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Abstract

An explosive bonding 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 bond tensile and impact strengths and the amount of bonded material across the surface of the plate. This procedure improves upon previous efforts, in which the 9.5 mm thick niobium plate is bonded 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. Bonds 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 bond properties because of the unique bond geometry. In order to ensure that differences in the thermal expansion coefficients of aluminum and niobium do not adversely affect the bond strength, the effects of thermal cycling at temperatures between -22ºC and 45ºC on the mechanical properties of these bonds 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 bonds produced using the optimized bonding parameters.

Introduction

A preliminary investigation of the feasibility of explosively bonding niobium to aluminum has been previously published.(Ref. 1) In that study, 9.5 mm thick commercially pure Nb is bonded to a 178 mm thick 6061 Al plate in the T4 condition. These initial bonds 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 treatment condition to facilitate the explosive bonding process. In order to transform the 6061-T4 Al to the desired T6 heat treat condition, a post-bonding heat treatment is required. An ultrasonic evaluation of these bonded plates shows that areas of dis-bonding are present on the side of the plate directly opposite from the detonator

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

In order to eliminate the post-bond heat treatment and to directly bond the niobium to the 6061 Al plate in the hardened (T6) condition, explosively bonded niobium and aluminum interlayers are introduced between the aluminum and niobium plates. Smaller explosive charges can be used to bond 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 bond are also investigated in this study.

The tensile properties of the initial bonds 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 bond line in the center of the gage 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 bond line, but not at the bond line, showing that the strength of the bond exceeds that of the niobium. Additional mechanical tests, using sample geometries optimized for testing the tensile, shear, and impact strengths of the bonds, have also been performed on samples taken from both the edge detonated and center detonated bonds. 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 bonds. For both sets of bonds, failure occurs at the Al-Nb bond line, and the notched (268±14.5 MPa and 287±35.4 MPa, respectively) and unnotched (351±17 MPa 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 (224±7 MPa and 180±5 MPa, 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 bonds. As shown in Table 1, the measured impact strengths of the edge and center detonated bond samples are low ($\leq$ 0.02 J/mm^2). All of the samples failed along the Al-Nb bond line, and the majority of the fracture surface displays a rather flat appearance, indicative of a brittle fracture mode. Figures 1(a) and 1(b) show 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 bond line morphology. An examination of the bond cross section, which is shown in Figures 4 and 5 in Reference 1, shows regions of intermixing of the Al and Nb. (Ref. 1) These regions consist primarily of sub-micron 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 bond interface caused by the melting of the Al during the explosive bonding process. It appears that these regions of Al and Nb intermixing result in a brittle bond being formed over a large area of the interface between the Al and Nb plates.

Changes to the bonding process are thus required in order to produce bonds with the desired tensile and impact strengths. In the current study, a three step explosive bonding process is developed to join Grade 1 (Reactor) niobium directly to 6061-T651 Al plate, thus removing the follow-on heat treatment. These bonds 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 bonded material across the surface of the thick Al plate must be maximized. In order to meet these requirements, a procedure involving the explosive bonding 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 bonds with the required tensile, shear, and impact strengths but also allows the thick Al plate to be bonded in the high strength (T-651) condition, thus removing the requirement for a post-bond heat treatment of the clad material.

Experimental

Explosive Bonding

The explosive welding (EXW) process is a solid state joining process used to join a wide variety of materials which can not 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 Figure 2. Prior to bonding, 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 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 bond interface. Since the plasma jet is located in front of the collision point, it is inferred that melting is not necessarily part of the bonding 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 bond 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 Figure 3. (Ref. 5) The presence of these intermetallic phases can lead to significant decreases in the bond 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 inter-mixing of the Al and Nb occurs, is required. Explosive bonding 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 mm x 508 mm, to be bonded.

In the development of this explosive bond, 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 bond 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 Bonds #1 and #2, which encompass the initial development work on single bonds. The first multiple bonds with a 0.8 mm thick Al interlayer in Bonds #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 Bonds #4a and #4b. Compositional variations between the different heats are not considered significant since the bond parameters play a much more dominant role than the material chemistry in producing an explosive bond with suitable properties.

The explosive bonding operations described here have been performed by High Energy Metals, Inc. All bonds are made using an ammonium nitrate-fuel oil (ANFO) based explosive mixture. In the explosive bonding process, there are several essential parameters which must be tightly controlled and monitored as part of the bonding process. These parameters include the surface finish and cleanliness of the bonded face of each material, the placement of the detonator, and the explosive 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 bonding operation by timing the speed of the explosive wave front over a distance of approximately 305 mm.

The surfaces to be bonded 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 mm x 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 bonding parameters has involved a number of iterations. Table 2 provides a summary of the various bonding parameters for both the preliminary single bonds, as well as the multiple bonds. The location of the detonator and the explosive energy are varied in an attempt to produce a bond with acceptable properties. The stand-off distances used in each of the bonds is approximately equal to the thickness of the sheet or plate being bonded. Smaller capacity detonators are used to bond the thin interlayers, which require lower explosive energies (approximately 1 MJ) during the bonding operation. A higher capacity detonator is used to bond the 9.5 mm thick Nb plate, which requires a higher explosive energy (> 3 MJ) during bonding.

Non-Destructive and Metallographic Evaluation of Bond Integrity

The quality of each explosive bond is examined in the as-bonded condition using an ultrasonic evaluation technique to inspect the integrity of the Al-Nb bond region. The ultrasonic evaluation of each explosive bond is performed by immersing the bonded 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 dis-bonding in the explosive bond. 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 bond region across the entire plate. The results of each scan are used to judge the extent of well bonded 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 bond, 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 bond line 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 bonded material is typically performed in the as-polished condition. In this condition, the different bond regions are visible. More detailed information about the bond 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 over-etched. With etching, the microstructure of the bond region is better revealed, making it much easier to identify areas of intermixing between the dissimilar metals. This examination of the bond cross section allows the bond wave pattern to be evaluated and determine if any changes to the bonding parameters are required in order to produce the most desirable bond pattern morphology.

Mechanical Testing

The mechanical properties of the explosive bonds produced during each bonding iteration are measured to ensure that the bonds produced during the explosive bonding process have the maximum possible strength. Mechanical test samples are removed from specific locations in each bonded plate. The samples taken from Bonds #1 and #3a are removed from the center region of the bonded plate. Samples taken from Bond #2 are removed from locations at the corners of the plate. Those samples used to test the mechanical properties of Bonds #3b, #3c, and #4(a&b) are also taken from the center region of the bonded 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 bonded material is used in the mechanical testing samples. The results reported for Bonds #3a, #3b, #3c, and #4a include results from only a single bonded plate, while those reported for Bond #4b are an average of results taken from three different Al-Nb clad plates bonded using identical procedures.

Modifications to traditional mechanical test geometries and procedures are required to test the strength of the bond. 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 bond. (Ref. 12-14)

The tensile strength of the bond is measured using the tensile testing set-up and corresponding ram tensile specimen schematically shown in Figures 4(a&b), respectively. (Ref. 12) This test specimen, shown in Figure 4(b), can be divided into two components. The first component encompasses the 6061-T651 Al side of the bond 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 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 bond line are tested. In the notched samples, a 60º±2º 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 bond 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 testing, the load is then converted to stress by dividing the measured load by the initial annular cross sectional area at the bond line. Figure 5 shows typical stress-displacement curves for tensile tests performed on explosively bonded samples in both the unnotched and notched configurations. The tensile tests continue until the sample fails, and the tensile strength of each bond is equivalent to the maximum stress measured during each test.

The shear strength of the bond is measured using the testing set-up and shear strength sample shown in Figures 6(a&b), respectively. (Ref. 12) In order to test the shear strength of the bond, a rectangular sample is fabricated from the explosively clad Al-Nb bond 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 the Al-Nb explosive bond region is placed in shear. The test continues, measuring load versus 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 bond line, as defined by the bond 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 bonded sample. The resulting shear strength of the bond corresponds to the maximum shear stress measured during this test.

In order to measure the impact strength of the Al-Nb explosive bond, a modified Izod impact testing procedure and sample, which are shown in Figures 8(a&b), respectively, 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 45º±5º angled notch with a depth of 2.54 mm ± 0.05 mm is machined into the Izod sample at the Al-Nb bond line 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 bond in tension during testing and subsequent failure of the sample. Different sample sizes, ranging from 3.2 mm x 12.7 mm to 12.7 mm x 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 EXW Bonds

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 x 10^{-6} K^{-1} for niobium and 2.36 x 10^{-5} K^{-1} for aluminum), thermal stresses can develop across the bond line with changes in temperature. As a result, residual stresses of a magnitude sufficient enough to affect the long-term bond integrity can build between the Al and Nb. In order to examine the effects of changes in temperature on the explosive bond 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 49ºC. 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 fifteen 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 -22ºC. The sample temperature is again allowed to equilibrate for five minutes, after which the samples are held in the bath for fifteen 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 bonds are then tested in the same manner as those samples in the as-received condition.

Results and Discussion

Development of Multiple Layer Bonds

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 bond development study discussed previously. (Ref. 1) With such a large explosive charge, temperatures at the bond 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 bond interface has been previously discussed.(Ref. 1) Since the impact strength of the bond produced using these procedures is not acceptable, improvements to the process are required in order to significantly increase the impact strength of the bonded 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 bonding must be developed.

