Development of an Explosive Welding Process for Producing High-Strength Welds between Niobium and 6061-T651 Aluminum

Thin interlayers of Nb and Al were used to improve the joining of thicker plates

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ABSTRACT. An explosive welding procedure for joining 9.5-mm-thick niobium plate to 203-mm-thick 6061-T651 Al plate has been developed in order to maximize the weld tensile and impact strengths and the amount of welded material across the surface of the plate. This procedure improves upon previous efforts, in which the 9.5-mm-thick niobium plate is welded directly to 6061-T4 Al plate. In this improved procedure, thin Nb and Al interlayers are explosively clad between the thicker niobium and aluminum plates. Welds produced using these optimized parameters display a tensile strength of approximately 255 MPa and an impact strength per unit area of approximately 0.148 J/mm^2. Specialized mechanical testing geometries and procedures are required to measure these weld properties because of the unique weld geometry. In order to ensure that differences in the thermal expansion coefficients of aluminum and niobium do not adversely affect the weld strength, the effects of thermal cycling at temperatures between –22° and 45°C on the mechanical properties of these welds have also been investigated by testing samples in both the as-received and thermal cycled conditions. Based on the results obtained from this series of mechanical tests, thermal cycling is shown to have no adverse effect on the resulting tensile and impact strengths of the welds produced using the optimized welding parameters.

Introduction

A preliminary investigation of the feasibility of explosively welding niobium to aluminum has been previously published (Ref. 1). In that study, 9.5-mm-thick commercially pure Nb is welded to a 178-mm-thick 6061 Al plate in the T4 condition. These initial welds are produced in a conventional manner with the detonator placed at the edge of the plate. The aluminum plate is required to be in the softened (T4) heat treated condition to facilitate the explosive welding process. In order to transform the 6061-T4 Al to the desired T6 heat treated condition, a postwelding heat treatment is required. An ultrasonic evaluation of these welded plates shows that areas of disbonding are present on the side of the plate directly opposite from the detonator.

Radially symmetric welding across the weld interface can be achieved by moving the detonator to the center of the plate. A divot, surrounded by a small area of nonwelded material, is produced at the detonator location in the center of the plate. Additional areas of disbonding, as confirmed by ultrasonic scans, tend to be isolated near the edges of the plate, far from the locations where well-welded material is required. A ring of well-welded material extends radially outward more than 430 mm from the nonwelded region in the center of the plate.

In order to eliminate the postweld heat treatment and to directly weld the niobium to the 6061 Al plate in the hardened (T6) condition, explosively welded niobium and aluminum interlayers are introduced between the aluminum and niobium plates. Smaller explosive charges can be used to weld these interlayers to the thick aluminum plate, thus making it much easier to work with the aluminum plate in the hardened condition. The effects of the introduction of these interlayers on the resulting mechanical properties of the explosive weld are also investigated in this study.

The tensile properties of the initial welds produced with the detonator located at the edge of the plate were investigated using conventional tensile tests with a dog-bone geometry (Ref. 1). In order for the samples to have a sufficient length to place the Al-Nb weld interface in the center of the gauge length of the tensile bar, niobium extension bars were electron beam welded to the niobium-clad plate. During testing, these samples failed in the explosively clad niobium at locations near the weld interface, but not at the weld interface, showing that the strength of the weld exceeds that of the niobium. Additional mechanical tests, using sample geometries optimized for testing the tensile, shear, and impact strengths of the welds, have also been performed on samples taken from both the edge-detonated and center-detonated welds. These procedures are discussed further in a following section.

Table 1 provides a summary of the mechanical properties of the edge-detonated (Ref. 1) and center-detonated explosive welds. For both sets of welds, failure occurs at the Al-Nb weld interface, and the notched (268 ± 14.5 MPa and 287 ± 35.4 MPa, respectively) and unnotched (351 ± 17 and 268 ± 9 MPa, respectively) tensile strengths compare favorably with the ultimate tensile strengths of both niobium (310 MPa) and 6061-T6 Al (312 MPa) (Ref. 1). The measured shear strengths

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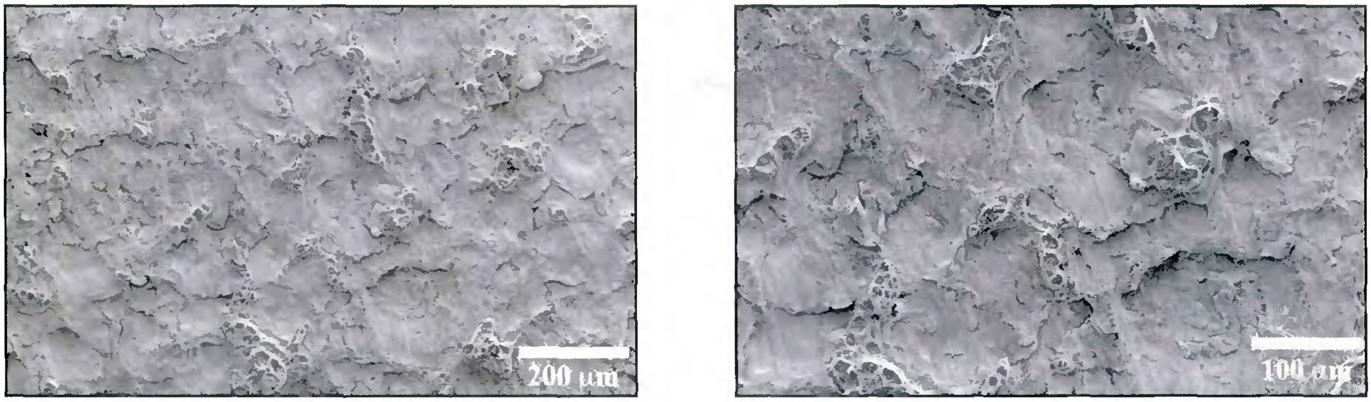

Fig. 1 — SEM micrographs of the fracture surface on one of the edge-detonated Izod samples.

Table 1 — Summary of Mechanical Properties of Preliminary Single-Welded Al-Nb Clad Plates

	Edge-Detonated Plates			Center-Detonated Plates		
	Number of Tests	Average	Standard Deviation	Number of Tests	Average	Standard Deviation
Tensile Strength (MPa)						
Unnotched	6	350.6	17.0	5	266.8	10.07
Notched	3	265.6	14.5	3	287.3	35.4
Shear Strength (MPa)	4	224.3	6.76	3	180.4	5.38
Impact Strength (J)	2/7	0.8/1.5[a]	0.1/0.1[a]	12	1[b]	0.2[b]
Impact Energy/Unit Area (J/mm2)	2/7	0.020/0.023	0.003/0.002	12	0.015	0.003

(a) Impact strength sample geometries are varied from a cross section of 3.2 x 10.2 mm to one of 6.4 x 10.2 mm.
(b) Impact strength sample geometry has a cross section of 12.7 x 10.2 mm.

(224 ± 7 MPa and 180 ± 5, respectively) are approximately 72% and 58%, respectively, of the measured tensile strength of the 6061-T6 Al. These measured shear strengths are consistent with the von Mises ductile failure criteria, which predict that the shear strength should be approximately 58% of the ultimate tensile strength (Ref. 2). It is also in line with the reported shear strength of 6061-T6 Al plate (207 MPa).

On the other hand, there are significant concerns about the impact strength of the resulting welds. As shown in Table 1, the measured impact strengths of the edge- and center-detonated weld samples are low (≥0.02 J/mm^2). All of the samples failed along the Al-Nb weld interface, and the majority of the fracture surface displays a rather flat appearance, indicative of a brittle fracture mode. Figure 1A and B shows micrographs taken of typical areas on a fracture surface obtained from an edge-detonated impact sample. While the majority of the fracture surface is characteristic of a brittle failure mode, there are small areas interspersed on the fracture surface displaying features similar to those more commonly associated with a more desirable ductile failure mode.

These low impact strengths and the brittle failure mode can be correlated with characteristics of the weld interface morphology. An examination of the weld cross section, which is shown in Figs. 4 and 5 in Ref. 1, shows regions of intermixing of the Al and Nb (Ref. 1). These regions consist primarily of submicron-sized Nb-rich particulates mixed with larger fragments of Nb in an Al-rich matrix. This behavior is consistent with the formation of Al-Nb intermetallic phases at the weld interface caused by the melting of the Al during the explosive welding process. It appears that these regions of Al and Nb intermixing result in a brittle weld being formed over a large area of the interface between the Al and Nb plates.

Changes to the welding process are thus required in order to produce welds with the desired tensile and impact strengths. In the current study, a three-step explosive welding process is developed to join Grade 1 (Reactor) niobium directly to 6061-T651 Al plate, thus removing the follow-on heat treatment. These welds must meet minimum criteria for tensile, shear, and impact strengths, which are measured using specialized mechanical testing geometries and procedures. In addition to meeting these mechanical property requirements, the amount of well-welded material across the surface of the thick Al plate must be maximized. In order to meet these requirements, a procedure involving the explosive welding of thin sheets of Al and Nb between the thicker Al and Nb plates, has been developed. The introduction of these thin interlayers not only produces welds with the required tensile, shear, and impact strengths, but also allows the thick Al plate to be welded in the high-strength (T-651) condition, thus removing the requirement for a postweld heat treatment of the clad material.

