NASA TECHNICAL MEMORANDUM

NASA TM-78933

(NASA-TM-78933) THE USE OF ION BEAM CLEANING TO OBTAIN HIGH QUALITY COLD WELDS WITH MINIMAL DEFORMATION (NASA) 13 p HC A02/MF A01 CSCL 11F

N78-27257

Unclas G3/26 25210

NASA TM-78933

THE USE OF ION BEAM CLEANING TO OBTAIN HIGH QUALITY COLD WELDS WITH MINIMAL DEFORMATION

by Bernard L. Sater and Thomas J. Moore
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at the
Tenth National Technical Conference
sponsored by the Society for the Advancement of Material and Process Engineering
New York, New York, October 17-19, 1978

THE USE OF ION BEAM CLEANING TO OBTAIN HIGH QUALITY COLD WELDS WITH MINIMAL DEFORMATION

Bernard L. Sater* and Thomas J. Moore**
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-9676

Abstract

This paper describes a variation of cold welding which utilizes an ion beam to clean mating surfaces prior to joining in a vacuum environment. High quality solid state welds were produced with minimal deformation. Due to experimental fixture limitation in applying pressure work has been limited to a few low yield strength materials.

1. INTRODUCTION

Welding processes play a critical role in modern fabrication technology. A myriad of processes are available within the broad categories of fusion welding, solid state welding and brazing. Each process has its advantages and disadvantages.

In this paper we discuss a solid state cold welding process variation which utilizes ion beam cleaning to prepare the mating surfaces. Ion beam cleaning is potentially useful and beneficial for a wide variety of materials in cold welding applications. To date, however, the work has been limited in scope to a few of the low yield strength materials, such as aluminum, copper, nickel, and silver, because of limitations in the experimental fixture for applying pressure to the weld interface. High quality cold welds in these materials were produced with minimal deformation.

2. DISCUSSION OF SOLID STATE WELDING THEORY

In theory, if two perfectly clean metal surfaces are forced into intimate contact, the metallic bond is produced across the original interface. Thus, the members are welded in the solid state. In order to produce such a weld between two similar or dissimilar metals, the atoms of one metal must be brought sufficiently close ($\lesssim 0.25$ nm) to the atoms of the other metal so that normal interatomic forces of attraction will become effective [1,2]. In reality, because metal

*Physicist, Space Propulsion and Power Division

**Materials Engineer, Materials and Structures Division

surfaces are generally covered with a film of oxides, nitrides, adsorbed gases, water vapor, organic contaminations, etc. sufficient intimacy for metal-to-metal contact can not be readily established. The effectiveness of an oxide layer to interrupt or prevent the establishment of metal-to-metal bonds has been shown to exist down to one or two monolayers of coverage [3].

When two perfectly clean metal surfaces are obtained they must not be exposed to atmospheric conditions prior to joining because a monolayer of gasses would form in less than 10^{-8} seconds [4]. However, in a vacuum environment of 10^{-6} Torr or less the time to form a monolayer of gasses on a clean metal surface requires several seconds or more. The oxygen content of the background gasses leads to the formation of surface oxides which are especially difficult to remove [4]. The tenacity with which oxide monolayers are attached to most metal surfaces make them stable even at vacuum levels well below their bulk vapor pressure. Thus, an effective cleaning method is necessary to completely remove the oxide and contamination layer in order to obtain a high quality cold weld with minimal deformation. In addition the method must incorporate a vacuum environment with sufficiently low concentrations of certain gas molecules, especially oxygen, such that recontamination will not occur before the surfaces are joined.

All conventional welding processes effectively disrupt surface films and establish the necessary intimacy of metal-to-metal contact in either of two ways:

(1) the general formation of a molten zone and subsequent wetting of the welding interfaces, or

(2) the use of severe localized shear deformation to break up and disperse the surface film while pressure is applied normal to the weld interface.

According to the American Welding Society [5], Cold Welding is a solid state welding process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation at the weld. However the Cold Welding process variation described in this paper deviates from the American Welding Society definition in that only minimal ($< 1\%$) deformation is produced for high quality welds.

Researchers have shown that for conventional cold welding of aluminum no welding was detected with less than 40% deformation. At about 70% reduction, however, the weld strength approached the strength of parent metal which had been weakened by the same amount [6]. Such large amounts of deformation may result in undesirable work hardening and reduction in structural integrity due to thinning of the metal at the weld.

