AIAA 2000-3406

Explosive Joining for the Mars Sample Return Mission

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36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
July 17-19, 2000 / Huntsville, AL

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ABSTRACT

A unique, small-scale, ribbon explosive joining process is being developed as an option for closing and sealing a metal canister to allow the return of a pristine sample of the Martian surface and atmosphere to Earth. This joining process is accomplished by an explosively driven, high-velocity, angular collision of the metal, which melts and effaces the oxide films from the surfaces to allow valence electron sharing to bond the interface. Significant progress has been made through more than 100 experimental tests to meet the goals of this on-going developmental effort. The metal of choice, aluminum alloy 6061, has been joined in multiple interface configurations and in complete cylinders. This process can accommodate dust and debris on the surfaces to be joined. It can both create and sever a joint at its midpoint with one explosive input. Finally, an approach has been demonstrated that can capture the back blast from the explosive.

INTRODUCTION

This section describes the Mars Sample Return Mission and provides the background, goals, objectives and approach on developing a candidate explosive joining process for providing a permanent seal for a sample-return canister.

Mission Description

The primary goal of the Mars Sample Return Mission is to obtain a pristine sample of the surface and atmosphere of Mars for analysis on Earth. The sample should not be polluted with Earth materials on the Martian surface, in transit to the Earth, reentry or recovery. Although details of the approach for collecting this sample have not been finalized, the fundamentals are:

a. Land a spacecraft on the surface of Mars
b. Collect and transfer Martian surface samples (rocks, drill cores and loose materials) to a canister
c. The canister will be closed and sealed within the Martian atmosphere
d. The canister will be transferred to an orbit around Mars
e. A second spacecraft will go to Mars and capture the orbiting sample
f. This spacecraft will then return the sample to a pre-selected site on the Earth's surface for final recovery.

Joining Requirements

A highly reliable joining process is needed to seal and maintain an unpolluted Martian solid and atmospheric sample within a canister. The joining process should have capabilities to operate:

a. remotely
b. within the Martian environment of 0.1 psi, carbon dioxide atmosphere
c. at temperatures from -50^{o} C to $+20^{o}$ C
d. with the surfaces to be joined having wind-blown dust or Martian materials spilled in the manipulation of the surface samples

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e. without affecting the performance of the functions of the mission
f. without degrading the science quality of the Martian sample

The joining of interfacing cylinders was the preferred assembly approach to simplify mechanical processes in the mission. A cylindrical joint also offered the benefit of creating opposing, balanced forces during the explosive joining process. To accommodate sealing and canister-transfer requirements, approaches needed to be developed to simultaneously bond and sever the midpoint of the bond. Finally, high-strength joints were needed for the sample-return canister to survive a potentially severe impact at Earth-entry.

Explosive Joining Principles

The basic principles (reference 1) of explosive joining, which were invented in the late 1950's, are well understood. Surface oxide films are removed from the surfaces to be joined and the surfaces are pressed together to allow bonding through valence electron sharing at the atomic level. Figure 1 of reference 1, top sketch, which is a stop-action illustration, shows how this is accomplished. An explosive material, placed over the flyer plate, was initiated at the left with the pressure front moving to the right to drive the plate into a high-velocity angular collision with the base plate. On impact, the kinetic energy of the flyer is converted to heat to produce a skin-deep melt of the surfaces of both plates. This melt is jettisoned by the closing angle, thus, effacing the surfaces and the oxide film. The valence electrons on the surfaces are shared across the interface to achieve the same bond as that within the parent metal. Figure 2 of reference 1 shows a typical explosive joining interface, the wavy line at the midpoint. This line is no thicker than the metallic grain boundary in the 2024 alloy. Large-area bonds (cladding) of 4 X 12-foot sheets have been demonstrated.

This is not a heat-induced fusion or diffusion process, but depends on extreme dynamics. The explosive reaction creates pressures of millions of psi to drive the flyer into a virtual fluid state. The flyer plate, which initially can be spaced from the base plate by as little as 0.020 inch in a parallel-plate configuration, is accelerated to velocities of several thousand feet per second in achieving the necessary collision conditions.

The NASA seam joining process (reference 1), invented at the Langley Research Center in the late 1960's, differs from the cladding process described above. As shown in figure 1, lower sketches, a "ribbon" of explosive material (up to 0.35 inch in width has been demonstrated) is placed over the flyer. The explosive propagates down the ribbon's length, instead of from left to right. The flyer is driven into the base plate in a 60^{o} vector from the direction of explosive propagation. The ribbons contain very small quantities of explosive material, measured in grains/foot (0.2125 grams/meter). Typical explosive loads under consideration would be 20 to 30 grains/foot, or 4.250 to 6.375 grams/meter.