Experimental

Explosive Welding

The explosive welding (EXW) process is a solid-state joining process used to join a wide variety of materials that cannot be joined using traditional fusion welding processes (Ref. 3). A schematic diagram showing the basic components of this process (the explosive charge, a base metal, and a clad metal) is shown in Fig. 2. Prior to welding, the clad metal is offset a given distance above the base metal, and a predetermined amount of explosive is placed on top of the clad metal. A controlled explosive detonation is used to accelerate this clad metal into the base metal at a sufficient velocity that the collision

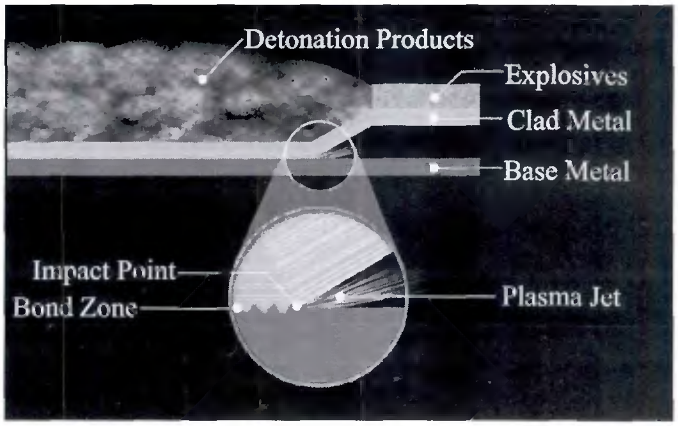

Fig. 2 — Schematic figure showing the basic features of the explosion welding process and the properties of the resulting weld.

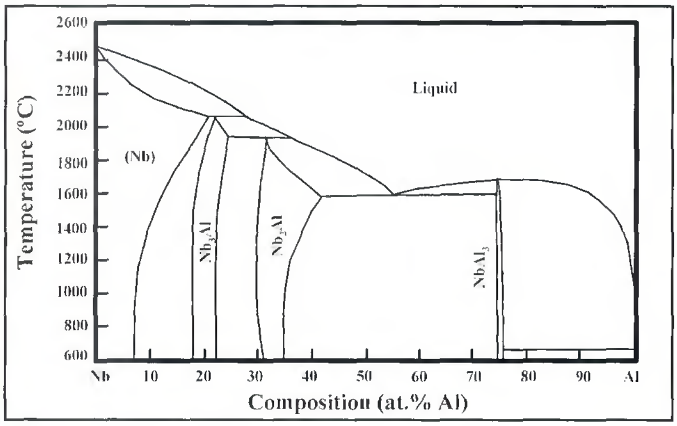

Fig. 3 — Plot showing the Al-Nb phase diagram (Ref. 5).

Table 2 — Summary of Explosion Welding Parameters Used during the Development of the Al-Nb Weld

Welding Parameter Identification	Detonator Location	Material Thickness (mm) Al Plate	Al Interlayer	Nb Interlayer	Nb Plate	Explosive Energy (MJ) Al-Al Bond	Al-Nb Bond	Nb-Nb Bond
Single Welds								
1[a]	Edge	203	—	—	9.5	—	3.1	—
2[a]	Center	203	—	—	9.5	—	3.1	—
Multiple Welds								
0.8-mm Al Interlayer								
3a	Center	203	0.8	0.33	9.5	0.9	1.0	3.08
3b	Center	203	0.8	0.33	9.5	1.01	0.95	3.76
3c	Center	203	0.8	0.33	9.5	0.82	1.0	3.08
1.0-mm Al Interlayer								
4a	Center	203	1.0	0.33	9.5	1.37	1.54	3.08
4b	Center	203	1.0	0.33	9.5	1.37	1.54	3.08

(a) A postweld heat treatment is required to convert the 6061 Al plate from the T4 heat treatment condition to the T6 heat treatment condition.

causes the two metals to fuse together. The force of the explosion sets up an angular collision, which produces a plasma phase, which is ejected ahead of the leading edge of the weld interface. Since the plasma jet is located in front of the collision point, it is inferred that melting is not necessarily part of the welding occurring behind it. This plasma jet removes impurities from the surfaces of both the base and clad plates, thus leaving clean metal surfaces for joining. The pressures at the collision point (690 to 4137 MPa) are enough to cause the metals to behave like viscous fluids. This behavior is responsible for the wave-like weld pattern produced at the interface of the two materials and shown in the figure (Refs. 3, 4).

The joining of niobium to aluminum is hindered by the potential formation of several intermetallic phases, as shown in the Al-Nb phase diagram in Fig. 3 (Ref. 5). The presence of these intermetallic phases can lead to significant decreases in the weld strength, thus making the use of fusion welding techniques to join these two materials impractical. Therefore, a solid-state joining process, where no melting or significant intermixing of the Al and Nb occurs, is required. Explosive welding is preferable to other solid-state joining processes in this case because of the thickness of the niobium plate (9.5 mm) and the large surface area, approximately 508 × 508 mm, to be welded.

In the development of this explosive weld, a number of different materials are used. These materials include a 203-mm-thick 6061-T651 Al plate, a thin (0.8/1.0 mm) 6061-O Al sheet, a thin (0.33-mm) Nb sheet, and a thick (9.5-mm) Nb plate. The 6061-T651 Al base plate meets the chemistry and mechanical property requirements in ASTM B209M-02a (Ref. 6) and AMS-QQ-A-250/11 (Ref. 7), while the Nb sheet and plate materials meet the requirements for R04200-Type 1 Reactor Grade material, which appears in ASTM B393-03 (Ref. 8).

Because of the nature of the weld development process, which evolved over an extended period of time, a number of different heats have been used for each of the materials defined in Table 2. Changes in material heats are made between Welds #1 and #2, which encompass the initial development work on single welds. The first multiple welds with a 0.8-mm-thick Al interlayer in Welds #3a through #3c use a single heat of each material. Different heats of each material are used when the 0.8-mm Al interlayer is replaced by a 1.0-mm-thick Al interlayer in Welds #4a and #4b. Compositional variations between the different heats are not considered significant since the weld parameters play a much more dominant role than the material chemistry in producing an explosive weld with suitable properties.

The explosive welding operations described here have been performed by High Energy Metals, Inc. All welds are made using an ammonium nitrate-fuel oil (ANFO)-based explosive mixture. In the explosive welding process, there are several essential parameters that must be tightly controlled and monitored as part of the welding process. These parameters include the surface finish and cleanliness of the welded face of each material, the placement of the detonator, and the ex-

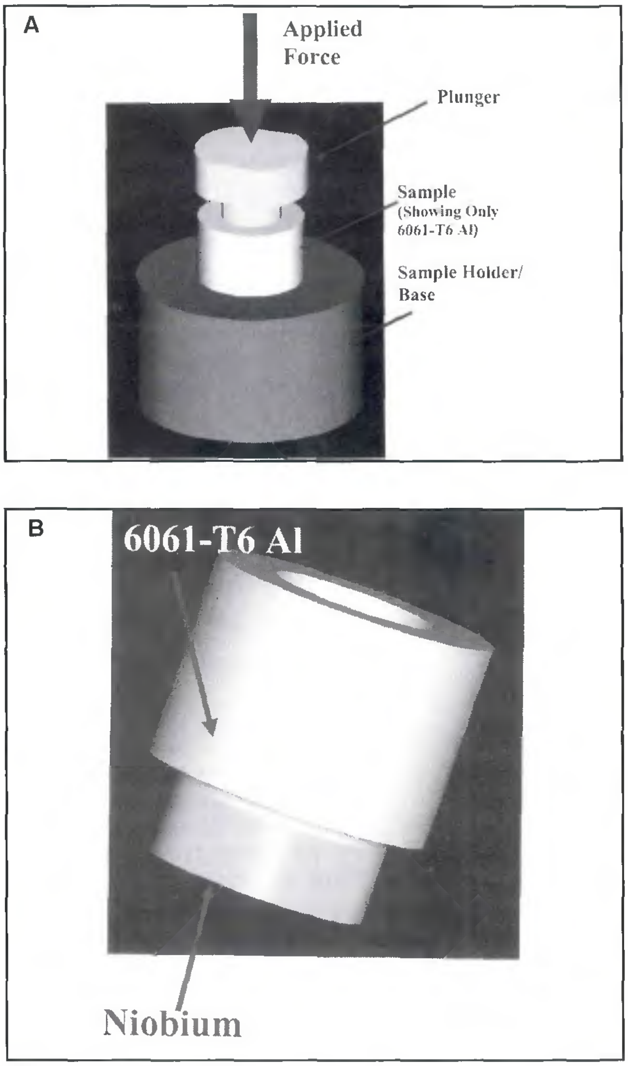

Fig. 4 — Schematic diagrams. A — The tensile testing setup used to measure the tensile strength of the Al-Nb explosion weld; B — the ram tensile specimen.