It should be recognized that heat is generated during conventional cold welding because of the work involved with the large amount of plastic deformation. Thus, the weld zone is heated above room temperature. Likewise, in the cold welding process variation described herein the metal specimens were heated by the ion beam during the cleaning interval. The maximum temperature produced was about 180° C. However, by the time the weld was made, the temperature was lower but still above room temperature.

In this work an inert gas ion beam source was used to sputter clean the bonding surfaces by removing the oxides and other contaminations while in a vacuum environment. Then, the two cleaned mating surfaces were cold welded by applying only a force sufficient to crush surface asperities and to produce intimate contact at the weld interface. Nothing more is required to achieve a high quality cold weld.

3. APPARATUS AND PROCEDURE

3.1 Ion Beam Source and Sputtering Process

The ion beam source used for cleaning is based on the technology developed by NASA for ion propulsion space applications [7]. A schematic diagram of the source modified for inert gas ion beam cleaning with the metal specimens and roller system are shown in figure 1. The ion beam source and roller system are mounted in a vacuum tank with a typical background pressure in the low 10^{-6} Torr range. When the ion source is operating the pressure rises to the mid 10^{-5} Torr range. However, during typical operation the pressure near the experimental fixture may rise to the low 10^{-4} Torr range.

The ion beam source (fig. 1) operates as follows: Argon, an inert gas that is easily ionized, relatively inexpensive and readily available, is introduced into the cylindrical main discharge chamber. Here the argon atoms are bombarded by electrons and ionized as they flow through the discharge chamber. The electrons are emitted from the cathode and accelerated to anode potential with an energy of the order of 40 eV. At the discharge operating pressure the electrons must travel an average distance of one meter before encountering an ionizating collision with an argon atom. Thus a magnetic field is applied in order to increase the electron mean path and enhance the ionization process within the limited dimension of the discharge chamber. Argon ions from the discharge plasma as they approach the acceleration grids are extracted and accelerated through the large number of small holes in the grids by the electrostatic field associated with the high voltages applied to the grid elements. These ions are directed onto the surface of the material to be sputter cleaned, typically with an energy of 1000 eV and with a current density of 1 mA/cm^2.

When a 1000 eV ion beam bombards a metal surface it imparts sufficient energy to break any chemical bond between the surface and near surface atoms. Most materials can be sputtered by this process although the sputter etch rate for a given material is predominately dependent upon three parameters: (1) ion beam current density, (2) ion beam energy, and (3) ion beam incident angle. In general, the sputter etch rate is directly proportional to ion beam current density, increases somewhat with ion beam energy and incident angle up to 45 to 60 degrees [8]. Different materials, however, have different sputtering etch rates. Typical sputtering etch rates may vary from less than one atom or molecule per ion (carbon, alumina) to more than ten (silver, gallium arsenide).

Sputtering is an atom-to-atom process in that incoming ions transfer their kinetic energy through inelastic collisions with the surface atoms and molecules being bombarded thereby causing these atoms and molecules to be ejected from the surface as well as heating the surface in the process. For an ion beam of 1 mA/cm^2 current density impinging upon an aluminum target, each surface atom on the target is bombarded on the average of 4 times per second. Thus, the sputter removal rate is, in general, in the range of several atomic layers per second.

At a 1 mA/cm^2 ion beam current density most of the ion beam energy density of 1000 eV/cm^2 for our typical operating condition is absorbed in the target material with only a small percentage carried away with the sputtered atoms. Typically these sputtered atoms leave with an energy of less than 50 eV. This rather low beam power density (1 W/cm^2) results in a minimum level of heating of the material being sputtered. However, thermal dissipation in the vacuum-environment is primarily by radiation to the surrounding surfaces. Thermocouples were attached to aluminum specimens mounted for cold welding to measure the temperature rise associated with ion beam power density. At 1 W/cm^2 ion beam power density the steady state temperature for 0.127 mm aluminum foil was 180° C maximum. In practice the temperature of the materials would depend on its thermal mass, ion beam power density and cleaning time interval, emissivity of the surfaces and the thermal characteristics of the surrounding environment.

3.2 Cold Welding Roller System

As mentioned before a schematic of the roller system used to cold weld the ion beam cleaned surfaces is also shown in figure 1. A photograph of the experimental fixture actually used is shown in figure 2. Metal specimens are inserted between the two steel rollers at one end and are separated and bent outwards as indicated schematically in figure 1.