The interdependent explosive joining parameters (reference 1) are:

- Explosive quantity and location
- Materials; mass, thickness and properties
- Plate separation and interface configurations
- Mechanical shock

These parameters often are totally contradictory. For example, higher explosive loads will produce stronger joints in thicker material than would smaller explosive loads, but the higher explosive loads produce more mechanical shock and require more supporting structure.

The advantages of the explosive joining process are:

a. The explosive is a small-volume, low-mass, easily transportable, highly reproducible energy source.
b. Nothing is needed from the surrounding environment to support combustion.
c. Explosive materials, such as hexanitrostilbene (HNS) are available that are highly stable under thermal/vacuum environments.
d. Explosive initiation requires only low-energy (milli-joule) electrical detonators.
e. It creates a narrow (0.2-inch width), predictable bond area.
f. It produces absolute hermetic seals.
g. The joints exhibit parent metal properties (no heat-affected zone, as in fusion welding).
h. The explosive forces balance in creating a cylindrical joint.

The disadvantages are:

a. High levels of mechanical shock, created by the several million-psi explosive pressure and high-velocity collision of the plates, can not only damage surrounding structure and components, but also can damage the bond itself.

b. The "back blast" (a high-pressure gas wave and debris) from the explosion can damage surrounding structure and components. The pressure wave rapidly attenuates with distance from the source by a factor of at least the $1/distance^3$. The debris is whatever materials surround the explosive for handling and installation (sheath and holder) and unreacted carbon dust. This carbon dust is extremely fine and can coat critical spacecraft surfaces. This carbon dust also is flammable, when mixed with air; it will ignite and produce further volumes of gas.

c. Fully annealed metals are crushed (reducing cross-sectional thicknesses) by the explosive stimulus, thus appreciably reducing structural strength.

Goal/Objectives - The goal of this effort was to develop and demonstrate an explosive joining process for closing and sealing a canister on Mars.

Guided by the Mars Sample Return mission requirements listed above, the specific objectives of this portion of the explosive joining developmental effort were to:

1. Select the optimum canister material, based on demonstrations of its performance in meeting mission requirements.
2. Develop several candidate joint configurations to provide flexibility in canister design.
3. Demonstrate the ability to join cylindrical interfaces
4. Demonstrate the effects of surface debris (dust and dirt) on the explosive joining process and sealing.
5. Develop methods of creating a joint, while severing it at its midpoint (join/sever) in a single operation.
6. Develop approaches to contain the explosive back blast.

Approach - The approach for this effort was to:

1. Use a plastic explosive to provide a capability to easily change the shape and quantity of the ribbon explosive and maximize the flexibility in experimental testing.
2. Select aluminum alloy 6061 as the most likely material for evaluation.
3. Optimize the interface between plates to achieve the highest-strength 6061 joints, using flat stock (0.060-inch thickness flyers). Also, develop different types of explosive joints to accommodate possible mission interfaces.
4. Determine the structural parameters needed to explosively join and seal cylinders.
5. Evaluate the effect of surface debris on explosive joining.
6. Evaluate the strength of a variety of explosively joined aluminum alloys and tempering conditions. Determine the effects of explosive load on joining 6061-T0.
7. Develop approaches to join an area, while severing the mid-point of the area.
8. Develop a containment system to capture explosive back blast.

TEST APPARATUS

Metals to be joined

Aluminum alloy 6061 was selected, due to its demonstrated history of explosive joining. It also is readily available, malleable and amenable to conventional fabrication processes (machining and fusion welding). Three tempering conditions were evaluated in this study, the highest-strength, T6 condition (heated, water-quenched and age-hardened), the intermediate T4 condition (heated and water-quenched with no age-hardening) and T0 (fully annealed). Also evaluated was 2024-T3 ALCLAD, a high-strength aluminum alloy that is clad with a pure aluminum coating, which is approximately 5% of the overall thickness of the plate. It was selected to evaluate bond areas; since the surface is pure aluminum, the bond fails before the parent material.

Ribbon explosive

A plastic explosive was used, containing 65% pentaerythritoltetranitrate (PETN), 8% nitrocellulose with the remaining portion a binder. This binder exhibits properties like "silly putty." It can be mixed, kneaded and shaped like modeling clay. To control the explosive load, grooves were carefully machined into 0.100-inch thick X 0.500-inch wide acrylic strips, and the explosive packed into the grooves to produce the explosive loads below:

Explosive load Grains/foot	width inch	thickness inch
10	0.113	0.020
15	0.170	0.020
20	0.227	0.020
30	0.250	0.027

1. Also used was aluminum-sheathed hexanitrostilbene (HNS). Both the plastic and

HNS have explosive propagation velocities of 22,000 feet/second.