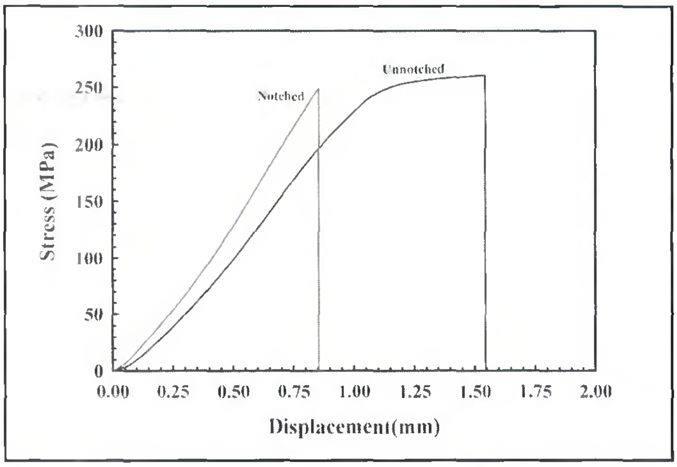

Fig. 5 — Typical stress-strain curve obtained during the tensile testing of an explosively welded sample in the unnotched and notched configurations.

plosive energy. The explosive energy is defined as the kinetic energy of the impacting plate for a given explosive detonation velocity, which is controlled by mixing the ANFO-based explosive with fine silica, and stand-off distance between the two plates. The explosive velocity of a small portion of the explosive mixture is measured before the welding operation by timing the speed of the explosive wave front over a distance of approximately 305 mm.

The surfaces to be welded are ground to a surface finish of 3.2 μm root mean square (RMS) or better and cleaned in order to remove any oxide, dirt, or other foreign objects. Each of the plates, which are all 508 × 508 mm in size, must also meet a flatness tolerance, of at least 0.2 mm over its length, in order to maintain a uniform stand-off distance between the clad and base metals. The development of a set of suitable welding parameters has involved a number of iterations. Table 2 provides a summary of the various welding parameters for both the preliminary single welds, as well as the multiple welds. The location of the detonator and the explosive energy are varied in an attempt to produce a weld with acceptable properties. The stand-off distances used in each of the welds is approximately equal to the thickness of the sheet or plate being welded. Smaller-capacity detonators are used to weld the thin interlayers, which require lower explosive energies (approximately 1 MJ) during the welding operation. A higher-capacity detonator is used to weld the 9.5-mm-thick Nb plate, which requires a higher explosive energy (> 3 MJ) during welding.

Nondestructive and Metallographic Evaluation of Weld Integrity

The quality of each explosive weld is examined in the as-welded condition using an ultrasonic evaluation technique to inspect the integrity of the Al-Nb weld region. The ultrasonic evaluation of each explosive weld is performed by immersing the welded plates into a water tank and using a pulse echo ultrasonic examination technique (Refs. 9–11) to detect indications of voids, defects, and areas of disbonding in the explosive weld. A 5-MHz, 12.7-mm-diameter, 32-mm spherical focus transducer, which has a theoretical spot size of 0.76 mm, is used. During each scan, the transducer is automatically rastered over the surface of the plate with a maximum step size of 0.5 mm in order to provide a complete picture of the weld region across the entire plate. The results of each scan are used to judge the extent of well-welded material on each plate and as a means of determining whether any defects are present in the region where mechanical testing samples are removed.

An ultrasonic calibration standard, fabricated from a piece of explosively clad Al-Nb weld, is used to calibrate the equipment prior to each scan and to ensure that the system is able to detect defects of a given size. Known reflectors, in the form of flat bottomed holes and rectangles with a minimum area of 0.79 mm^2, are placed in the standard at the Al-Nb weld interface and are used to establish the primary reference responses of the equipment. The sizes of the individual defects in the calibration standard are chosen to ensure that the system is able to detect defects smaller than the maximum allowable defect size in the final part.

Metallographic examination of the cross section of the explosively welded material is typically performed in the as-polished condition. In this condition, the different weld regions are visible. More detailed information about the weld regions can be obtained by etching the sample in a chemical bath containing 20 mL of glycerol, 10 mL of hydrofluoric acid, and 10 mL of nitric acid. Because the aluminum etches at a more rapid rate than the niobium, care must be taken to ensure that the aluminum is not overetched. With etching, the microstructure of the weld region is better revealed, making it much easier to identify areas of intermixing between the dissimilar metals. This examination of the weld cross section al-

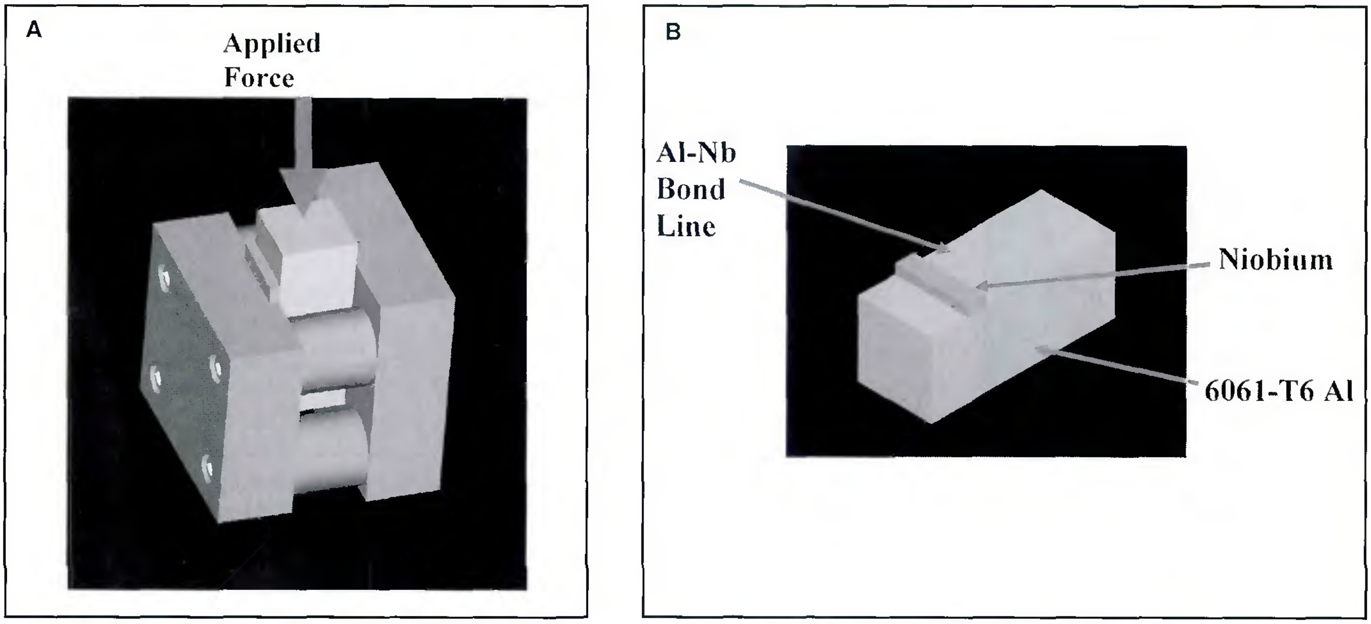

Fig. 6 — Schematic diagrams. A — The shear testing setup used to measure the shear strength of the Al-Nb explosion weld; B — the shear strength specimen.

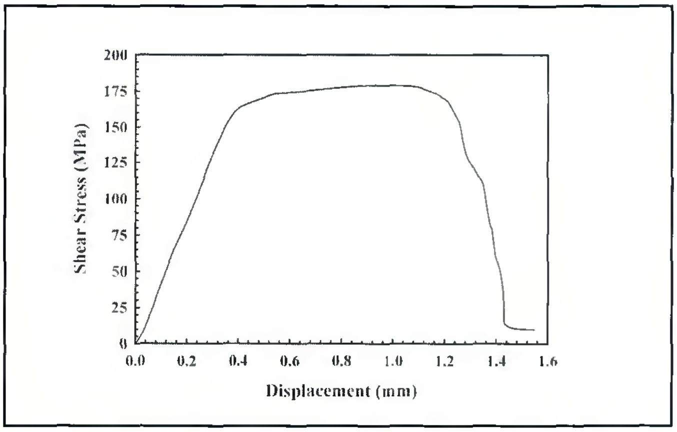

Fig. 7 — Typical stress-strain curve obtained during the shear testing of an explosion welded sample.

lows the weld wave pattern to be evaluated and determine if any changes to the welding parameters are required in order to produce the most desirable weld pattern morphology.

