Joining Depleted Uranium to High-Strength Aluminum Using an Explosively Clad Niobium Interlayer

Explosive and electron beam welding processes were developed to produce joints between the two materials

BY J. W. ELMER, P. TERRILL, D. BRASHER, AND D. BUTLER

ABSTRACT. A uranium alloy was joined to a high-strength aluminum alloy using a commercially pure niobium interlayer. The Nb interlayer was joined initially to the aluminum alloy using an explosive welding process, while the Nb interlayer was subsequently joined to the uranium alloy using an electron beam welding process. Explosive welding was selected to bond Nb to the aluminum alloy and minimize the formation of brittle intermetallic phases. Electron beam welding was selected to join the uranium alloy to the Nb to precisely control melting of the uranium alloy so it would wet the Nb substrate with minimum melting. A modified Faraday Cup (MFC) technique using computer-assisted tomography was employed to determine the power distribution of the electron beam so the welding parameters could be directly transferred to other welding machines. Optical microscopy, scanning electron microscopy, microhardness, and tensile testing of joints were used to characterize the resulting joints. This paper presents the joining techniques and processing parameters developed to produce joints between these materials.

Introduction

A component consisting of a high-strength 6061 aluminum alloy and a depleted uranium alloy was designed with the requirement of having a high-integrity joint between the two alloys. This very unusual combination of materials was difficult to join because of the widely differing physical and mechanical properties between aluminum and uranium alloys. Direct-fusion welding, brazing, and diffusion bonding were all initially considered for producing the joint, however, each of these joining methods posed certain problems. For example, a direct-fusion weld was not possible due to the creation of $U\text{-}Al_2$ and $U\text{-}Al_3$ brittle intermetallic phases in the fusion zone (Ref. 1). Vacuum brazing was not possible because the aluminum-based braze alloys required to braze aluminum would also form brittle phases with the uranium at the joint interface (Refs. 2, 3). Diffusion bonding of Al to U-6 wt-% Nb using a thin interlayer such as silver might have been possible. However, a diffusion-welded joint would be difficult and costly to make due to the size of the components, and the mechanical properties of the thin, silver interlayer joint may not have been sufficient for the intended application (Refs. 4, 5).

To overcome the problems associated with making a direct joint between U-6 wt-% Nb and Al, an intermediate metal was selected to form the transition between them. Requirements for the intermediate metal were that it be joined to aluminum on one side of the transition and electron beam welded to U-6 wt-% Nb on the other. Candidate materials to form the transition between aluminum and U-6 wt-% Nb that also had the highest likelihood of success were refractory metals because many of them can be alloyed with uranium alloys. Niobium was selected for this purpose since it does not form intermetallic compounds with uranium, the U-6 wt-% Nb alloy already contains some Nb, and the density of Nb is approximately halfway between that of Al and U-6 wt-% Nb.

From a fusion welding standpoint, the only difficulty with joining Nb to U-6 wt-% Nb was the melting point of Nb is considerably higher than the liquidus of the uranium alloy. However, with careful weld-joint design and precision welding techniques, this difference in melting points did not pose a problem. The aluminum side of the joint was a bit more challenging because fusion welding and brazing of aluminum to all metals other than aluminum alloys is difficult (Ref. 2). Therefore, it was necessary to make the aluminum side of the joint using a solid-state joining process to avoid contact of liquid aluminum with the U-6 wt-% Nb alloy. To accomplish this, an explosive welding procedure (EXW) was developed to join the Nb to the aluminum. This technique was chosen because it is well established for aluminum alloys, and because the flat-plate geometry and large surface area of the component were ideally suited for the EXW process (Ref. 6).

The design of the finished component required the aluminum to be in the high-strength condition. Since EXW of aluminum alloys in their low-strength condition is preferred to the high-strength condition, the Nb plate was first explosively clad to 6061 aluminum in the solution annealed and quenched (T4) condition. This composite joint was later heat treated to bring the 6061 aluminum to the high-strength –T6 condition prior to electron beam welding the clad material to the U-6 wt-% Nb side of the component.

This paper describes the welding techniques and processing parameters for

KEY WORDS

Explosive Welding
Dissimilar Metal Welding
Aluminum
Niobium
Uranium
Mechanical Properties
Metal Claddings
Electron Beam Welding
Power Density Distribution
Electron Beam Diagnostics

J. W. ELMER (Elmer1@LLNL.GOV) and P. TERRILL are with Lawrence Livermore National Laboratory, University of California, Livermore, Calif. D. BRASHER and D. BUTLER are with High Energy Metals, Inc., Port Townsend, Wash.