This configuration exposes both mating surfaces to a normal incident ion beam for sputter cleaning. For our experimental set up the surfaces are mounted approximately 10 cm from the ion beam source. After ion beam cleaning the exposed mating surfaces, the rollers are rotated to pull the specimens through. Rotational torque is applied manually from outside the vacuum chamber through a vacuum shaft feedthrough.

The outside diameter of each roller is 2.22 cm and they are geared to turn as indicated. The length of each roller is 4.45 cm but the upper roller is machined so that pressure is applied over a width of 3.2 mm at the center of the roller as can be seen in the inset of figure 2. The contact surfaces of each roller are smooth.

The force between the rollers is controlled by the spring compression which is approximately 670 N (150 lb) maximum for 0.25 mm separation. Typically, metal specimens are cut from 0.127 mm foil into 25 mm wide strips with a length of 12 to 15 cm for test purposes. Welding occurs down the center of the strips where the upper roller forces the specimens together.

4. RESULTS

Several low yield strength materials were successfully cold welded using the procedures and experimental fixture described. A high quality cold weld could not be pulled apart in a peel test. That is, the base metal would fail adjacent to the weld in tension. The design of the experimental fixture limited the maximum loading and thus the range of materials and alloys that could be cold welded. For example, two specimens of type 1100 aluminum foil with a thickness of 0.127 mm each could be cold welded but two specimens of type 2024-T3 aluminum alloy of 0.356 mm thickness could not. Also, the 1100 aluminum foil with a thickness of 0.127 mm was cold welded to 2024-T3 aluminum alloy with a thickness of 0.356 mm. Ion beam cleaning time is on the order of 2 to 4 minutes depending upon the materials.

The force between the rollers in the experimental fixture resulted in a calculated welding pressure of 207 MPa (30,000 psi) maximum. This calculation was based on the measurement of the imprint for two 0.127 mm thick 1100 aluminum foil specimens. This pressure was sufficient to cause local plastic flow of the surface asperities since the yield strength of this material was exceeded. In our high quality cold welds, no deformation could be measured at the cold welded joint at ×100 magnification.

Preliminary investigations were conducted to obtain a basic understanding of the interrelationships involved with ion beam cleaning and cold welding which we briefly discuss here:

(1) Heating the metal specimens in the vacuum environment by infrared radiation (without ion beam cleaning, but to temperatures similar to that which would have occurred if the ion beam were cleaning the surfaces) failed to produce any cold welding.

(2) The quality of cold weld strength was definitely a function of the ion beam current and power density and cleaning duration after some minimum cleaning level was obtained.

(3) Ion beam cleaning only one of the two mating surfaces failed to produce any cold welding.

(4) Re-exposing of ion beam cleaned surfaces to the atmosphere prior to pressure rolling failed to produce any cold welding.

(5) Ion beam cleaning with an incident angle of the order of 45 degrees with the surfaces produced cold welds with poor strength. Apparently the oxides and contamination material sputtered from one surface would deposit on the opposite surface and vice versa. Thus, a much longer cleaning time for complete removal may be required than that required for normal incident ion beam cleaning.

(6) The quality of cold weld strength slowly degrades as a function of the delay interval between ion beam cleaning termination and the pressure rolling process.

At this time preliminary results indicate that with our typical ion beam current and power density of 1 mA/cm^2 and 1 W/cm^2, respectively, approximately four minutes of cleaning duration would provide high quality cold welding with aluminum-to-aluminum materials when cleaning occurs up to the time of pressure rolling. Allowing delays of 2 minutes between the cleaning interval and pressure rolling degraded the cold welding adhesion to the point that separation of the weld interface occurred in a peel test. Also, high quality cold welding with copper-to-copper materials was observed with approximately 2 minutes of cleaning duration with our typical ion beam power density and cleaning up to the time of pressure rolling.

Cold welding experiments with dissimilar materials were also conducted. High quality cold welds were obtained with copper-to-aluminum, copper alloy-to-nickel, and silver-to-iron. The copper alloy-to-nickel cold welding was accomplished with ion beam cleaning intervals of 1 minute but with an increased ion beam current density of 2 mA/cm^2.

Previous researchers have reported that no adhesion was observed in their cold welding experiments with silver-to-iron using other cleaning processes [9]. The cold welding of silver and iron is unique because the metals are insoluable in each other and do not form an intermediate metallic phase. Since they were successfully cold welded using the ion beam cleaning process, however, this would tend to confirm the theory that adhesion energies and electronic barriers at the interface between the materials play an important role in cold welding [2].