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

Bonds #3a through #3c utilize a 0.8 mm thick 6061-O Al sheet, which is bonded 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 bonded with a rather low explosive energy (0.8 to 1.0 MJ). After the bonding of this thin Al interlayer, a 0.25 mm thick niobium sheet is bonded directly on top of it. Since a low explosive energy (0.95 to 1.0 MJ) is used to make this bond, the possibility of intermixing between the Al and Nb is significantly decreased. As a final step, the 9.5 mm thick niobium plate is bonded 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 (2468ºC).

Figures 10(a&b) provide views of a typical bond cross section taken at an orientation perpendicular to the explosive wave front in Bond #3a. In Figure 10(a), the entire bond region, including the Al-Al, Al-Nb, and Nb-Nb interfaces, is shown. In this figure, the Al-Nb bond 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 bond line displays a wavy appearance, which is typical of explosive bonds. Of the three bond lines shown in this figure, the Al-Al interface displays the most prevalent wavy bond line appearance. The Al-Nb bond line, which is highlighted in Figure 10(b), is also much wavier in appearance than that observed with the single layer bonds. 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 bond interface observed in the previous work. (Ref. 1)

Results from the tensile and shear strength testing for Bonds #3a to #3c are summarized in Table 4. Taking an average of the results from these three bonds, 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 bonds in both the unnotched and notched conditions are approximately 9% and 20%, respectively, lower than those observed in the single bonded plates. In addition, failure in the ram tensile specimens in the multiple bonds (Bonds #3a through #3c) occurs within the thin Al interlayer, as compared with the Al-Nb bond interface in the single bonds (Bonds #1 and #2).

Bonds #3a through #3c 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 bonds 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 single bond plates, a distinct failure surface at the Al-Nb interface is observed in the shear strength samples after testing. The multiple bonds 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 Bonds #1 and #2, this decrease in bond strength is not a concern because the tensile and shear strengths are still acceptable. Most importantly, though, these multiple bonds 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 bond plates increases to a level of 19 J (0.147 J/mm^2), which is much higher than that observed in the single bond 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 explosive bonding process has dramatically increased the impact strength of the Al-Nb bond, while maintaining desirable levels of tensile and shear strength. However, there is a rather wide range of impact strength values observed in the bonds produced using the 0.8 mm thick Al interlayer. In Bond #3a, in particular, a bimodal distribution in impact strengths, as shown in Figure 11, is observed. The average values of the two levels vary by nearly a factor of three (0.052 J/mm^2 and 0.148 J/mm^2).

The bi-modal distribution of impact strengths which appears in Figure 11 is attributed to the presence of two distinct failure modes. In the first failure mode, which results in low bond impact strength, the bond failure occurs very close to the Al-Al bond interface. Figures 12(a-c) display the cross section and fracture surface of an Izod impact sample with low impact strength taken from Bond #3a. In this figure, the Al-Nb bond line 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 Figure 12(a) that the 0.8 mm Al interlayer remains nearly intact, and the resulting fracture surface is generally flat. Figures 12(b) and 12(c) show images of the same fracture surface at different magnifications. In these figures, 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 bonds with the higher impact strength, failure occurs within the 6061-O Al interlayer. As shown in the cross section view in Figure 13(a), the region of failure displays a tortuous morphology across the width of the Al interlayer. Micrographs of the fracture surface, shown in Figures 13(b) and 13(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 Figures 12(a) and 13(a) provides evidence that the explosive bonding pattern is playing a role in the formation of these two distinct failure mechanisms. In Figure 13(a), it appears that the tortuous fracture surface morphology correlates with the wavy bond pattern observed in the bond cross section in Figure 10(a). On the other hand, the failure mechanism shown in Figure 12(a) for the low impact strength sample indicates that the explosive bonding pattern at this location in the bonded plate does not develop the clearly defined waves observed in Figure 10(a). These differences in failure mechanism can thus be correlated with corresponding differences in bond morphology

The formation of the characteristic wavy bond line morphology in explosive bonds is known to be controlled by the flyer plate collision velocity.(Ref. 17) In order for this preferred bond line morphology to form, the interface kinetics governing the bonding 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 bond 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, leading to the formation of either voids or brittle zones, and a resulting decrease in strengths. This condition dominates in Bonds #1 and #2, where evidence for melting at the Al-Nb bond interface is observed. 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 bond line morphology is devoid of the wave patterns characteristic of turbulent flow.

In the case of Bond #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 bond line morphologies are observed. The presence of this non-uniform bonding pattern across the surface of the bonded plate also creates a large degree of uncertainty in the bond strength and subsequent performance. Therefore, changes in the explosive energies used to bond the thin Al interlayer to the thick Al plate are made in an attempt to produce more uniform bond 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 bond line morphology without the appearance of either a flattened bond line morphology or intermixed regions resulting from excessive turbulent flow. By increasing the explosive energy, a collision velocity can be attained where the entire bonded area consists of a wavy interface. Table 2 shows that Bond #3b uses a higher explosive energy to bond the 6061-O Al sheet to the 6061-T651 Al plate than Bonds #3a and #3c. With this higher explosive energy, the collision velocity is now of a sufficient magnitude to produce turbulent flow across the entire bond interface. As a result, the bimodal distribution of impact strengths and multiple failure modes are not observed in this bond.

On the other hand, Bond #3b does not contain an adequate region of acceptable bonding, thus prohibiting the use of these bonding parameters. The increase in explosive energy required to achieve the wavy interface when using the 0.8mm 6061-O sheet in Bond #3b not only decreases the amount of well-bonded 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 explosive wave pattern through the thickness of the sheet. Changes to the bonding procedures are therefore required in order to produce bonds with the desired wave pattern bond line morphology and resulting high impact strength levels.

In order to use higher explosive energies to bond the 6061-O Al interlayer 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 bond between the 6061-O and 6061-T651 Al and allow for an enhanced amount of acceptable bonding area across the surface of the plate. Bonds #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 Bonds #3a through #3c, to be used for both the Al-Al and Al-Nb bonds.

Figure 14(a) shows a micrograph of the bond cross section at an orientation perpendicular to the explosive wave front taken from Bond #4a, which utilizes the 1.0 mm thick Al interlayer and higher explosive bonding energies. When compared with the bond formed using a thinner Al interlayer, which is shown in Figures 10(a) and 10(b), the increased thickness of the Al interlayer is apparent, as is the desired wavy bond pattern. In Figure 14(b), the Al-Nb and Nb-Nb bonds are shown at a higher magnification. Both bonds display the desired wavy bond pattern, and the Al-Nb bond 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 bond, as summarized in Table 4. In general, the tensile and shear strengths are equivalent to those observed in the bonds which use the 0.8 mm thick Al interlayer. During the testing of the impact strengths of these bonds, as summarized in Table 5, the bonds with the thicker Al interlayer display a significantly higher impact energy, approaching 21 J for a 12.7 mm x 10.2 mm cross sectional area in Bond #4a, than the bonds 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 which indicate a ductile fracture mode, similar to that shown in Figure 13(c).

Even though the results of the mechanical testing of Bond #4a are a significant improvement over those observed in Bonds #3a, #3b, and #3c, additional changes are made to the bonding procedures. These changes are primarily related to how the Al and Nb sheets and Nb plate are fixtured during the explosive bonding process in order to achieve more uniform bonding 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 explosive bonds during the manufacture of many clad plates. With these changes in place, the tensile and impact strengths of Bond #4b are similar to those observed in Bond #4a.

In summary, the development of an explosive bonding process for joining a 9.5 mm thick Nb plate to a 203 mm thick 6061-T651 Al plate has been successful in producing bonds with high tensile and impact strengths. In this process, thin 6061-O Al and Nb sheets have been utilized to produce a bond 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 bonds produced using this process (19.2±3.5 J) exceed the impact strength of the 6061-T6 Al base metal (9.8±0.5 J) by nearly a factor of two. The explosive energies and fixturing of the individual layers during the bonding process have also been optimized to maximize the area of acceptable bonding across the surface of the 203 mm x 203 mm 6061-T651 Al plate.

Effects of Thermal Cycling on Bond Properties

Thermal cycling tests have been performed in order to determine if the mechanical properties of the bonds are affected by exposures to extremes of temperature. Notched and unnotched ram tensile and Izod impact samples taken from multiple bonds with both 0.8 mm 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 Bond #3a, which has a 0.8 mm thick Al interlayer, and Bonds #4a and #4b, which both have a 1.0 mm thick Al interlayer. In general, the bonds made with the thicker Al interlayer display significantly higher tensile and impact strengths after thermal cycling than the bond 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 Figures 15 and 16, respectively, for the tensile and impact strengths of the bonds. 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 bonds made using a thicker Al interlayer (1.0 mm) display no such decrease in impact strength after thermal cycling. In both of the bonds 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, Bond #4b shows the highest mechanical property values of all of the bonds tested. Failure in each bond 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.

Bond #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 Bond #4b is 19.4±2.9 J. 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 bonds produced with the 1.0 mm thick Al interlayer are unaffected by the thermal cycling.

Summary and Conclusions

An explosive bonding procedure has been developed to clad 9.5 mm thick niobium plate to 203 mm thick 6061-T651 Al plate using a three step procedure. This bond 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 bonded to the Al plate in the high strength (T-651) condition, thus removing the need for a post-bonding heat treatment required in earlier bonds. Metallographic examination of the multiple bond region also shows no evidence for melting or intermetallic formation.