2. The ribbon explosive was attached to the surface with double-back tape and with room temperature vulcanizing silicone compound (RTV) for this experimental development. The double-back tape and RTV act like an incompressible fluid, transferring the explosive pressure with a very high degree of efficiency. The material of choice for space flight would be low-outgassing epoxy.
3. Note that the plastic explosive was selected only for the development of this explosive joining process; it would not be the material of choice for a deep space mission. PETN sublimes under vacuum conditions. The material of choice would be hexanitrostilbene (HNS), which is vacuum stable.

Tapered plates - 0.023 to 0.100-inch thick tapers were machined in 2 X 12-inch aluminum sheet stock. The principle of using tapered flyer plates in testing is that the maximum possible joining thickness can be determined in each test, while fixing other joining variables, such as explosive load or flyer material.

Anvil - A 24 X 24 X 3/4-inch, 2024-T4 aluminum plate was used as an anvil to transfer the explosive mechanical shock away from the joining process for flat-stock specimens. Other materials, such as steel can be used, but the shock transfer efficiency (coupling) is reduced, due to the mismatch of physical properties. Special anvil shapes were machined from 6061-T6 stock to establish appropriate interfaces between the flyer and base plates for several joint applications.

Explosive initiation - Two initiation sources were used for this experimental development, blasting caps and explosive transfer lines. Blasting caps, containing 260 mg of PETN in a 0.250-inch diameter aluminum cup, are inexpensive, commercially available, and electrically initiated. Explosive transfer lines, which must be initiated by a separate explosive input (blasting cap or detonator), contain 100 mg of HNS in a 0.150-inch diameter steel cup (reference 2). These end tips exhibit a highly reproducible, more efficient, output performance of an explosive pressure impulse and high-velocity fragments. This output not only initiates the ribbon explosive, but also provides the necessary explosive stimulus to begin the explosive joining process, while the ribbon explosive is building to a steady-state explosive propagation.

TEST PROCEDURES

This section describes procedures for the preliminary experimental efforts conducted to demonstrate the capabilities of the NASA Langley Research Center explosive joining process to meet the Mars Sample Return Mission requirements. More than 100 experiments have been conducted to date. The following were the most informative.

Flyer-to-base plate interface - A series of tests, figure 3, were conducted to maximize joint strengths through evaluating possible flyer-to-base plate interface configurations. The following fixed parameters were used:

- 30 grains/foot ribbon explosive in an acrylic holder
- A 6061-T4, flyer plate
- 0.250-inch thick, 6061-T6 base plates
- The interface angles were 9^{o}

Moving through the sketches from the top, left, downward, the plate and explosive was moved off of a central location over a peak to the side, then to a machined angular interface and finally to a plate that was bent upwards. The joined plates were sawed into 1-inch widths and pull-tested.

Variable-angle base plate - To determine the optimum interface angle between the flyer and base plates, a test was conducted with a variable-angle, 6061-T6 base plate, as shown in figure 4. The angle in the base plate was machined in a continuous variation from 3 to 15^{o}. The joint was sawed into 1-inch widths and pull-tested.

Ring test - A series of cylindrical joints were created to determine the joint strength, seal integrity and structural support needed to withstand the forces created during the explosive joining process. Figure 5 shows the test configuration. Cylindrical base rings, 5.7 inches in diameter, were machined from solid stock 6061-T6. The first test was conducted with a solid plate (no cutout). The diameter of the cutout was changed to leave cylindrical walls of 1.0, 0.5, and 0.25 inch. Upper 6061-T0 cylinders were placed over the base rings, and the 30-grains/foot ribbon explosives were installed. The holders for the ribbon explosive were created by heat-softening the acrylic to allow for shaping around the cylinder. The explosive was then packed into the grooves in the acrylic, and each assembly was installed on the cylinder with double-back tape. The explosive was initiated with a single end tip from an explosive transfer line. Identical test conditions were repeated for joining each of the four cylinders. To evaluate the strengths of the joints, the cylinders were sawed into one-inch wide strips and pull tested. The lower, extended portion of the cylinder provided a grip interface for the pull tests.

A closed-dome cylinder (can) was joined to a solid base plate to evaluate the seal integrity of the joint. A helium leak detector was attached to a port in the base plate. The internal volume of the can was evacuated to a pressure of at least 1 X 10^{-4} torr and the exterior of the joint was flooded with helium.