Mechanical Testing

The mechanical properties of the explosive welds produced during each welding iteration are measured to ensure that the welds produced during the explosive welding process have the maximum possible strength. Mechanical test samples are removed from specific locations in each welded plate. The samples taken from Welds #1 and #3a are removed from the center region of the welded plate. Samples taken from Weld #2 are removed from locations at the corners of the plate. Those samples used to test the mechanical properties of Welds #3b, #3c, and #4(a and b) are also taken from the center region of the welded plate outside the center defect area. In these plates, though, the samples are removed from better defined radial locations, 152 mm from the center of the plate. The locations where the samples are removed in each plate have been ultrasonically scanned to ensure that only properly welded material is used in the mechanical testing samples. The results reported for Welds #3a–c and #4a include results from only a single welded plate, while those reported for Weld #4b are an average of results taken from three different Al-Nb clad plates welded using identical procedures.

Modifications to traditional mechanical test geometries and procedures are required to test the strength of the weld. Typical tensile and Charpy impact specimen geometries would require an extension be welded onto the rather thin niobium clad layer, as done in the previous study (Ref. 1). Because the addition of these welded extensions introduces an additional level of complexity to the testing, a set of modified mechanical testing geometries and procedures, based on existing standard techniques, are employed to test the tensile, shear, and impact strength of the Al-Nb weld (Refs. 12–14).

The tensile strength of the weld is measured using the tensile testing setup and corresponding ram tensile specimen schematically shown in Fig. 4 A and B (Ref. 12). This test specimen, shown in Fig. 4B, can be divided into two components. The first component encompasses the 6061-T651 Al side of the weld and has an outer diameter of 33.3 mm and a height of 25.4 mm. An internal hole with a diameter of 19.1 mm is machined through the height of the aluminum and into the niobium-clad layer. The second component of the ram tensile specimen consists of the niobium- clad layer, which is machined to a diameter of 25.4 mm. In the design of these specimens, the niobium portion of the specimen in contact with the plunger is made thick enough (8.89 mm) so that the niobium does not yield during testing. Samples with and without a notch machined at the Al-Nb weld interface are tested. In the notched samples, a 60-deg ± 2 deg notch with a depth of 0.635 ± 0.127 mm is used. During testing, a plunger is inserted into the center hole, and a compressive force is exerted while the Al portion of the sample is held in place. As a result, the strength of the weld is measured in tension.

All of these ram tensile tests are performed on an Instron electromechanical test machine, equipped with an 89-kN load cell. The load (N)-displacement (mm) behavior of the tensile sample is monitored at a constant crosshead speed of 0.5 mm/min during each test. After test-

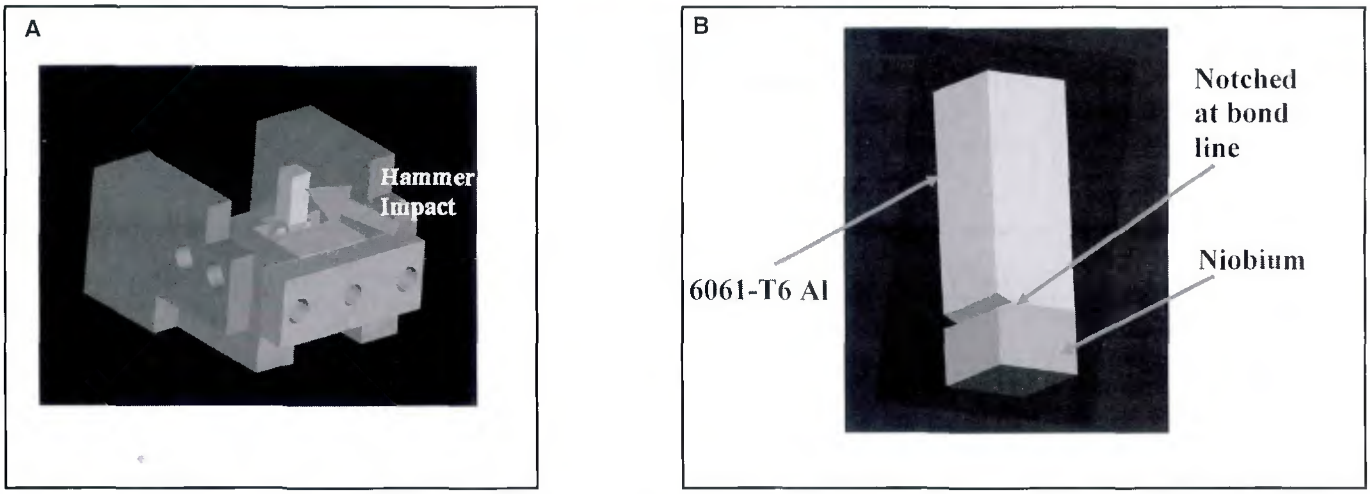

Fig. 8 — Schematic diagrams. A — The Izod impact testing setup used to measure the impact strength of the Al-Nb explosion weld; B — the modified Izod specimen.

Table 3 — Summary of the Base Metal Room-Temperature Mechanical Properties for Niobium and Aluminum Demonstrating Their Differences in Mechanical Properties (Refs. 15–16)

	Youngs' Modulus (GPa)	Poisson's Ratio	Coefficient of Thermal Expansion (K^{-1})	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
Niobium	104.9	0.397	7.20×10^{-6}	207	585
6061-T6 Al	70.6	0.345	2.36×10^{-5}	280	310
6061-O Al	70.6	0.345	2.36×10^{-5}	48.3	117

ing, the load is then converted to stress by dividing the measured load by the initial annular cross-sectional area at the weld interface. Figure 5 shows typical stress-displacement curves for tensile tests performed on explosively welded samples in both the unnotched and notched configurations. The tensile tests continue until the sample fails, and the tensile strength of each weld is equivalent to the maximum stress measured during each test.

The shear strength of the weld is measured using the testing setup and shear strength sample shown in Fig. 6A and B (Ref. 12). In order to test the shear strength of the weld, a rectangular sample is fabricated from the explosively clad Al-Nb weld material by removing a majority of the niobium-clad layer, leaving only a small nub of niobium measuring 6.35 mm wide. The aluminum portion of the sample is 63.5 mm in length by 12.7 mm in width and 25.4 mm high. When the sample is placed in the fixture, it is supported by this niobium nub, which is located 19.05 mm from the end of the sample and extends across the 12.7 mm width of the sample.

With the niobium nub restrained by the fixture, a compressive force is applied to the top of the sample placing the Al-Nb explosive weld region in shear. The test continues, measuring load vs. sample displacement, until the sample fails. The load-displacement behavior of the shear sample is monitored at a crosshead speed of 0.5 mm/min on the Model 4400R1225 Instron electromechanical test machine. After testing, the load is converted to stress by dividing the measured load by the cross-sectional area at the weld interface, as defined by the weld interfacial area between the aluminum and the niobium nub on the shear specimen. Figure 7 shows a typical stress-strain curve for a shear strength test performed on an explosively welded sample. The resulting shear strength of the weld corresponds to the maximum shear stress measured during this test.

In order to measure the impact strength of the Al-Nb explosive weld, a modified Izod impact testing procedure and sample, which are shown in Fig. 8A and B have been developed (Refs. 13, 14). The holding fixture of the Izod tester has been modified to grasp the undersized niobium-clad layer, which is 8.89 mm thick. The 6061-T651 aluminum portion of the sample is 31.75 mm in length, which allows the hammer to strike the sample in the appropriate location, as defined by the governing standards (Refs. 13, 14). A 45-deg ± 5 deg angled notch with a depth of 2.54 mm ± 0.05 mm is machined into the Izod sample at the Al-Nb weld interface using a slitting saw to minimize potential machining damage.

During testing, the notch is positioned so that it points in the direction of hammer impact, thus placing the weld in tension during testing and subsequent failure of the sample. Different sample sizes, ranging from 3.2 × 12.7 mm to 12.7 ×12.7 mm, are tested. All of the Izod impact tests are performed on a Tinus Olsen Charpy-Izod impact test machine, Model 66, with a maximum capacity of 22.6 J. The resulting fracture surfaces of selected samples have been examined using an FEI Model XL30 S FEG scanning electron microscope in order to identify the prevailing failure modes and mechanisms.

Thermal Cycling of Al-Nb Explosion Welds

A comparison between several pertinent mechanical properties of niobium and 6061 Al is shown in Table 3. (Refs. 15, 16). Since niobium and aluminum have significantly different thermal expansion properties, as shown by the differences in their respective coefficients of thermal expansion (7.20×10^{-6} K^{-1} for niobium and 2.36×10^{-5} K^{-1} for aluminum), thermal

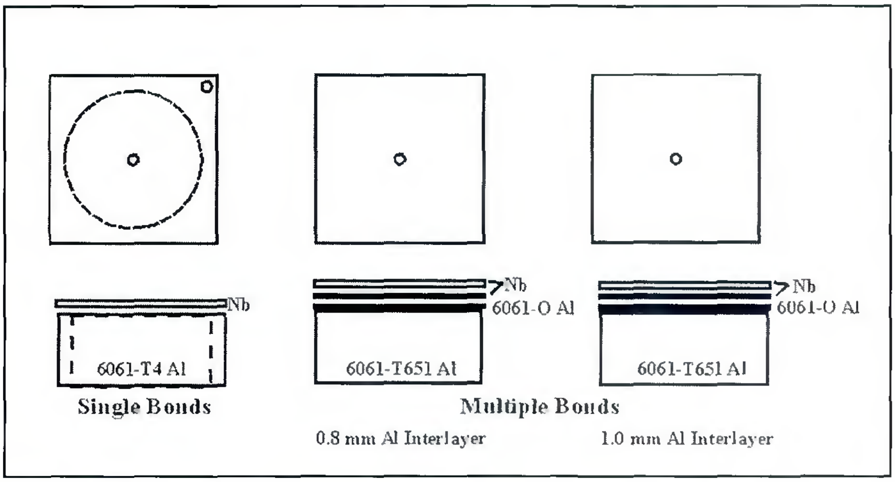

Fig. 9 — Schematic diagram summarizing the evolution of the explosion weld development. The circles on the top view of the explosion weld schematics indicate the locations of the detonators. In the single bonds shown in part A, the dotted lines indicate the circular shape of the Al plate during welding with the detonator placed at the edge of the niobium plate.

stresses can develop across the weld interface with changes in temperature. As a result, residual stresses of a magnitude sufficient enough to affect the long-term weld integrity can build between the Al and Nb. In order to examine the effects of changes in temperature on the explosion weld properties, selected ram tensile and Izod specimens are subjected to a series of ten thermal cycles.