In the final bonding process, the detonator is located in center of plate, and different explosive energies are used to make the three bonds. For the bond 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 bond the Nb sheet to the 6061-O Al sheet, and an explosive energy of 3.08 MJ is used to bond the thick Nb plate to the thin Nb sheet. The resulting bond 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 bonds, which is 19.2 J ± 3.5 J, is also three times that of the high strength aluminum.

Selected tensile and impact strength samples have also been exposed to accelerated thermal cycling treatments between temperatures of -22ºC and 45ºC in order to determine if the significant differences in the coefficients of thermal expansion for the niobium and aluminum cause the bond to be weakened over time. After being exposed to these extremes of temperature, the tensile and impact strength samples have been tested and compared with results from as-bonded samples. These thermally cycled samples show 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. In each case, the differences between the tensile and impact strength of the as-bonded and thermally cycled bonds is insignificant.

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Figure 16. Comparison between measured Izod impact strengths in the as-received and thermal cycled multiple bonded plates.

Table 1. Summary of mechanical properties of preliminary single-bonded 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	267.6	8.69
Notched	3	267.6	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*	0.1/0.1*	12	1**	0.2**
Impact Energy/Unit Area (J/mm^2)	2/7	0.020/0.023	0.003/0.002	12	0.015	0.003

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

Table 2. Summary of explosive bonding parameters used during the development of the Al-Nb bond.

Bonding Parameter Identification	**Detonator Location**	**Material Thickness (mm)**				**Explosive Energy (MJ)**		
		Al Plate	**Al Interlayer**	**Nb Interlayer**	**Nb Plate**	**Al-Al Bond**	**Al-Nb Bond**	**Nb-Nb Bond**
Single Bonds								
1*	Edge	203	-----	-----	9.5	-----	3.1	-----
2*	Center	203	-----	-----	9.5	-----	3.1	-----
Multiple Bonds								
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 post-bonding heat treatment is required to convert the 6061 Al plate from the T4 heat treatment condition to the T6 heat treatment condition.

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

Table 4. Summary of tensile and shear strengths measured in each Al-Nb explosive bond.

Bonding Parameter Identification	**Tensile Strength (MPa)**					**Shear Strength (MPa)**		
	Number of Tests	**Unnotched**		**Notched**		**Number of Tests**	**Average**	**Standard Deviation**
		Average	**Standard Deviation**	**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 explosive bond.

Bonding Parameter Identification	**Number of Tests**	**Impact Energy (J)**		**Impact Energy/Unit Area (J/mm^2)**	
		Average	**Standard Deviation**	**Average**	**Standard Deviation**
0.8 mm Al Interlayer					
3a*	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*	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

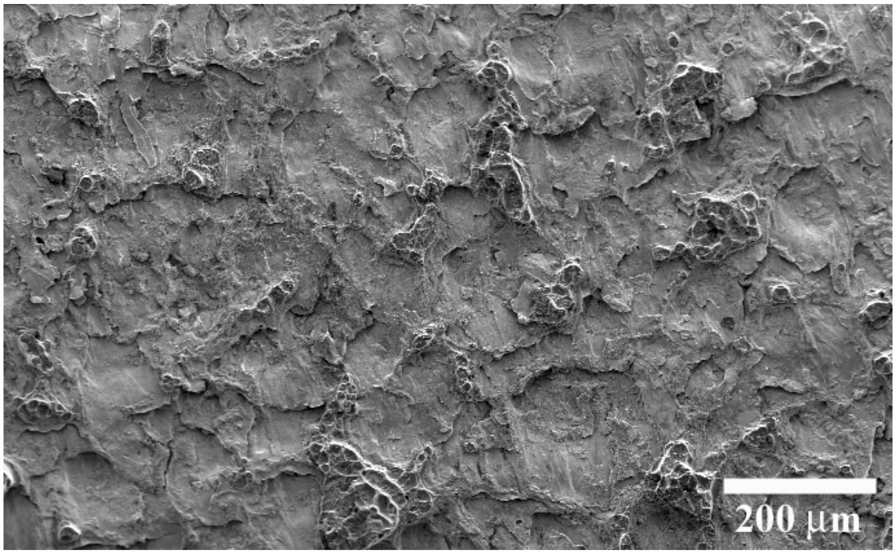
* Two distinct failure modes (Al-Al interface and Al interlayer) are observed.

Table 6. Summary of tensile and impact strengths measured in thermal cycled samples.

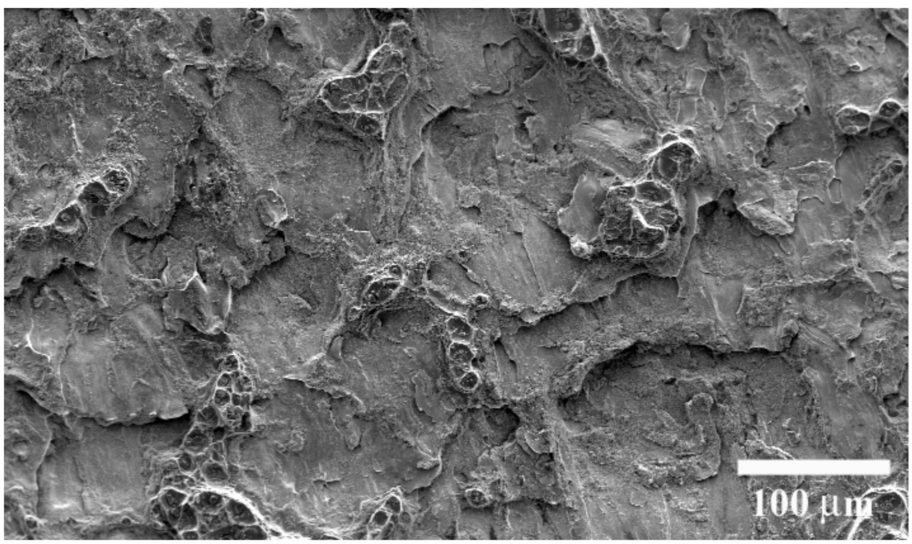
Bonding Parameter Identification	**Tensile Strength (MPa)**					**Impact Strength (J)**		
	Number of Tests	**Unnotched**		**Notched**		**Number of Tests**	**Average**	**Standard Deviation**
		Average	**Standard Deviation**	**Average**	**Standard Deviation**			
0.8 mm Al Interlayer								
3a*	4/4	175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

* Izod impact samples display failure at the Al-Al interface.

** Izod impact samples display failures within the Al interlayer.



(a)



(b)

Figure 1(a&b). SEM micrographs of the fracture surface on one of the edge detonated Izod samples.

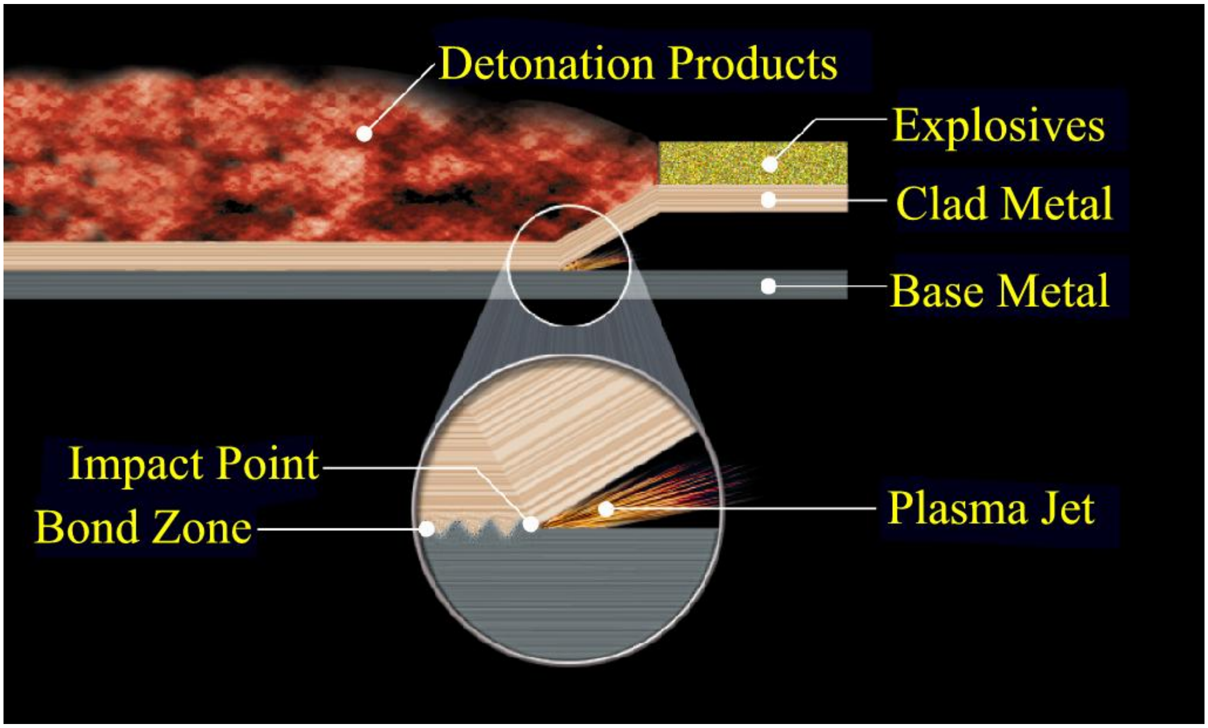


Figure 2. Schematic figure showing the basic features of the explosive welding process and the properties of the resulting bond.