Surface debris - A series of tests were conducted to determine how surface debris, such as wind-blown dust or dirt spillage, affects the explosive joining operation. Figure 6 shows the 6.5-inch diameter disc test configuration. Flyer plates of 0.050-inch thickness, both 6061-T6 and 6061-T0, were evaluated, using a 30-grains/foot ribbon explosive. The 6^{o} angular interface in the outer 0.375-inch width of the 1/4-inch base plate was covered at select sites with first of all soft-textured talcum powder, then hard-grit carborundum.

Talcum powder - magnesium silicate, particle size ~ 5 microns
Carborundum grit - aluminum oxide, particle size 25 to 50 microns

Alternate areas around the circumference were dusted; a 0.375 X 2-inch dusted area was separated by a half inch, followed by another 0.375 X 2-inch area. Dusting completely around the circumference followed this sequence. The test setup involved carefully weighing out a sample of particles and manually spreading the material, as uniformly as possible over the designated area. Areas were covered with 2.07, 4.13 and 5.94 mg/cm^{2} of carborundum grit. Figure 7 shows a test setup, where an approximate load of 4.13 mg/cm^{2} of carborundum was spread around the complete circumference. (The surface was nearly obscured. In fact, if the plate were rotated to the vertical, very little of the material would remain adhered to the surface). After the joint was made, the specimen was submerged under water and pressurized with 30-psi air through the threaded port to determine leak sites. For those specimens that did not leak to 30 psi, a helium leak test was conducted as described above. The specimen was then pressurized with nitrogen to burst failure. This process was repeated, increasing the quantity of debris until leaks were detected. The flyer plate was peeled off the bond at several sites to determine what surface debris remained.

Material parametric investigation - A variety of flyer plates alloys were joined with 30-grains/foot explosive ribbon to investigate strengths and uniformity of performance. Figure 8 shows the experimental setup. The flyer plates were bonded to the anvils with "Hot Stuff" to assure shock wave coupling; the adhesive was fractured during the joining process. The flyer plates were commercially available, constant-thickness sheet stock, as listed below:

Thickness, inch	Material
0.040	2024-T4 ALCLAD
0.040	6061-T6
0.050	6061-T6
0.050	6061-T0
0.063	6061-T6
0.063	6061-T4
0.063	6061-T0
0.063	2024-T4 ALCLAD
0.100	6061-T0

The joined plates were sawed into one-inch wide strips and pull-tested.

Effect of explosive load on joining 6061-T0 - Tapered plates, fabricated from 6061-T0 stock were used in experiments, as shown in figure 9, to evaluate the effects of explosive load on bonding. Tests were conducted with 10, 15, 20 and 30 grains/foot explosive loads. The plates were sawed into 1-inch strips and pull-tested. The maximum thickness at which the bond supported the full strength of the material was recorded.

Combined joining and severing - Several test configurations were conducted to develop an approach to join across an area, followed by longitudinally severing the joint at its midpoint with a single explosive input. A 0.032-inch, 6061-T6 flyer plates and 0.063-inch (and greater), 6061-T6 base plates were used for these experiments. Figure 10 shows the configuration for each test.

Back blast containment - High-strength Kevlar fabric, Kevlar 29 - style 735, 2 X 2 weave, was used in experiments to provide a low-mass approach for containing the back blast from the ribbon explosive. The first experiment, as shown in figure 11, positioned the fabric in open-ended, progressively expanding loops over the ribbon explosive. Both plastic explosive and metal-sheathed HNS ribbon explosives were tested

Figure 12 shows a system-level test configuration in which the explosive source was completely encapsulated. A 12-inch diameter envelope was created with a single layer of Kevlar. The interior and exterior edges were covered with Dacron tape and stitched with Dacron thread to strengthen the areas. A 20 grains/foot, aluminum-sheathed, HNS ribbon explosive was wrapped around the midpoint of the spool. The central portion of the spool was covered with a split, low-density, urethane foam cylinder to initially decelerate the aluminum fragments. The energy in the pressure wave was to be attenuated by the large volume within the bag. The Kevlar bag was mechanically attached to the top and bottom of the spool with a simple ring/fastener arrangement. A rigid explosive transfer line that was pushed through the weave without cutting any strands initiated the ribbon explosive.

RESULTS

The results of the experiments are presented here in the same order as that of the Test Procedures section.

Flyer-to-base plate interface - The results of this test series are summarized in figure 3. The numbers to the right of each sketch indicate the maximum thickness and strength, where the coupon failed. In joints B through D, where joining was accomplished over a single angle, D achieved the highest value. Joint E had a considerably lower capability. Recognizing that the stimulus from the ribbon explosive is finite, joining configuration A required more energy to bend and join the flyer in two directions, than did the remaining configurations that required only a single bend. More energy was consumed in configuration B, as compared to C. For B, the plate had to bend and deflect the remainder of the flyer plate; for C, much less mass was accelerated. Configuration D had the highest efficiency, because the least amount of mass was accelerated. Configuration E had poor efficiency, largely due to the poor, rounded angular interface created in bending the plate.

