THE EFFECTS OF ALUMINUM OXIDE ON INERTIAL WELDING OF ALUMINUM IN SPACE APPLICATIONS

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Submitted to the Department of Ocean Engineering on 8 May 1992 in partial fulfillment of the requirements for the degrees of Naval Engineer and S. M. Mechanical Engineering

ABSTRACT

Inertial friction welding of 2219 aluminum alloy studs to 2219 aluminum alloy plates is investigated in air and in an argon atmosphere to determine the effects of an intact oxide layer on weld quality. Scratch-brushing of plates and studs was performed in an argon atmosphere to break up the oxide layer and prevent reformation prior to testing. Argon was used to simulate the near-oxygen free space environment. Weld quality was determined by a bend test and by measurement of the fraction of the weld surface area that was dimpled in appearance following fracture of the weld.

The fundamental theories of friction and wear that are applicable to friction welding are reviewed. A brief survey of current welding methods that may have application in space is presented, as well as a discussion of their feasibility and limitations. Characteristics of the space station are discussed as well as their consequences on welding in space.

A qualitative model of the process of inertial friction welding based on the theories of friction and observations of welds and weld fractures is developed and presented.

Thesis Supervisor: Dr. Koichi Masubuchi
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CHAPTER 1. INTRODUCTION

1.1. Applications of Friction Welding in Space

Inertial friction welding has been proposed as a technique for making welds in space because of its cleanliness, simplicity, low power requirements, lack of consumables, and amenability to the space environment compared to some other welding techniques [Guza, 1988 and Jacoby, 1991]. Although somewhat limited in application, there are many possible uses for friction welding, some of which are shown in Figure 1.4. Some other possible uses that may have application in space are:

- Welding plates together using conical studs. The plates would be machined to have a V-groove prior to joining. This weld would not produce an airtight joint, but could be used for structural purposes. A schematic of this application is shown in Figure 1.1.

![Figure 1.1. Plate Joining by Friction Welding.](image)

Figure 1.1. Plate Joining by Friction Welding.
An alternative method of joining plates is by vibro-friction, where the filler material is vibrated over the joint or in a groove to conduct the weld [Vavilov and Voinov, 1964]. A schematic of this technique is shown in Figure 1.2.

Figure 1.2. Vibro-Friction Welding of Plates.

Building up material that has been removed by wear using friction welding [Vavilov and Voinov, 1964]. The setup for this application could be similar to that depicted in Figure 1.3.

Figure 1.3. Building Up by Friction Welding.
Other welding techniques have serious drawbacks when considered for welding in space, some of which are discussed later. Inertial friction welding is not subject to many of these drawbacks. As welding techniques are being investigated for use in space, inertial friction welding should be among them.
Figure 1.4. Some Possible Joint Designs for Friction Welding.
1.2. Parameters for Friction Welding From Previous Research

Guza’s research determined that inertial friction welding is possible in a vacuum and determined parameters necessary to produce a sound weld [Guza, 1988]. The parameters developed for inertial welding a 1/4-inch aluminum alloy rod to an aluminum alloy plate are shown in Table 1.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stud Tip Geometry</td>
<td>Flat</td>
</tr>
<tr>
<td>Rotation Speed</td>
<td>19,000 rpm</td>
</tr>
<tr>
<td>Axial Force</td>
<td>125 lbf</td>
</tr>
</tbody>
</table>

Table 1.1. Friction Welding Parameters for 1/4 inch Rod to Plate.

Experiments have shown that welds made in a vacuum are slightly superior to those made in air.

Jacoby repeated some of Guza’s experiments to verify the results [Jacoby, 1991]. In both cases, experiments were limited to a vacuum lower than would be encountered in space. The limitation was not in the ability of obtaining a sufficient vacuum (approximately $10^{-7}$ torr at the altitude of the proposed space station Freedom), but in the failure of the flywheel drive motor at only moderate vacuum, probably caused by overheating. Previous experiments were limited to vacua of less than 1 torr.

A schematic of the experimental apparatus used by Guza and Jacoby is shown in Figure 1.5. Vacuum must be broken and
the bell jar raised to gain access to the apparatus for loading the plate and stud for welding. Once the stud and plate have been loaded, the bell jar is lowered over the welding apparatus and a vacuum is drawn. The flywheel motor accelerates the flywheel to the proper rotational speed. Once the desired speed has been reached, the electric power to the motor is removed, allowing the flywheel and motor rotor to coast. The pneumatic piston is then activated, forcing the plate, which is held by the moveable table of the apparatus, onto the rotating stud. Depending on the vacuum desired, the delay between loading the stud and plate into the apparatus and the time of the experiment is between 10 and 20 minutes.