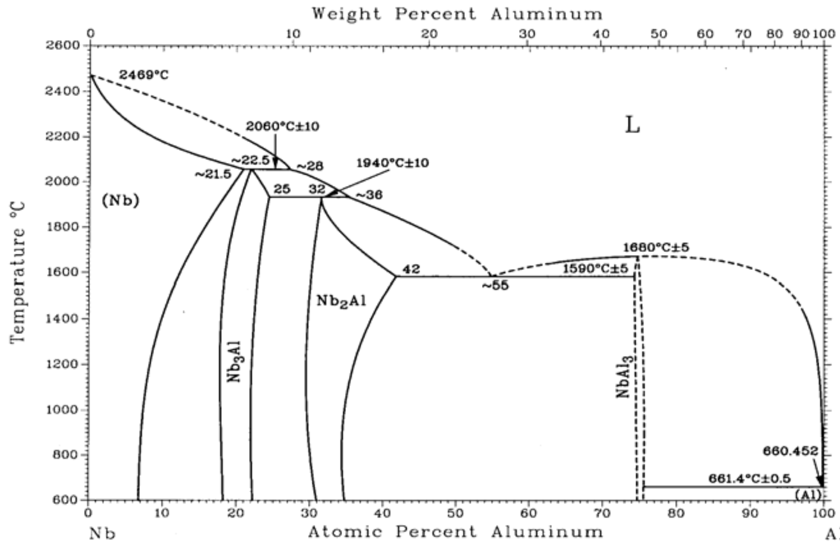
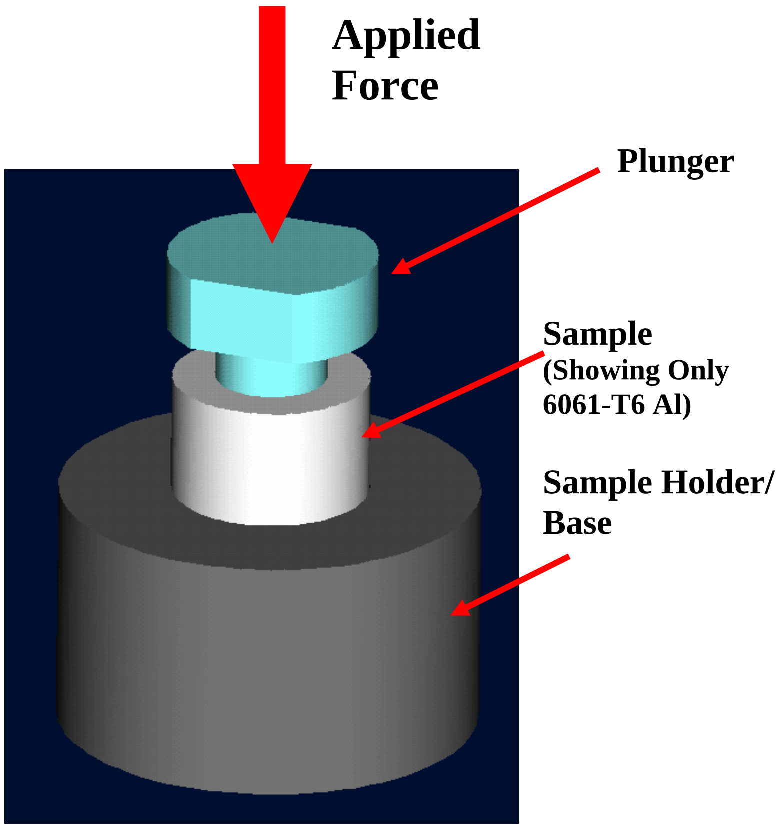
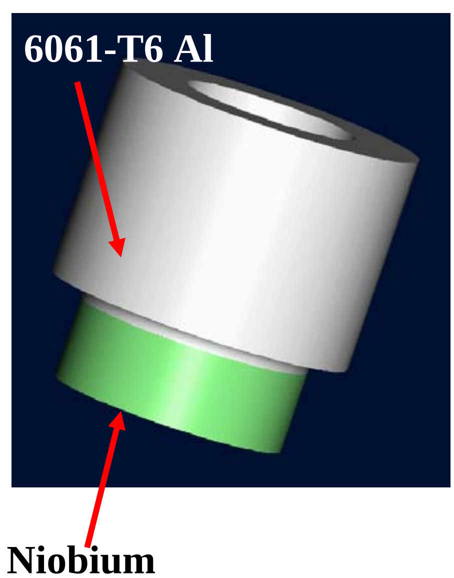


Figure 3. Plot showing the Al-Nb phase diagram. (Ref. 5)



(a)



(b)

Figure 4(a&b). Schematic diagrams showing (a) the tensile testing set-up used to measure the tensile strength of the Al-Nb explosive bond and (b) the ram tensile specimen.

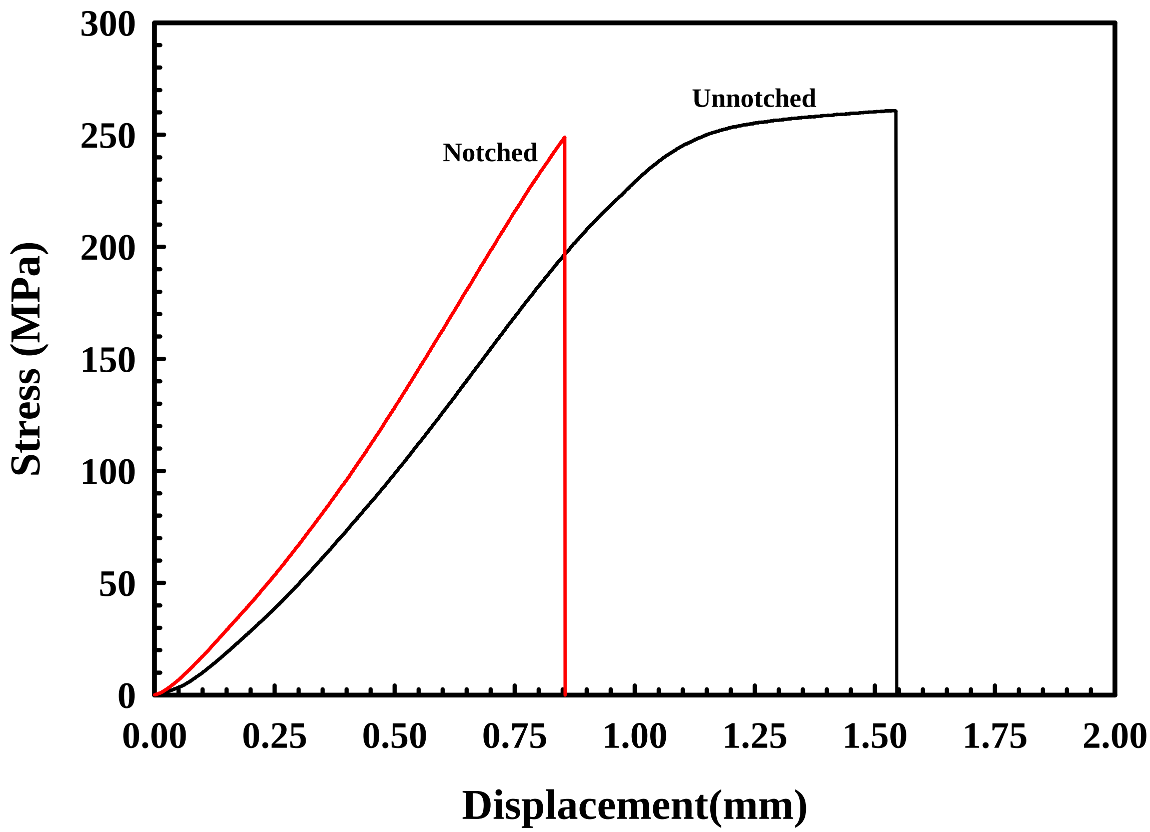
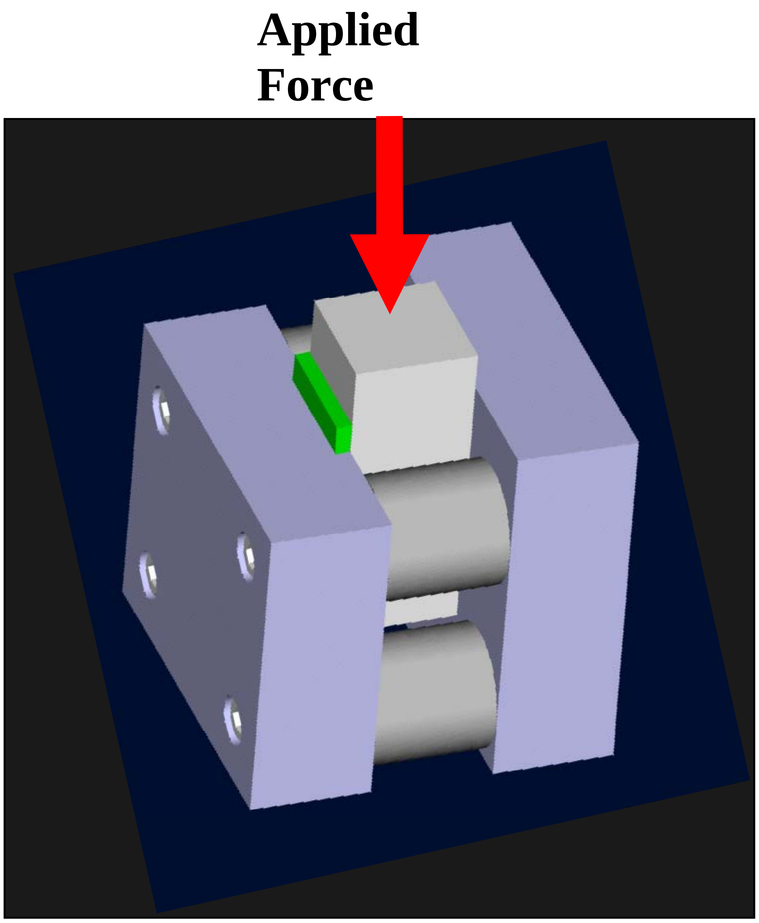
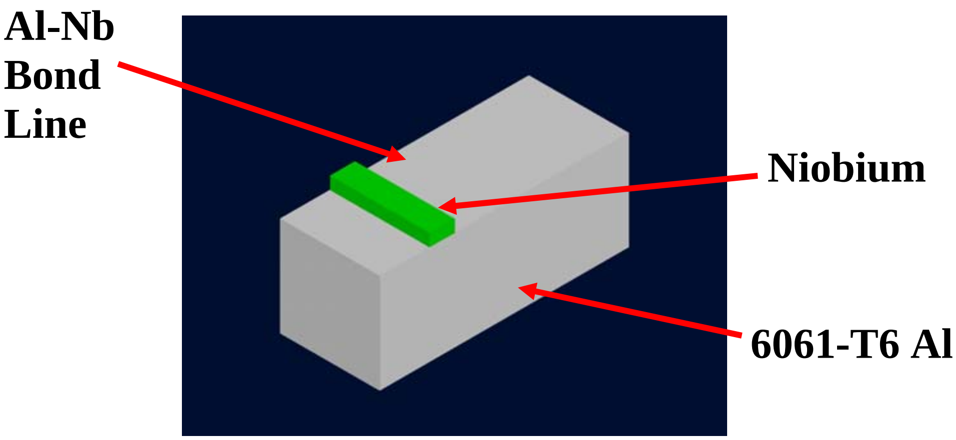


