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Summary

An investigation was conducted on the weldability of continuous tungsten fiber-reinforced copper matrix (W-Cu) composite sheet. The main thrust of this study was to fabricate and tensile test actual and simulated welded joints to determine the potential use of simulated welded joints in the design and application of W-Cu and other composite materials.

The simulated joints were fabricated concurrently during the consolidation of the composite panels by vacuum hot pressing. In the simulated welded joints, interruptions (breaks) in the continuous W fibers simulated those present in actual welded composites. The actual welded joints were produced in a vacuum hot press by diffusion welding and brazing. Metallographic examination revealed the presence of flaws in all of the actual welded joints; however, tensile tests indicated that at room temperature and at 250 °C, a number of these were as strong as the W-Cu composite base material. This study illustrates that simulated joints can provide strength and failure mode data which can be used in the subsequent design and application of actual weldments.

Introduction

Continuous tungsten fiber-reinforced copper matrix (W-Cu) composites have been studied as a model composite system in a series of research programs at the NASA Lewis Research Center (ref. 1). Welding W-Cu composites was excluded from these previous studies and limited information about welding metal matrix composites is available in the literature. However, it is known that the interruption of fiber continuity causes the main problem in joining metal matrix composites (ref. 2) because the fibers carry most of the load.

The majority of this work involved fabricating and tensile testing simulated joints in the W-Cu composite. These simulated joints were produced during consolidation of the composite panels. Breaks in the W fibers were aligned at preplanned locations that corresponded to those in actual welded joints. Simulated lap-butt joints and tongue-in-groove (TG) butt joints were produced with and without joint doublers for mechanical property testing. In this study, the effect of joint design on the strength and failure mode of simulated and welded butt joints in W-Cu composite sheet using three- and four-ply materials with unidirectional W fibers was determined.

The tensile test results from the simulated joints were used to design joints for the actual welding trials accomplished by using diffusion welding and brazing processes. In the welded joints, the objective was to weld the Cu matrix to itself. Although a specific amount of fiber overlap was present in each joint, no attempt was made to produce fiber-fiber welds. Several methods were investigated for improving joint integrity including Cu-foil interlayers and Cu-sputtered coatings. Various filler metals in the form of foils or sputtered coatings were also investigated. The resulting joints were evaluated on the basis of joint efficiency, failure mode, and microstructure. This study revealed that if simulated joints are successfully produced in composites, valuable information concerning their behavior can be obtained without producing actual joints.

Experimental Procedure

Fabrication of Materials and Panel

The W-Cu composites used in this study were fabricated using the arc-spray process developed at Lewis (ref. 3). The first step in fabricating composite panels was to produce a monotape consisting of a single layer of W fibers in a Cu matrix. Commercial W wire (designated 218CS by the manufacturer) with a nominal diameter of 200 μm was wound on a drum at a spacing of approximately 41 fibers/cm. Oxygen-free, high-conductivity (OFHC) Cu was then arc-sprayed onto the surface of the rotating wire-wrapped drum (ref. 3), forming one side of the monotape. The monotape was then removed from the drum and rewrapped so that the back face could be sprayed with Cu to complete the spraying process.

Three- and four-ply panels were prepared by stacking layers of the monotape in Mo tooling for subsequent consolidation by vacuum hot pressing. In a typical run, the chamber pressure during the 45-min ramp from room temperature to the 1000 °C pressing temperature was approximately $4x10^{-2}$ Pa. Upon reaching 1000 °C, the 34.5 MPa pressing pressure was applied, held for 20 min, and maintained during the cooling cycle. During the hold time at 1000 °C, the chamber pressure decreased from about $4x10^{-2}$ Pa at the start of the hold to about $7x10^{-3}$ Pa at the end. The consolidated panels were nominally 50 mm wide by 160 mm long with unidirectional fibers in each ply parallel to the length. Doublers with one or two plies of unidirectional fibers were made by similar procedures and used in the preparation of welded joints. After consolidation, individual plies were about 0.28 mm thick with 46 vol% W in a Cu matrix.

Fabrication of Simulated and Actual Joints

Simulated TG- and lap-butt joints were fabricated in panels by aligning breaks in the W fibers at preplanned locations. The TG-butt was selected because the joint does not rotate during tensile testing. In contrast, the lap-butt joint was selected because it rotates and produces a combination of bending and tensile stresses at the joint. The sketch of a consolidated panel in figure 1(a) represents a simulated TG-butt joint in a three-ply panel with single-ply doublers. In this longitudinal thickness section, five layers of monotape were required to form the simulated joint. A sketch of the actual welded joint fabricated from previously consolidated panels and doublers joined at Cu-Cu interfaces is shown in figure 1(b).

A simulated lap-butt joint in eight-ply W-Cu sheet is shown in a longitudinal thickness section sketch in figure 2(a). The actual four-ply welded butt joint made from preconsolidated panels and two-ply doublers is shown in figure 2(b).

The sketches in figures 3(a) and (b) illustrate how as-sprayed W-Cu monotapes and AISI 1010 steel inserts were assembled to form actual TG- and lap-butt joint configurations. After consolidation, the steel inserts were removed by selective leaching in hot, dilute sulfuric acid. No post consolidation machining of the joints was required. Photomicrographs of separate tongue and groove components and of a tongue inserted into a groove are shown in figure 4.

Welding of Butt Joints

Welded butt joints were produced by diffusion welding and diffusion brazing in a vacuum hot press. For convenience and in conformance with American National Standards (ref. 4), both processes are referred to herein as welding processes. The welding procedures and parameters are shown in table I. Pressure at the doublers, during both

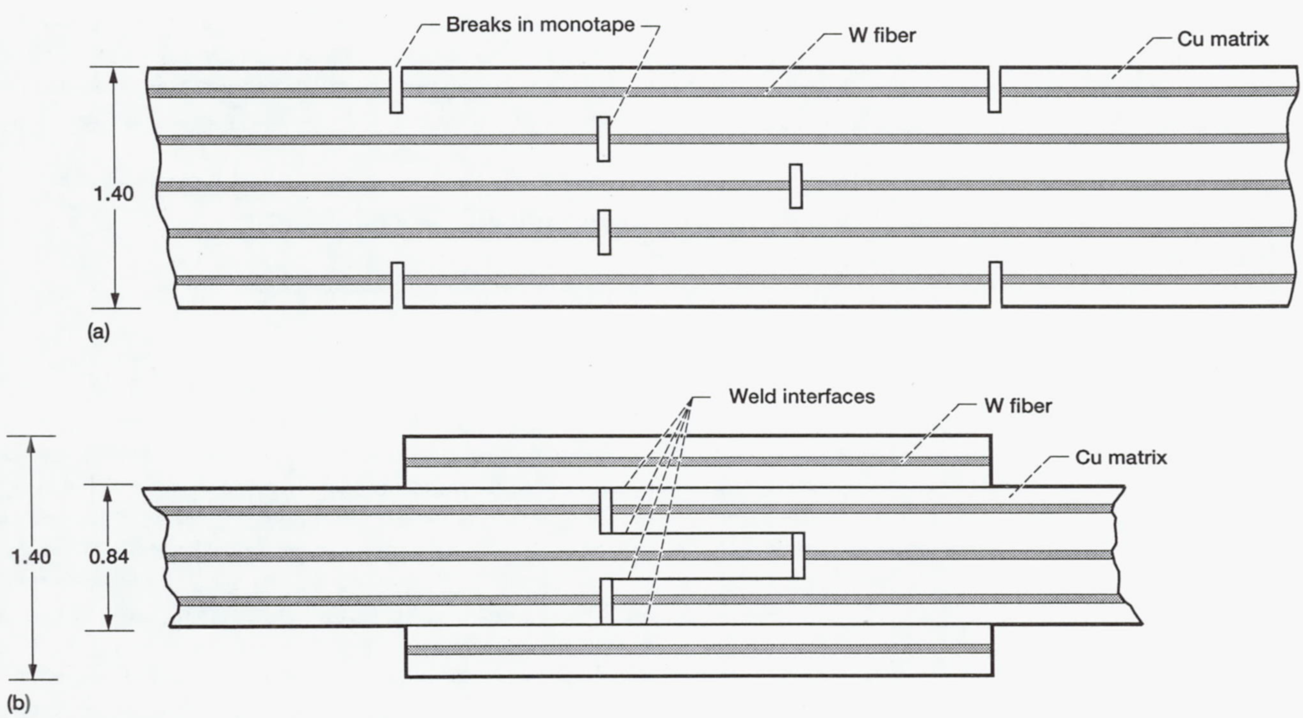


Figure 1.—Longitudinal thickness sections of simulated and welded tongue-in-groove butt joints in three-ply W-Cu sheet with single-ply doublers. Typical tongue length is 6 mm and doubler length is 20 mm. (Not to scale.) (a) Simulated joint in five-ply composite material in as-consolidated condition without weld interfaces. (b) Actual welded joint with consolidated tongue, groove, and doubler components joined at Cu-Cu weld interfaces. (Dimensions are in mm.)

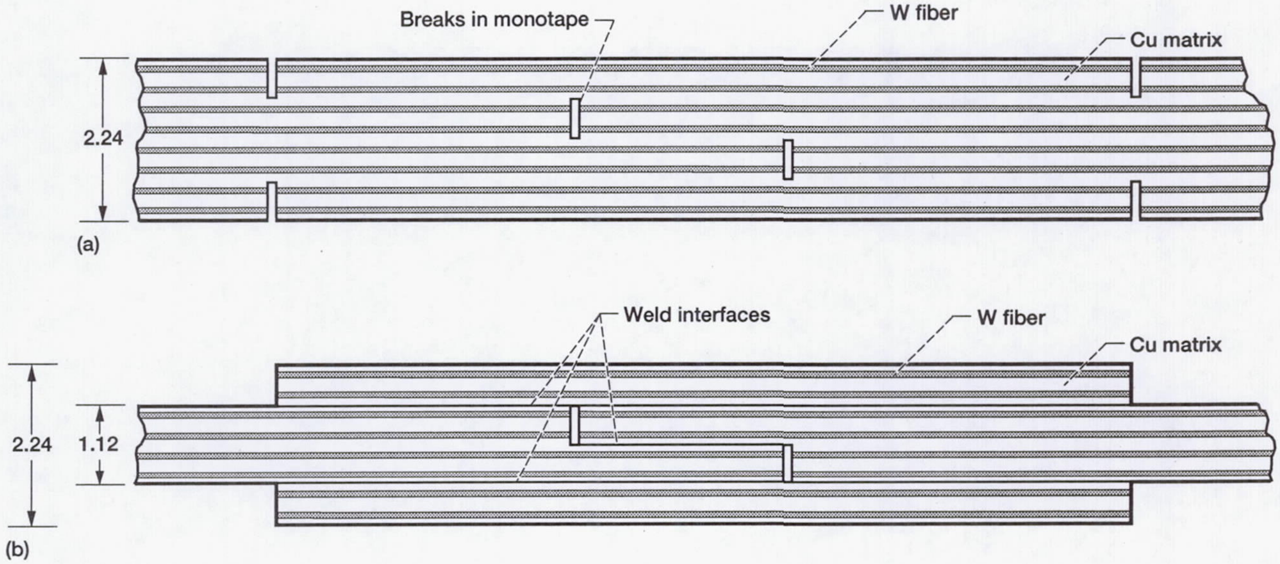


Figure 2.—Longitudinal thickness sections of simulated and welded lap-butt joints in four-ply W-Cu sheet with two-ply doublers. Typical lap joint length is 6 mm and doubler length is 20 mm. (Not to scale.) (a) Simulated joint in eight-ply composite material in as-consolidated condition without weld interfaces. (b) Actual four-ply welded butt joint with consolidated lap and two-ply doubler components joined at Cu-Cu weld interfaces. (Dimensions are in mm.)

