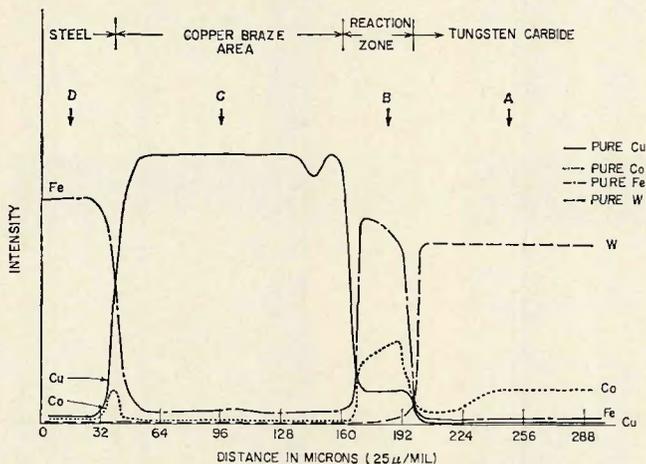


Fig. 13—Electron microprobe traces across sample No. IR-11 (Ti coated surface) as shown in Fig. 16. The indicated positions are points of intensity read-outs

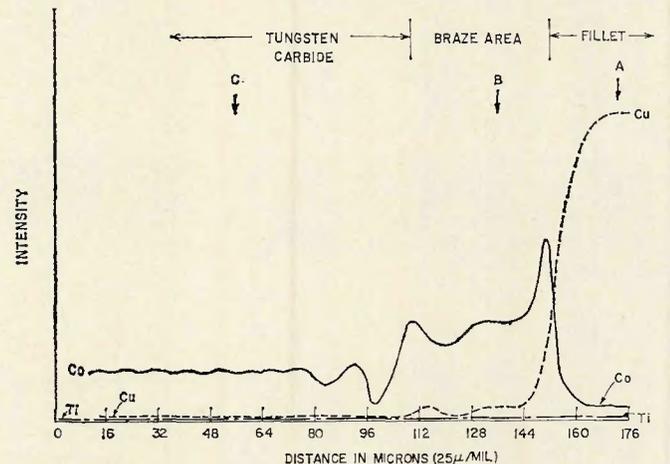


Fig. 14—Electron microprobe traces across sample No. IR-14 (uncoated surface) as shown in Figs. 17 and 18. The indicated positions are points of intensity read-outs

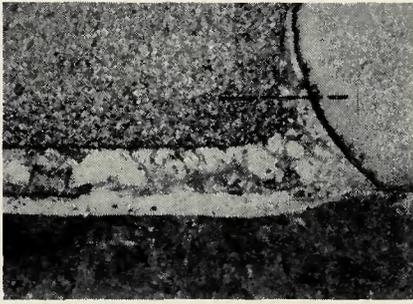


Fig. 15—Micrograph of copper brazed WC/steel joint. The WC had been vapor coated prior to brazing with approximately 0.5 microns of Ti. Note indication of trace. Etchant: 1% nital. X1000 (reduced 42% on reproduction)

were a characteristic of electron beam brazed joints was considered to be the major cause of these strength variations. It should be pointed out that, while this heat source did not exhibit good joint-producing qualities in this study, greater care in technique as to uniform heat distribution, maximum temperature control, etc. would probably reverse the noted experimental results. If such techniques were more fully developed and refined, one could efficiently use such advantages as rapid and localized heating and easy visual observation during brazing.

The curves of Fig. 9, showing true shear stress vs. true shear strain for various joint clearances, offer some speculation as to their general form. Normally, true stress-true strain curves do not exhibit a decrease in stress as strain increases, mainly because rapid reduction in cross sectional areas of the specimen compensates for the fall in load near the end of the test. It is believed that the data presented from this study suffer from the inability to determine the true cross sectional area of the specimen during the latter part of the shear test. It has been metallographically verified that numerous microcracks and porosity are nucleated after the maximum load has been observed. In addition, the fractographic studies support the generation of voids and ultimate reduction of joint cross section when coalescence of these voids occur. Thus, the decrease in area by crack and porosity formation in addition to the decrease in shear surface length (as discussed earlier) would probably result in a curve shape which more closely agrees with the normal true stress-true strain plot.

The reduction of true shear stress has been called "strain softening," but such effects are not believed to have been observed in copper. Therefore, it is assumed that if the true area could be determined the plot of true shear stress versus true shear strain would exhibit a normal behavior.