![Diagram of experimental apparatus]

**Figure 1.5. Experimental Apparatus of Guza and Jacoby**

In the experiments of Guza and Jacoby, the surface of the aluminum plate was usually abraded with steel wool to break up and remove the oxide layer prior to being loaded into the apparatus. The delay between the loading of the specimen and welding allowed the oxide layer to reform before
welding could take place. In space, the oxide layer could easily be abraded and, even after a lengthy delay, the oxide layer would not reform due to the scarcity of oxygen.

Since the oxide layer is much harder than the aluminum base metal, it is reasonable to assume that the friction between aluminum oxide, present on the stud and plate, is very different than the friction between bare aluminum alloy if the oxide layer was removed. It has been shown that, generally, softer metals slid against one another have higher coefficients of friction than harder metals [Suh, 1986]. Thus, the friction between stud and plate should be higher with the oxide layer removed. How this affects the weld is the purpose of this thesis. Higher friction would greatly increase the heat input in friction welding and affect the weld. Thus, the values of parameters developed by Guza [1988] and verified by Jacoby [1991], which determine the heat input, may be too high. Removing the oxide layer may allow the decrease of the welding parameters without sacrificing weld quality.

The inertial welding parameters determined by Guza and Jacoby of 19,000 rpm and 125 lbf may be difficult to achieve in space. Such a high rotation speed may take up to 20 minutes to achieve because of the low power of motors that are available for use in a vacuum. In a hand-held friction welder, the torque developed in spinning up the flywheel would require that the astronaut be anchored against a large mass to avoid being spun out of control by the welder. The
ability to create an axial force of 125 lbf by hand would be nearly impossible in the near weightlessness of space. Lowering either the axial force or the rotational speed may lessen these problems with inertial friction welding. In space, the ability to abrade and possibly remove the oxide layer, and thereby increase the friction of the weld and the heat input, may reduce the required amount of rotational speed and axial force to conduct the friction weld.

1.3. Scope of Study of Present Thesis

The primary objective of this thesis is to determine the effect of the presence of an intact aluminum oxide layer on the inertial friction welding of aluminum in the range of parameters previously investigated. Such a determination will enable researchers to assess the validity previous work which was done with an oxide layer present. The secondary objective is to develop a qualitative model of the mechanism of friction welding based on the theories of friction and the observations of inertial friction welds. This will enable the prediction of effects of various parameters on inertial friction welding. A tertiary objective is to present a brief review of considerations and techniques of welding in space. To fulfill the above objectives, this thesis will accomplish the following:

- A review of the most promising methods of welding in space to determine their advantages and disadvantages.
• Examine the fundamental mechanisms of friction to develop a qualitative model of how friction welding is achieved, as a basis for further research.

• Review the literature of the friction welding of materials in general, and of friction welding of aluminum alloys in space or vacuum in particular.

• Determine the effects of the presence of an intact oxide layer compared to an abraded oxide layer, and the effect of the degree of abrasion.

• Explain the effects of abrasion, or lack of effects, based on the available knowledge of friction and friction welding.
CHAPTER 2. BACKGROUND

2.1. Introduction

Over the next thirty years NASA has plans for an aggressive space exploration program. By the mid-1990's a permanently manned space station will be constructed and placed in operation. A permanent moon base is scheduled to be in operation within the next ten years. Within another fifteen years there is to be a manned exploration of Mars as a prelude to a permanent base there. The Space Station Freedom is the United States' first step in the sustained occupation of space and the manned exploration of the solar system beyond our moon. It is likely that the station will be the construction point for some of the vehicles required for manned interplanetary travel.

Detailed design of the space station has been underway for some time. The space station itself is constructed in modular form, will be transported to space aboard several flights of the space shuttle and other unmanned rockets and then finally assembled in space. The design of other vehicles for some of the other missions mentioned above has been limited to the concept level. The concept design of a vehicle for a manned mission to Mars includes an aero-brake that is too large to construct on earth and then launch into space. Such large structures will have to be constructed, or at least finally assembled, in space.
At present, there are no plans to use welding in the final space assembly of the space station. The requirements of the space station design were that no welding in space would have to be performed. All of the station’s final assembly will be done by mechanical fasteners and/or locking joints.