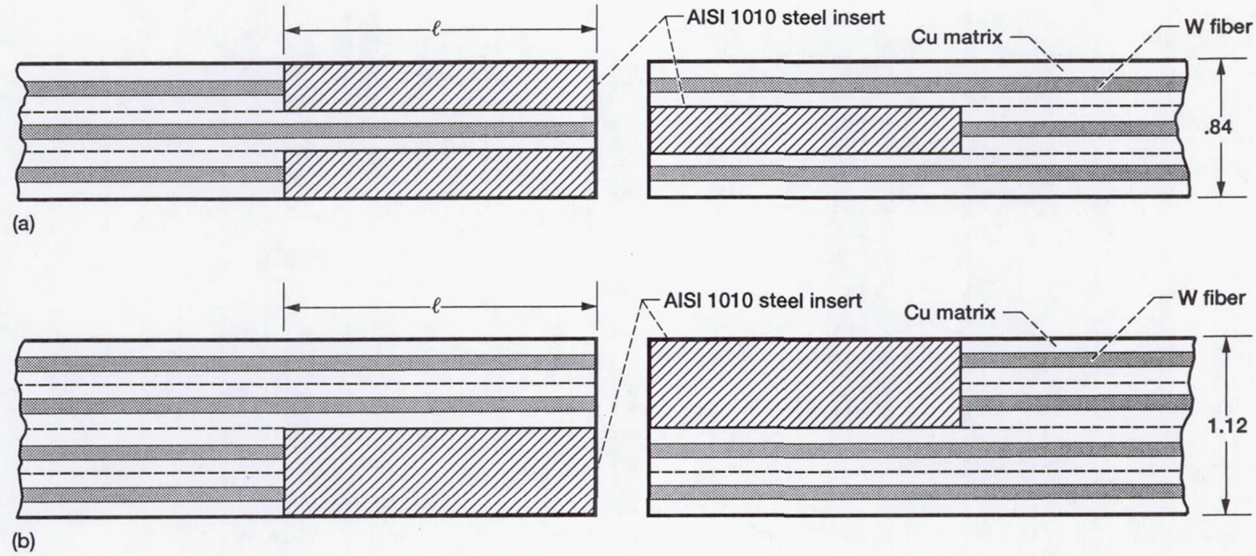


Figure 3.—Longitudinal thickness sections of W-Cu monotape and steel inserts demonstrating how as-sprayed W-Cu monotapes are utilized to form butt joints for subsequent welding runs. The typical joint length ℓ is 6 mm. (Not to scale.) (a) Tongue-in-groove joint with three layers of monotape. (b) Lap joint with four layers of monotape. (Postconsolidated thickness dimensions are in mm.)

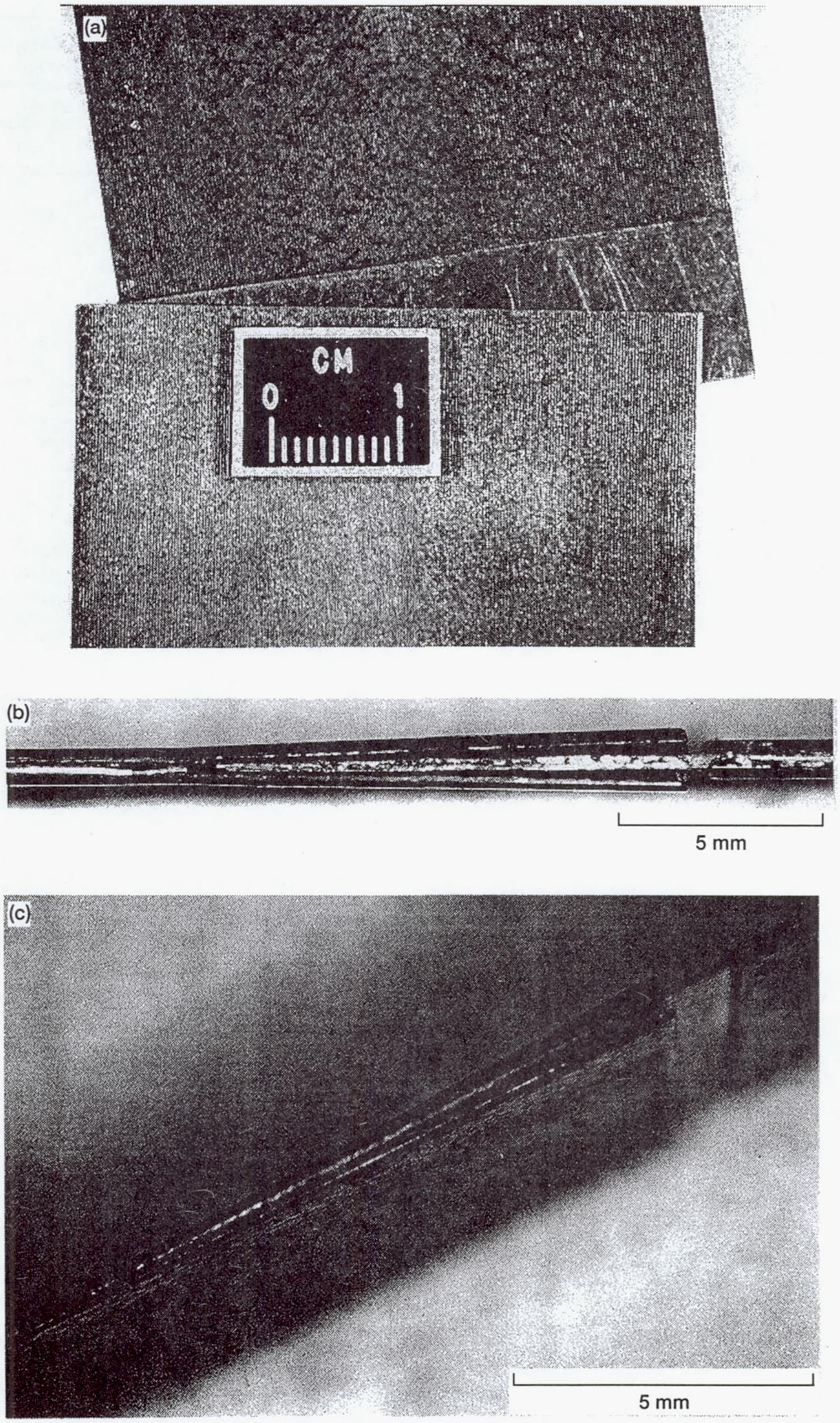


Figure 4.—Several views of fabricated components ready for welding; tongue-in-groove butt joint in three-ply, 0.84-mm-thick W-Cu composite sheet. The tongue is placed in the groove and welded in a vacuum hot press. (a) Plain view. (b) Edge view. (c) Oblique view.

TABLE I.—HOT PRESS WELDING PROCEDURE AND PARAMETERS FOR ACTUAL BUTT JOINTS

[Pressure at doublers, 34.5 MPa; typical vacuum prior to heating, $4x10^{-2}$ Pa; typical vacuum is 15 min into run, $7x10^{-3}$ Pa.]

Panel	Welding process	Joint design	Doublers	Sputter coating		Filler metal		Hot press parameters	
				Material	Thickness, μm	Material	Thickness, μm	Temperature, °C	Hold time, min
A	DFW[a]	TG-butt	One-ply	Cu	2.0	-------------	---	1000	60
B	DFW			Cu	2.3	-------------	---		
C	DFB[b]			Ag	2.8	-------------	---		
D				Ag	2.6	-------------	---		
E				---	---	72Ag-28Cu	25	900	
F				---	---	72Ag-28Cu	25	900	
G	DFW	Lap-butt		---	---	Cu	51	1000	
H				---	---				
I				---	---				
J				---	---				
K			Two-ply	---	---				
L				---	---				
M				Cu	2.8	-------------	---		
N				Cu	3.0	-------------	---		
O	DFB			Ag	2.0	-------------	---		
P				Ag	2.5	-------------	---		
Q				Cu		Ti	25	900	15
R				Cu		Ti	25		
S				Ti[c]		-------------	---		
T				Ti[c]		-------------	---		

[a]DFW - Diffusion welding.

[b]DFB - Diffusion brazing.

[c]Ti-6Al-2Sn-4Zr-6Mo (wt %).

processes, was 34.5 MPa. All TG-butt joint panels were fabricated with single-ply doublers. Single-ply doublers also were used for four of the lap-butt joint panels; two-ply doublers were used for the remaining ten panels.

As indicated in table I, TG-butt joints in four panels and lap-butt joints in eight panels were sputter coated with a 2- to 3-μm layer of Cu, Ag, or a Ti-6Al-2Sn-4Zr-6Mo (wt%) alloy. The Cu sputter coating was used to increase the probability of joint soundness in subsequent Cu-Cu diffusion welding. The Ag sputter coating interdiffused with the Cu matrix to form the Ag-Cu eutectic and produce a brazed joint. The Ti alloy sputter coating also interdiffused with the Cu matrix and produced a diffusion-brazed joint by the formation of the Ti-Cu eutectic (ref. 5).

Prior to the sputter coating, the surfaces were degreased in ethanol, sandblasted with 3-μm alumina particles, rinsed in deionized water, and oven dried. An example of a Ag sputter-coated tongue member is shown in figure 5. Note that the panel surface which will be in contact with the doubler and the tongue are coated; however, neither the interior faying surfaces of the groove nor the faying surfaces of the doublers were coated. For the lap-butt joints, the faying surfaces in the lap region and the doubler regions of the panels were coated. As with TG-butt joints, the faying surfaces of the doublers were not coated.

In selected panels, foil filler metal was placed between the faying surfaces within TG- and lap-butt joints, including the panel/doubler interfaces (table I). For panels E and

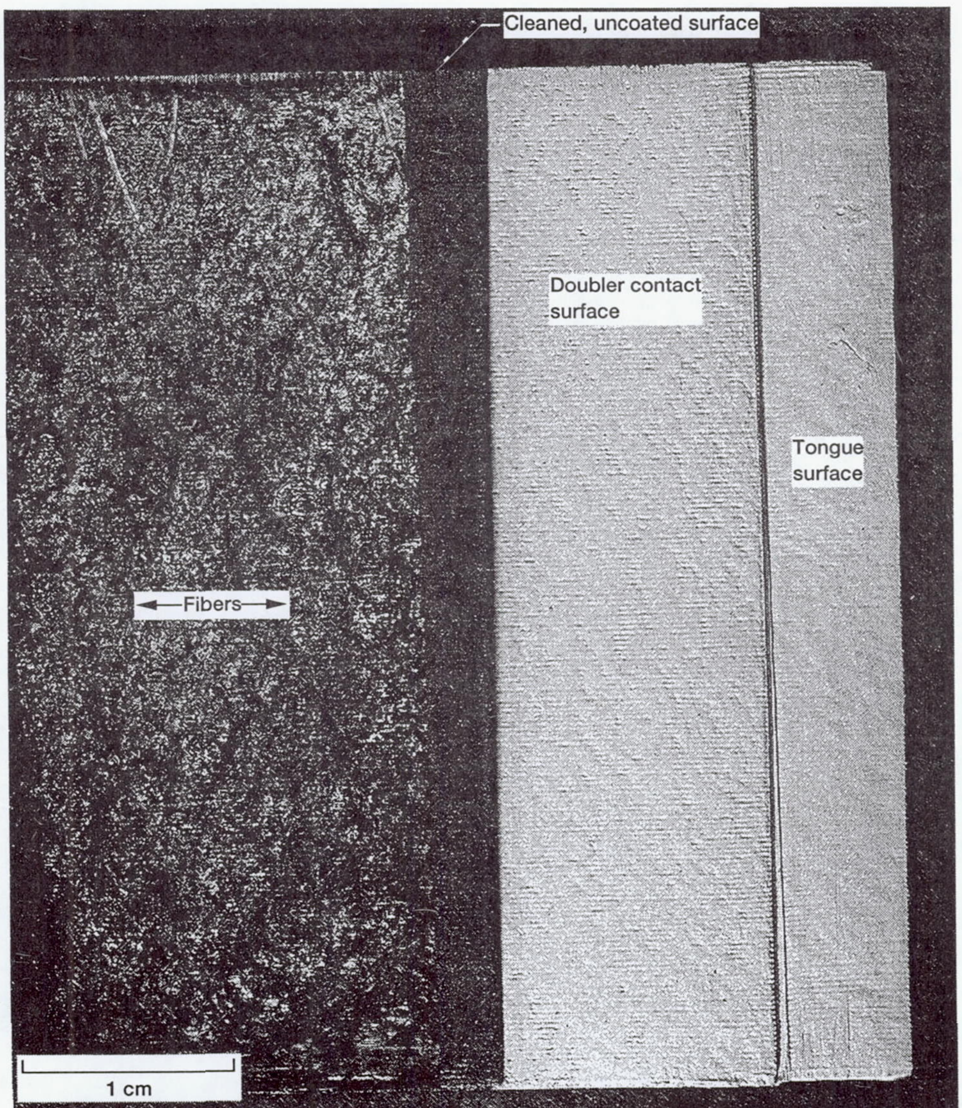


Figure 5.—Sputter-coated tongue and doubler contact surfaces of panel C tongue-in-groove joint. Light area is coated with 2.8 μm of Ag.