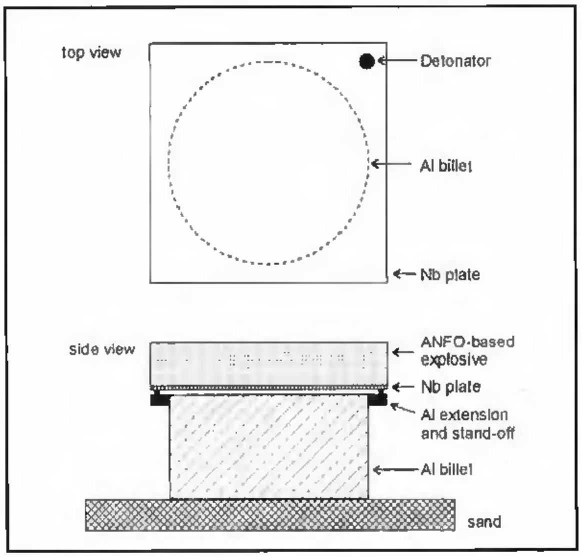


Fig. 1 — Schematic drawing of the explosive welding setup. The cylindrical aluminum billet is clad using an oversized square Nb plate to promote good bonding near the edge of the aluminum billet.

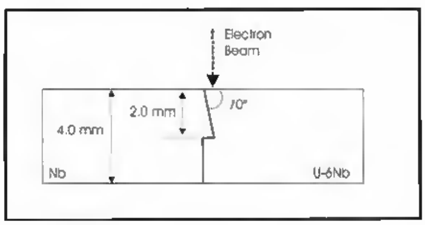


Fig. 2 — Schematic cross section of the electron- beam, weld-joint design. The beam is offset 0.5 mm into the U-6 wt-% Nb alloy from joint interface on the top surface of the component. A beveled joint design is employed to minimize mixing of the two alloys.

producing both the explosively clad joint between 6061 Al and Nb and the electron-beam-welded joint between U-6 wt-% Nb and Nb. The joints were examined using both optical metallography and scanning electron microscopy and the mechanical properties of both the explosive weld and the electron beam weld were investigated using uniaxial tensile testing and microhardness testing. Results showed the mechanical properties obtained across the composite joint were similar to that of the niobium and these joints ultimately failed within the Nb interlayer.

Materials and Experimental Procedures

Materials

Aluminum alloy 6061 was obtained in 15-in.-diameter circular billets that were 7 in. thick. These billets were then solution annealed at 530°C for 12.5 h before quenching in water to place them into the –T4 heat-treated condition. The composition of the 6061 Al (wt-%) was 0.68 Si, 0.36 Fe, 0.30 Cu, 0.103 Mn, 0.93 Mg, 0.06 Cr, 0.19 Zn, and 0.04 Ti based on the mill analysis. Commercially pure Nb was purchased in annealed 17-in.^{2}, 0.375-in.-thick sheets. The composition of the Nb was 10 ppm C, 95 ppm O, 35 ppm N, <5 ppm H, 400 ppm Ta, 15 ppm Fe, and 15 ppm Si, based on the mill analysis. The U-6 wt-% Nb alloy was acquired in plate form and had been heat treated at 200°C for 2 h; the composition of this plate was not measured. After explosive cladding, the aluminum was heat treated from the –T4 to the –T6 condition. This heat treating was performed in a vacuum furnace at 178°C for 8 h followed by a furnace cool to room temperature.

Explosive Welding

Explosive welding was performed at High Energy Metals, Inc., to join the Nb plates to the aluminum-alloy billets. All surfaces to be joined were ground flat to within 0.80 mm per meter with a surface finish better than 1.6 μm root-mean-square and cleaned with an organic solvent in preparation for explosive welding. The surfaces to be joined were assembled parallel to each other using a constant standoff distance of 3 mm provided by aluminum shims, as illustrated in Fig. 1. To help ensure good bonding as far out on the outer diameter of the aluminum billet as possible, an aluminum frame was fabricated around it to support the edges of the square Nb plate. A wooden box was then constructed around this assembly to contain the explosive mixture above the Nb plate.

The explosives used were an ammonium nitrate-fuel oil- (ANFO) based proprietary mixture. The charge load was adjusted to not exceed 9 lb/ft^2, for an estimated detonation velocity of 2000 to 2400 m/s. A blasting cap was placed near one corner of the Nb plate and detonated. After bonding, a visual inspection was performed at the blast site to assess edge deformation and relative flatness of the joint. Ultrasonic inspections were then performed in accordance to ASTM A578M-96 to assess the quality of the bond.

Electron Beam Welding

Electron beam welding was performed at Lawrence Livermore National Laboratory using a 150 kV/50 mA Hamilton Standard welding machine (No. 175) fitted with a ribbon filament and an R-40 gun. A 10-mA, 100-kV sharp-focused electron beam was used to weld the parts in a vacuum chamber pumped down to 10^{-5} torr. The parts were located 7 in. below the top of the vacuum chamber, and the weld was made by moving the parts at a constant travel speed of 40 in./min beneath the stationary electron beam.

In order to minimize melting of the Nb, a weld-joint design was developed on flat test pieces with a 70-deg angle to help match the natural wedge shape of the electron beam fusion zone to the U-6 wt-% Nb alloy being melted. In this design, the electron beam was concentrated on the U-6 wt-% Nb side of the joint in order to melt the U-6 wt-% Nb and allow it to wet the higher melting point Nb. This weld joint design helped mitigate the large difference in melting points between the Nb (2469°C) and U-6 wt-% Nb (1140°C).