Though ruled out for the space station final assembly, it is possible that welding equipment may find its way onboard the station. When one looks at the probable missions of the space station, welding has a distinct advantage over other types of metal joining. The present and probable future missions of the space station include:

- Conducting microgravity experiments.
- Earth observation.
- Repair and maintenance of satellites.
- Assembly and/or construction of vehicles and/or their components for missions to other planets, manned and unmanned.
- Serve as a relay station for communications between ground stations and various missions.
- Act as an outboard terminal for missions, a space-based extension of earth. As such, the station would act as a “launching platform” for some missions.
In each of these missions, welding in space, either in the space environment or within a pressurized module of the station, may play an important role.

Many experiments in microgravity will be conducted. Most of these experiments will require specialized apparatus that needs to be transported from earth. Other experiments may allow for the fabrication of the apparatus from materials derived from previously completed experiments or from stock material available on the station. Welding may greatly simplify the construction of such apparatus.

The space station will contain a large number of instruments for earth and space observation. During the thirty-year service life of the station, it is conceivable that new instruments will be brought from earth and mounted on the station. Welding may simplify and reduce the expense of the construction and transportation of any necessary mounting foundations.

Many of the satellites now being constructed and launched are designed with space-borne maintenance in mind. There are access covers and fittings that allow for the regeneration of liquid helium (used to cool instruments as it boils away) and the replacement of batteries and other components. Some of the old satellites, however, were not designed to be maintained—once a critical component failed or the liquid helium ran out, the satellite was assumed to have completed its useful life. With the space station, however, such satellites may be retrieved, serviced, and
returned to operation, extending their useful. Gaining access to components may require cutting and welding. The ability to perform a maintenance function when none was initially envisioned may save millions of dollars per satellite by not having to go through the expense of design, construction and launch of a new satellite. Even in satellites that were initially designed to be maintained, accidents may require welding technology to perform repairs.

The construction of large space structures in space might be greatly facilitated by welding in space. Mechanical fasteners add considerable weight to a structure and the joints are not inherently airtight. Some of the conceivable structures, such as the aero-brake for a Mars vehicle, are too large to be launched from earth fully assembled. It is conceivable that such a structure may be designed to be transported into space using currently available means and assembled in space using mechanical fasteners - however this would greatly add to the weight of the structure, increasing material and transportation costs. Welding in space would reduce its size and the cost of transportation.

The preclusion of welding also limits the size of hermetically sealed units to that of the largest object that can be transported aboard a shuttle or rocket. For example, the space station modules are just large enough to fit in the space shuttle cargo bay. These modules are then interconnected, but the connections are much smaller than the full diameter of the modules. Where a larger size structure
is required, welding in space may provide the only possible means of construction.

In summary, the need for welding in space exists, and may become an absolute necessity in overcoming some of the construction and repair problems that will arise in space, just as it has here on earth. Welding technology on earth, though continually improving, is fairly well established and welding parameters and techniques have been developed to cover a wide variety of situations and conditions. Work in the development of welding technologies for space has only just begun.

2.2. Space Station Attributes

A brief summary of some of the important attributes of the Space Station Freedom follows. Since detailed design of the station is underway, the missions and mode of operation of the station can be readily envisioned. As such, the space station has some important limitations that are critical in the envisioning and development of useful welding techniques.

2.2.1. Service Life

The space station has an expected service life of approximately thirty years. Three factors become important because of this: (1) growth, (2) maintenance, and (3) repair. A vehicle with a thirty year service life can be expected to undergo upgrades and modernization as well as the installation of new equipment as the missions and technology change. The thirty year service life is similar to U. S. Navy
warships. Navy ships routinely undergo overhauls and maintenance periods to keep the ships in repair and up to date. Unlike warships, however, the space station cannot be brought to a "spaceyard" for overhauls and maintenance. The entire maintenance load will have to be borne by the personnel and systems installed on the station.

It is estimated that the space station will require 2,200 hours of maintenance annually [Kuvin, 1990]. Much of the maintenance is designed to be accomplished by robotic systems, however some will require personnel, both EVA and IVA.