Figure 5. Typical stress-strain curve obtained during the tensile testing of an explosively bonded sample in the unnotched and notched configurations.



(a)



(b)

Figure 6(a&b). Schematic diagrams showing (a) the shear testing set-up used to measure the shear strength of the Al-Nb explosive bond and (b) the shear strength specimen.

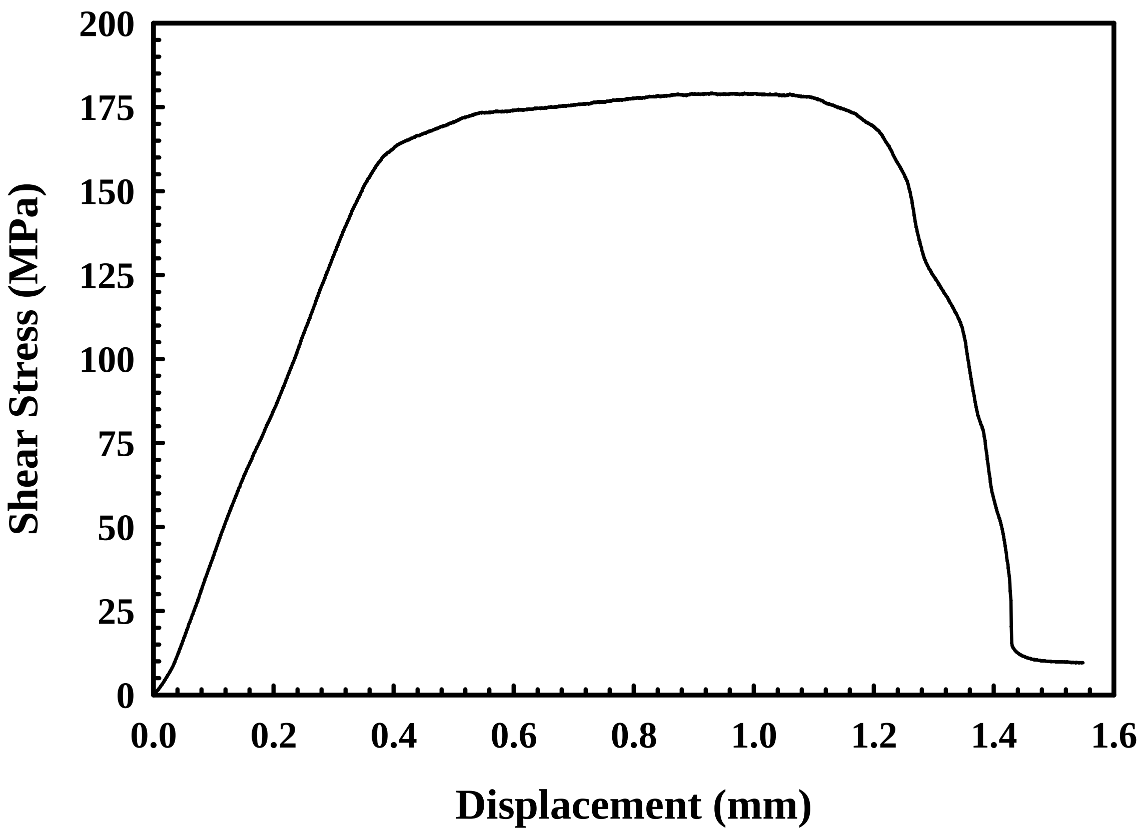
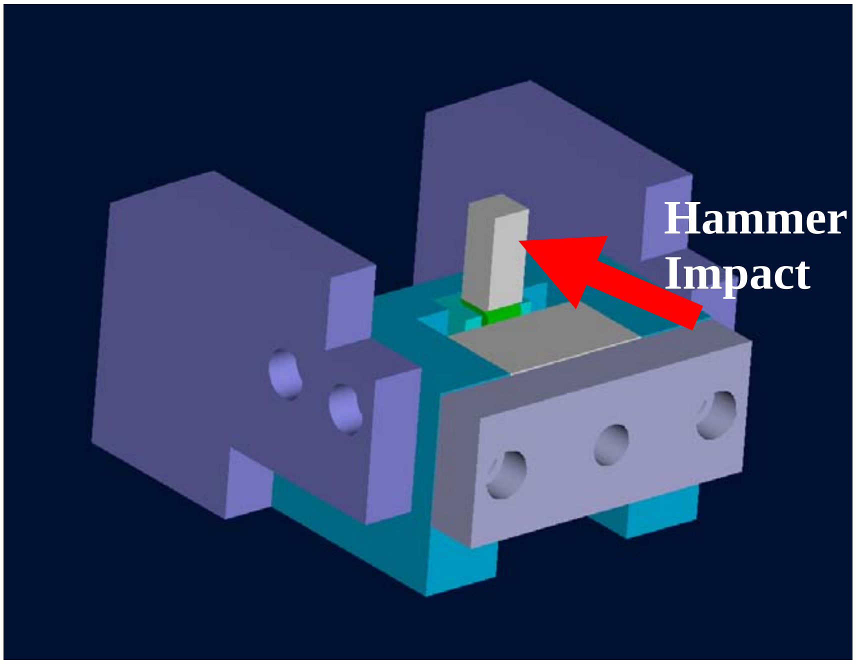
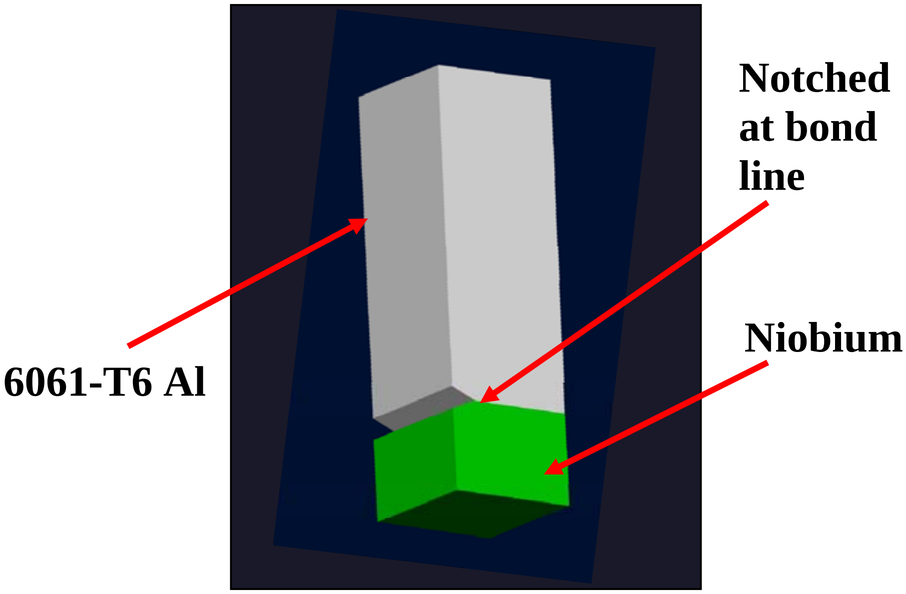


Figure 7. Typical stress-strain curve obtained during the shear testing of an explosively bonded sample.