In each thermal cycle, the samples are first placed in a bath heated to a temperature of 49°C. The temperature of the samples is monitored by a thermocouple attached to one of the samples. After the samples are immersed in the bath, the samples are allowed five minutes to reach the desired temperature. At the completion of this time period, the samples are then held in the bath for a period of 15 minutes. After this 15-minute hold is complete, the samples are removed from the bath and immediately placed in a second bath cooled to a temperature of –22°C. The sample temperature is again allowed to equilibrate for five minutes, after which the samples are held in the bath for 15 minutes. This process is repeated until a total of ten hot/cold cycles are completed on each sample. After the completion of the thermal cycling of these samples, the tensile and impact strengths of the welds are then tested in the same manner as those samples in the as-received condition.

Results and Discussion

Development of Multiple-Layer Welds

An explosive charge of 3.1 MJ is originally used to clad the 9.5-mm-thick Nb plate directly to the 203-mm-thick 6061-T4 Al plate in the initial weld development study discussed previously (Ref. 1). With such a large explosive charge, temperatures at the weld interface can become high enough to melt the aluminum, which then reacts with the niobium to form brittle intermetallic phases. Visual confirmation for intermixing of the aluminum and niobium at the weld interface has been previously discussed (Ref. 1). Since the impact strength of the weld produced using these procedures is not acceptable, improvements to the process are required in order to significantly increase the impact strength of the welded material while maintaining the tensile and shear strengths at or near their current levels. In order to achieve this goal, a means for avoiding melting and intermetallic formation during welding must be developed.

Figure 9 provides an overview of the ensuing weld development process undertaken in an attempt to produce explosion welds with the desired mechanical properties. In this figure, the evolution of the welding process from the single weld procedure described previously (Ref. 1) to the ensuing multiple weld procedures is summarized. These multiple welds are produced using a three-step welding process based on the addition of thin sheets or interlayers of aluminum and niobium between the 9.5-mm-thick niobium and the 203-mm-thick aluminum plates. The welding of each thin interlayer requires a smaller explosive charge, thus decreasing the likelihood for melting and intermetallic formation and allowing the explosion welds to be made directly on the 6061-T651 Al plate, thus removing the final heat treating step. A summary of the explosion energies required to join these interlayers is provided in Table 2.

Welds #3a–c utilize a 0.8-mm-thick 6061-O Al sheet, which is welded directly to the 6061-T651 Al plate. Since the Al sheet is in an annealed condition, it is much more ductile than the Al plate, allowing it to be welded with a rather low explosive energy (0.8 to 1.0 MJ). After the

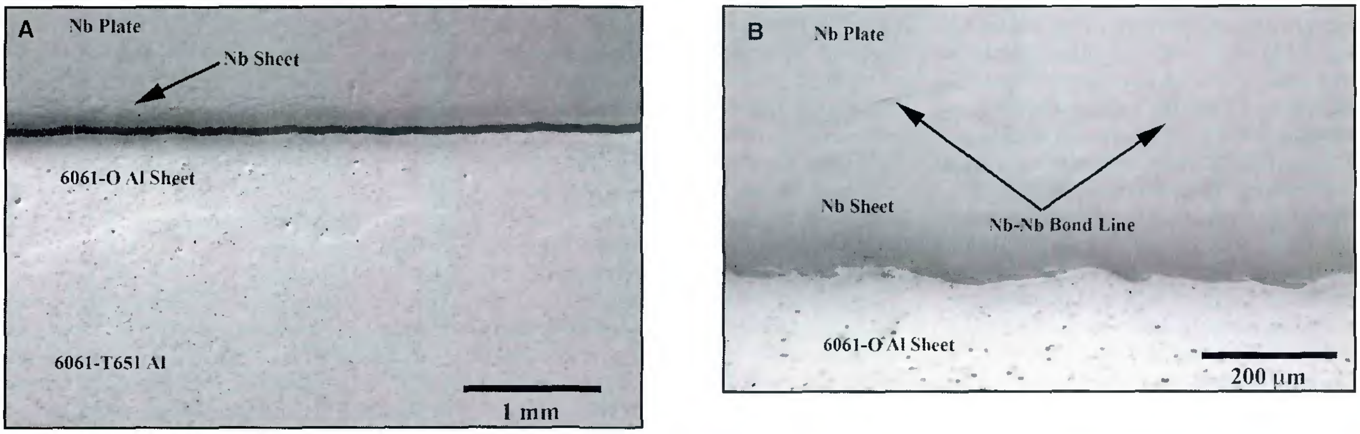

Fig. 10 — Micrographs of the weld cross section taken at an orientation perpendicular to the explosive wave. A — The overall weld, including the Al-Al, Al-Nb, and Nb-Nb weld interfaces. B — a closer view of the Al-Nb and Nb-Nb weld interfaces.

welding of this thin Al interlayer, a 0.25-mm-thick niobium sheet is welded directly on top of it. Since a low explosive energy (0.95 to 1.0 MJ) is used to make this weld, the possibility of intermixing between the Al and Nb is significantly decreased. As a final step, the 9.5-mm-thick niobium plate is welded onto this thin niobium interlayer using a much larger explosive energy (3.08 to 3.76 MJ). By joining the thick niobium plate (9.5 mm) to the thin niobium sheet, the possibility of creating conditions under which any melting can occur is nearly eliminated because the niobium has a high melting point (2468°C).

Figure 10A and B provides views of a typical weld cross section taken at an orientation perpendicular to the explosive wave front in Weld #3a. In Fig. 10A, the entire weld region, including the Al-Al, Al-Nb, and Nb-Nb interfaces, is shown. In this figure, the Al-Nb weld interface appears as a dark line. This feature is a remnant of the metallographic preparation of the sample and results from the difference in the height of the niobium and 6061-T651 Al after polishing, caused by the difference in hardness of the two materials. Each weld interface displays a wavy appearance, which is typical of explosive welds. Of the three weld interfaces shown in this figure, the Al-Al interface displays the most prevalent wavy weld interface appearance. The Al-Nb weld interface, which is highlighted in Fig. 10B, is also much wavier in appearance than that observed with the single-layer welds. There is also no visual evidence of melting, intermetallic formation, or a mixed zone along the Al-Nb interface, which is an improvement over the weld interface observed in the previous work (Ref. 1).

Results from the tensile and shear strength testing for Welds #3a–c are summarized in Table 4. Taking an average of the results from these three welds, average tensile strengths of 243 ± 20 MPa and 231 ± 25 MPa are observed for the unnotched and notched conditions, respectively. The tensile strengths of the multiple welds in both the unnotched and notched conditions are approximately 9% and 20%, respectively, lower than those observed in the single-welded plates. In addition, failure in the ram tensile specimens in the multiple welds (Welds #3a–c) occurs within the thin Al interlayer, as compared with the Al-Nb weld interface in the single welds (Welds #1 and #2).

Welds #3a–c also display lower shear strength values (112 ± 22 MPa) than those observed in the edge- and center-detonated plates (224 ± 7 MPa and 180 ± 5 MPa, respectively). Results of the shear strength testing of these welds are also summarized in Table 4. This decrease in measured shear strength is due, in part, to the addition of the interlayers between the aluminum and niobium plates. In the sin-

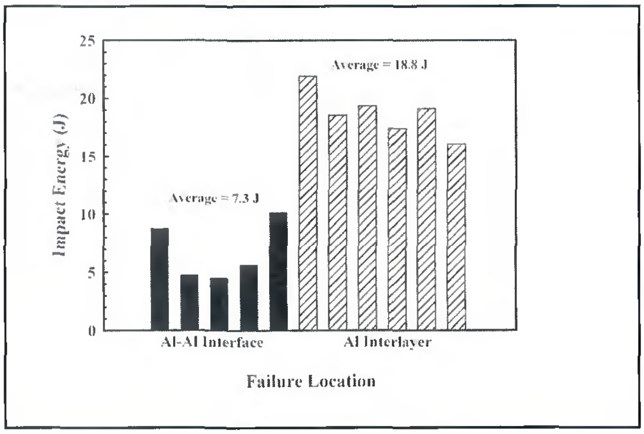

Fig. 11 — Summary of measured impact strengths for the multiple weld plate made using parameters #3a, showing the effects of differences in failure location on the measured impact strength.