At some point the space station may undergo damage that requires repair. The most likely causes of damage are impact with the space shuttle during docking maneuvers, loss of control of the manipulator arm (possibly while handling some heavy component), impact with space debris, and impact with a micrometeoroid. Studies show that small micrometeoroids are energetic enough to penetrate the skin of a space station module creating a petaled hole, leading to a depressurization of the module [Levoy, 1987]. Other collisions may result in holes or tears in the habitat skin, or bent or broken truss members. Over a thirty year service life, one must assume that the space station will undergo some damage and personnel must prepare for that eventuality.

2.2.2. Limited Continuous Power

Any welding system that is envisioned for the space station must be able to work within the power constraints of
the station. In the present design, the continuous power available for the entire space station is 75 kW. The power comes from a array of four large solar panels located at the ends of the truss. Should damage occur to one or more of these panels, the available power might be considerably less. The power available would also be reduced by the critical electrical loads necessary for the survival of the station. Some of the installed instruments on the station may be very sensitive to magnetic fields caused by welding as well as the high currents and the probable power fluctuations. For normal maintenance, one would not like to have to shut down and possibly isolate the systems that might be negatively affected by welding. In the case of a critical repair, where the survival of the station is at stake, one may be willing to take some risks with some installed equipment.

2.2.3. Repair

Although redundant communications systems will exist and it is not expected that communications with earth will be lost, some of the possible damage scenarios involve a complete or partial loss of communications with earth. Also, it is not expected that personnel manning the station will be professional welders or experts in damage control and repair. Some repair techniques, especially welding, require at least a minimal amount of proficiency. Therefore astronauts, who may be tasked with making welds, should receive some training in welding.
Communications with earth could make experts in repair and welding available so that advice and a discussion of techniques could take place. Loss of communications may make repair contingent upon the resourcefulness and abilities of the astronauts. Expert advice and knowledge may be unavailable. To help alleviate this problem, the development of a computer-based expert space-welding system is currently underway at MIT under the auspices of Professor Koichi Masubuchi.

2.3. Space Environment

The environment of space is a hostile one to many of the welding techniques that have been developed on earth. Not only do the effects of wide temperature variations, microgravity and vacuum have to be considered, but also the suitability of the techniques to unwieldy spacesuits, exposure of personnel to hazardous materials or harmful emissions, a lack of available materials, and a lack of available expertise.

2.3.1. Temperature

Temperature extremes on the space station are expected to be ±250°F. These extremes will greatly affect the cooling rates of metals and affect the heat input required for welding. For fusion welding techniques, temperatures at the lower extreme may have increased cooling rates which may increase the strength of welds due to a fine micro structure, however the detrimental effects of the Heat Affected Zone
(HAZ) may be greater due to the larger heat input required for melting. Because of the high conductivity of aluminum, heat input solely from the welding apparatus may not be enough to melt the material, requiring some preheat, especially for large components [Philips, 1967]. The required power to preheat and weld may not be available on the station or may put a strain on the station power grid.

Cold welding techniques may be enhanced at the higher temperature extreme. Ductile metals are easier to cold weld because of their increased susceptibility to plastic deformation. Higher temperatures make metal more ductile. The amount of energy input required for cold welding may be less for metals exposed to the higher temperature extreme. Cold welding at the lower extreme may greatly increase the required heat input.

2.3.2. Microgravity

Gravity at the altitude of the space station is approximately ±0.01G. Experiments aboard Soyuz-6 have shown that microgravity affects gas metal arc welding to produce less pronounced weld beads and less penetration than welds produced on earth [Paton, 1972]. Consumable electrode techniques have shown that drops grow in size in microgravity [Shulym et al., 1991]. Greater effects of surface tension have been noted. Microgravity can also lead to reduced sedimentation and a reduction in buoyant effects, which can prevent bubbles from escaping the weld pool, causing porosity [Agapakis and Masubuchi, 1985].
Microgravity is beneficial in some instances. On earth gravity acts on the weld pool to pull the molten metal from the joint, causing burn through in some cases. In microgravity the molten material is held at the joint by surface tension [Shulym et al., 1991]. For this reason, greater heat input can sometimes be used in microgravity compared to earth gravity.

Microgravity appears to enhance capillary action in brazing [Siewart et al., 1977]. Though no experiments in cold welding have been conducted in microgravity, there should be little or no effect due to a lack of liquid phase in the materials.