(a)



(b)

Figure 8(a&b). Schematic diagrams showing (a) the Izod impact testing set-up used to measure the impact strength of the Al-Nb explosive bond and (b) the modified Izod specimen.

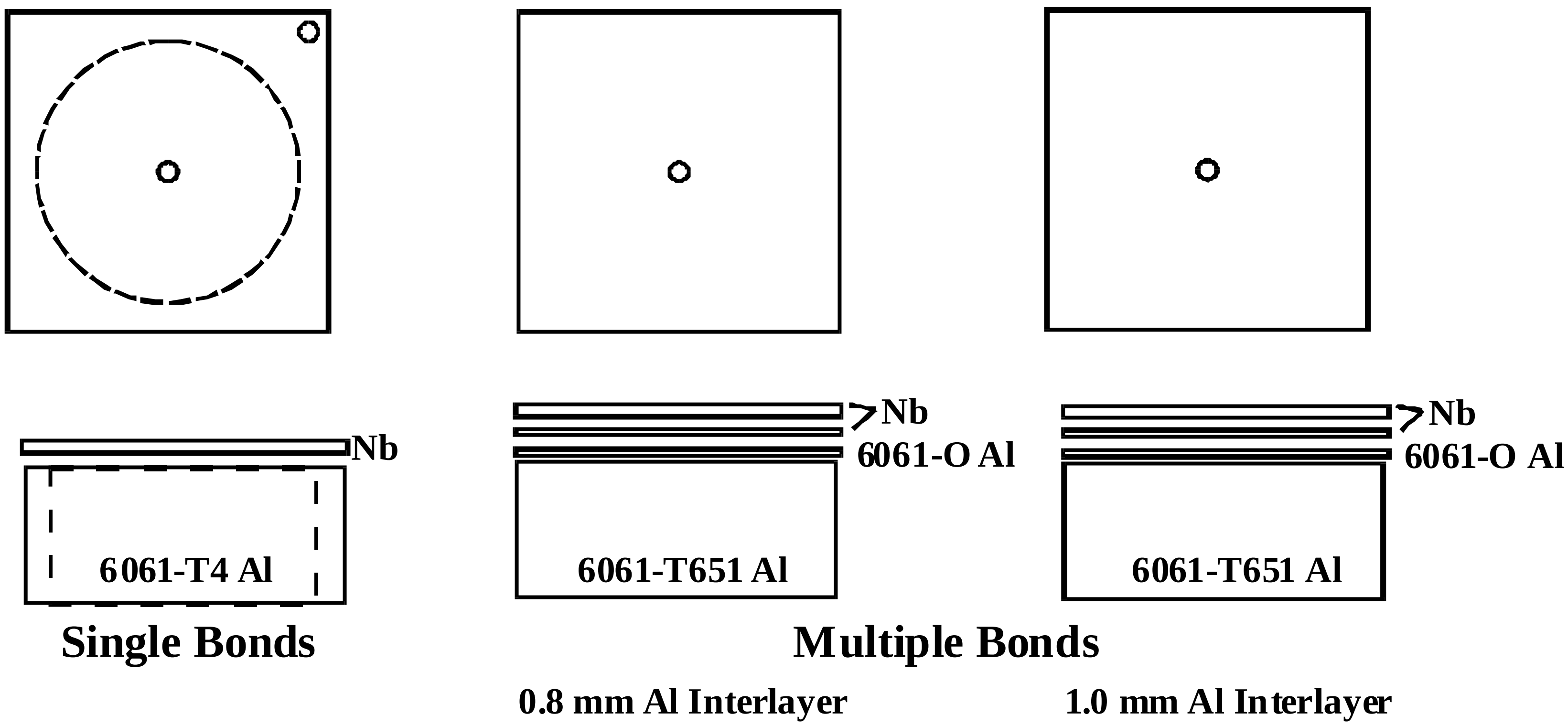
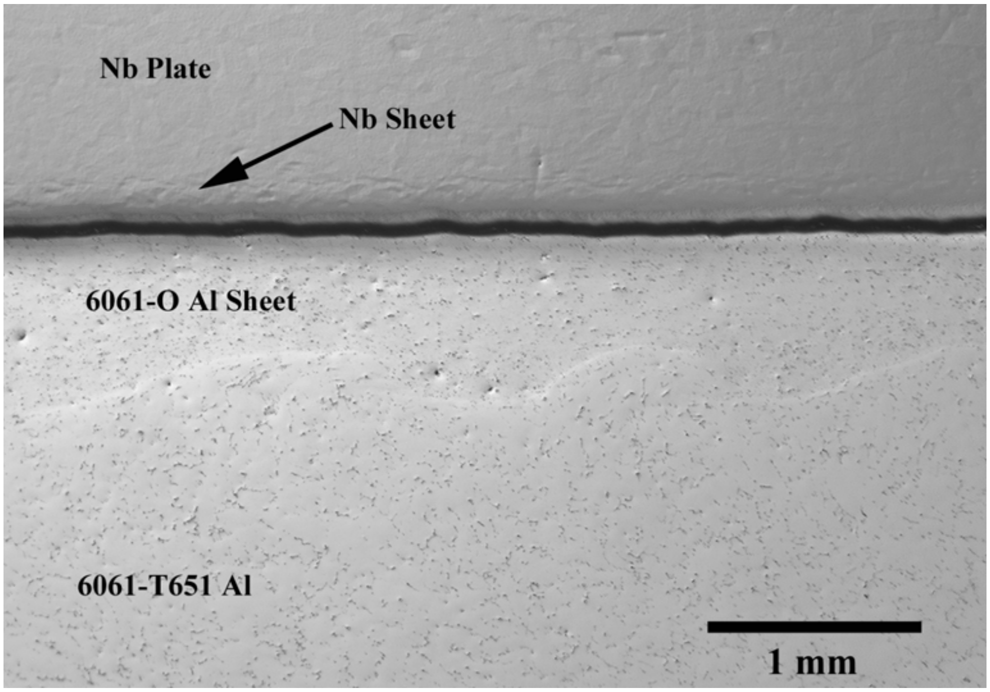
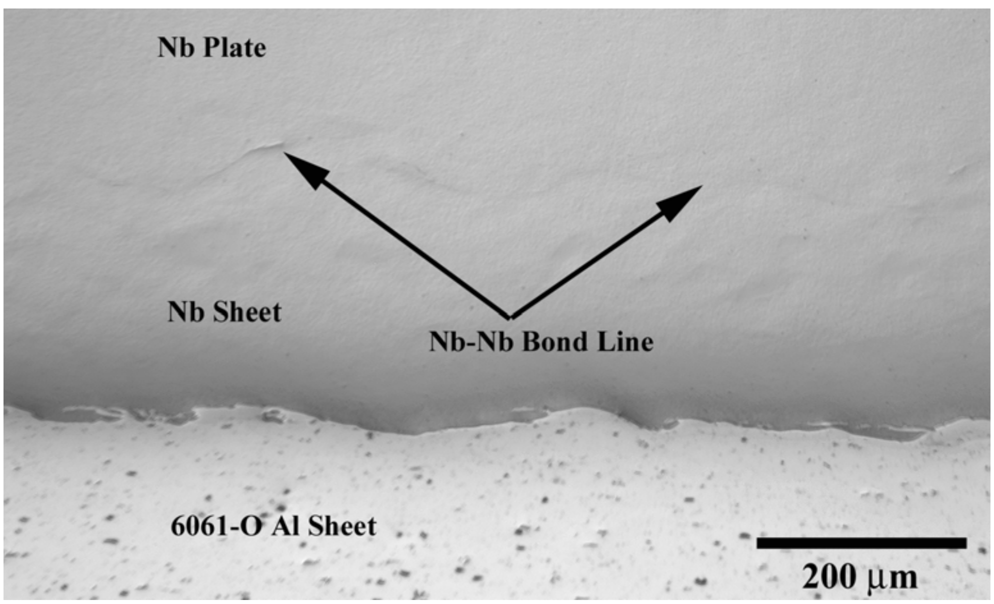


Figure 9. Schematic diagram summarizing the evolution of the explosive bond development. The circles on the top view of the explosive bond schematics indicate the locations of the detonators.



(a)



(b)

Figure 10(a&b). Micrographs of the bond cross section taken at an orientation perpendicular to the explosive wave front showing (a) the overall bond, including the Al-Al, Al-Nb, and Nb-Nb bond interfaces and (b) a closer view of the Al-Nb and Nb-Nb bond interfaces.