F, 25-μm-thick, 72Ag-28Cu brazing foil was used. As seen in table I, Cu foil interlayers (51 μm thick) were used for six panels with lap joints. The soundness of diffusion-welded joints was expected to improve with the Cu foil interlayers. Finally, in panels Q and R, Ti foil was used in conjunction with sputter coating the faying surfaces with 2.5 μm of Cu. Diffusion between Ti and Cu was expected to produce a diffusion-brazed joint.

Tensile Testing

Duplicate tensile specimens of the design shown in figure 6 were electrical discharge machined from each 50- by 160-mm panel containing either simulated or welded joints which were located in the middle of the reduced section. Serrated grips were used in the tensile tests and the crosshead speed was 30.6 mm/sec for tests at room temperature, 230, and 250 °C. After each test, the failure location was determined, and the joint efficiency (JE) was calculated for each weldment. Joint efficiency (expressed in percent) is defined as the ratio of joint tensile strength to a calculated baseline tensile strength of as-consolidated unwelded material. The baseline tensile strength of the W-Cu composite was determined at room temperature and at 250 °C using the simulated welded joint specimens.

Specimens for metallography were obtained from each welded panel from the cutout area shown in figure 6. The joints were examined transverse to and parallel to the fibers. The solution used for etching consisted of 2 g $K_2Cr_2O_7$, 8 mL H_2SO_4, 100 mL H_2O, and 4 drops HCl.

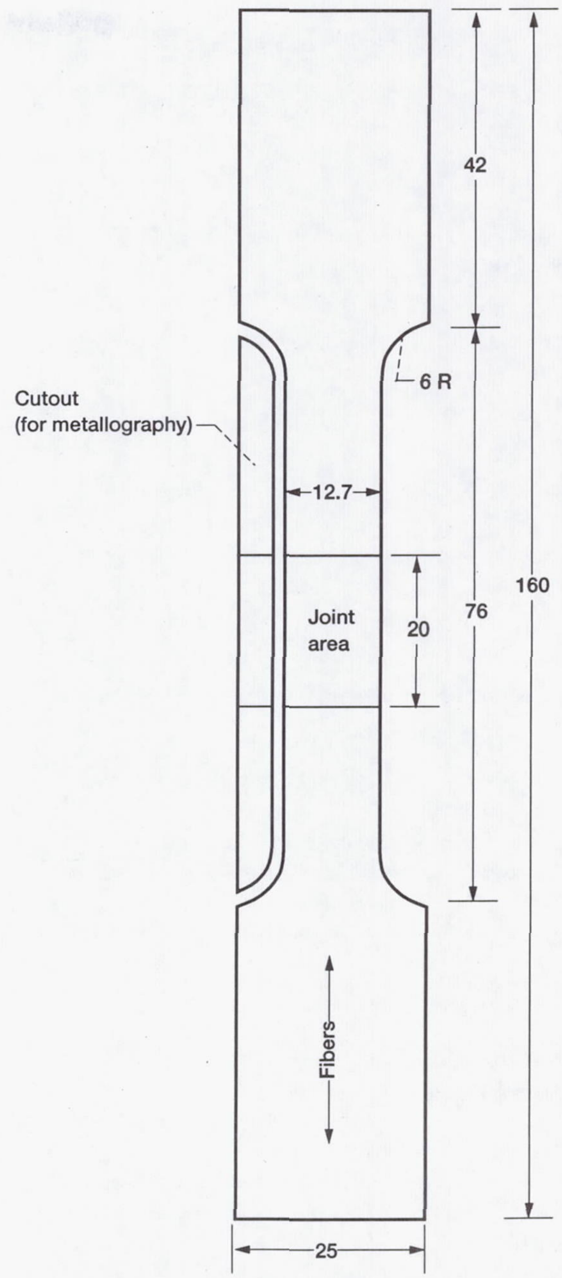


Figure 6.—Typical tensile test specimen for testing simulated and welded joints in three- and four-ply W-Cu composite sheet. (Dimensions are in mm.)

Metallographic Results

Both actual welded joint designs listed in table I used diffusion welding and brazing processes with either single- or two-ply doublers and sputter coatings applied to some joints. Filler metal foil was used in other joints. Two panels were welded with a sputter coating and a filler metal foil. Sections taken transverse to the W fibers generally produced the most graphic information. For this reason, all but two of the photomicrographs in figures 8 to 16 were taken from these sections.

Tongue-In-Groove-Butt Joints With Cu-Sputtered Coating

Panels A and B were diffusion welded after sputter coating Cu on the tongue and panel surfaces under the doublers. The longitudinal section in figure 7 shows a sound condition in the tongue-in-groove region although some discontinuous oxides (not evident in this figure) are present. Note the presence of a crack in the W fiber; it is believed that it occurred during diffusion welding in the hot press. Fiber cracking was not observed in any other W-Cu panel. The weld quality in the panel/doubler regions of the joints was poor as evidenced in figure 7 by unwelded areas and lines of continuous oxides at weld interfaces. The reason for the poor quality of the welds in the panel/doubler regions of the joints was unclear, since, similar to the tongue-in-groove region of the joint, one faying surface was sputter coated with Cu.

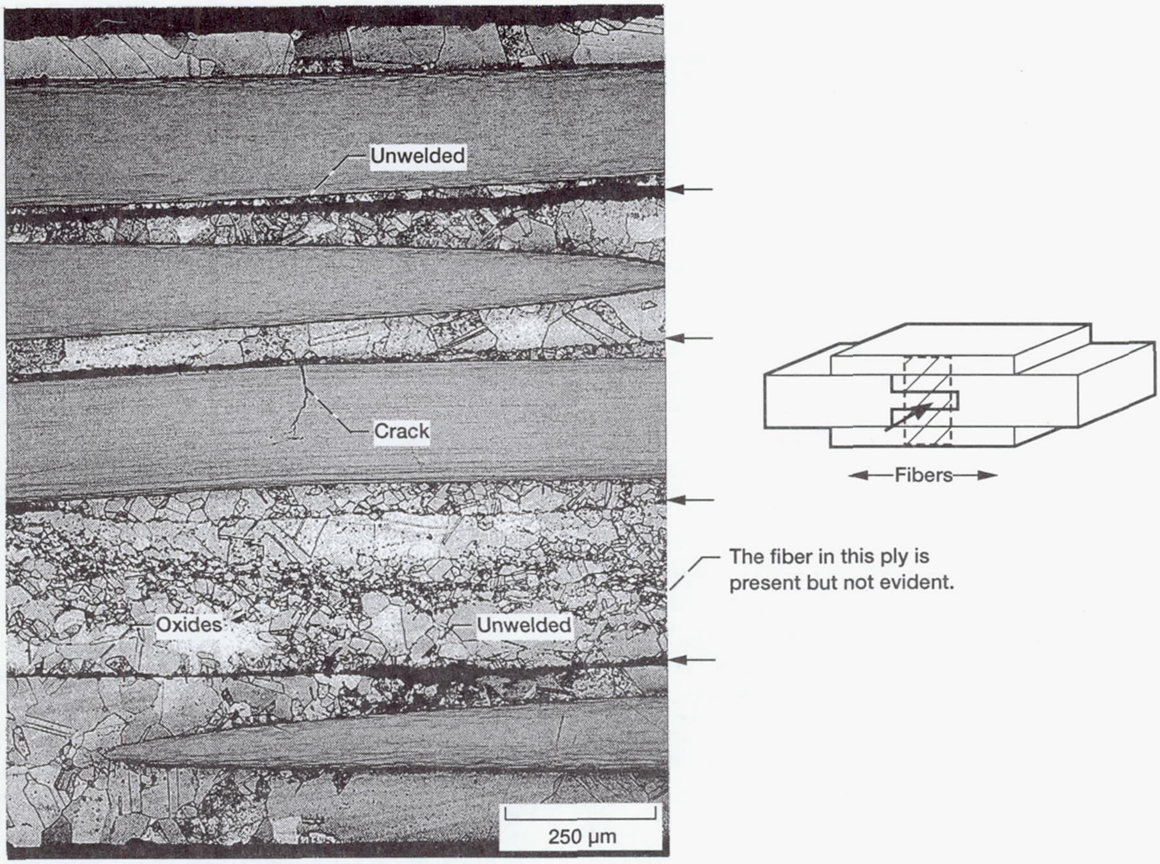


Figure 7.—Longitudinal section of panel B tongue-in-groove butt joint in three-ply W-Cu composite. Tongue and panel surfaces under doublers were sputter coated with Cu prior to diffusion welding. Arrows indicate weld interfaces. Etched.

Tongue-In-Groove-Butt Joints With Ag-Sputtered Coating

Panels C and D were diffusion brazed after sputter coating Ag on the tongue surfaces and on the panel surface under the doublers. The transverse section in figure 8 shows that the tongue-in-groove region of the joint was generally sound although some oxide stringers and microvoids were present. Most panel/doubler regions were poor quality because of the presence of unbrazed regions and lines of oxides.

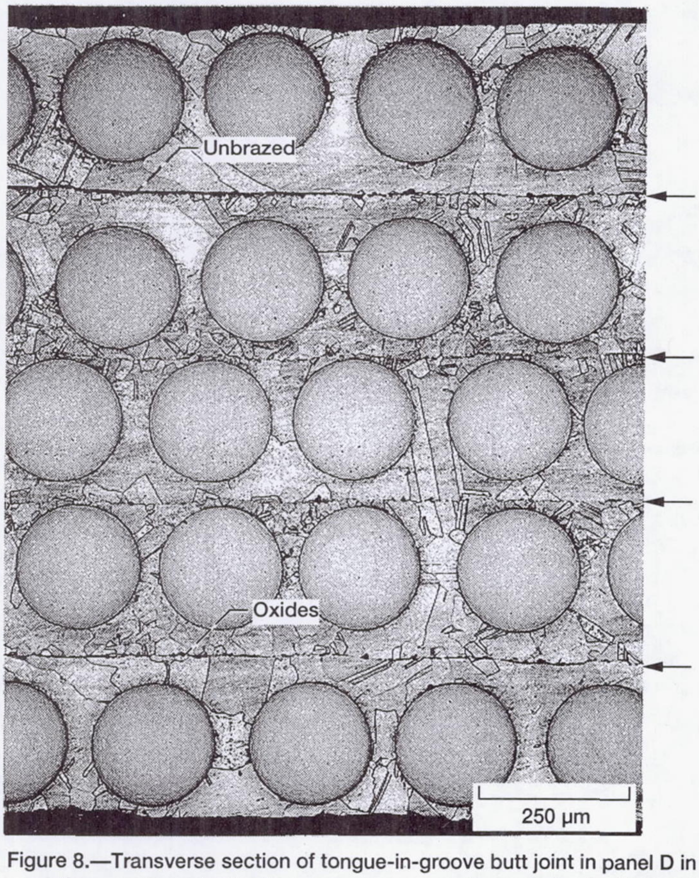
Tongue-In-Groove-Butt Joints With 72Ag-28Cu Filler Metal

A transverse section of panel E is shown in figure 9. Both the tongue-in-groove and panel/doubler regions are generally sound although the latter region contained scattered void and oxide stringers (not shown). Excess filler metal, expelled from the joint during the hot-press diffusion brazing process, wet and flowed onto the panel adjacent to the doublers.