Variable-angle base plate - The variable-angle base plate indicated that a 6^{o}-angle was optimum to obtain the maximum joint strength (the coupon failed, rather than the bond) for the 0.063-inch thick, 6061-T4 flyer plate. The joint strength dropped dramatically above 9^{o}.

Ring test - Full-strength bonds were achieved in all of the ring tests. However, the 0.250-inch thick ring suffered a great deal of deformation. The ring diameter decreased by 0.090 inch in diameter. An additional 0.105-inch deflection occurred beneath the initiation point (figure 13), caused by the explosive stimulus from the end tip of the rigid explosive transfer line. No appreciable deflection occurred in the 0.50-inch thick ring. The experiment with the closed dome produced a hermetically sealed joint.

Surface debris - Tests in which the entire joining surface was covered with the relatively low-density talcum powder yielded joints that exhibited both hermetic seals and high strength with 6061-T6 flyer plates. However, the experiments with 6061-T6 flyer plates and carborundum grit exhibited leaks with 4.08 and 5.94 mg/cm^2 surface loads. The experiment with a continuous surface load of approximately 4.13 mg/cm^2 and a 6061-T0 flyer plate (figure 7) achieved a hermetic seal. The assembly failed at a burst pressure of 243 psi, nitrogen. The flyer plate failed inside the bond line. Peel tests revealed that the carborundum grit had been crushed into considerably smaller particles and that much of it had been ejected. Quantities of the material remained embedded in the bond.

Material parametric investigation - The results of this investigation are summarized in figure 14. At thicknesses of 0.063 and below, the 6061-T6 and 6061-T0 exhibited both the smallest ranges of values and standard deviations. For the 0.040-inch, 6061-T6 flyer, bond failure was the limiting factor. The 6061-T6 and 6061-T4 data points at the 0.061-inch thickness were virtually identical, because the base plates failed, rather than the flyers. Failures occurred at the edge of the bond, where the plate was thinned by the crushing force of the explosive. The ALCLAD stock exhibited considerable variation; the bonds in the relatively weak pure aluminum coating were likely damaged by the mechanical shock generated during the explosive joining process. The 0.100-inch thick, 6061-T0 flyer had lengths at the ends of the joint that were totally unbonded. Again, the bonds were likely damaged by complex mechanical shock waves reflected off the ends of the base plate.

Effect of explosive load on joining 6061-T0 - The results of joining 6061-T0 with a range of explosive loads is shown in figure 15. As the explosive load is increased, greater thicknesses can be joined. This data corroborates the above data, indicating that 0.100-inch thick 6061-T0 cannot be joined to achieve parent strength with a 30 grains/foot ribbon explosive.

Combined joining and severing - Joining configurations A, B and C in figure 10 have indicated the potential of achieving bonds on both sides of a bond area centerline separation plane. For joining configurations A and C, sufficient plate thinning and transverse forces were created during the explosive joining process to part the 0.032-inch flyer plate. However, for A and C, no bond would be achieved on the centerline, because the angular-collision joining mechanism cannot be established at that point. Joining configuration B overcomes that disadvantage; the explosive joining mechanism sweeps across the entire area, and the pre-weakened, notched plates are parted by transverse forces and mechanical shock. Unfortunately, configuration D, the apparently logical next step from B, failed. Although bonds were achieved on both sides of the notches, transverse forces and mechanical shock destroyed them. It should be noted that although successful joints were created, the strength of half of the bond area would result in joints that cannot support the full strength of the material.

Back blast containment - Experiments with multiple loops of Kevlar fabric, as shown in figure 11, revealed that the debris created by the acrylic or metal housing around the ribbon explosive was initially decelerated by the first Kevlar fabric layer. The second layer completed the capture. The explosive gas wave was attenuated by venting through multiple layers of the porous Kevlar fabric and by distance from the source. It became immediately apparent that the plastic explosive created considerably more gas, as was evidenced by the destruction of several more layers of fabric, than did the metal-sheathed HNS.

The totally encapsulated system experiment, shown in figure 12, was highly successful. The Kevlar bag remained completely intact. No explosively driven fragments penetrated the bag, and the bag seams and attach points withstood a very dynamic, pressure-driven full expansion. A small quantity of gases and unreacted carbon vented through the weave, as expected. The particles, which appeared after full expansion, had no appreciable velocity, and were carried upward in heat-induced thermal drafts. An advantage of using explosive joining on Mars is that the carbon-dioxide atmosphere will not support any further combustion of carbon particles. Thus, confinement will be more easily accomplished, since less gas will be generated.