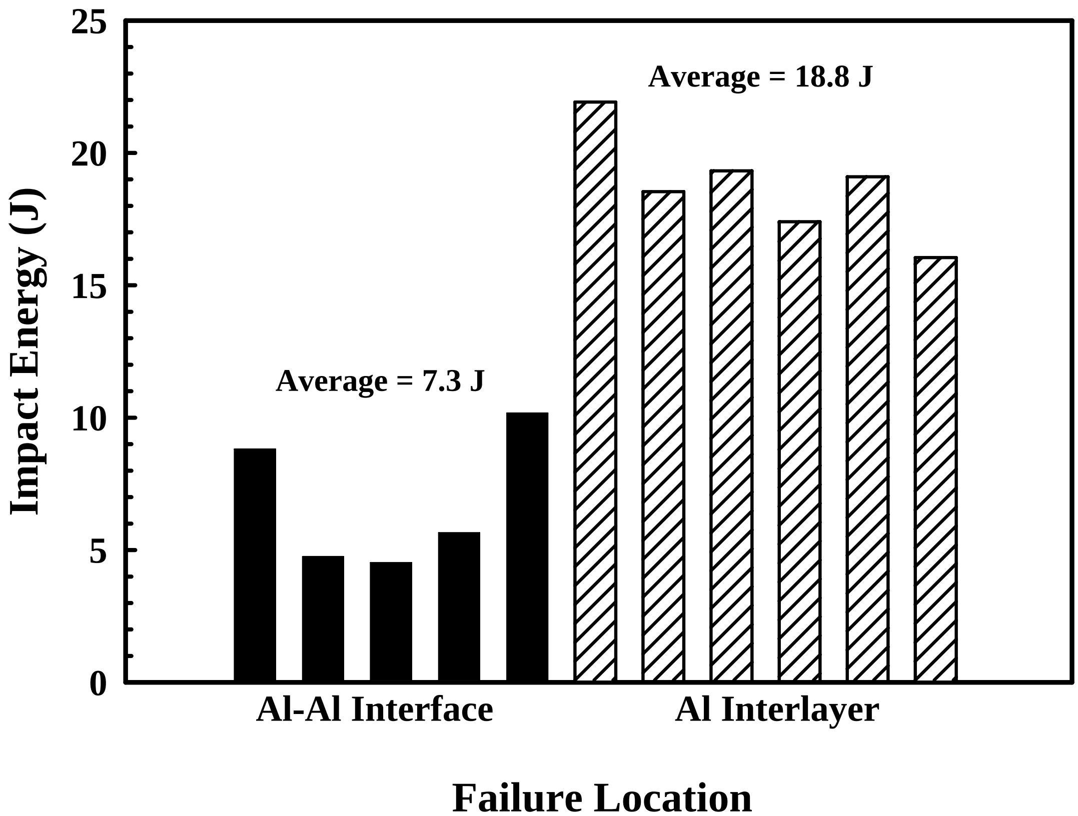


Figure 11. Summary of measured impact strengths for the multiple bond plate made using parameters #3a, showing the effects of differences in failure location on the measured impact strength.

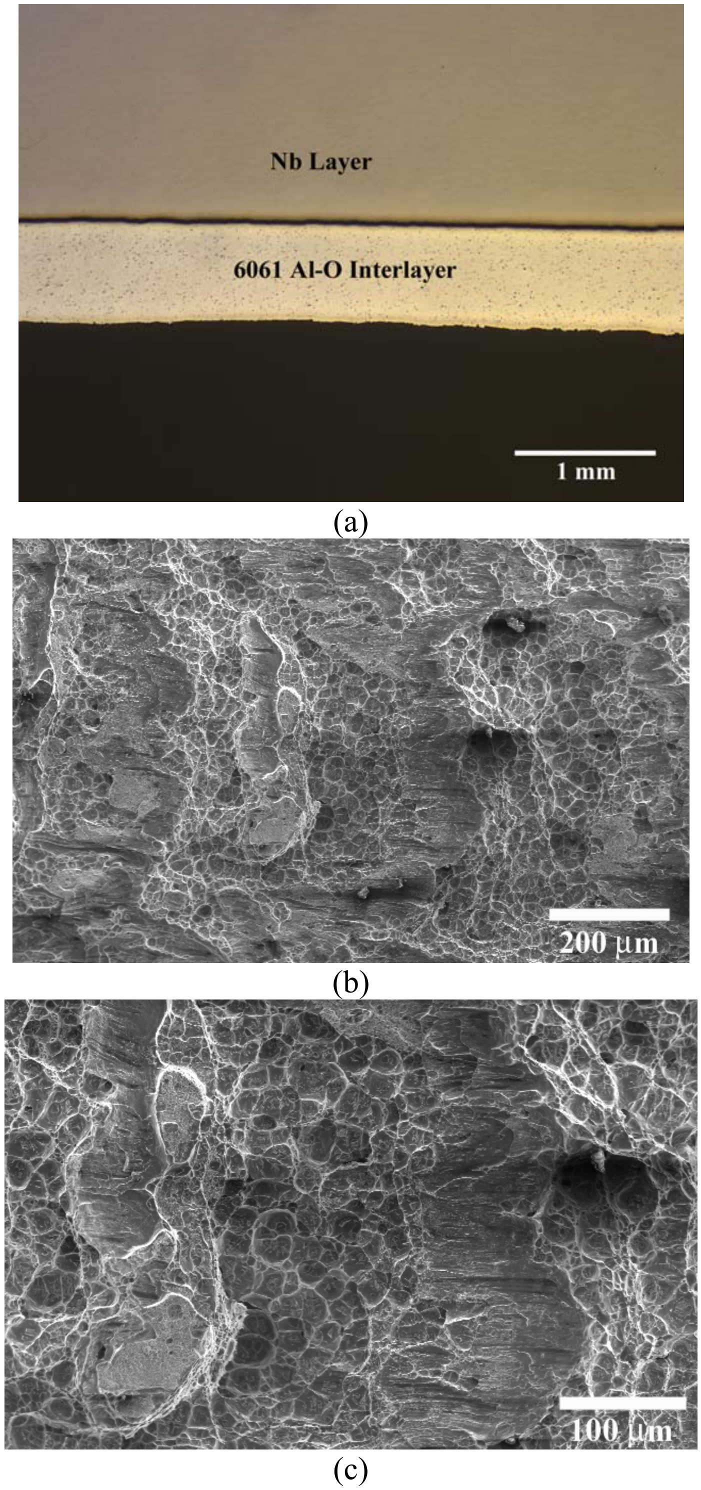
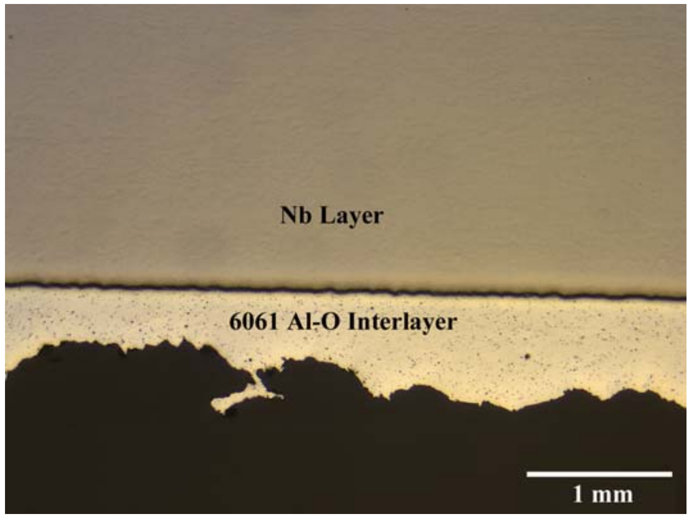
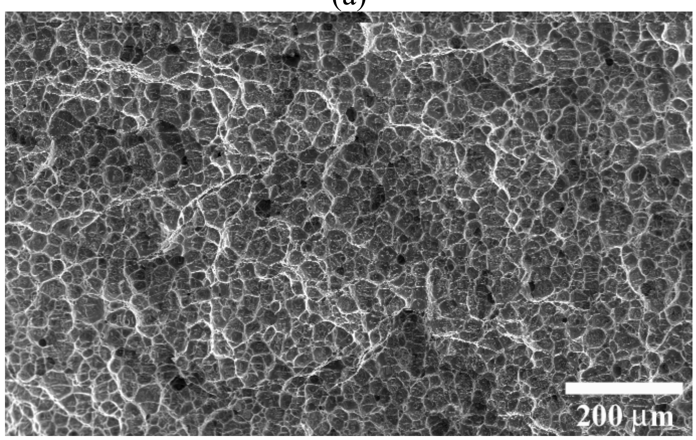


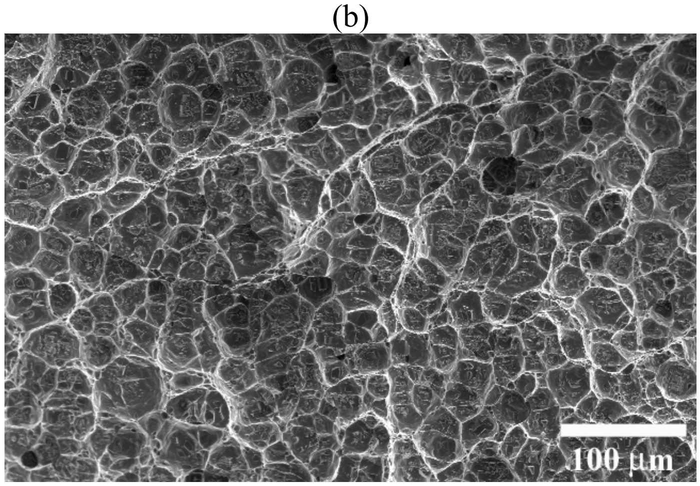
Figure 12(a-c). Micrographs showing the (a) cross section and (b&c) fracture surface of an Izod impact sample which fails at the Al-Al bond interface.