Lap-Butt Joints With Cu Foil Filler Metal

Some differences were observed among the lap-butt joint panels which were diffusion welded using Cu foil filler metal. For example, the lap joint region of panel G was sound and had some grain growth across the weld interfaces. The panel/doubler region with no foil was mostly unwelded.

Panels J and L both had Cu foil at the lap and panel/doubler regions and were welded under identical conditions. The transverse section in the lap region of panel L (shown in fig. 10) was generally sound with some grain growth across the weld interfaces. The panel/doubler portion of the joint in panel L was about 90 percent sound. The lap region of the panel J joint was only about 50 percent welded and only about 10 percent of the joint's panel/doubler portion was welded. As will be discussed in the Tensile Test Results section, the tensile properties of specimens from these particular panels reflected the differences in weld soundness.



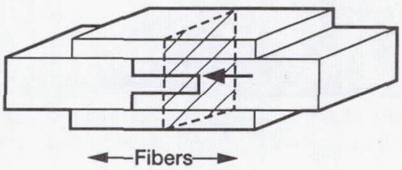


Figure 8.—Transverse section of tongue-in-groove butt joint in panel D in three-ply W-Cu composite sheet. Ag sputter coatings were applied to tongue and panel surfaces under doublers prior to diffusion welding. Arrows indicate weld interfaces. Etched.

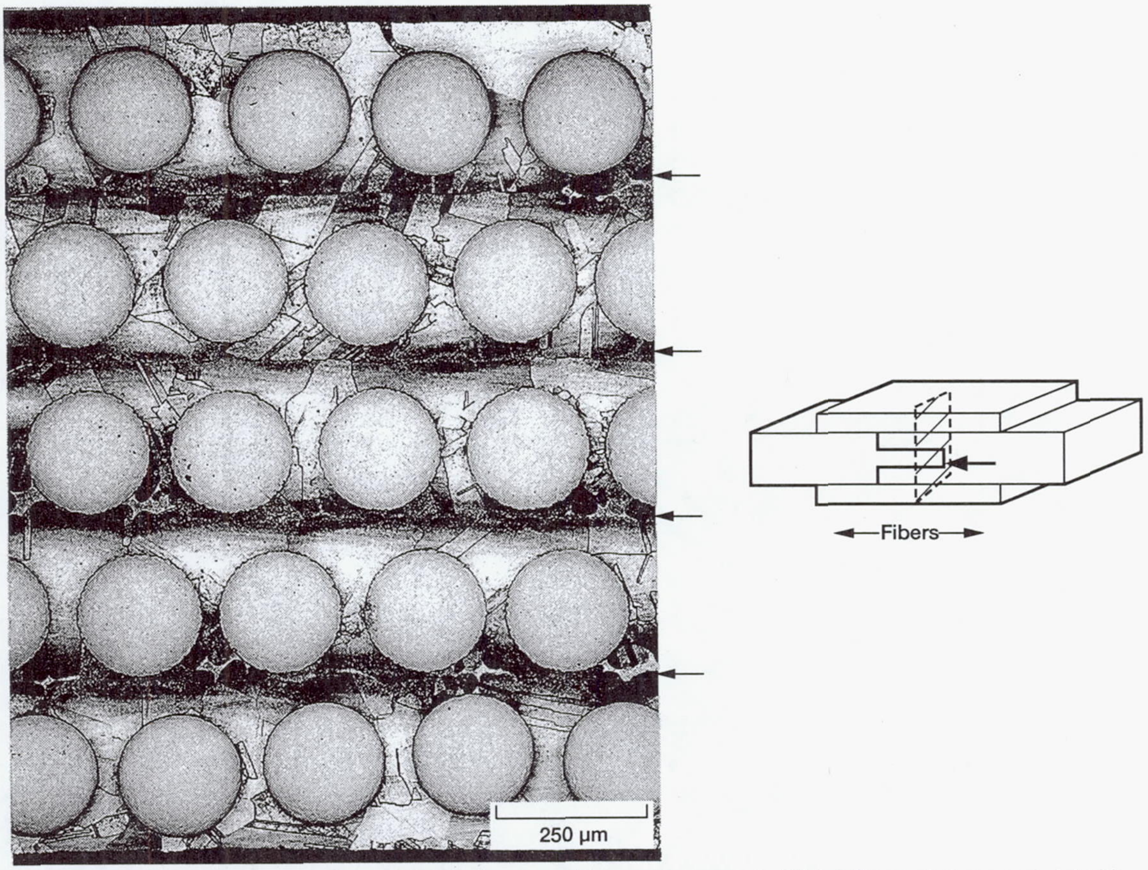


Figure 9.—Transverse section of panel E. Diffusion-brazed tongue-in-groove butt joint. Three-ply base material with single-ply doublers and 25-µm, 72 Ag-28 Cu filler metal. Arrows indicate brazed joints. Etched.

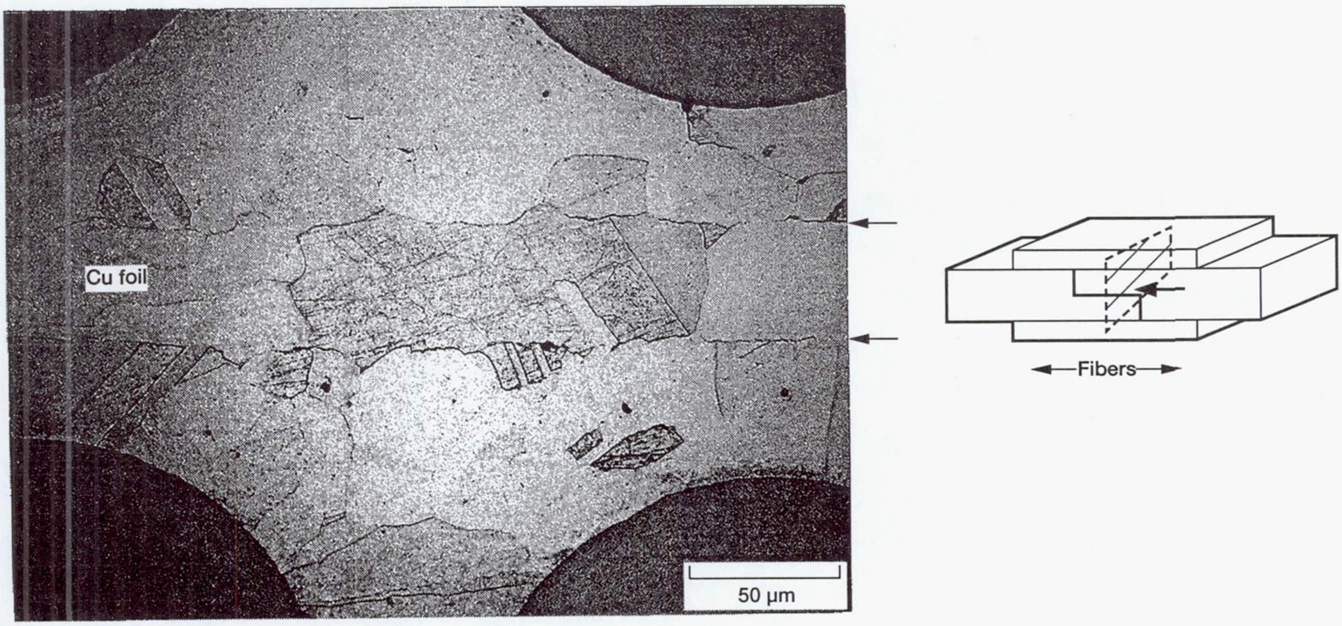


Figure 10.—Transverse section of four-ply lap-butt joint in panel L in W-Cu composite sheet (lap region). A 51-mm-thick Cu foil filler metal was placed between faying surfaces at two-ply lap and panel/doubler regions prior to diffusion welding. Arrows indicate weld interfaces. Etched.

Lap-Butt Joints With Cu-Sputtered Coating

A Cu-sputtered coating was applied to both faying surfaces of the lap region and to the panel sides of the panel/doubler region for panels M and N. The lap region was generally sound, although some oxides and microvoids were present. The panel/doubler joint was about 10 percent unwelded.

Lap-Butt Joints With Ag-Sputtered Coating

Both faying surfaces in the lap region and the panel surfaces in contact with the doublers were coated with Ag. The transverse section in the lap region (fig. 11) shows a basically sound Ag-Cu diffusion-brazed joint except for the presence of small oxides and microvoids. The panel/doubler region had a similar quality.

Lap-Butt Joints With Cu-Sputtered Coating and Ti Foil

Both faying surfaces of the lap joint and the panel surfaces under the doublers were sputter coated with Cu for panels Q and R. Titanium foil was placed between the faying surfaces in the lap and panel/doubler regions. As shown in the transverse section in figure 12(a), the lap region of the Ti-Cu eutectic brazed joint was sound except for a few widely scattered oxide particles. The short, wavy lines above and below the braze metal appeared after etching and are believed to represent regions of chemical segregation. The panel/doubler regions were similar in appearance except for the presence of oxide stringers (shown in figure 12(b)) located on the doubler side of braze interface which had not been sputter coated. No oxides were observed on the side of the panel sputter coated with Cu.

The longitudinal section in figure 13 shows a portion of the panel R lap joint region where a chemical reaction occurred between the W fiber and the Ti-Cu eutectic braze. An unknown phase growth was detected in the braze metal from the fiber substrate.

Lap-Butt Joints With Ti Alloy Sputter Coating

Panels S and T, which were sputter coated with the Ti-6Al-2Sn-4Zr-6Mo alloy, were diffusion brazed with the Ti-Cu eutectic. A transverse section at the lap region in figures 14(a) and (b) shows a joint which was mostly sound with some oxides present at the joint. It was also observed that the braze metal reacted with the W fibers in localized areas. The panel/doubler region was generally sound (figure 14(c)), although some oxide particles and stringers were present. Similar to figure 12(b), the oxide stringer was located on the side which had not been sputter coated. The sputter-coated panel side showed no oxides.