Table 4 — Summary of Tensile and Shear Strengths Measured in Each Al-Nb Explosion Weld

Welding Parameter Identification	Number of Tests	Tensile Strength (MPa) Unnotched Average	Unnotched Standard Deviation	Notched Average	Notched Standard Deviation	Shear Strength (MPa) Number of Tests	Average	Standard Deviation
0.8-mm Al Interlayer								
3a	3/3	264	9	246	26	3	88	39
3b	3/1	225	8	202	—	3	128	5
3c	3/3	240	52	244	52	3	12	1
1.0-mm Al Interlayer								
4a	3/—	251	21	—	—	3	127	2
4b	6/6	255	13	284	25	—	—	—

Table 5 — Summary of Impact Strengths Measured in Each Al-Nb Explosion Weld

Welding Parameter Identification	Number of Tests	Impact Energy (J) Average	Impact Energy (J) Standard Deviation	Impact Energy/Unit Area (J/mm^2) Average	Impact Energy/Unit Area (J/mm^2) Standard Deviation
0.8-mm Al Interlayer					
3a(a)	11	6.8/19.2	2.6/1.7	0.052/0.148	0.020/0.013
3b	10	16.8	3.6	0.130	0.028
3c(a)	10	9.2/13.3	0.8/1.0	0.071/0.103	0.006/0.008
1.0-mm Al Interlayer					
4a	3	21.2	2.6	0.164	0.020
4b	19	19.2	3.5	0.148	0.027

(a) Two distinct failure modes (Al-Al interface and Al interlayer) are observed.

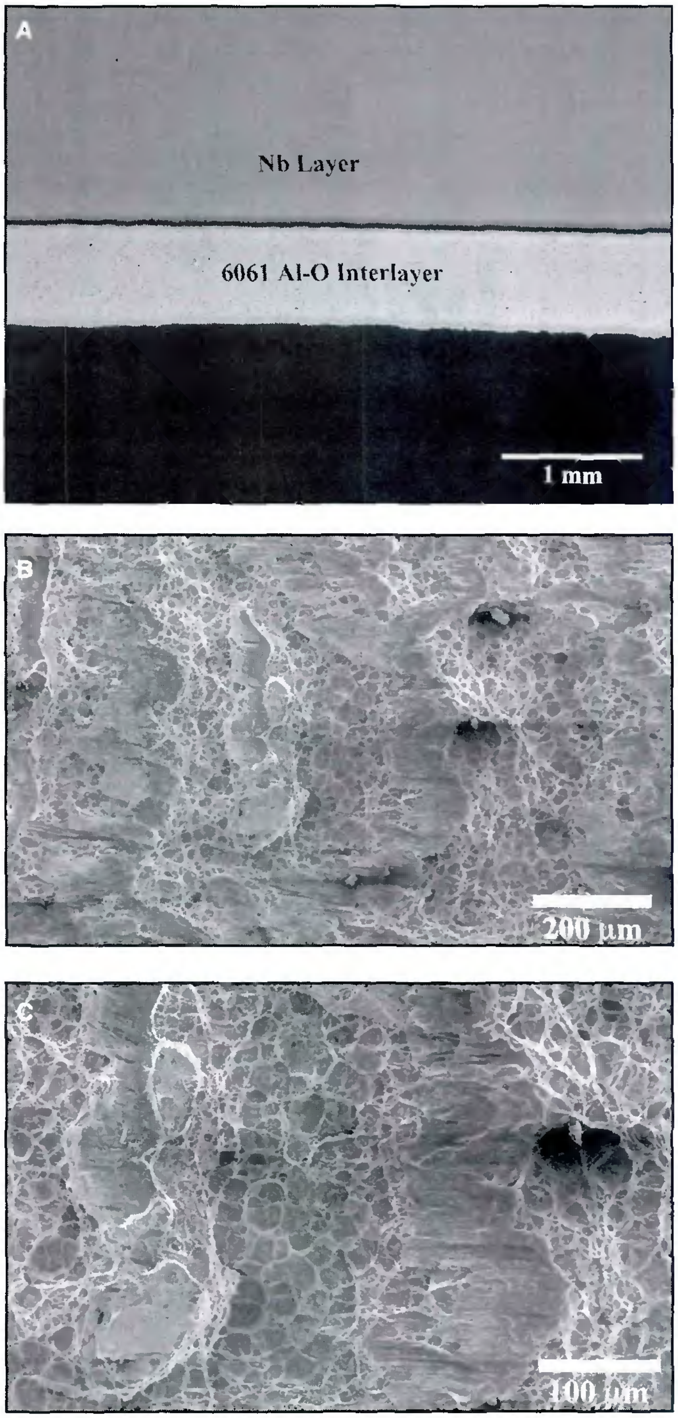

Fig. 12 — Micrographs. A — Showing the cross section; B and C — fracture surface of an Izod impact sample, which fails at the Al-Al weld interface.

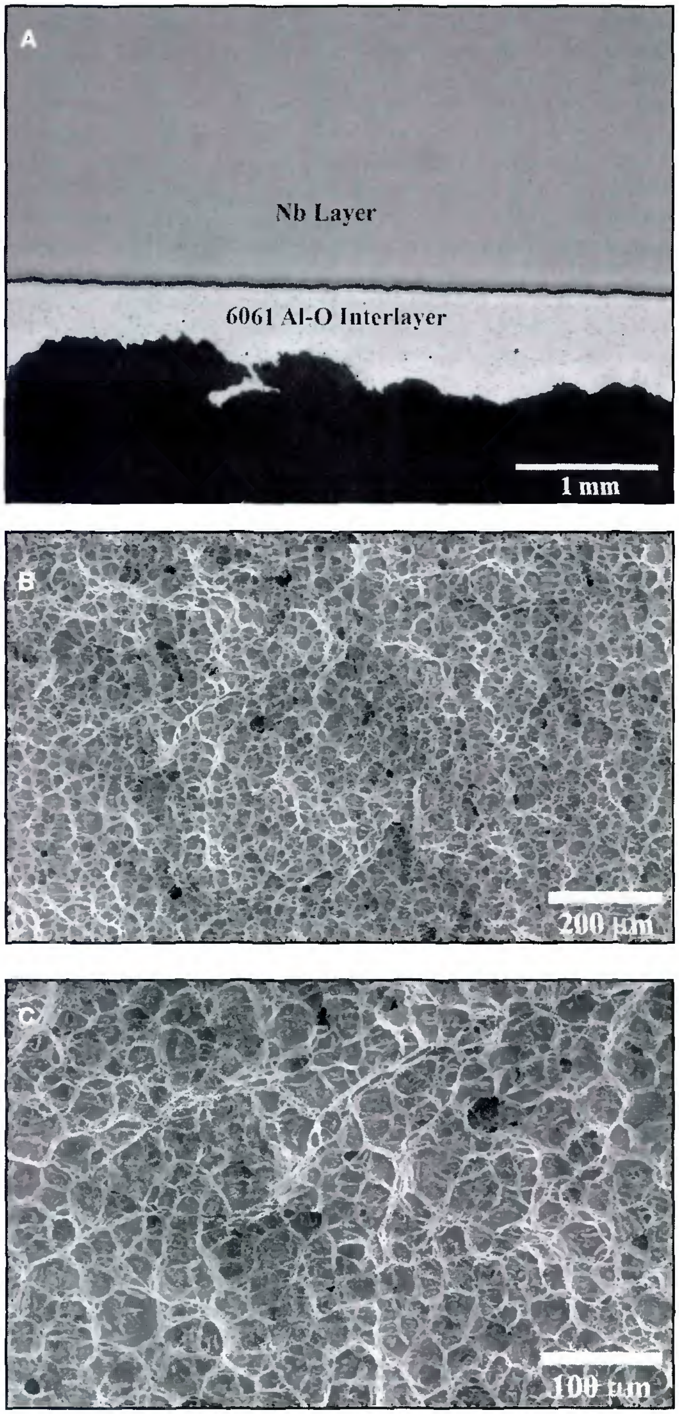

Fig. 13 — Micrographs. A — Showing the cross section; B and C — fracture surface of an Izod impact sample, which fails in the Al interlayer.

gle-weld plates, a distinct failure surface at the Al-Nb interface is observed in the shear strength samples after testing. The multiple welds display no such clear failure mode. Rather, during testing, the thin Al interlayer yields, causing the explosively clad niobium layer on the shear strength sample to only be displaced and not be removed from the Al plate during testing.