A schematic drawing of the electron beam joint design is shown in Fig. 2, indicating the location of the electron beam is offset 0.5 mm from the location where the Nb and U-6 wt-% Nb come together on the top surface of the plates. This amount of offset was chosen from the results of several practice welds, which showed the molten U-6 wt-% Nb may not wet the entire Nb interface to the top of the joint if the beam is offset more than 0.5 mm from the interface with these welding parameters. Undesired melting of the Nb occurred if the offset was less than 0.5 mm.

The power density of the electron beam was measured using a modified Faraday Cup device (Refs. 7, 8) so the electron beam parameters could be repeated on the same machine and also transferred to other electron beam welding machines. The MFC design contained 17 slits, 1 measuring 0.2 mm wide and the other 16 measuring 0.1 mm wide (Ref. 8). Data was taken while scanning the beam over the MFC at 60 Hz and in a 25-mm-diameter circle over the slit disk using the on-board deflection coils of the electron beam welding machine. Electron beam profile information was gathered as the electron beam passed over each slit by measuring the voltage drop across a 200-Ω resistor. Rapid data collection was performed using an analog-to-digital converter sampling at a frequency of 500 kHz, and was tomographically reconstructed using LLNL-developed software written on LabView 5.0 (Ref. 7). Figure 3 shows the reconstructed power distribution of the electron beam, which has a nearly circular Gaussian shape with a full

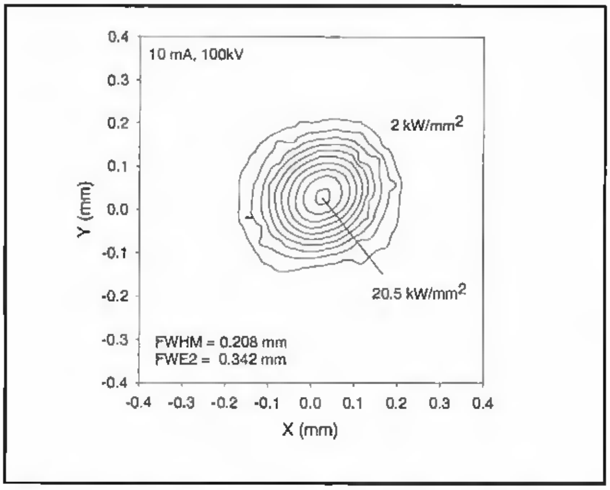


Fig. 3 — Tomographically reconstructed power density distribution of the electron beam used to make the U-6 wt-% Nb alloy to Nb-dissimilar metal weld. This beam has a peak-power density of 20.5 kW/mm^2 and a full width at half maximum (FWHM) of 0.208 mm.

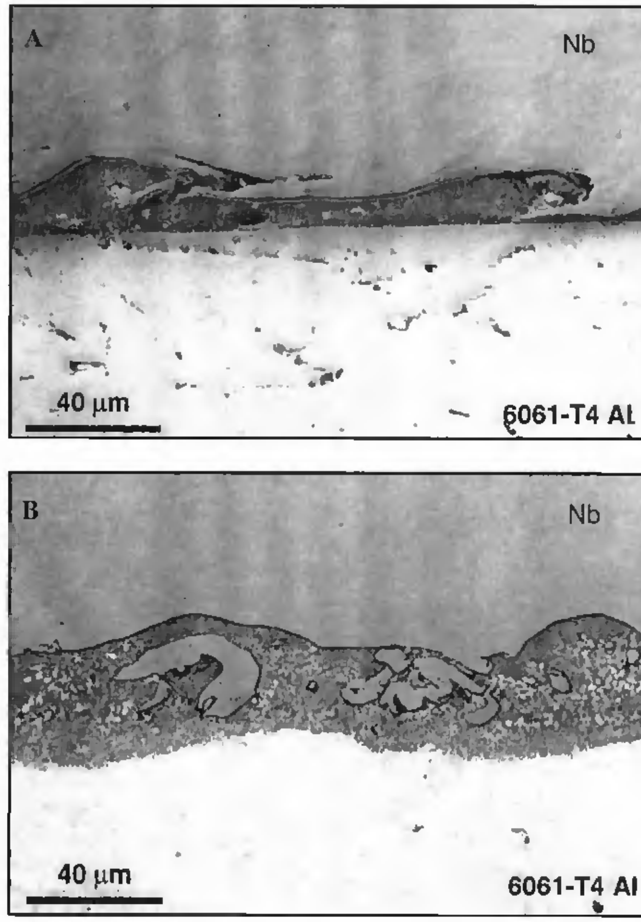


Fig. 4 — Optical metallographic cross sections of the explosive weld joint. A — Interface as viewed perpendicular to the explosive front direction; B — interface as viewed parallel to the explosive front direction.

width half maximum (FWHM) value of 0.208 mm, a full width at 1/e^2 (FWE2) value of 0.342 mm, and a peak power density of 20.5 kW/mm^2. This quantitative description of the electron beam will be used later for transferring this weld to other electron-beam welding machines.