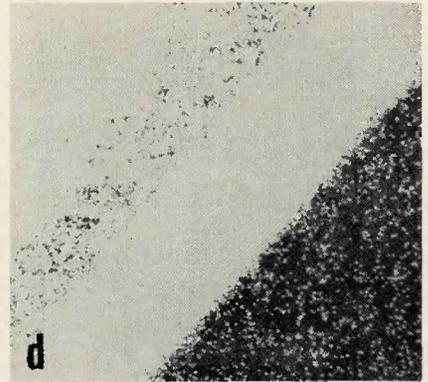
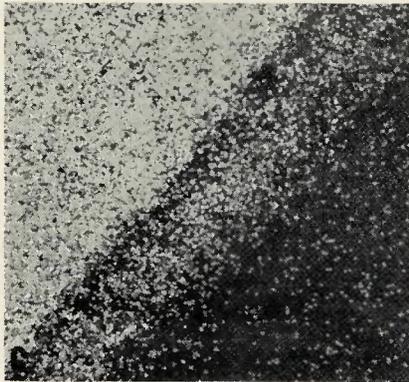
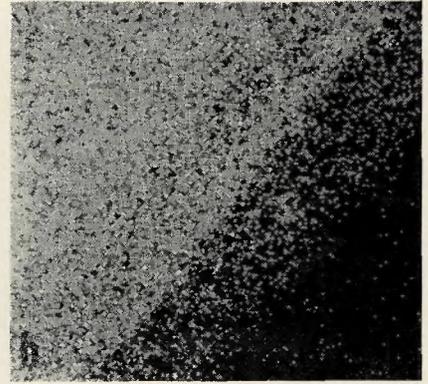
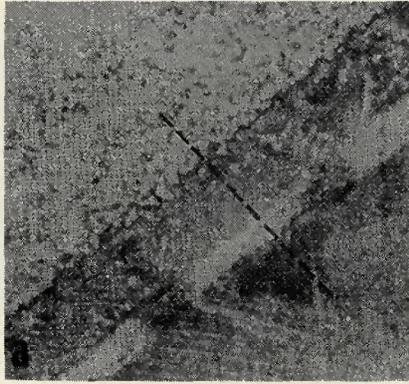


Fig. 16—Area scans for (b) tungsten, (c) iron, and (d) cobalt at a position on sample No. IR-11 similar to that shown in (a). The trace shown in Fig. 13 is indicated on this titanium coated sample: 1% nital. X350 (reduced 21% on reproduction)

The abnormally large amounts of plastic shear strain exhibited by the copper brazed joints was a most pleasant surprise and suggests that this material possesses excellent properties

necessary to absorb the mechanical shocks constantly experienced during rock drilling operations. In addition, it should be noted that strength is not regarded as a criterion of significance

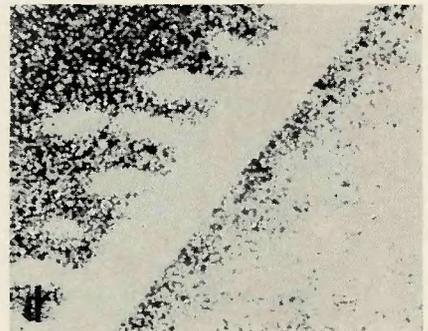
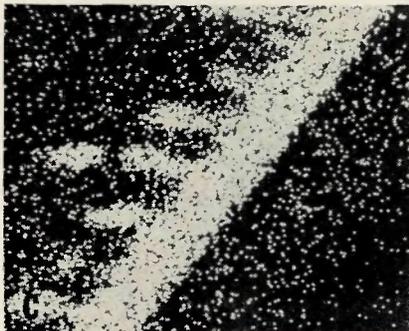
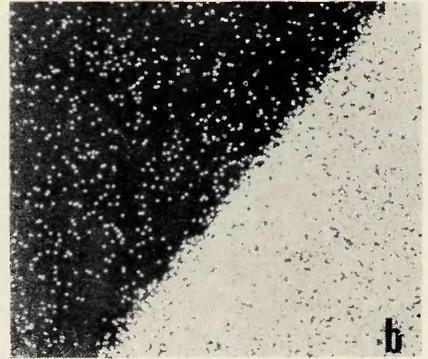
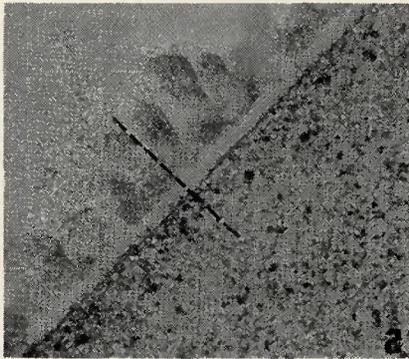