Even though the tensile and shear strengths are lower than those observed in Welds #1 and #2, this decrease in weld strength is not a concern because the tensile and shear strengths are still acceptable. Most importantly, though, these multiple welds display significant enhancements in the measured impact strength when compared with the edge- and center-detonated plates. As shown in Table 5, the impact strength of the multiple weld plates increases to a level of 19 J (0.147 J/mm^2), which is much higher than that observed in the single weld plates (0.020 J/mm^2). Based on these results, it is clear that the use of a 0.8-mm-thick Al interlayer in the explosion welding process has dramatically increased the impact strength of the Al-Nb weld, while maintaining desirable levels of tensile and shear strength. However, there is a rather wide range of impact strength values observed in the welds produced using the 0.8-mm-thick Al interlayer. In Weld #3a, in particular, a bimodal distribution in impact strengths, as shown in Fig. 11, is observed. The average values of the two lev-

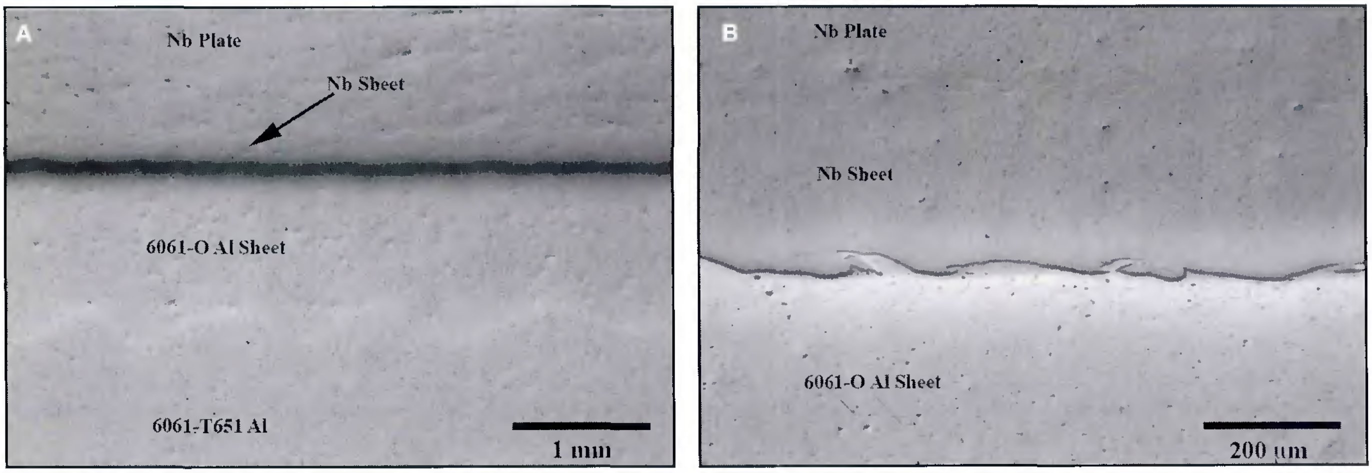

Fig. 14 — Micrographs. A — Showing the entire weld cross section; B — the Al-Nb and Nb-Nb welds taken at an orientation perpendicular to the explosive wave front for a multiple weld plate with a 1.0-mm Al interlayer.

Table 6 — Summary of Tensile and Impact Strengths Measured in Thermal Cycled Samples

Welding Parameter Identification	Number of Tests	Tensile Strength (MPa) Unnotched Average	Unnotched Standard Deviation	Notched Average	Notched Standard Deviation	Impact Strength (J) Number of Tests	Average	Standard Deviation
0.8mm Al Interlayer								
3a[(a)]	4/4	175	50	256	65	9	4.3	1.6
1.0mm Al Interlayer								
4a[(b)]	3/—	243	17	—	—	3	17.3	8.4
4b[(b)]	13/6	267	28	277	38	19	19.4	2.9

(a) Izod impact samples display failure at the Al-Al interface.
(b) Izod impact samples display failures within the Al interlayer.

els vary by nearly a factor of three (0.052 and 0.148 J/mm^2).

The bimodal distribution of impact strengths, which appears in Fig. 11, is attributed to the presence of two distinct failure modes. In the first failure mode, which results in low weld impact strength, the weld failure occurs very close to the Al-Al weld interface. Figure 12A–C displays the cross section and fracture surface of an Izod impact sample with low impact strength taken from Weld #3a. In this figure, the Al-Nb weld interface appears as a single dark line, as a result of the differences in the heights of the aluminum and niobium in the as-polished specimen, resulting from the metallographic preparation. It is apparent in the cross section shown in Fig. 12A that the 0.8-mm Al interlayer remains nearly intact, and the resulting fracture surface is generally flat. Figure 12B and C shows images of the same fracture surface at different magnifications. In this figure, the fracture surface displays a mixed mode fracture appearance with areas exhibiting both brittle and ductile fracture modes present.

In the second failure mode, which is observed in the welds with the higher impact strength, failure occurs within the 6061-O Al interlayer. As shown in the cross-section view in Fig. 13A, the region of failure displays a tortuous morphology across the width of the Al interlayer. Micrographs of the fracture surface, shown in Fig. 13B and C, display a dimpled morphology, indicative of a ductile fracture mode. No regions indicative of brittle fracture are observed, and the dimpled morphology covers the entire fracture surface. This failure mechanism is desirable.

A closer examination of the cross sections of the two fracture surfaces in Figs. 12A and 13A provides evidence that the explosion welding pattern is playing a role in the formation of these two distinct failure mechanisms. In Fig. 13A, it appears that the tortuous fracture surface morphology correlates with the wavy weld pattern observed in the weld cross section in Fig. 10A. On the other hand, the failure mechanism shown in Fig. 12A for the low-impact strength sample indicates that the explosion welding pattern at this location in the welded plate does not develop the clearly defined waves observed in Fig. 10A. These differences in failure mechanism can thus be correlated with corresponding differences in weld morphology.

The formation of the characteristic wavy weld interface morphology in explosion welds is known to be controlled by the flyer plate collision velocity (Ref. 17). In order for this preferred weld interface morphology to form, the interface kinetics governing the welding of the two plates must be controlled by a turbulent flow mechanism. Sufficient collision velocities are required in order for this mechanism to dominate and for the preferred weld line morphology to be formed. If the collision velocity becomes excessive, the turbulence can become extreme, leading to very large waves, which can result in a mixing and melting of the constituent metals at the wave crests and troughs, and the formation of either voids or brittle zones, resulting in a decrease in strength. This condition dominates in Welds #1 and #2, where evidence for melting at the Al-Nb weld interface is observed. On the other hand, at collision velocities below the threshold value where turbulent flow dominates, the resulting interface kinetics is controlled by laminar flow. When laminar flow dominates, the resulting weld interface morphology is devoid of the wave patterns characteristic of turbulent flow.

In the case of Weld #3a, it can be assumed that the collision velocity, driven by the explosive energy, is in a transition region, where both laminar and turbulent flows are present. As a result, both flat and wavy weld interface morphologies are observed. The presence of this nonuniform welding pattern across the surface of the

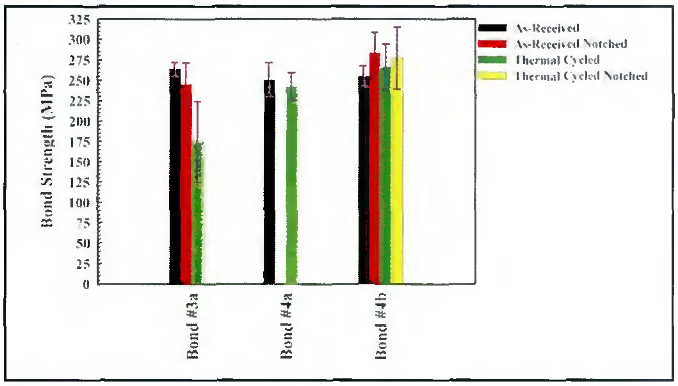

Fig. 15 — Comparison between measured tensile strengths in the as-received and thermal cycled multiple welded plates.

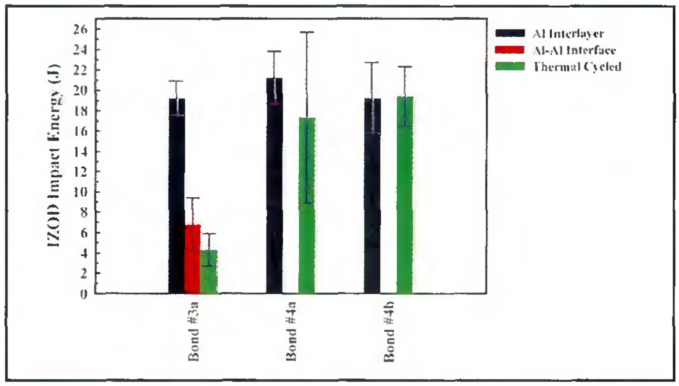

Fig. 16 — Comparison between measured Izod impact strengths in the as-received and thermal cycled multiple welded plates.

welded plate also creates a large degree of uncertainty in the weld strength and subsequent performance. Therefore, changes in the explosive energies used to weld the thin Al interlayer to the thick Al plate are made in an attempt to produce more uniform weld properties and to promote the desired failure mechanism within the Al interlayer during impact testing.