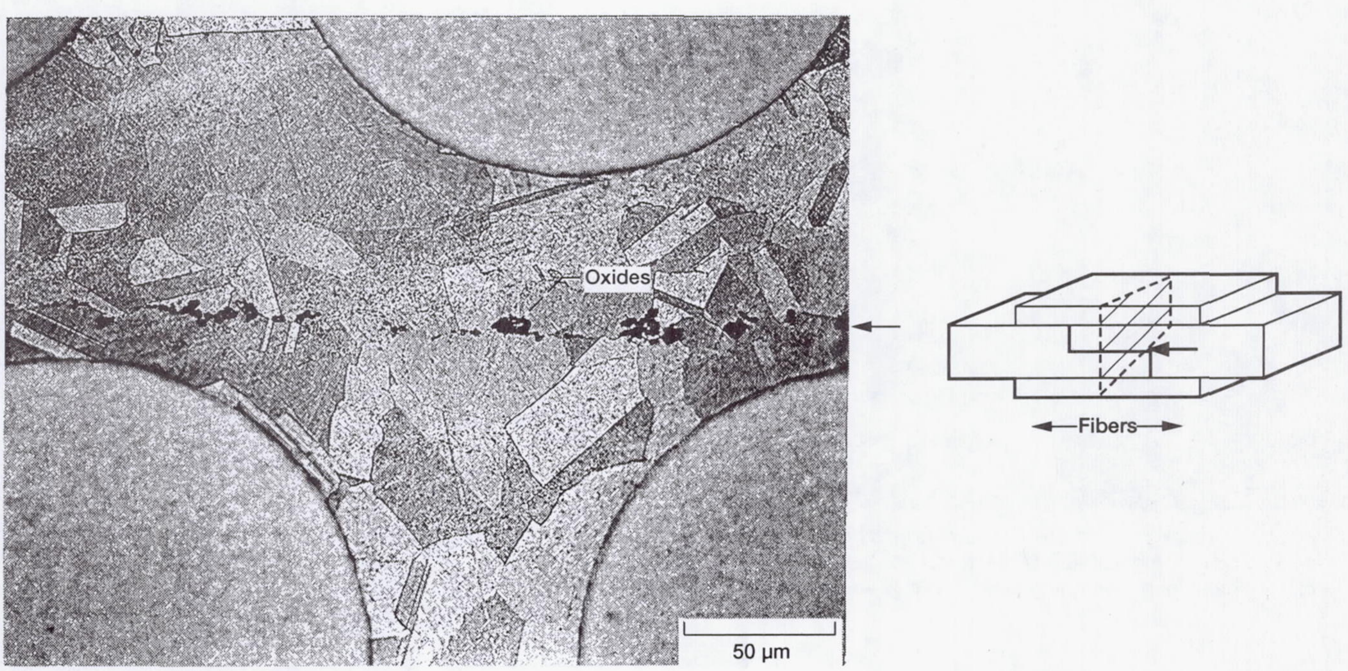


Figure 11.—Transverse section of lap-butt joint in panel P in four-ply W-Cu composite sheet with two-ply doublers. Both faying surfaces in lap region (shown above) were sputter coated with Ag and joint was diffusion brazed. Arrow indicates weld interface. Etched.

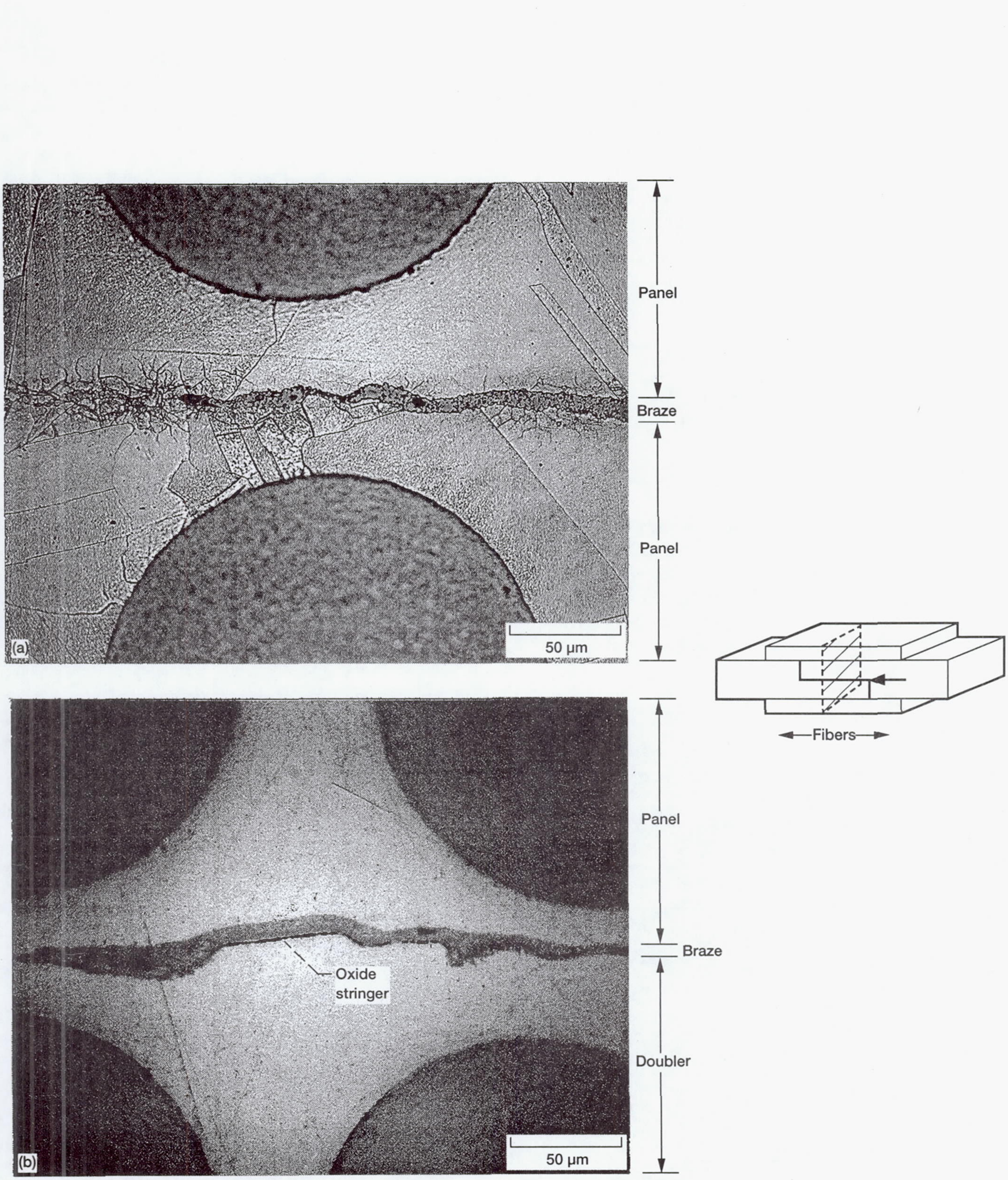


Figure 12.—Transverse section of lap-butt joint in panel R in four-ply W-Cu composite sheet with two-ply doublers. Diffusion brazing was accomplished using a 25-μm Ti filler metal interlayer. (a) Lap joint region where both faying surfaces were sputter coated with Cu. Etched. (b) Panel/doubler region where only panel side was sputter coated with Cu. Unetched.

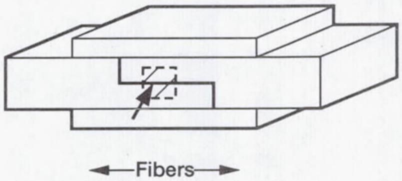


Figure 13.—Longitudinal section of panel R lap-butt joint in four-ply W-Cu composite material with two-ply doublers. Lap joint region shows reaction between W fiber and Ti-Cu eutectic braze and new phase growth from fiber into braze. Etched. (a) Braze joint with phase growth from W fiber into braze metal. (b) Closeup showing new phase growth into braze metal.

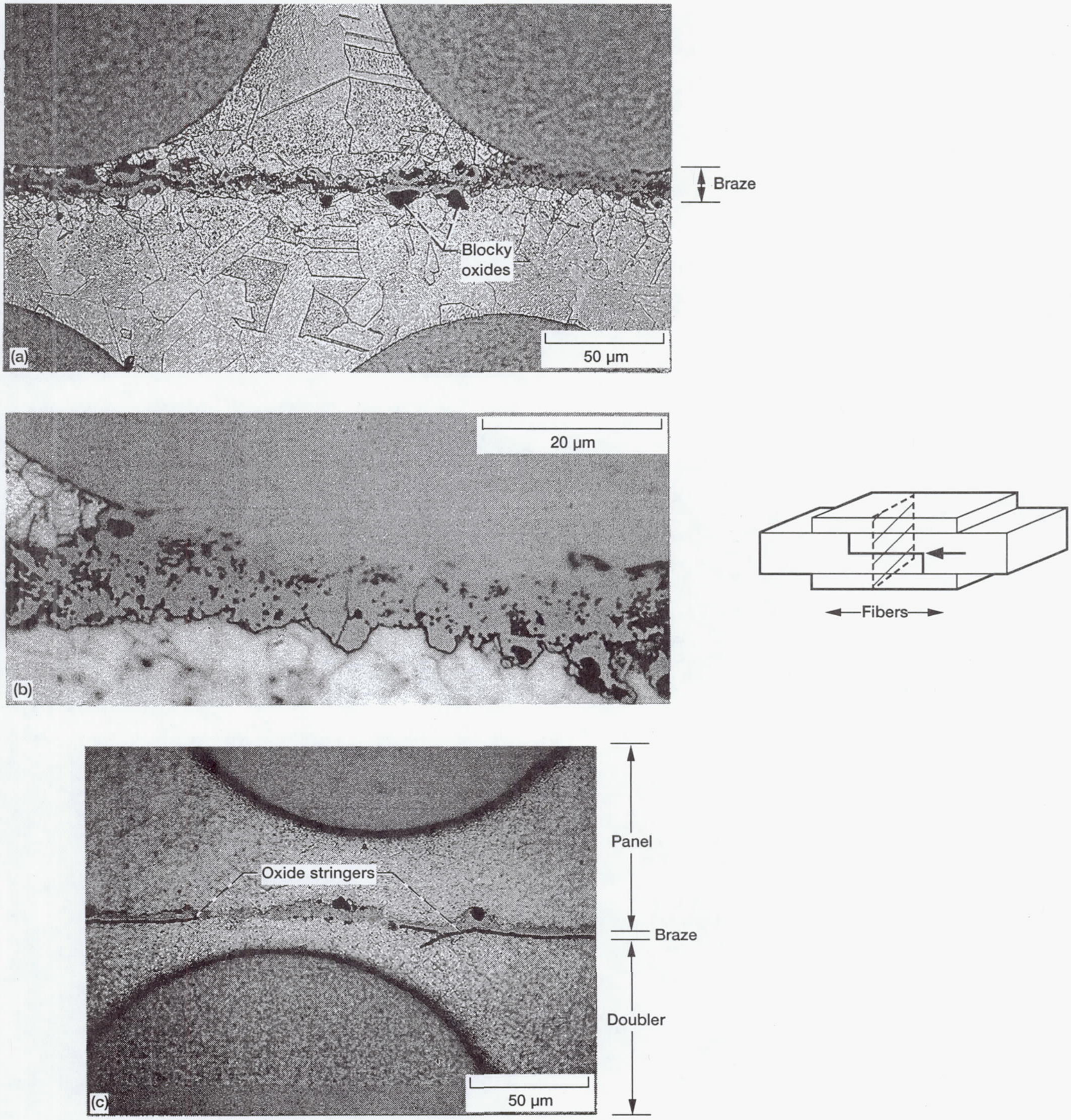


Figure 14.—Transverse section of lap-butt joint in panel T in four-ply W-Cu composite sheet with two-ply doublers. Diffusion brazing accomplished by sputter coating Ti-6Al-2Sn-4Zr-6Mo alloy. (a) Lap joint region showing localized brazing of W fiber. Etched. (b) Fiber/braze reaction zone. (c) Panel/doubler region showing oxide stringers on doubler side of braze metal. Unetched.