2.3.3. Vacuum

Vacuum has a marked affect on inert gas welding techniques. Vacuum causes the inert gas to evacuate the region surrounding the weld. This evacuation greatly reduces the stability of the arc. Some attempts have been made to counter the effects of evacuation by constricting the gas through a nozzle (plasma welding) or by the use of hollow electrodes through which the gas is passed. These attempts have met with only limited success.

Vacuum may have some enhanced effect on cold welding due to a reduction in surface contaminants. Vacuum may volatilize some of the surface films. Vacuum will also inhibit oxide layer formation.

Electron beam welding is normally performed in a vacuum and therefore should not be adversely affected by the vacuum
of space. Laser beam welding is slightly enhanced by vacuum due to the reduction of scattering by particles and water vapor in air, and therefore should be slightly enhanced by the vacuum of space.

2.4. Attributes of Candidate Welding Techniques

Of the over one hundred welding techniques available on earth, only a few are compatible with the conditions present in space or on the space station. It is assumed that no one welding technique will fill all requirements and circumstances. It seems likely that several different welding techniques will have to be developed for the many different situations that might arise in space.

Candidate welding techniques for use on the space station must have the following characteristics.

**Minimum Power Requirements.** They must have low power requirements. It is preferable that the total power requirements be low, but it is permissible that only the peak power be low. A technique may have the capability of using stored energy, such as electric charge (current) in a capacitor, inertial energy in a flywheel or a force stored as hydraulic pressure. The energy in such systems may be accumulated slowly and stored until needed, allowing the energy drawn from the space station grid to be low at any one time.
**Minimum Exposure to Personnel.** They must minimize the required exposure of personnel to EVA and to harmful emissions from the welding apparatus. Minimizing EVA time could be accomplished by a technique that can be performed by a robotic system or a remotely controlled manipulator arm. Some techniques, such as electron beam welding, have the potential of exposing an astronaut to harmful emissions.

**Minimal User Skill Required.** They should be relatively simple or user-friendly so that personnel can make effective welds with a minimal amount of skill or training. Any hand-held technique should also be able to be performed with the gloved hand of a space suit.

**NDT or Good Reliability.** The welding technique should be suitable for nondestructive testing to evaluate the quality of the weld, or the technique of such high reliability that the requirement for testing is eliminated.

**Minimal Contamination.** They should not produce fumes or gases than may contaminate the outer surfaces of the space station if conducted EVA, or contaminate life support system if conducted IVA. Experience with Skylab has shown that gases
released into space tend to fog the windows and optics nearby and place a thin coating on solar panels [Disher].

**Few Consumables.** Due to the extreme high cost of transportation of materials to the space station and the lack of storage, a candidate welding technique should require a minimum of consumables. Consumables may readily be classified into two groups: (1) those that directly contribute to the weld, such as filler metal (these consumables may allow for the welding of materials with poorer fitup), and (2) those that contribute to the welding technique, but not directly to the weld, such as inert gas. Those in the first group typically end up as part of the weld, while those of the latter group end up as waste. Of the two, the former are more desirable than the latter.

**Versatility.** Though it is likely that no one welding technique will be suitable for all situations, one would not want to have a separate technique for each possible situation that may require welding. Two or three welding techniques that cover the majority of probable situations will have to be developed. One method of achieving versatility is to develop a
2.5. Possible Techniques for Welding in Space

Of the few welding techniques proposed for use in space, none are without their difficulties. Many are desirable because of their high deposition rates, while others are desirable because they can take advantage of the unique environment of space and the space station.

2.5.1. Electron Beam Welding

In the electron beam process, electrons emitted by a heated tungsten element are focused magnetically upon a workpiece [Watson, 1986]. The collision of the electrons with the workpiece causes the workpiece to heat up, resulting in a molten weld puddle. The technique can be used for welding, cutting, brazing or spray coating [Shulym et al., 1991].

Electron beam welding is normally performed in a vacuum of $10^{-4} - 10^{-6}$ torr and is therefore well suited to the vacuum of space. Microgravity actually enhances electron beam welding in some circumstances by preventing burn-through. Burn-through occurs when the weld puddle flows or is blown away from the joint by pressure or other forces such as gravity. In microgravity surface tension of the puddle holds the puddle in place until it solidifies.