(a)

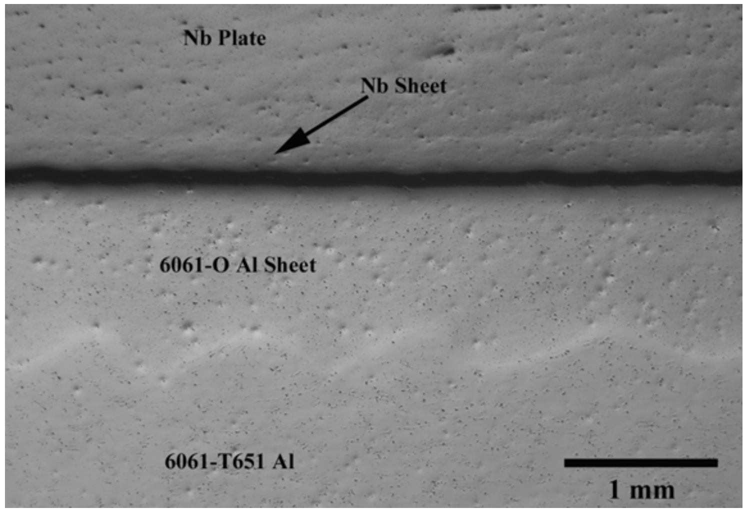


(b)

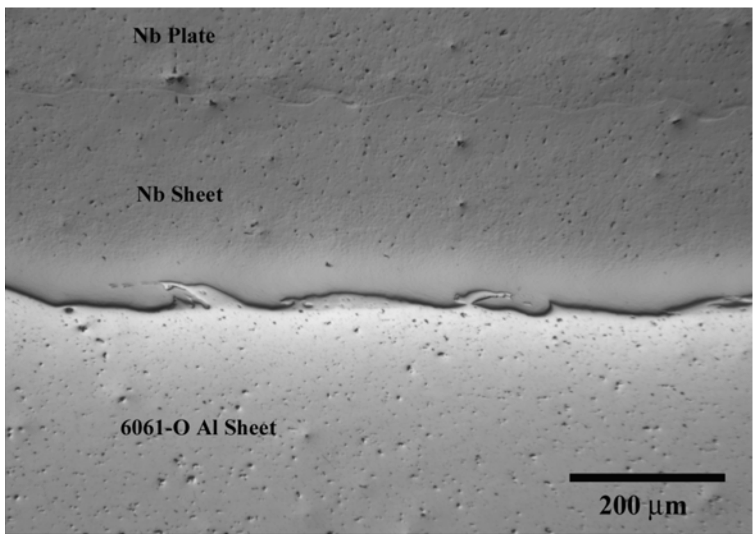


(c)

Figure 13(a-c). Micrographs showing the (a) cross section and (b&c) fracture surface of an Izod impact sample which fails in the Al interlayer.



(a)



(b)

Figure 14(a&b). Micrographs showing (a) the entire bond cross section and (b) the Al-Nb and Nb-Nb bonds taken at an orientation perpendicular to the explosive wave front for a multiple bond plate with a 1.0 mm Al interlayer.

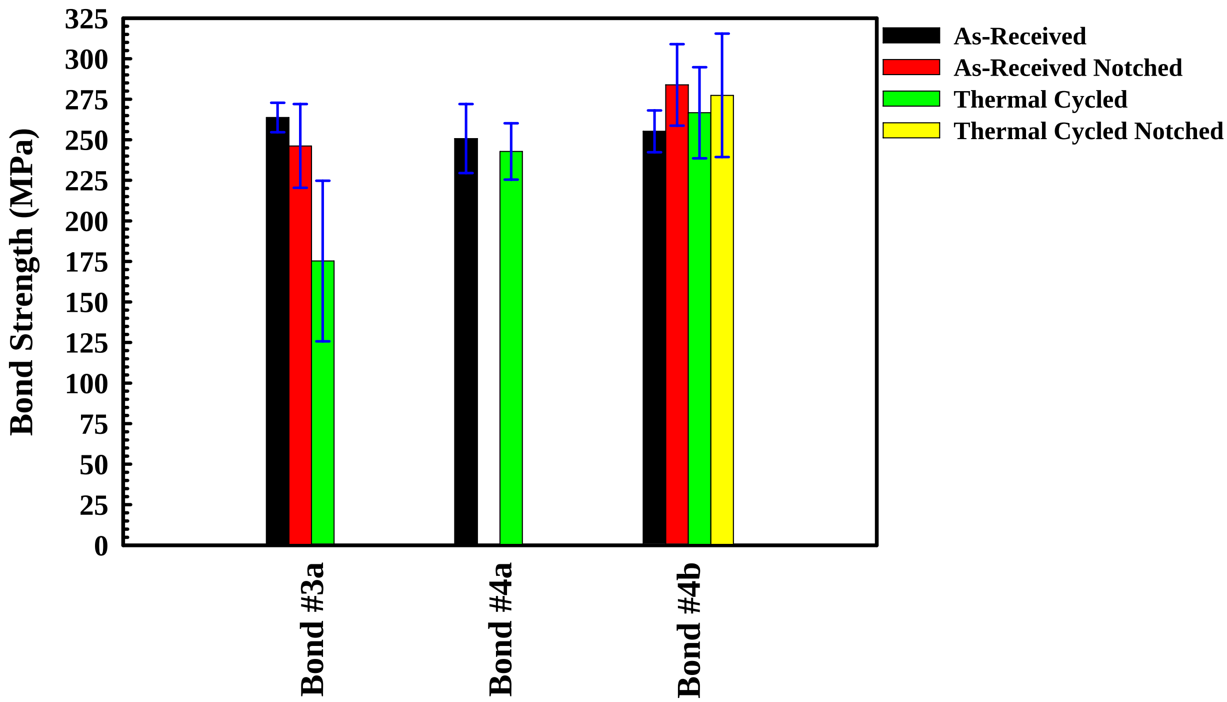


Figure 15. Comparison between measured tensile strengths in the as-received and thermal cycled multiple bonded plates.

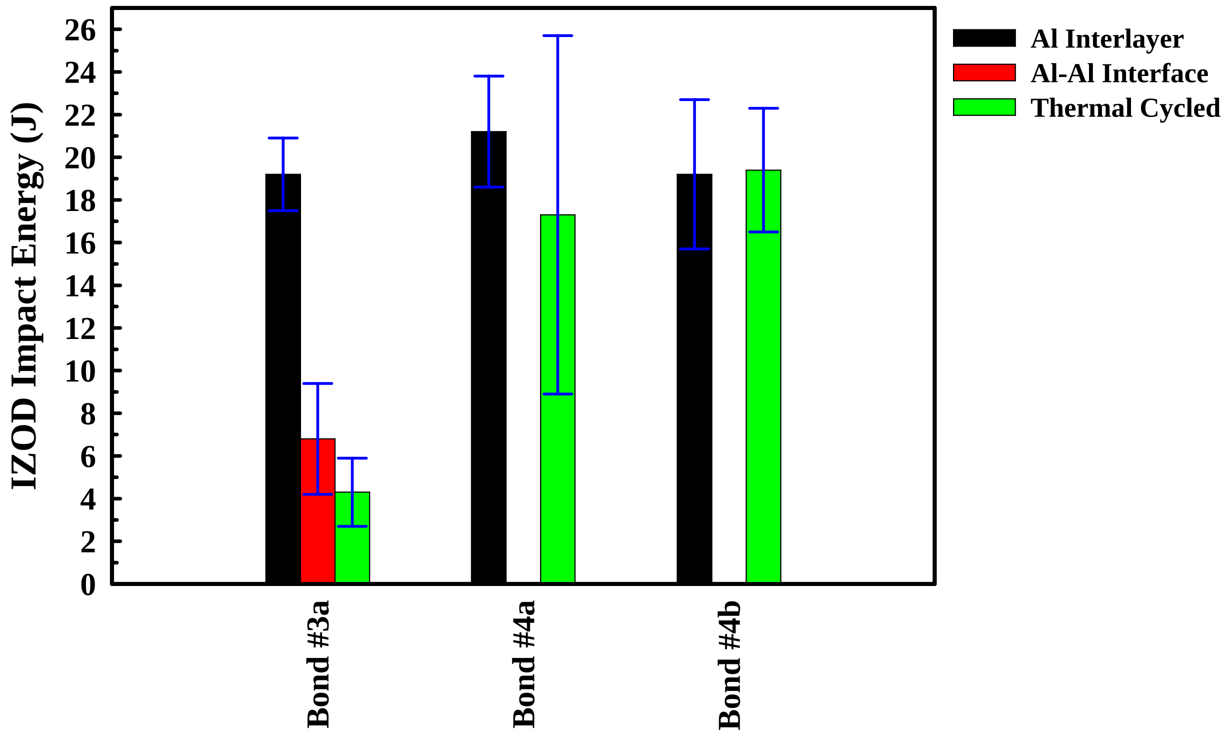


Figure 16. Comparison between measured Izod impact strengths in the as-received and thermal cycled multiple bonded plates.