Materials Characterization

Optical metallography was performed using conventional polishing and etching techniques; the samples were viewed in both as-polished and etched conditions. The Al/Nb samples were etched in a chemical bath of glycerol (20 mL), hydrofluoric acid (10 mL), and nitric acid (10 mL). Due to the difference in etching behavior between these two metals, the aluminum etched more rapidly than the Nb, leaving the Nb underetched in most of the micrographs. The U-6 wt-% Nb/Nb samples were electrolytically etched in a 10% oxalic acid bath, which etched the U-6 wt-% Nb side of the joint more aggressively than the Nb side of the joint. Photographs of the microstructures were obtained under both normal and polarized light conditions. Scanning electron microscopy was performed using a 5 keV beam to show the detail of the explosive weld interface. These micrographs were obtained with the SEM in backscatter mode to reveal the location of the Al and Nb phases where the Nb-rich areas appear light and the Al-rich areas appear dark in contrast.

Microhardness measurements were made on polished samples using a diamond pyramid hardness (DPH) tester. Hardness measurements near weld interfaces were made using a 50-gf load, whereas bulk hardness measurements were made using a 300-gf load. The hardness measurements were calibrated using a standard test block with a 704 ± 8 DPH value at 300-gf loads. The microhardness measurements made near the interface at the lower load level of 50 gf can only be used for relative hardness values since these data were uncalibrated.

Tensile testing was performed on 1.5-mm-thick dog-bone-shaped tensile bars. All tests were performed using a crosshead rate of 1.3 mm/min and run at room temperature. A 50% strain extensometer with 5.0-mm gauge length was used to measure strain across the explosive welded joint while a 50% strain extensometer with a 25.4-mm gauge length was used for base metal samples and samples containing electron beam welds. Tensile samples taken perpendicular to the explosive bond required Nb extensions to be welded on to the Nb-clad layer to allow a large enough sample to be machined from the clad plate. The Nb extensions were welded onto the clad plate using an electron beam welding technique that placed this electron beam weld in the grip portion of the tensile bar so as not to interfere with the reduced section of the tensile bar. Scribe lines were placed on all samples for elongation to failure measurements. A Micro-Measurements model 1120 signal conditioning amplifier was incorporated to provide the signal output for the extensometers, which were then used for elastic modulus and yield strength determination. All tests were performed using an Instron 1125 electromechanical test machine with a 1000 lb load cell, and the data was acquired with a National Instruments PC-based data acquisition system. Elongation and cross-sectional measurements were obtained using a Nikon optical comparator before and after testing.

Results and Discussion

Explosive Welding 6061 Al to Nb

One of the 15-in.-diameter, explosively clad billets was cross sectioned to determine the quality of the joint. Figure 4 shows photomicrographs taken from this joint viewed from two different orientations: A — perpendicular to the wave front propagation, and B — parallel to the wave front propagation. The view perpendicular to the explosive front direction (Fig. 4A) shows the wave-like nature of the explosive bond interface.

Table 1 — Summary of the Tensile and Hardness Properties Measured on the Base Metals and on the Completed Joints (Sample gauge lengths (GL) vary as indicated.)

Material	Hardness (DPH)	Number of tests	$\sigma_{y,0.2\%}$ (ksi)	σ_{UTS} (ksi)	Elongation (%)	E (Msi)	Fracture
Base Metals							
6061 Al-T4	95	2	33.6	40.2	8.2**	10.2	—
6061 Al-T6	115	2	41.9	45.2	6.4**	10.3	—
Nb, at the bond line	130	2	46.9	48.1	12.9**	12.2	—
Nb, >3 mm from bond line	105	6	40.6	44.9	17.1**	13.2	
U-6 wt-% Nb	220	2	44.8	130.4	6.2**	9.8	—
Welds							
Nb/Al-T6	—	3	39.7	47.1	39.5*	13.1	Nb
U-6 wt-% Nb/Nb	—	3	31.1	37.1	11.5**	9.93	Nb
U6 wt-% Nb/Nb/ 6061 Al-T6	—	3	34.7	45.0	21.0***	13.8	Nb

* 5 mm GL; ** 25 mm GL; *** 10 mm GL.

Here, the Nb has formed into waves above what appears to be a mixed region containing both aluminum and niobium constituents. This mixed region resides on a relatively flat base of aluminum. The view parallel to the explosive front direction (Fig. 4B) shows these same regions where ostensible, isolated islands of Nb observed in this view are most likely the cross-sectioned crests of the Nb waves that were seen in Fig. 4A.

The optical micrographs indicate some degree of mixing occurs between the Nb plate and the 6061 Al billets during the explosive bonding process. This mixed region was investigated further at higher magnifications using scanning electron microscopy. Figure 5 shows the results of one of these SEM micrographs, where Nb appears as high-intensity regions (light areas) and aluminum appears as low-intensity regions (dark areas). This SEM micrograph reveals an interfacial region that is complex, containing a mixture of large, relatively unaffected Nb pieces and a dispersion of smaller, submicron-sized, Nb-rich particulates. These small Nb-rich particulates have irregular shapes and oftentimes have nonsmooth surfaces. The origin of the dispersed Nb phase has not been evaluated at this time, and will require additional characterization to determine its microstructural evolution.