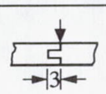
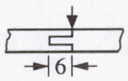
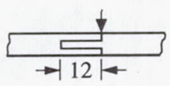
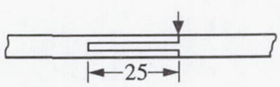
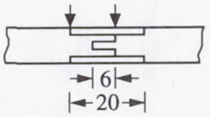
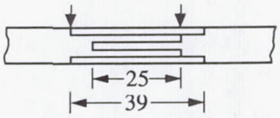
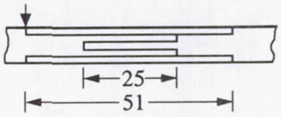
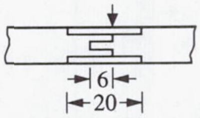
Tensile Test Results

Tensile test results for the simulated joints are presented in tables II and III and for the actual welded joints in tables IV and V. The sketches in these tables illustrate the joint designs used, and the arrows on the sketches indicate the failure location. Where one arrow appears, both specimens from a particular panel failed in tension at the location indicated. In cases where the mode of failure was shear, it is so indicated. Where two or more arrows appear, either simultaneous failure occurred at these locations, or the second test specimen from a particular panel failed at a different location.

At room temperature, the average baseline tensile strength of the W-Cu base material was 1100 MPa and at 250 °C, 925 MPa. A typical tensile failure of the composite base material is shown in figure 15. The backscatter image in figure 15(a) shows no evidence of adhesion between the W fibers and the Cu matrix. The source of the Al particles shown on the fibers in figures 15(a) and (b) is unknown.

TABLE II.—TENSILE PROPERTIES OF SIMULATED TONGUE-IN-GROOVE BUTT JOINTS

[Joints in three-ply W-Cu composites with and without single-ply doublers.]

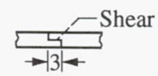
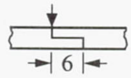
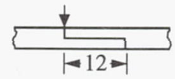
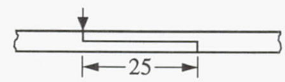
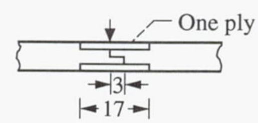
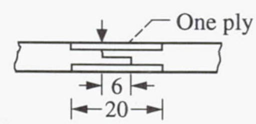
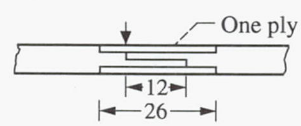
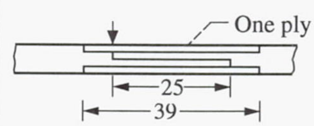
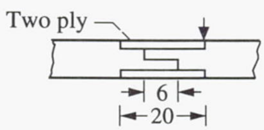
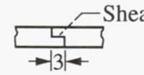
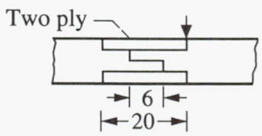
Panel	Specimen code	Test temperature, °C	Fracture load, kN	Fracture stress, MPa[a]	Joint efficiency, percent	Simulated joint design and fracture location[b], mm
1	1-1	23	4.04	381	34	
	1-2		3.99	376	34	
2	2-1		3.77	354	32	
	2-2		3.98	374	34	
3	3-1		3.92	367	33	
	3-2		4.27	400	36	
4	4-1		3.88	352	32	
	4-2		4.05	368	33	
5	5-1		11.3	1000	91	
	5-2		11.6	1020	93	
6	6-1		12.7	1190	100	
	6-2		12.7	1160		
7	7-1		12.5	1140		
	7-2		12.6	1160		
8	8-1	250	10.1	895	97	
	8-2	250	9.7	843	91	

[a]Calculated for a three-ply thickness of 0.84 mm.

[b]Arrows indicate fracture location.

TABLE III.—TENSILE PROPERTIES OF SIMULATED LAP-BUTT JOINTS

[Joints in four-ply W-Cu composites with and without doublers.]

Panel	Specimen code	Test temperature, °C	Fracture load, kN	Fracture stress, MPa[a]	Joint rotation, deg	Joint efficiency, percent	Simulated joint design and fracture location[b], mm
9	9-1	23	4.29	310	8	28	
	9-2		4.02	284	6	26	
10	10-1		7.30	526	7	48	
	10-2		7.29	526	8	48	
11	11-1		7.56	547	6	50	
	11-2		4.52	327	5	30	
12	12-1		7.66	554	3	50	
	12-2		7.54	552	3	50	
13	13-1		11.8	872	10	79	
	13-2		11.7	863	8	78	
14	14-1		12.8	929	10	84	
	14-2		12.5	945	5	86	
15	15-1		13.8	1050	2	95	
	15-2		13.9	1050	3	95	
16	16-1		13.5	972	1	88	
	16-2		14.3	1040	2	94	
17	17-1		15.0	995	---	90	
	17-2		16.0	1070	---	97	
18	18-1	250	2.78	201	6	22	
	18-2		3.35	242	6	26	
19	19-1		14.2	982	---	100	
	19-2		13.9	981	---	100	

[a]Calculated for a 4-ply thickness of 1.12 mm.

[b]Arrows indicate fracture location.

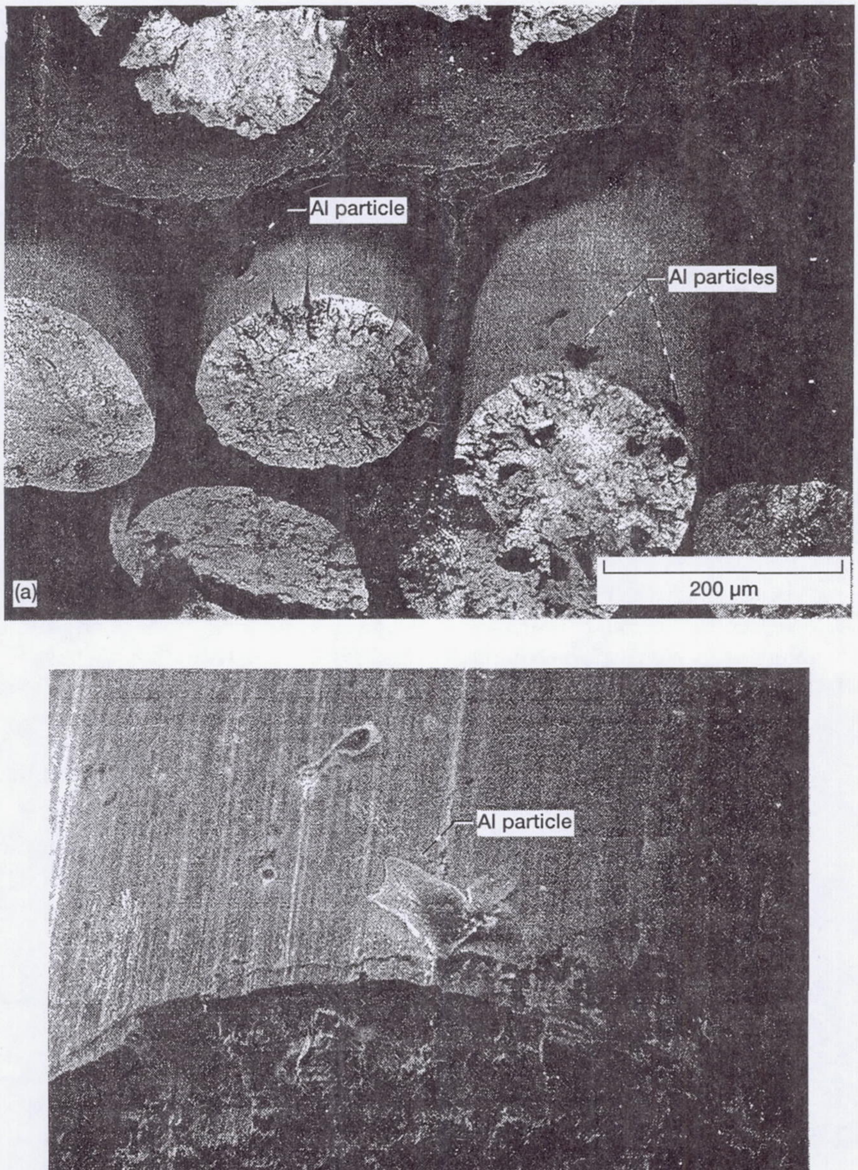


Figure 15.—Typical scanning electron photomicrographs of W-Cu base material at fracture surface of tensile specimen. (a) Backscatter image shows no evidence of adhesion between fibers and matrix and Al particles present on fiber surface. (b) Al particle on fiber surface.

The results that follow will show that, although metallographic examination revealed that some flaws in all of the welded joints, only a few of these joints were below 75 percent JE. Regions of incomplete welding were revealed by a shear failure mode.

Simulated Tongue-In-Groove-Butt Joints

The room temperature specimens without doublers (panels 1 to 4 in table II) failed in the middle ply at the base of the tongue. In the simulated TG-butt joint design, the tongue carried the entire load. A tongue length of 3 mm (panel 1) was sufficient to produce tensile failure through the single-ply thickness rather than pullout of the tongue by matrix shear. The JE for these specimens ranged from 32 to 36 percent.

Simulated doublers provided two more plies at the joint to carry the load in panels 5 to 7. This change in joint design increased the room temperature JE to 91 percent or higher. Specimens from panels 5 and 6 failed at two locations in three-ply regions: through the doublers at the base of the tongue and at the edge of the doubler. The specimens from panel 5 had significantly lower fracture stresses, although the reason for this is unknown. Both of the panel 7 specimens failed at the edge of the doublers.

As shown in table II, only tensile specimens 8-1 and 8-2 were tested at 250 °C. For these specimens, failure was in tension through the doublers at the base of the tongue, with 97 and 91 percent JE, respectively.

Simulated Lap-Butt Joints

As shown in table III, joint rotation and low JE were problems for the lap-butt joints without doublers. The angle of joint rotation for the tested specimens was approximated using a protractor. Panel 9 specimens with a 3-mm overlap and no doublers failed at the joint in shear through the copper matrix with a 26- and 28-percent JE with 6° and 8° of joint rotation, respectively. Figure 16(a) illustrates the joint rotation of 8° in specimen 9-1. Specimens from all other simulated lap joint panels failed in tension through the thickness. Table III shows that an increase from a 3- to a 6-mm overlap without doublers increased the JE to 48 percent but the joint rotation was still high at 7° and 8°. Further increases in joint overlap for specimens without doublers (panels 11 and 12) did not produce an additional increase in JE although joint rotation was reduced.

Single-ply doublers improved the JE but joint rotation was still a problem, as illustrated by panel 13 specimens. The improvement in JE over similar joints without doublers occurred even with the 8 and 10 degree joint rotation. Increasing the overlap to 6 mm in panel 14 produced higher JE (84 and 86 percent), although the joint rotation was still high at 5° and 10°. Higher JE and reduced joint rotation occurred for joints in panels 15 and 16 with 12- and 25-mm overlap, respectively. These joints had an 88- to 95-percent JE with 3° or less joint rotation. However, the use of two-ply doublers essentially eliminated joint