CONCLUSIONS

Significant progress has been made in the development of a small-scale explosive joining process to meet the requirements of sealing a cylindrical joint for the Mars Sample Return Mission. This process relies on explosively driving metal plates together to produce a high-velocity (several thousand feet/second) angular collision. This collision induces a surface melt, which is then ejected to efface surface oxide films and allow surface bonding through the sharing of atomic-level valence electrons. The selection of aluminum alloy, 6061, as the canister material has proven to be an excellent decision, based on tests that created high-strength, small-tolerance, hermetically sealed joints. A variety of joint configurations have been developed with this material in thicknesses to 0.063 inch that can maximize explosive joining efficiency and reproducibility. A series of tests on the explosive joining of cylindrical joints demonstrated not only the capability to produce parent-strength, hermetic seals, but also the necessary structure to support the dynamic loads induced in the joining process. The use of fully annealed 6061 flyer plates onto surfaces that have been covered with dust and grit, have indicated that this joining process can accommodate far more surface debris than would be expected in Mars robotic surface operations. Several joint configurations have been created that indicate the capability to both join and sever the joint at its midpoint in the same process. Preliminary experiments have shown that explosive back blast, a major disadvantage, can be managed by a low-weight, flat, 12-inch diameter, Kapton/Dacron bag and urethane foam.

ACKNOWLEDGEMENTS

The following have contributed to the experimental process of this paper:

Ronnie B. Perry of ZIN Technologies, NYMA, Inc.

Gale A. Harvey in the NASA LaRC Cleanliness Measurements, High-Vacuum Diagnostics, and Optical Characterization Laboratory.

REFERENCES

1. Bement, Laurence J.: Applying NASA's Explosive Seam Welding. Presented at the TECHNOLOGY 2001 Conference in San Jose, CA, December 3 to 5, 1991.

2. Bement, Laurence J.; Kayser, Eleonore G.; and Schimmel, Morry L.: Service Life Evaluation of Rigid Explosive Transfer Lines. NASA Technical Paper 2143, August 1983.

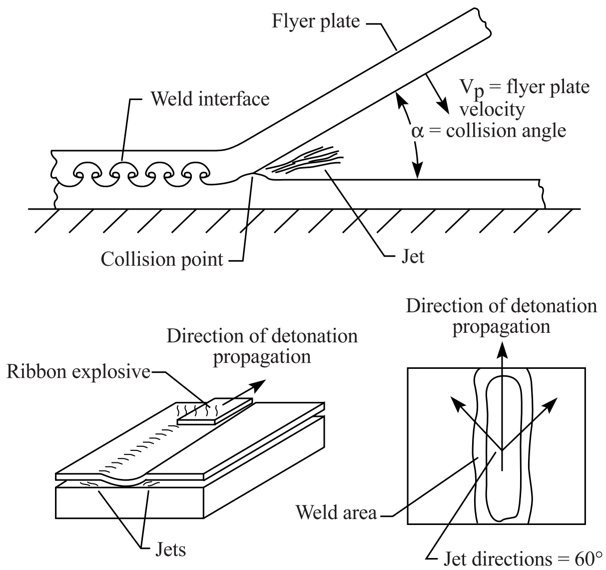

Figure 1. High-velocity, angular impacts of the two explosive joining processes: cladding in the top sketch and the NASA explosive seam welding in the bottom sketch.

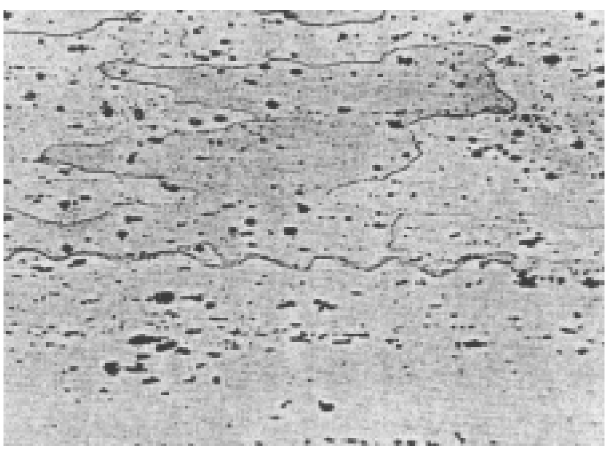

Figure 2. Microphotograph example of an explosively joined interface of 2024-T4 (top half of photograph to 6061-T6 (lower half).