Fig. 17—Area scans for (b) tungsten, (c) iron, and (d) cobalt to a position on sample No. IR-14 similar to that shown in (a). The trace shown in Fig 14 is indicated. This sample was uncoated with a 0.005 in. joint clearance. Etchant: 1% nital. X350 (reduced 23% on reproduction)

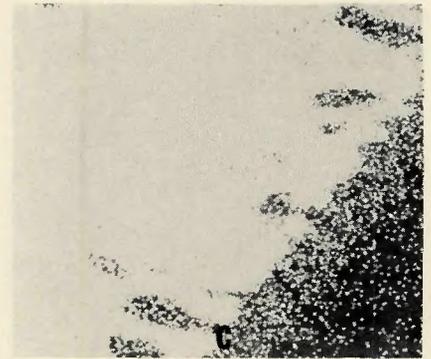
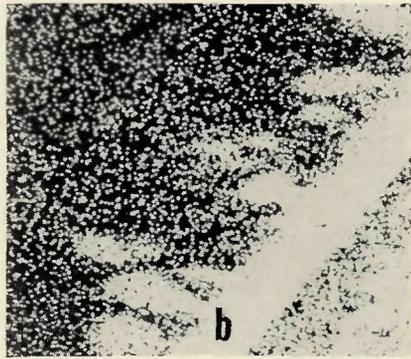
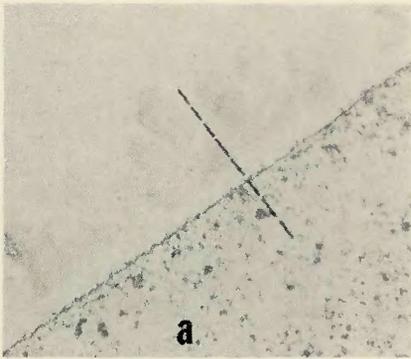


Fig. 18—Area scans for (b) cobalt and (c) copper at a position on sample No. IR-14 similar to that shown in (a). Etchant: 1% nital. X350 (reduced 28% on reproduction)

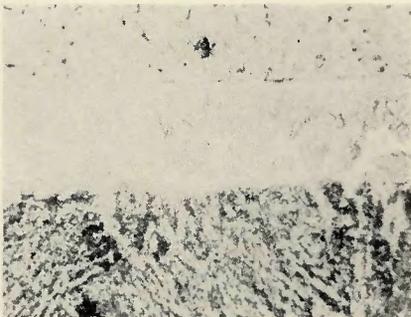


Fig. 19—The cross section at higher magnification of Fig. 10A. Note the large amount of the precipitated phase in the "zero clearance" joint. Etchant: 1% nital. X1000 (reduced 38% on reproduction)

in a brazing filler metal. More important is the ductility and location of fracture. In this connection, all failures were observed to occur within the braze, which is preferred to failure at the braze-base metal interface or even in the base metal. Indeed, sometimes the lower the strength of the brazing filler metal, the better the service performance. Therefore, the use of copper as a brazing filler metal to join tungsten carbide to steel exhibits not only a very high shear ductility but also a reasonable ultimate strength of the order of 35,000 to 40,000 psi.

Conclusions

The results of this investigation allow the following conclusions to be made:

1. Joints of adequate strength can

be made between tungsten carbide and steel using copper as a brazing filler metal. Copper is both inexpensive and easy to use in comparison with most other brazing filler metals.

2. No fluxes or special pre-braze surface preparations (i.e., vapor coated titanium surface films) are required to provide wetting and capillary flow on tungsten carbide when performing brazing operations in a vacuum atmosphere.

3. Most consistent results were obtained when brazing operations were performed in a vacuum atmosphere using resistance heating, rather than a diffused electron-beam heating source.

4. Joint strengths (both ultimate shear strength and fracture strength) were found to vary slightly with joint clearance, reaching a maximum between 0.010 and 0.020 in. clearance. No explanation is yet available to define this phenomenon, but current investigations at the M. I. T. Welding Laboratory suggest that the restraint provided by the base metal, in part, effects these results.

5. Extraordinary elongations and shear strains were observed during shear deformation of these joints. Elongations before fracture as high as $\frac{3}{16}$ in. and per cent strains above 660% were first seen when testing using variable strains. Later similar values were obtained using a constant 0.01 ipm strain rate. The large amounts of plastic deformation indicate that copper-brazed joints would be highly suited to rock drilling appli-



Fig. 20—The fracture surface of a copper brazed 4340 steel/tungsten carbide joint deformed in shear. Note the elongated voids (dimples) prominently displayed on the fracture surface. The arrow indicates the direction of applied force

cation, since such joints can thereby absorb the mechanical shock of a bit slamming into solid rock.

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