The thickness of the interfacial region was measured at different locations from the point of detonation and was shown to be the thickest (40 μm) close to the detonation initiation area and to be thinnest (5 μm) near the far edge of the plate. This nonuniformity is not thought to be a problem for the intended application; however, additional EXW experiments are being considered where the explosive is detonated from the center of the plate in order to minimize the variation in the interfacial region thickness.

Microhardness measurements were made through the joint region in both the as-explosively clad condition and also in the heat-treated condition. The 6061 Al prior to heat treating (–T4 condition) had a hardness of 95 DPH and after heat treating (–T6 condition) had a hardness of 115 DPH. These bulk hardness measurements were made using a 300-g load. A hardness gradient was observed in the commercially pure Nb adjacent to the EXW bond line. Figure 6 shows the results of a microhardness traverse through the Nb using a 50-g load. At the bond line, the hardness of the Nb was measured to be 130 DPH, and this value decreased to the base metal value of 110 DPH at a distance of approximately 1.5 mm from the bond line.

Electron Beam Welding U-6 wt-% Nb to Nb

Figure 7A shows a metallographic cross section made from the welded joint at low magnification. The weld is free of cracks, free of porosity, and the weld penetration exceeded the depth of the step by 0.36 mm. It is clear the fusion boundary followed the 70-deg angle of the original joint preparation on the Nb side of the

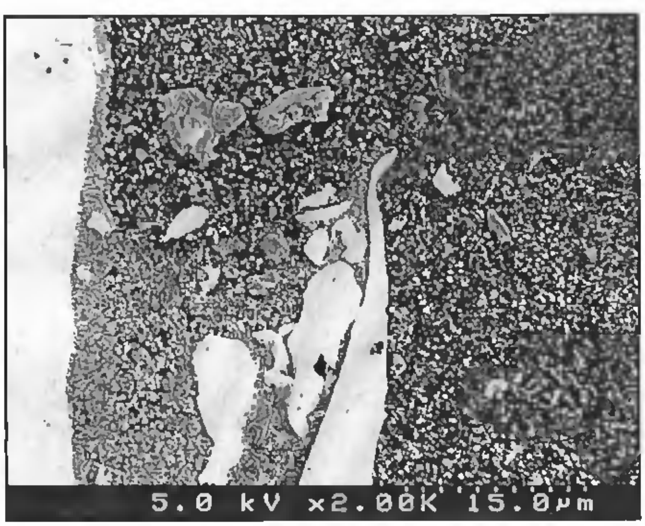


Fig. 5 — Scanning electron microscope image taken at the Nb/Al interface. The Nb-clad plate is on the left side of the micrograph and appears light in contrast to the backscattered electron-image mode. The 40-mm-wide interfacial region is composed of a fine distribution of submicron Nb-rich particles with occasional large fragments of the Nb.

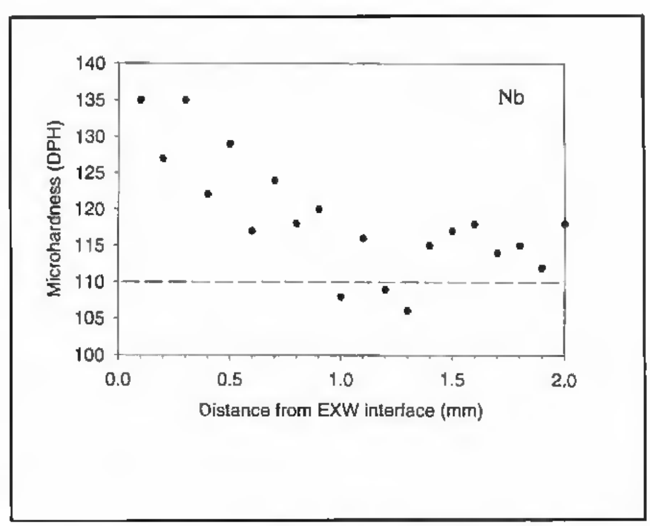


Fig. 6 — Microhardness traverse in the explosively clad Nb interlayer, showing an increase in hardness within 1.5 mm of the explosively bonded interface. The horizontal-dashed line represents the as-received Nb base metal hardness.

weld, showing minimal dissolution of Nb into the fusion zone. The entire Nb interface above the step in the joint was wet by the molten U-6 wt-% Nb alloy, leaving no undercut on the top surface of the weld joint. The final part could then be machined from the completely fused portion of the weld above the step in the joint.

Figure 7B shows a close-up view of the Nb side of the fusion zone, indicating perfect wetting of the Nb interface by the molten U-6 wt-% Nb alloy. Dendritic solidification occurred on this side of the joint with epitaxial growth occurring from the Nb base metal/U-6 wt-% Nb interface. Figure 7C shows a close-up view of the U-6 wt-% Nb side to the fusion zone, indicating the molten U-6 wt-% Nb alloy solidified in a cellular/dendritic mode with epitaxial regrowth from the U-6 wt-% Nb base metal.