Photomicrographs and addition discussion of ion beam cleaned cold welding results in several different material follows:

4.1 Aluminum-to-Aluminum

A photomicrograph of an aluminum-to-aluminum ion beam cleaned cold weld is shown in figure 3. This was for a 4 minute cleaning interval with our typical ion beam and 534 N (120 lb) roller force. The as welded interface is shown in the upper portion photograph and the same weld after exposure to 400° C for 2 hours in air is shown in the lower portion photograph. In high quality cold welds, no degradation of the interfacial grain boundary due to heat treatment was observed. Alternately, there was very little grain growth across the weld interface due to heat treatment. This effect gives evidence of grain boundary pinning by submicroscopic particles of aluminum oxide [1].

In poor quality welds which could be peeled apart by hand, degradation of the interfacial grain boundary due to heat treatment was observed. The interfacial grain boundary region becomes oxidized because of poor quality and intermittent welding.

4.2 Copper-to-Copper

The photomicrograph of a copper-to-copper ion beam cleaned cold weld is shown in figure 4. This weld was made after a 2 minute cleaning interval with typical ion beam settings and 670 N (150 lb) roller force. The as welded microstructure is shown in the upper photomicrograph and the same weld after exposure to 800° C for 2 hours in vacuum is shown below (fig. 4). The grain growth across the interfacial grain boundary with heat treatment is evidence that metallic bonds were achieved. It can also be noted in figure 4 that the grain size of the base metal was increased markedly by the heat treatment.

4.3 Aluminum-to-Copper

Photomicrographs of an aluminum-to-copper cold weld are shown in figure 5. For this weld an ion beam cleaning time of 4 minutes was used. The roller force was 670 N (150 lb). The upper photomicrograph shows the as welded grain boundary interface. The lower photomicrograph is the same weld after heat treatment at 500° C for 1 hour in a vacuum. The grain growth in copper is pronounced as would be expected. A brittle intermetallic Al/Cu phase also has formed at the weld inteface.

5. CONCLUDING REMARKS

The use of ion beam technology to obtain high quality cold welds with minimal deformation has been demonstrated. The ion beam is an effective tool for removing the oxide and contamination layer that normally prevent metal-to-metal contact. Photomicrographs of as welded and heat treated weld specimens demonstrated that metal-to-metal bonding has been achieved.

Although this study has been limited to low yield strength materials due to limitation of the experimental fixture, it appears reasonable that the process could be extended to other metals of higher yield strength.

5. REFERENCES

1. R. R. Tylecote, The Solid State Welding of Metals, St. Martin's Press Inc., New York (1968).
2. J. Ferrante and J. R. Smith, "Metal Intefaces: Adhesive Energies and Electronic Barriers," Solid State Commun., 20, (4) 393 (1976).
3. Adhesion on Cold Welding of Materials in Space Environments, ASTM Spec. Tech. Publ. No. 431, Philadelphia, PA (1967).
4. D. J. Santeler, et al., "Vacuum Technology and Space Simulation," NASA SP-105 (1966).
5. Welding Terms and Definitions, AWS A 3.0-76, American Welding Society, New York (1976).
6. L. R. Vaidyanath, M. G. Nicholas, and D. R. Milner, "Pressure Welding by Rolling," Brit. Weld. J. 6, (1) 13 (1959).
7. W. R. Hudson, "Nonpropulsive Applications of Ion Beams," AIAA paper No. 76-1015 (1976).
8. W. Laznovsky, "Advances in Low-Energy Ion Beam Technology," Res./Develop. 26 (8) 47 (1975).
9. T. H. Batzer and R. F. Bunshah, "Warm-Welding of Metals in Ultra High Vacuum," J. Vac. Sci. Technol. 4 (1) 19 (1967).