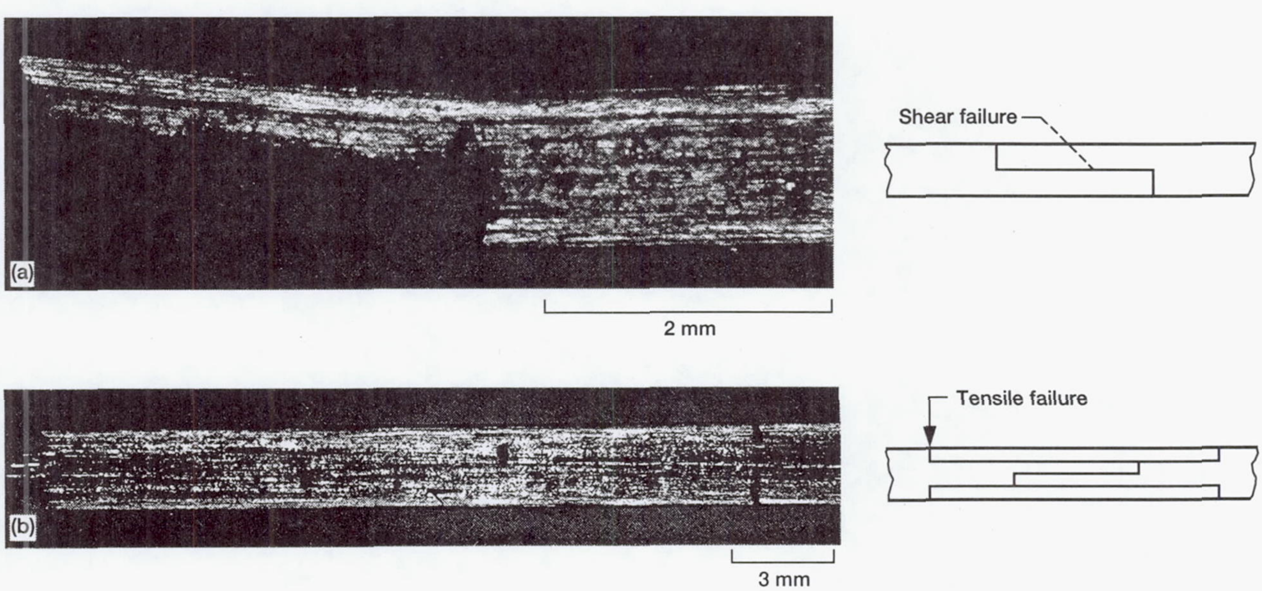


Figure 16.—Failure mode of simulated lap-butt joints in W-Cu composite sheet. Edge views of fracture in four-ply base material with and without doublers. (a) Specimen 9-1. Shear failure (no doublers) through Cu matrix. Joint overlap, 3 mm; 8° joint rotation. (b) Specimen 17-1. Tensile failure in base material at edge of doublers. Joint overlap, 6 mm; no joint rotation.

rotation (table III). For example, the panel 17 specimens with a 6-mm overlap and 20-mm-long two-ply doublers failed at the edge of the doubler with JE's of 90 and 97 percent (fig. 16(b)).

The effect of joint overlap on the JE of the simulated lap-butt joints is plotted in figure 17. With no doublers, the JE increases sharply when the overlap is increased from 3 to 6 mm; however, there is no further improvement above 6 mm. Figure 17 also illustrates that JE is almost doubled for joints with single-ply doublers at any amount of overlap. With single-ply doublers, JE improves as the overlap is increased up to 12 mm. Finally, with a 6-mm overlap, two-ply doublers provide a higher JE than the single-ply doublers.

In tests at 250 °C, panel 18 specimens with a 3-mm overlap and no doublers rotated 6° during testing (table III). This rotation was comparable to that observed at room temperature with the same overlap. The 250 °C failure was also by a shear mode with a 22- and 26-percent JE. Panel 19, a 6-mm overlap and two-ply doublers, failed in tension at the edge of the doubler with no joint rotation. These joints were stronger than the calculated baseline strength of 925 MPa.

Welded Tongue-In-Groove-Butt Joints

Table IV displays the tensile properties of welded TG-butt joints in three-ply W-Cu composites with single-ply doublers. The panels listed in the table had various sputter coatings or filler metal interlayers applied as indicated in table I. The JE of duplicate test specimens varied significantly in some panels because of a variation in weld quality or a variation in base material properties. However, the fact that JE ranged from 67 to 100 percent is encouraging. The tensile test results are summarized in figure 18 where an "x" above the bar indicates failure in the base material away from the joint. Panel A specimens, with a Cu-sputtered coating and a 6-mm- long tongue, had 77- and 81-percent JE's at room temperature. Panel C, with the same tongue length but sputtered with Ag, had 67- and 78-percent JE's. The specimens from panels E and F had a 12-mm-long tongue-in-groove joint and were diffusion brazed with 72Ag-28Cu filler metal. These specimens exhibited the highest average JE at 94 percent. As shown in figure 18, three of the four specimens from these panels failed in the composite base material, indicating that the use of this filler metal produced the strongest weldments.

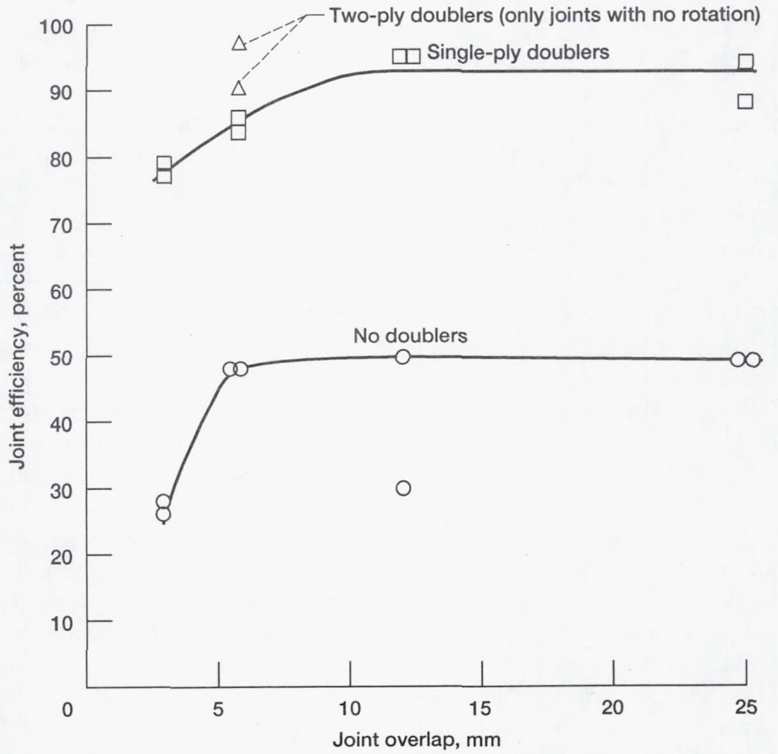


Figure 17.—Joint efficiency versus joint overlap for simulated four-ply lap-butt joints. W-Cu composite material tensile tested at room temperature.

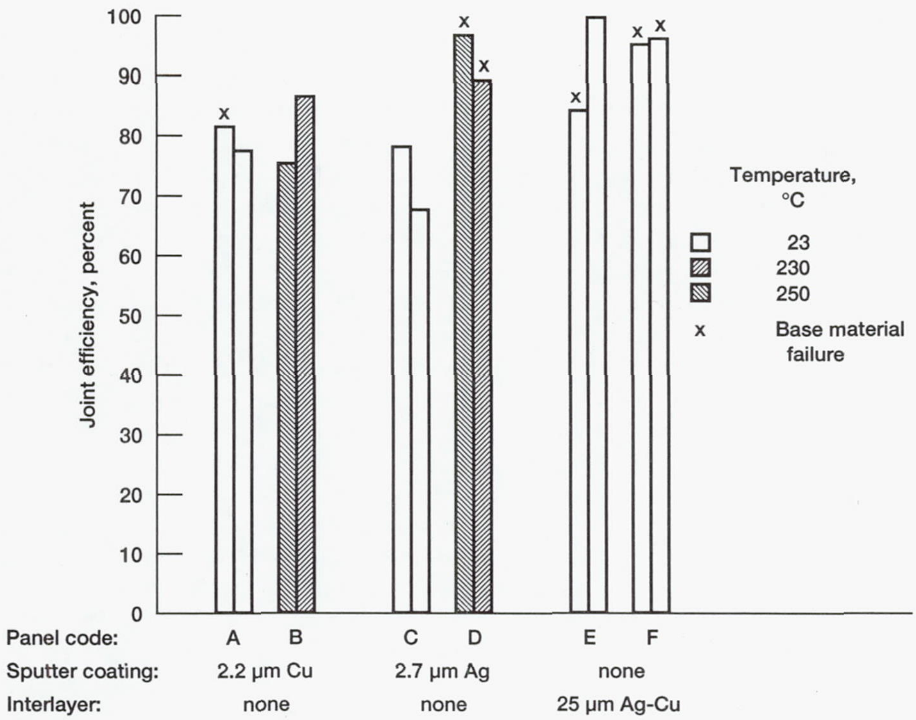


Figure 18.—Joint efficiency of three-ply tongue-in-groove butt joint weldments with single-ply doublers. Tensile tests in W-Cu composites at 23, 230, and 250 °C.

The fourth specimen, E-2, failed at the joint but with a calculated JE of 100 percent.

As shown in table IV, tests at 250 °C were conducted on specimens from panels B and D. Inadvertently, one of the specimens from each panel was tested at 230 °C. Diffusion brazed panel D which was Ag sputter coated had a JE of 96 percent at 230 °C and 89 percent at 250 °C. Both specimens failed in the base material away from the joint and the JE was higher than the room temperature JE (fig. 18). Specimens from panel B, which were sputter coated with Cu and diffusion welded, had JE's of 75 percent at 230 °C and 86 percent at 250 °C. Failure in both cases was at the joint with some shear at the panel/doubler interface. As shown in figure 18, the JE was similar to the room-temperature JE for panel A.

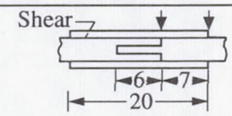
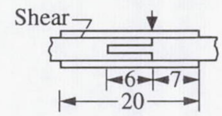
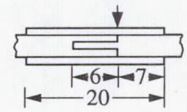
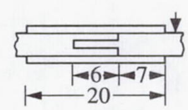
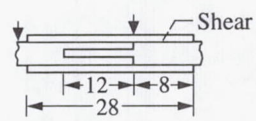
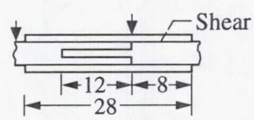
Welded Lap-Butt Joints

Tensile test results and failure locations are presented in table V for joints in four-ply W-Cu composites with single- and two-ply doublers. Slight joint rotation (3° or less) was observed in the testing of joints with single-ply doublers. No rotation was observed for the joints with two-ply doublers, except for specimen L-2. Joint efficiency with single-ply doublers varied from 60 to 90 percent and with two-ply doublers, from 67 to 100 percent. Reproducibility of test results for the duplicate specimens from each panel was good, since panels H, I, and O were the only panels which exhibited significant variations in JE. The tensile test results are summarized in the bar chart in figure 19 where a calculated JE is shown for each panel and the "x" indicates specimen failure in the base material.

In room-temperature tests of panels with two-ply doublers, panel S, which was sputtered with a Ti alloy and diffusion brazed, showed the highest JE's (99 and 100 percent). Failure was located in the composite base material away from the joint. Panel Q, which was sputter coated with Cu and diffusion brazed with Ti, had JE's of 82 and 85 percent and also failed in the base material. Panel M specimens, which were sputter coated with Cu and diffusion welded, failed in the base material. The calculated JE's were only 74 and 79 percent. These results indicate that this particular panel was relatively weak. Panel O specimens, which were sputter coated with Ag and diffusion brazed, exhibited significantly different JE; both specimens failed in relatively weak base material. The failure of all sputter-coated specimens in the base material indicates that these were strong joints. In contrast, the specimens from panel K, which were diffusion welded using a Cu foil interlayer, had 74 and 78 percent JE's. Failure was observed at the joint and at the panel/doubler interface.

TABLE IV.—TENSILE PROPERTIES OF ACTUAL WELDED TONGUE-IN-GROOVE BUTT JOINTS

[Joints in three-ply W-Cu composites with single-ply doublers.]

Panel	Specimen code	Test temperature, °C	Fracture load, kN	Fracture stress, MPa	Joint efficiency, percent	Joint design and failure location[a], mm
A	A-1	23	9.21	892	81	
	A-2	23	8.87	847	77	
B	B-1	230	7.34	699	75	
	B-2	250	8.27	802	86	
C	C-1	23	8.67	853	78	
	C-2	23	7.45	732	67	
D	D-1	230	9.05	892	96	
	D-2	250	8.36	822	89	
E	E-1	23	9.54	925	84	
	E-2	↓	11.4	1100	100	
F	F-1	↓	10.8	1040	95	
	F-2	↓	11.0	1060	96	

[a]Arrows indicate failure location.