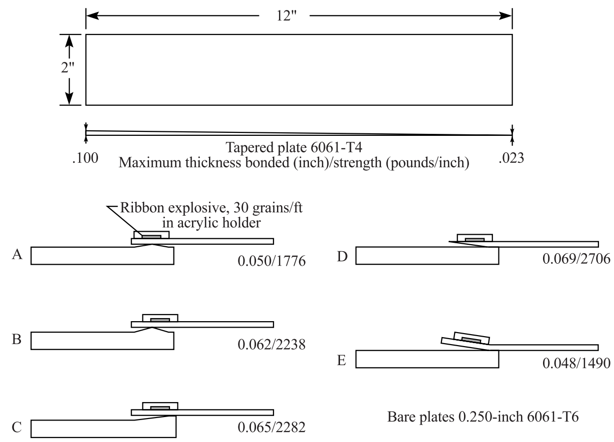

Figure 3. Test configurations used for development of plate interfaces. All angles are 9º.

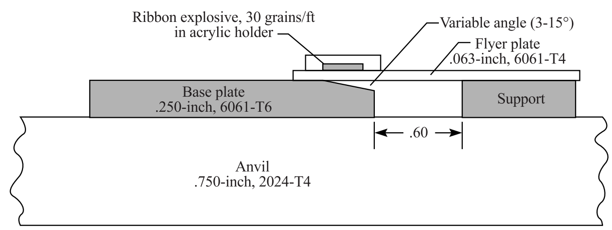

Figure 4. Test setup for evaluating variable-angle, flyer-to-base-plate performance.

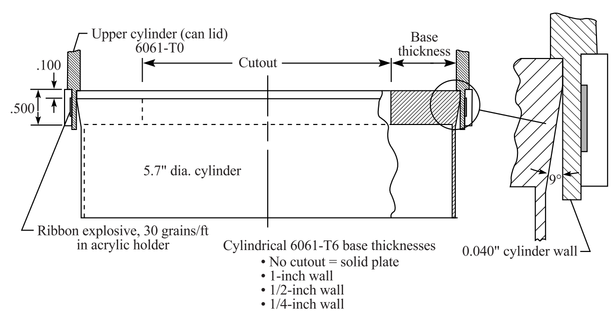

Figure 5. Cross-sectional view of the 5.7-inch diameter cylindrical joint. The base ring was 6061-T6. The 6061-T0 upper cylinder was open or closed.

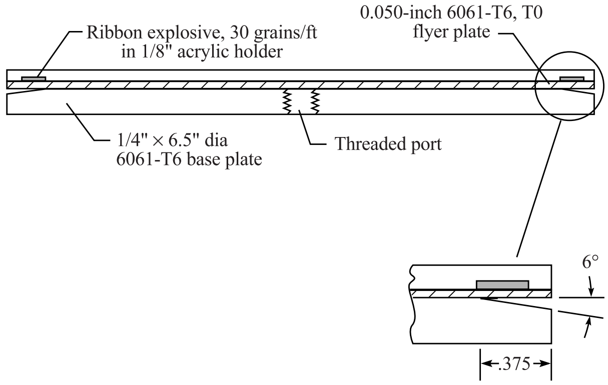

Figure 6. Cross-sectional view of surface debris test configuration.

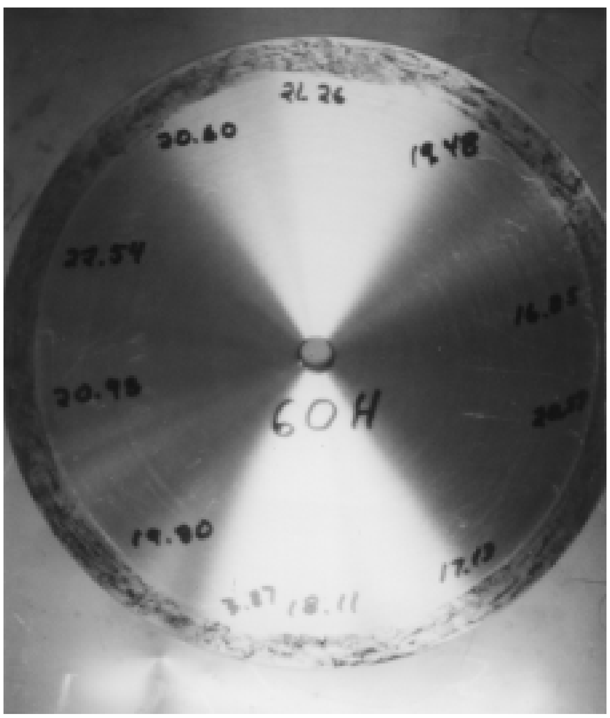

Figure 7. Experimental setup for a surface debris experiment with 25 to 50-micron carborundum grit. The interior numbers indicate the milligram loading for a 0.375-inch wide X 2-inch long area. A load of 20 mg is the equivalent of 4.13 mg/cm^2. The 3.87 value covered a 0.4-inch length.