Microhardness measurements were made in and around the U-6 wt-% Nb/Nb electron-beam-welded joint to determine if any hard phases were formed in the fusion zone and to determine if any softening occurred on either side of the joint. The hardness of the U-6 wt-% Nb alloy was measured to be 220 DPH in the base metal, 180 DPH in the HAZ, and 240 DPH in the middle of the fusion zone of the electron beam weld. The Nb adjacent to the electron beam weld measured 104 DPH. Thus, the fusion zone had a hardness very similar to that of the base metal U-6 wt-% Nb, and some softening occurred in the HAZ on both sides of the electron beam weld.

Tensile Test Results

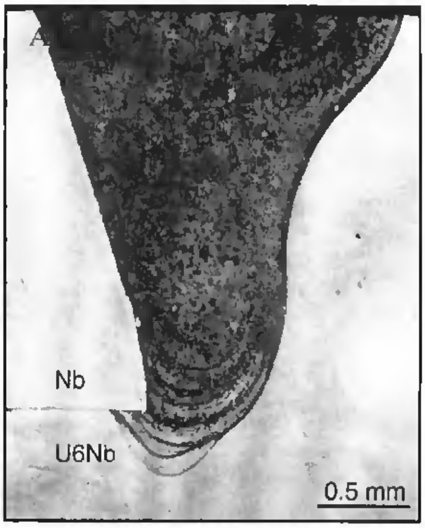
Tensile tests were performed on both the base metals and joined dissimilar metal combinations. All samples containing welds were prepared as cross-weld tensile samples with the weld perpendicular to the tensile axis, as illustrated in Fig. 8. The 25.4-mm extensometer was used to measure the strain on all base metal samples for the tensile bar configuration shown in Fig. 8A. The 5.0-mm gauge-length extensometer was used to measure the strain of the explosively welded Nb/Al joint for the joint configuration schematically shown in Fig. 8B.

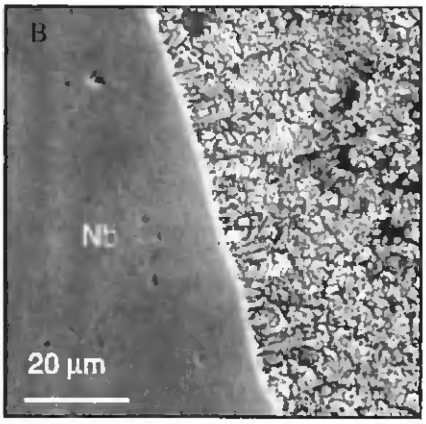
Figure 9 plots representative stress-strain curves for the different base metals; these results are summarized in Table 1. The Nb is the most ductile of the base metals and exceeds 10% elongation at failure, as measured using scribe lines placed 25 mm apart. The Nb was shown to have a gradient in properties, being stronger and harder near the bond line than in the bulk of the explosively bonded base metal. Tensile samples removed parallel to the explosive bond and from a region within 2 mm from the bond line had a yield strength of 46.9 ksi, which is 15% higher than the Nb base metal (40.6 ksi).

The effect of heat treating on the properties of the aluminum alloy was studied by pulling tensile bars in the as-received, –T4 condition, and in the heat-treated, –T6 condition. Before heat treating, the yield strength of the 6061 Al measured 33.6 ksi. After heat treating, the yield strength of the aluminum increased to 41.9 ksi, which is similar to the yield strength of the Nb base metal. The ultimate strength of the 6061 Al-T6 and Nb were also similar and were both approximately 45 ksi; however, the ultimate strength of the U-6 wt-% Nb is significantly higher at 130.4 ksi. The aluminum in the –T6 condition and the U-6 wt-% Nb were the least ductile base metals, having elongations at failure of 6.4 and 6.2%, respectively, as measured using scribe lines placed 25 mm apart. The modulus of elasticity of the 6061 Al was measured to be 10.3 Msi, which is about 30% lower than the Nb (13.2 Msi) and slightly higher than the U-6 wt-% Nb (9.8 Msi).

Figure 10 compares the tensile curves of the cross-weld samples with the Nb base metal. In all cases, the welded joints failed in the Nb in a ductile manner. These results clearly indicate, in these mismatched joints, that Nb is the softest material and undergoes preferential deformation. The tensile curves for the welded joint were acquired using only one extensometer and, therefore, do not account for the individual localized strains that develop on either side of the joint (Ref. 9). However, the stress-strain curves shown here do provide useful information regarding the overall behavior of these joints and thus provide an indication of how well the joints would perform in service.

Tensile bars consisting of Nb/6061 Al-T6 taken from the explosively welded joint were tested with the joint configuration illustrated in Fig. 8B. These samples failed in the Nb and had an average yield strength of 39.7 ksi, which is very close to that of the Nb base metal strength (40.6 ksi). The ultimate strength of this joint measured 47.1 ksi, which was slightly higher than the Nb base metal (44.9 ksi). The elongation of this joint, as measured by 5-mm-wide scribe lines placed on the sample, measured 39.5% elongation at failure. This elongation was significantly larger than that indicated by the stress-strain curve shown in Fig. 10 and higher than that measured on the base metal samples. These differences are due to a combination of the smaller gauge length of the scribe lines than those used on the base metal samples and the fact that the