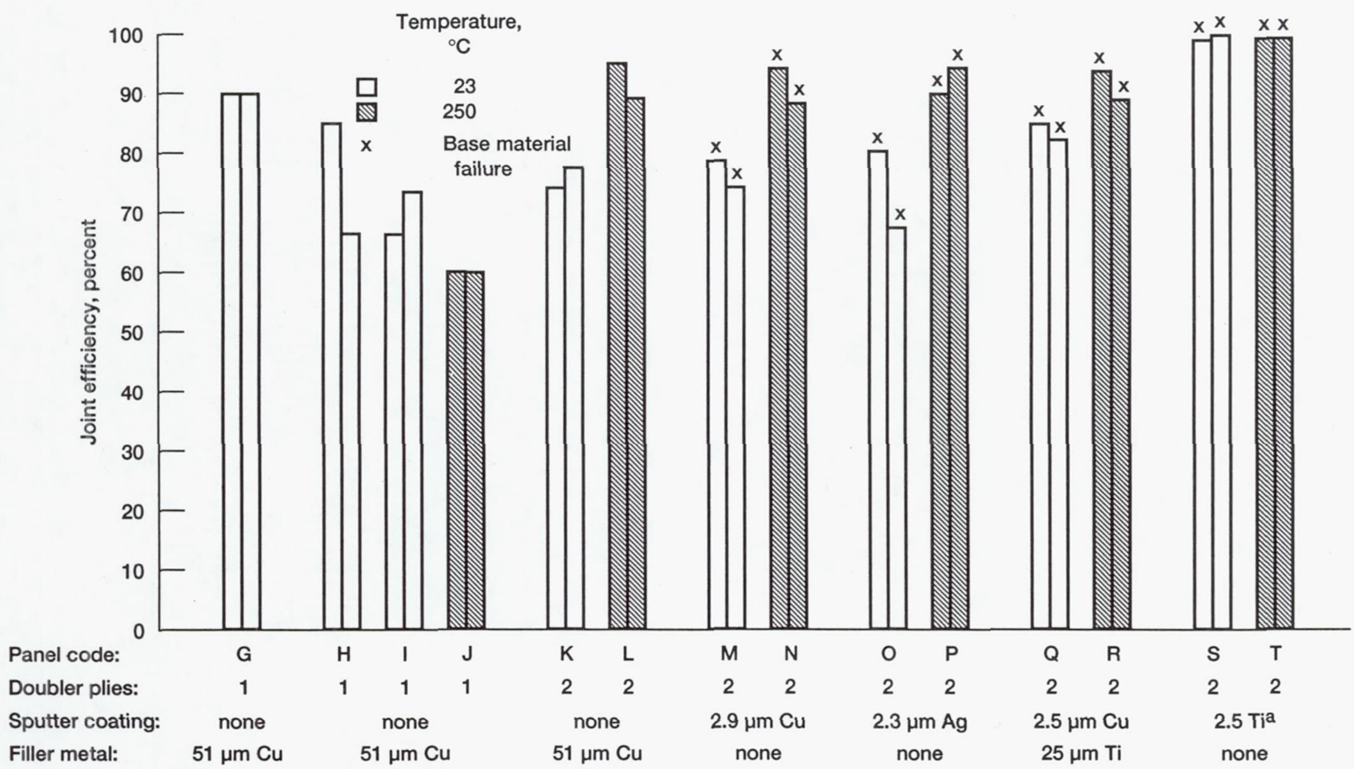
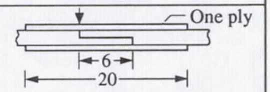
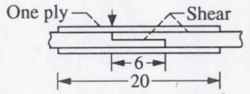
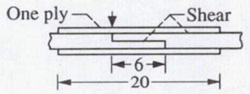
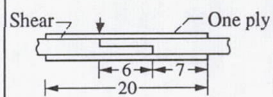
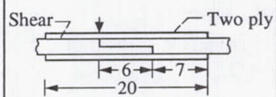
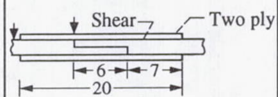
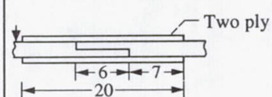
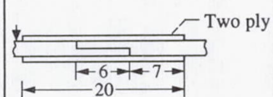
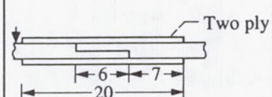
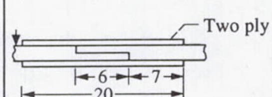
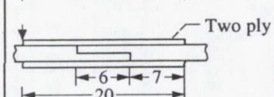
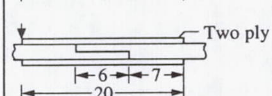
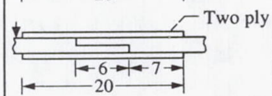
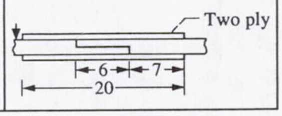


Figure 19.—Joint efficiency of four-ply lap-butt joint weldments. Tensile tests in W-Cu composites at 23 and 250 °C.
[a]Ti-6Al-2Sn-4Zr-6Mo.

TABLE V.—TENSILE PROPERTIES OF ACTUAL WELDED LAP-BUTT JOINTS

[Joints in four-ply W-Cu composites with single- and two-ply doublers.]

Panel	Specimen code	Test temperature, °C	Fracture load, kN	Fracture stress, MPa	Joint rotation, deg	Joint efficiency, percent	Joint design and failure location[a], mm
G	G-1	23	14.0	988	2	90	
	G-2	↓	13.7	988	3	90	
H	H-1		13.1	930	2	85	
	H-2		10.2	727	1	66	
I	I-1		10.2	726	0	66	
	I-2	↓	11.3	811	↓	74	
J	J-1	250	7.96	554		60	
	J-2	250	8.01	558		60	
K	K-1	23	10.9	809		74	
	K-2	23	11.9	850		77	
L	L-1	250	11.8	879	↓	95	
	L-2	250	11.0	825	2	89	
M	M-1	23	12.0	865	0	79	
	M-2	23	11.3	817		74	
N	N-1	250	12.5	868		94	
	N-2	250	11.8	817		88	
O	O-1	23	12.2	881		80	
	O-2	23	10.0	739		67	
P	P-1	250	10.9	832		90	
	P-2	250	12.2	870		94	
Q	Q-1	23	13.0	937		85	
	Q-2	23	12.5	906		82	
R	R-1	250	12.2	875		94	
	R-2	250	11.8	823		89	
S	S-1	23	14.5	1091		99	
	S-2	23	14.7	1110		100	
T	T-1	250	12.3	918		99	
	T-2	250	12.4	917	↓	99	

[a]Arrows indicate failure location.

In room-temperature tests of panels with single-ply doublers, panel G specimens with Cu foil at only the lap portion of the joint had 2° and 3° joint rotation but a high (90 percent) JE. Tensile failures were through the joints. Panels H and I, diffusion welded with Cu foil interlayers, had lower JE's (66 to 85 percent). Failure occurred at the joints by a combination of mixed shear and tensile modes.

Test results at 250 °C for panels with two-ply doublers are also presented in table V and figure 19. Panel T specimens, which were sputter coated with a Ti alloy and diffusion brazed, had a 99-percent JE. Failures were in the composite base material, away from the joint. Test specimens from panel N (sputtered with Cu), panel P (sputtered with Ag), and panel R (sputtered with Cu and diffusion brazed with Ti) had JE's ranging from 88 to 94 percent. As reported earlier in this section for the room-temperature tests, all sputter-coated specimens tested at 250 °C also failed in the base material with no evidence of shear failure at the panel/doubler interface. Panel L specimens, diffusion welded using a Cu foil interlayer, had very good JE's (89 and 95 percent); however, failure occurred through the joint and the panel/doubler interface.

Panel J was the only panel with single-ply doublers, tested at 250 °C. Panel J specimens with Cu foil interlayers failed partly by shear at the doublers and the JE was only 60 percent.

Discussion

Simulated butt joints in three- and four-ply W-Cu composite sheet were successfully fabricated and tested. The tensile strength and failure mode of the simulated joints provided useful information which could be used in the design and construction of composite hardware or components. For example, tensile tests of three-ply simulated TG-butt joints showed that a 3-mm tongue length was of sufficient length to produce tensile failure at the base of the tongue rather than a shear failure through the Cu matrix. Simulated TG-butt joints with 20-mm-long single-ply doublers produced JE greater than 90 percent. Tests of simulated lap-butt joints in four-ply sheet with a 3-mm overlap showed that this amount of overlap was insufficient. These joints were weak and failure was by shear through the Cu matrix with joint rotation during testing. However, matrix shear and joint rotation were avoided with a 6-mm overlap and 20-mm-long two-ply doublers; the JE was over 90 percent.

On the basis of the simulated joint tests, TG-butt and lap-butt weld joint designs were selected for actual welded joints in the W-Cu composites. These joint designs were successfully fabricated and used in the welding studies. In the cursory welding program that followed, all of the joints contained flaws. However, tensile testing showed that these butt joints with doublers could be as strong as or stronger than the W-Cu base material.

For TG-butt joints, the process of diffusion brazing with 25-μm 72Ag-28Cu foil or with Ag sputter-coated faying surfaces produced the strongest joints although an excessive amount of filler metal was present at the 72Ag-28Cu joints. It is possible that this could be eliminated with further optimization of this process. Diffusion brazing with a sputter coating of a Ti alloy produced the highest tensile strengths for lap-butt joints and failure in the base material. The 72Ag-28Cu filler metal was not used in the lap joints but is recommended in future studies. Promising results were also obtained in lap-butt joints by diffusion brazing with a 25-μm Ti foil interlayer between Cu sputter-coated surfaces. However, since an excessive quantity of Ti-Cu filler metal was produced, a future run with a much thinner Ti interlayer is recommended. Diffusion brazing an Ag-sputtered coating and diffusion welding with a Cu-sputtered coating also produced strong joints. All lap-butt joints, whether sputter coated with Cu, Ag, or a Ti alloy, produced joints with tensile failure in the base material. Sputter coating is recommended for both faying surfaces in order to avoid oxide stringers at the braze metal/doubler interface. Instead of direct diffusion welding of the Cu matrix to itself, a Cu foil interlayer is recommended to improve joint soundness.

Metallographic studies of the TG- and lap-butt joints revealed that flaws, including porosity, unwelded regions, scattered oxides, and oxide stringers, were present in all joints. Additional work, such as stress rupture and thermal cycling testing, is necessary to characterize the effects of weldment flaws on mechanical properties.

Conclusions

Simulated butt joints for three- and four-ply sheet were designed and fabricated in unidirectional W-Cu composite sheet. After simulated joints were evaluated by tensile testing, panels were produced with selected joint designs for actual welding experiments and tensile tests. On the basis of the test results of simulated joints and actual weldments, the following conclusions are offered.

1. Simulated welded joints can be fabricated successfully in composite sheet by utilizing preplanned breaks in the reinforcing fibers. These simulated joints provide strength and failure mode information for the joint design of actual weldments.

2. Tongue-in-groove- and lap-butt joint weldments in W-Cu sheet with doublers can match the tensile strength of the W-Cu base material at room temperature and at 250 °C.

3. Complex joint configurations can be fabricated for subsequent welding runs during the consolidation of the composite panels.

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13. ABSTRACT *(Maximum 200 words)*

The weldability of W-Cu composite sheet was investigated using simulated and welded joints. The welded joints were produced in a vacuum hot press. Tensile test results showed that simulated joints can provide strength and failure mode data which can be used in joint design for actual weldments. Although all of the welded joints had flaws, a number of these joints were as strong as the W-Cu composite base material.

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