There is an optimization point at which the turbulent flow is sufficient to produce a wavy weld interface morphology without the appearance of either a flattened weld interface morphology or intermixed regions resulting from excessive turbulent flow. By increasing the explosive energy, a collision velocity can be attained where the entire welded area consists of a wavy interface. Table 2 shows that Weld #3b uses a higher explosive energy to weld the 6061-O Al sheet to the 6061-T651 Al plate than Welds #3a and #3c. With this higher explosive energy, the collision velocity is now of a sufficient magnitude to produce turbulent flow across the entire weld interface. As a result, the bimodal distribution of impact strengths and multiple failure modes are not observed in this weld.

On the other hand, Weld #3b does not contain an adequate region of acceptable welding, thus prohibiting the use of these welding parameters. The increase in explosive energy required to achieve the wavy interface when using the 0.8-mm 6061-O sheet in Weld #3b not only decreases the amount of well-welded material but also leaves a roughened top surface on the thin aluminum sheet. Because of the small thickness of the Al sheet (0.8 mm), the associated surface roughness nearly reaches the depth of the explosion wave pattern through the thickness of the sheet. Changes to the welding procedures are therefore required in order to produce welds with the desired wave pattern weld interface morphology and resulting high impact strength levels.

In order to use higher explosive energies to weld the 6061-O Al interlayer to the 6061-T651 Al plate, a thicker Al interlayer is used. The combination of the thicker Al interlayer and the increased explosive energy is expected to produce a stronger weld between the 6061-O and 6061-T651 Al and allow for an enhanced amount of acceptable welding area across the surface of the plate. Welds #4a and #4b, as summarized in Table 2, utilize a 1.0-mm-thick Al interlayer, allowing an explosive energy, on the order of nearly 50% higher than those used in Welds #3a through #3c, to be used for both the Al-Al and Al-Nb welds.

Figure 14A shows a micrograph of the weld cross section at an orientation perpendicular to the explosion wave front taken from Weld #4a, which utilizes the 1.0-mm-thick Al interlayer and higher explosion welding energies. When compared with the weld formed using a thinner Al interlayer, which is shown in Fig. 10A and B, the increased thickness of the Al interlayer is apparent, as is the desired wavy weld pattern. In Fig. 14B, the Al-Nb and Nb-Nb welds are shown at a higher magnification. Both welds display the desired wavy weld pattern, and the Al-Nb weld shows no evidence of a mixed region or intermetallic formation.

The use of a 1-mm-thick 6061-O Al interlayer does not adversely affect either the tensile or shear strength of the weld, as summarized in Table 4. In general, the tensile and shear strengths are equivalent to those observed in the welds that use the 0.8-mm-thick Al interlayer. During the testing of the impact strengths of these welds, as summarized in Table 5, the welds with the thicker Al interlayer display a significantly higher impact energy, approaching 21 J for a 12.7 × 10.2 mm cross-sectional area in Weld #4a, than the welds formed with the thinner Al interlay. This impact energy corresponds to a value for the impact energy per unit area of 0.119 J/mm^2. In addition, only a single failure mode, occurring in the Al interlayer, is observed in all of the tests. The resulting fracture surfaces exhibit only features that indicate a ductile fracture mode, similar to that shown in Fig. 13C.

Even though the results of the mechanical testing of Weld #4a are a significant improvement over those observed in Welds #3a–c, additional changes are made to the welding procedures. These changes are primarily related to how the Al and Nb sheets and Nb plate are fixtured during the explosion welding process in order to achieve more uniform welding properties across the surface of the Al-Nb clad plate. They are also meant to minimize any potential plate-to-plate variations in the properties of the Al-Nb explosion welds during the manufacture of many clad plates. With these changes in place, the tensile and impact strengths of Weld #4b are similar to those observed in Weld #4a.

In summary, the development of an explosion welding process for joining a 9.5-mm-thick Nb plate to a 203-mm-thick 6061-T651 Al plate has been successful in producing welds with high tensile and impact strengths. In this process, thin 6061-O Al and Nb sheets have been utilized to produce a weld having a tensile strength (255 ± 13 MPa) approximately 80% of the 6061-T6 Al base metal ultimate tensile strength (312 MPa). The impact strength of the welds produced using this process (19.2 ± 3.5 J or 0.148 ± 0.0027 J/mm^2) exceed the impact strength of the 6061-T6 Al base metal (9.8 ± 0.5J or 0.076 ± 0.004 J/mm^2) by nearly a factor of two. The explosive energies and fixturing of the individual layers during the welding process have also been optimized to maximize the area of acceptable welding across the surface of the 203 × 203 mm 6061-T651 Al plate.

Effects of Thermal Cycling on Weld Properties

Thermal cycling tests have been performed in order to determine if the mechanical properties of the welds are affected by exposures to extremes of temperature. Notched and unnotched ram tensile and Izod impact samples taken from multiple welds with both 0.8- and 1.0-mm-thick Al interlayers have been tested. Table 6 provides a summary of the tensile and impact strength measurements made on samples exposed to the thermal cycling sequence described above. Tests have been performed on samples taken from Weld #3a, which has a 0.8-mm- thick Al interlayer, and Welds #4a and #4b, which both have a 1.0-mm-thick Al interlayer. In general, the welds made with the thicker Al interlayer display significantly higher tensile and impact strengths after thermal cycling than the weld with the thinner Al interlayer.

Comparisons of these results with those obtained from the testing of similar samples in the as-received condition are given in Figs. 15 and 16, respectively, for the tensile and impact strengths of the welds. In the case of the thinner Al interlayer, there is an evident decrease in the tensile (175.3 ± 49.5 MPa) and impact energy per unit area (0.027 J/mm^2) after thermal cycling, with the most prominent decrease occurring in the impact strength. This decrease in impact strength can be traced to the appearance of only a single failure mode at the Al-Al interface for all of the samples tested in the thermal cycled condition.

On the other hand, the welds made using a thicker Al interlayer (1.0 mm) display no such decrease in impact strength after thermal cycling. In both of the welds tested with the thicker Al interlayer, the tensile and impact strengths measured after thermal cycling basically match those measured in the as-received condition. In fact, Weld #4b shows the highest mechanical property values of all of the welds tested. Failure in each weld is observed within the Al interlayer, with the resulting fracture surfaces showing evidence of ductile failure, similar to that observed in the as-received samples.

Weld #4b displays unnotched and notched tensile strengths of 267 ± 28 MPa and 277 ± 38 MPa, respectively, in the thermal cycled condition. Both values fall within 6% of the as-received values. The measured impact strength for the thermal cycled samples taken from Weld #4b is 19.4 ± 2.9 J (0.150 ± 0.22 J/mm^2). This value varies from that measured in the as-received condition by only 1%. Based on these results, it is thus apparent that the explosive welds produced with the 1.0-mm-thick Al interlayer are unaffected by the thermal cycling.

Summary and Conclusions

An explosion welding procedure was developed to clad 9.5-mm-thick niobium plate to 203-mm-thick 6061-T651 Al plate using a three-step procedure. This weld consists of three separate explosively clad layers: a 1.0-mm-thick 6061-O Al sheet, a 0.33-mm-thick Nb sheet, and a 9.5-mm-thick Nb plate. The introduction of the thin 6061-O Al and niobium sheets allows the 9.5-mm-thick niobium plate to be welded to the Al plate in the high-strength (T-651) condition, thus removing the need for a postwelding heat treatment required in earlier welds. Metallographic examination of the multiple weld region also shows no evidence of melting or intermetallic formation.

In the final welding process, the detonator is located in center of plate, and different explosive energies are used to make the three welds. For the weld between the 6061-O Al sheet and the 6061-T651 Al-plate, an explosive energy of 1.37 MJ is used. An explosive energy of 1.54 MJ is used to weld the Nb sheet to the 6061-O Al sheet, and an explosive energy of 3.08 MJ is used to weld the thick Nb plate to the thin Nb sheet. The resulting weld displays a tensile strength of approximately 255 ± 13 MPa in the unnotched and 284 ± 25 MPa in the notched condition. These values are approximately 80% of the ultimate tensile strength of the 6061-T6 Al. The impact strength of the welds, which is 19.2 J ± 3.5 J (0.148 ± 0.027 J/mm^2) is also three times that of the high-strength aluminum.

Selected tensile and impact strength samples were also exposed to accelerated thermal cycling treatments between −22° and 45°C to determine if the significant differences in the coefficients of thermal expansion for the niobium and aluminum cause the weld to be weakened over time. After being exposed to these extremes of temperature, the tensile and impact strength samples were tested and compared with results from as-welded samples. These thermally cycled samples showed no degradation in mechanical properties when compared with the as-received material. For example, the unnotched tensile strength of the thermal cycled samples is 267 ± 28 MPa, the notched tensile strength is 277 ± 38 MPa, and the impact strength is 19.4 ± 2.9 J (0.150 ± 0.22 J/mm^2). In each case, the differences between the tensile and impact strengths of the as-welded and thermally cycled welds are insignificant.

Acknowledgments

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