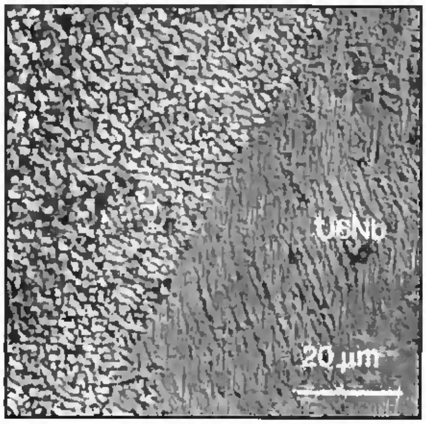


Fig. 7 — A — Optical metallographic cross section of the partial-penetration, electron beam weld fusion zone at low magnification. The U-6 wt-% Nb alloy is on the right-hand side of the micrograph, revealing a fusion zone shape consistent with a keyhole-penetration-mode weld. The Nb is on the left-hand side of the micrograph, revealing the largely unmelted 70-deg angled-joint preparation: B — high-magnification micrograph of the Nb side of the fusion zone; C — high-magnification micrograph of the U-6 wt-% Nb side of the fusion zone.

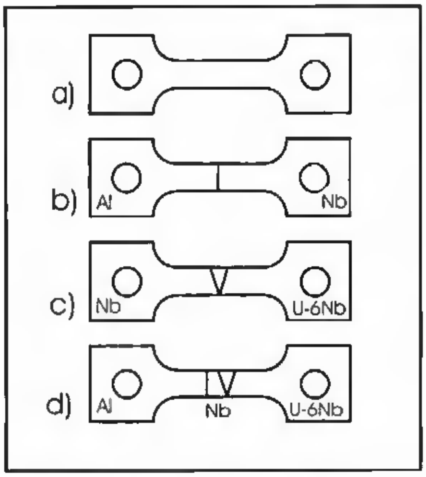


Fig. 8 — Schematic drawing of different tensile bar configurations. The vertical lines indicate the explosive bond and the V-shaped lines indicate the electron beam weld. A — A base metal sample; B — an explosive weld sample; C — an electron beam weld sample; D — explosive and electron beam weld sample.

failure occurred outside the gauge length of the extensometer.

The U-6 wt-% Nb/Nb tensile bars from the electron-beam-welded joint were separately tested using the joint configuration shown in Fig. 8C. The average yield strength of these welds measured 31.1 ksi and failure occurred on the Nb side of the joint. This lowered yield strength was the result of the electron beam weld, which had an annealing effect and reduced the strength of the Nb. The ultimate strength of this joint measured 37.1 ksi and the joint had an average elongation to failure of 11.5%, as measured with 25.4-mm-wide scribe lines.

The complete joint containing both an electron beam weld and an explosive weld was tensile tested after heat treating the aluminum to the –T6 condition. These U-6 wt-% Nb/Nb/Al-T6 tensile bars were tested with the joint configuration shown in Fig. 8D; all samples failed in the Nb interlayer. The average yield strength of these welds was 34.7 ksi, which was 15% lower than the Nb base metal. This lowered yield strength was again the result of the electron beam weld that had an annealing effect on the explosively clad Nb interlayer and thus softened the overall joint. The ultimate strength of this joint still remained high at 45.0 ksi, and was similar to the Nb base metal (44.9 ksi). The ductility of this joint, as measured by 10-mm-wide scribe lines placed on the sample, measured 21.0% elongation at failure. This elongation was again higher than that measured on the base metal due to the combination of strain concentration in the softer Nb and the use of smaller gauge-length scribe lines than were used for the base metal tests.

Summary and Conclusions

A method for joining 6061 Al to U-6 wt-% Nb was developed using a Nb interlayer between the two alloys. To this end, an explosive welding procedure was developed to join a 0.375-in.-thick Nb plate to a 6061 Al billet. The explosive welding procedure minimized the formation of brittle phases between Nb and Al, and was performed with the Al initially in the –T4 condition to facilitate explosive welding. The resulting joint between the Nb cladding and the 6061 Al-T4 was well bonded, as verified through ultrasonic testing. Rough machining of the Nb-clad aluminum joint was then performed; afterwards, the part was heat treated to put the 6061 Al into the high-strength –T6 condition. Following heat treating, the fusion-weld-joint details were machined into the Nb cladding, and it was electron-beam welded to the U-6 wt-% Nb alloy part. The component could then be final machined from this trimetallic part. Tensile tests, microhardness measurements, and metallographic characterization were performed on the joined components. The following conclusions were made:

- Commercially pure Nb can be explosively clad to 6061 Al. The resulting bond is strong and easily machined, thereby indicating Nb can be used to provide a transition between aluminum and other materials.
- During explosive welding, the strength and hardness of Nb increase. This effect was observed only within the first 1.5 mm from the explosive weld interface where the yield strength was observed to increase approximately 15% above that of the base metal.
- Explosive welding of Nb to Al worked well for 6061 Al in the –T4 condition. Heat treating the Nb-clad Al billet from the –T4 condition to the –T6 condition was performed after explosive welding and did not adversely affect the strength of the explosive-bonded joint.
- A method for electron beam welding U-6 wt-% Nb to Nb was developed. This method used a beveled joint design and concentrated the electron beam into the lower-melting-point