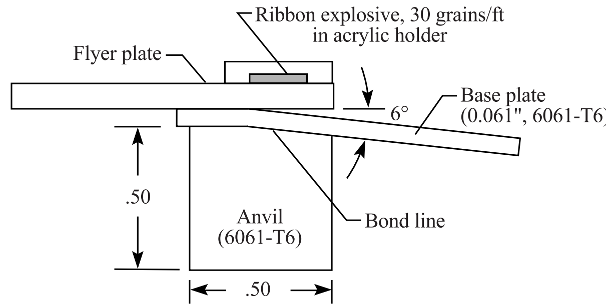

Figure 8. Test setup for material parametric investigation.

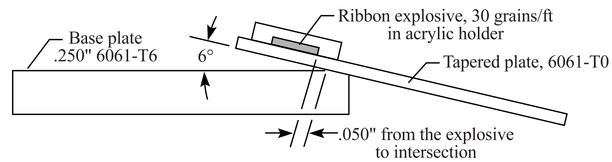

Figure 9. Test setup for determining the effect of explosive load on bonding 6061-T0.

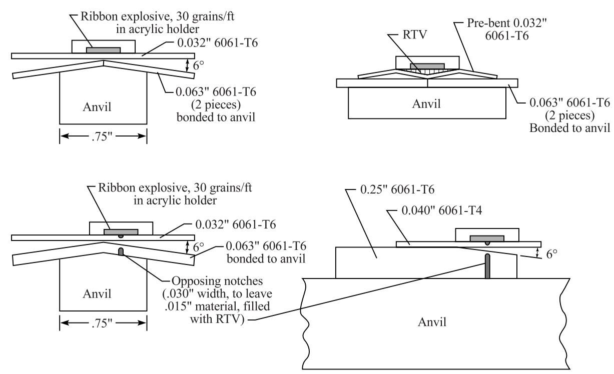

Figure 10. Test setup for explosive joining/severing experiments.

Figure 11. Test setup for multi-layer Kevlar fabric back blast containment.

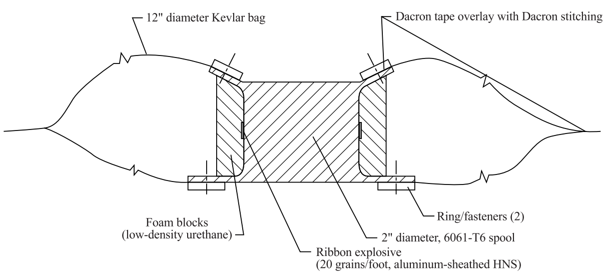

Figure 12. Cross-sectional view of Kevlar bag back blast containment approach.

Figure 13. Top view of explosively joined cylinder with 0.250-inch thick base ring.

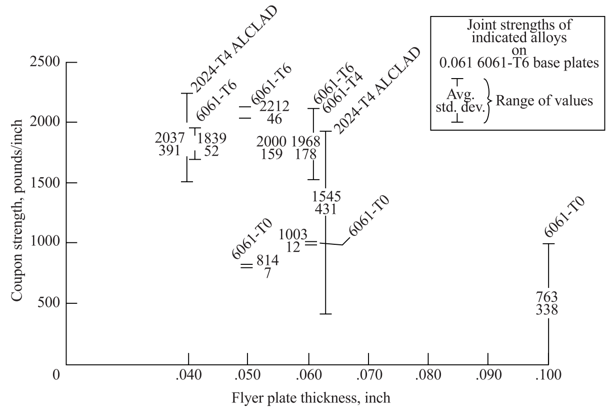

Figure 14. Results of parametric materials investigation of constant-thickness flyer plates of different alloys and conditions.

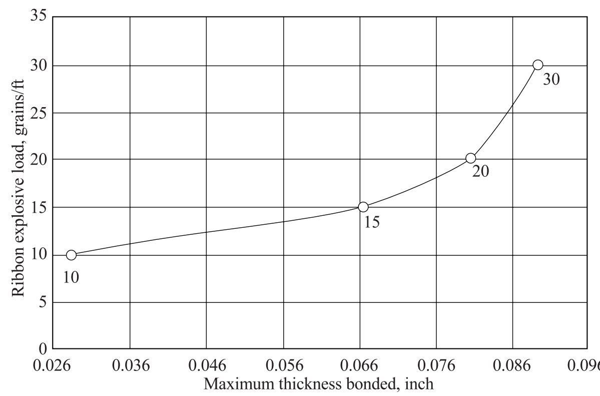

Figure 15. Results of experiments to determine maximum thickness of 6061-T0 versus explosive load.