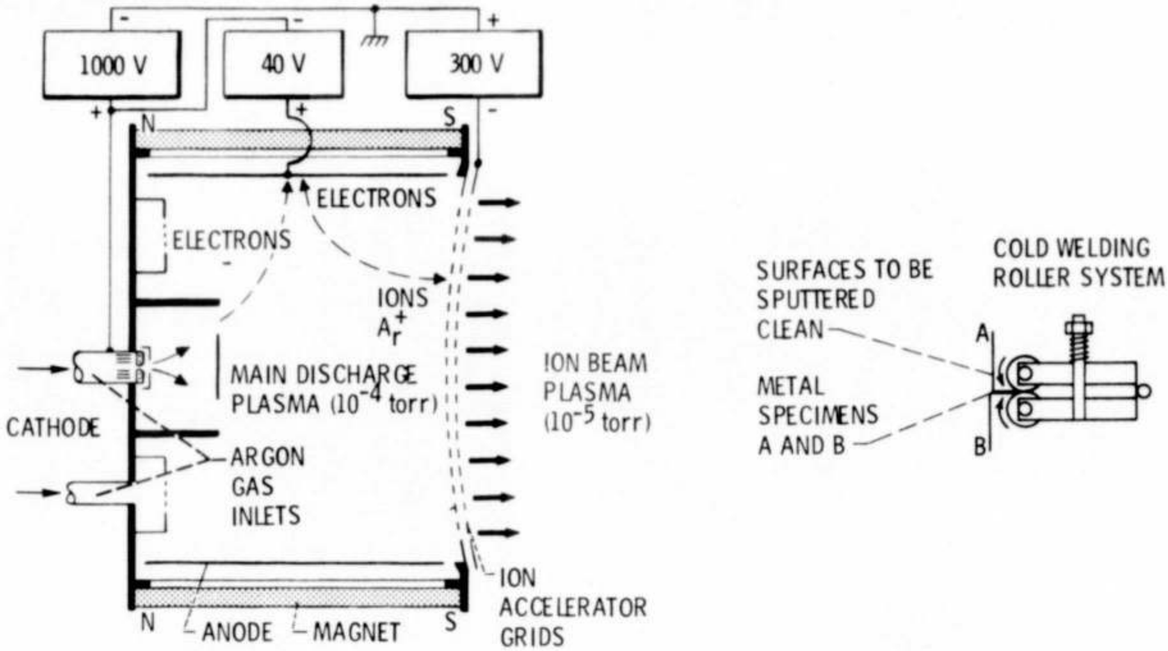


Figure 1. - Basic schematic for electron bombardment ion source and roller system.

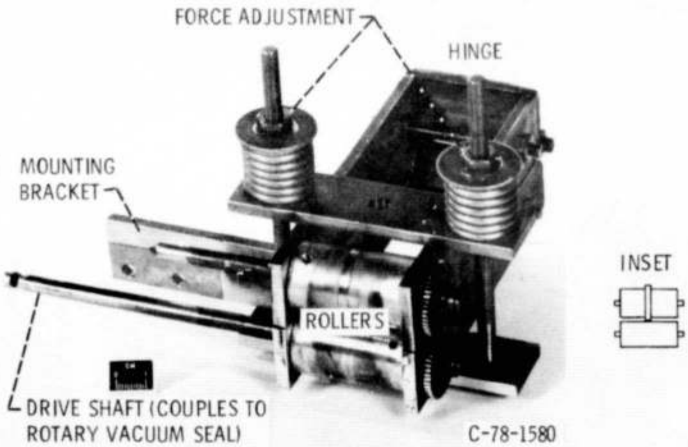
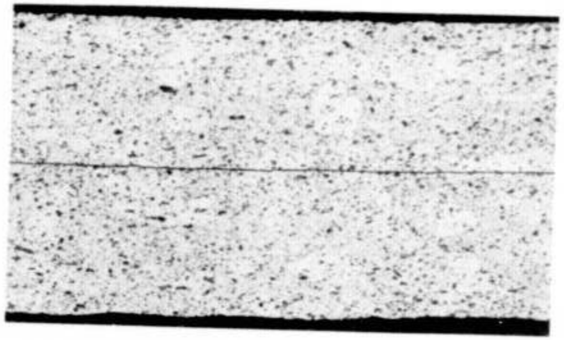
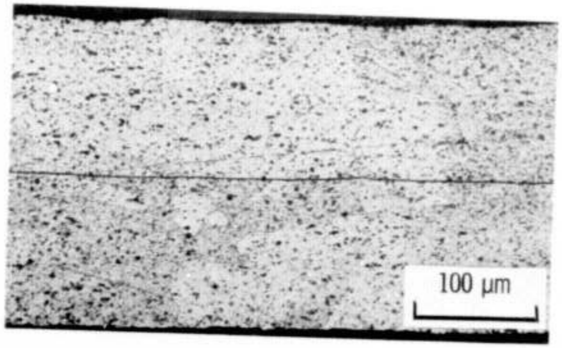


Figure 2. - Cold welding roller system fixture.