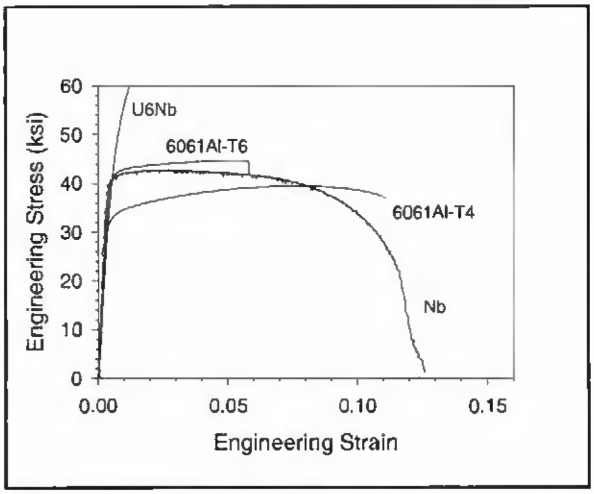


Fig. 9 — Tensile curves for the base metals of U-6 wt-% Nb, Nb, and the aluminum in the heat-treated, solution-annealed, and quenched conditions.

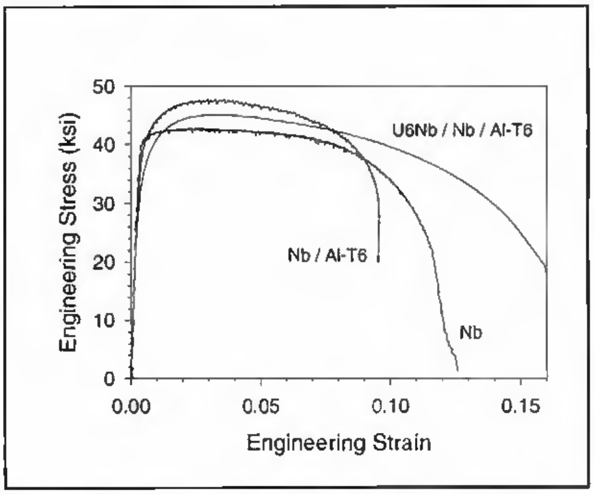


Fig. 10 — Tensile curves for the welded samples are compared to the Nb base metal.

U-6 wt-% Nb alloy to minimize mixing of the two metals. The resulting fusion zone did not display any brittle phases and had hardness values similar to the U-6 wt-% Nb base metal.

- The final trimetal joint contained both an explosive weld and electron beam fusion weld about 10 mm apart. Tensile tests across this joint showed the joint always failed in the Nb interlayer and had a yield strength of 34.7 ksi. This yield strength was somewhat lower than the Nb base metal due to the annealing effects of the electron beam weld on the Nb interlayer material.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy, Lawrence Livermore National Laboratory, under Contract No. W-7405-ENG-48. The authors would like to express their gratitude to many LLNL employees who contributed to this project including Alan Teruya for assisting with the electron beam diagnostics, Mark Gauthier for making the electron beam welds, Robert Kershaw and Bob Vallier for optical metallography and microhardness testing, Jim Ferriera for scanning electron microscopy, and Dave Hiromoto for tensile testing.

References

1. Massalski, T. B., ed. 1990. *Binary Alloy Phase Diagrams*, Vol. 3, 2nd ed. Materials Park, Ohio: ASM International.

2. ASM International. 1993. *ASM Metals Handbook: Welding, Brazing and Soldering*, Vol. 6, p. 937. Materials Park, Ohio: ASM International.

3. Schwartz, M. 1987. *Brazing*. Materials Park, Ohio: ASM International.

4. Rosen, R. S., Walmsley, D. R., and Munir, Z. A. 1986. The properties of silver-aided diffusion welds between uranium and stainless steel. *Welding Journal* 65(4): 83-s to 92-s.

5. Elmer, J. W., Kassner, M. E., and Rosen, R. S. 1988. The behavior of silver-aided diffusion-welded joints under tensile and torsional loads. *Welding Journal* 67(7): 157-s–162-s.

6. *ASM Metals Handbook: Welding, Brazing and Soldering*, Vol. 6, p. 896. 1993. Materials Park, Ohio: ASM International.

7. Elmer, J. W., Teruya, A. T., and O'Brien, D. W. 1993. Tomographic imaging of noncircular and irregular electron beam power density distributions. *Welding Journal* 72(11): 493-s–505-s.

8. Elmer, J. W., and Teruya, A. T. 1998. Fast method for measuring power-density distribution of noncircular and irregular electron beams. *Science and Technology of Welding and Joining* 3(2): 51.

9. Naumann, J., Vogel, J., Dobi, D., Angermann, T., and Koçak, M. 1997 Analysis of the elastic-plastic deformation behavior of austenitic-ferritic interface cracks using geometric Moiré, pp. 247–258, from the book, *Mis-Matching of Interfaces and Welds*, Schwalbe, K.-H., and Koçak, M., eds., pp. 247–258. Geesthacht, FRG: GKSS Research Center Publications.