E-9676

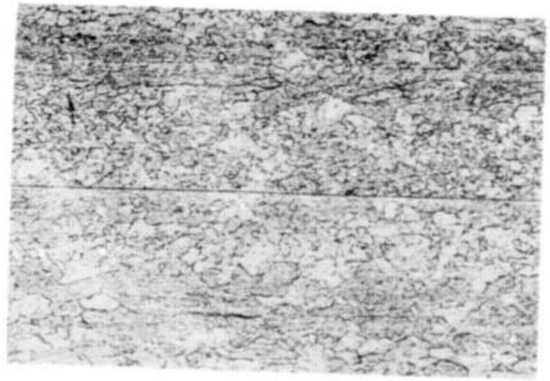


(a) AS WELDED.

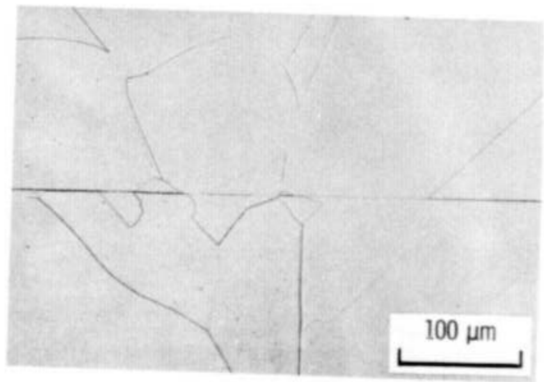


(b) HEAT TREATED AT 400^{0} C FOR 2 HOURS IN AIR.

Figure 3. - Aluminum - to - aluminum cold weld.

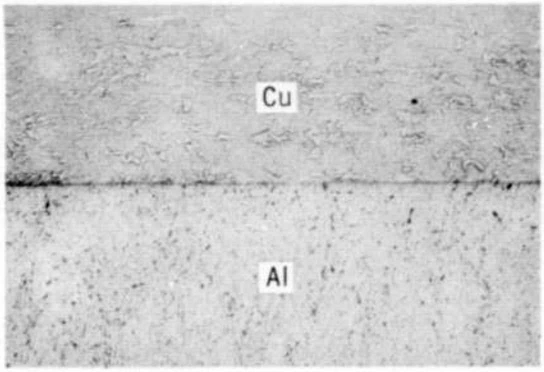


(a) AS WELDED.

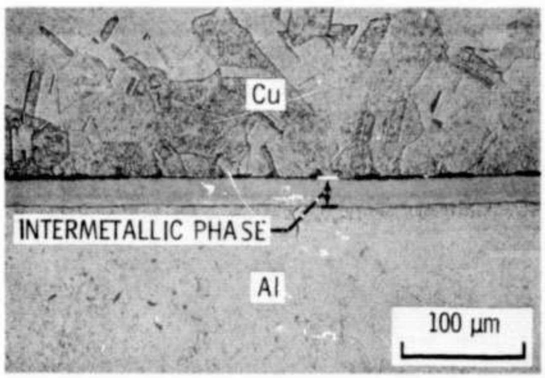


(b) HEAT TREATED AT 800^{0} C FOR 2 HOURS IN VACUUM.

Figure 4. - Copper - to - copper cold weld.



(a) AS WELDED.



(b) HEAT TREATED AT 500° C FOR 1 HOUR IN VACUUM.

Figure 5. - Copper - to - aluminum cold weld.

E-5575

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-78933		

4. Title and Subtitle	5. Report Date
THE USE OF ION BEAM CLEANING TO OBTAIN HIGH QUALITY COLD WELDS WITH MINIMAL DEFORMATION	6. Performing Organization Code
7. Author(s) Bernard L. Sater and Thomas J. Moore	8. Performing Organization Report No. E-9676
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	10. Work Unit No. 11. Contract or Grant No. 13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	Technical Memorandum 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This paper describes a variation of cold welding which utilizes an ion beam to clean mating surfaces prior to joining in a vacuum environment. High quality solid state welds were produced with minimal deformation. Due to experimental fixture limitation in applying pressure work has been limited to a few low yield strength materials.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Metallic bonding Cold welding Ion beam cleaning	Unclassified - unlimited STAR Category 26

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161