For welds that are performed automatically, the beam can be tightly focused resulting in a narrow heated zone and deep
penetration. Electron beam welding can be used to weld thick sections, up to 8-in. thick, in as little as two passes [Masubuchi, 1980]. Some defocusing of the beam is necessary if the weld is to be performed manually, resulting in less penetration.

Electron beam welding has been demonstrated in space by the former Soviet Union aboard the orbital station Salyut-7 in 1984 and subsequently aboard the station Mir [Paton, 1991]. Electron beam welding in space differs little from that done on earth [Shulym et al., 1991]. Microgravity allows for a somewhat higher heat input without burn-through because the weld puddle is not pulled from between the workpieces by gravity. Because of the tightness of the beam, electron beam welding requires fairly precise fitup. Murphy et al. [1990] have shown that some machining of the joint surfaces is necessary to prevent porosity in aluminum welds. (The paper studied aluminum alloy 5083, but the same should also be true for alloys used in space applications, usually 2219.)

The only consumable used by electron beam welding is filler material, if any is used at all. Since a gas is not used, the possibility of contamination of surfaces is greatly reduced.

2.5.2. Laser Welding

Laser welding uses a tightly focused beam of, usually, monochromatic light to heat the workpiece. The technique can be used for welding, cutting and brazing. Laser welding is normally performed in air on earth, but the method is
somewhat enhanced by vacuum because of the reduction in scattering from water vapor and particles suspended in the air. Microgravity may enhance laser welding for reasons similar to electron beam welding. Use of consumables is the same for electron beam welding. The requirement for close fit-up and joint preparation should be similar to electron beam welding, also.

A tightly focused beam is required to obtain enough heat input to melt metal, therefore the technique requires automation. Though useful for the welding of many materials, laser welding of aluminum alloys is difficult because of their high reflectivity [Masubuchi et al., 1983].

2.5.3. Gas-Shielded Arc Welding

There are two major types of gas-shielded arc welding: (1) Gas Metal Arc Welding (GMAW), and (2) Gas Tungsten Arc Welding (GTAW), and two minor types: (1) Plasma Arc Welding (PAW), and (2) Stud Welding. GMAW uses a consumable electrode while GTAW and PAW do not, though filler metal may be added. In the gas-shielded arc technique, the puddle and the arc are surrounded by a protective gas. Typical gases used are argon, helium, and mixtures of argon, CO2 and O2. Usually helium or argon is used for welding aluminum. Typical power requirements are 20-250 amps and 5-15 volts.

GTAW is commonly used in industry for the joining of aluminum alloy plates and for joining titanium. Filler metal is commonly used. Even thin plates require multiple passes. GMAW is commonly used for welding materials other than
aluminum and titanium and has the advantage over GTAW of greater deposition rate. For thin plates, less than 1/10 inch, the joints may be square butt. For plates of greater thickness, the joints are machined to either V or J-groove. For either V or J-groove joints, filler metal is necessary.

Both GTAW and GMAW have been attempted in a vacuum with only moderate success. Difficulties have been encountered in initiating and sustaining the arc in vacuum. The gas used to carry the arc evacuates so rapidly that the concentration is not great enough to sustain the arc. The rapidly evacuating gas tends to draw the arc with it, greatly spreading the arc and thereby cooling it. Attempts have been made to counter this by forcing the gas to flow through a hollow tungsten electrode - thus, the gas has to flow between the electrode and the workpiece as the gas evacuates [Rivett, 1987]. Studies have shown that the arc discharges inside the electrode and melts it, often blocking it.

Microgravity also affects GMAW by allowing the formation of much larger drops because gravity is not accelerating the drops toward the workpiece, resulting in shallower penetration than in a normal gravity environment. Of the two techniques, GTAW seems more promising because of the ability to use hollow electrodes and spooled filler metal.

Keyhole PAW is currently used to weld the external fuel tank of the space shuttle, greatly reducing the number of passes required to make the weld [Cary, 1991]. PAW has been demonstrated in a partial vacuum and this technique is
currently used for spray coating. An offshoot of plasma thruster technology may be useful for welding in space. This technique is currently under investigation by NASA George C. Marshall Space Flight Center, Huntsville, Alabama.

Stud welding is commonly used in industry to weld studs to plates. This technique uses an inert gas as a shielding medium. An arc is conducted from the nib of a stud to the base plate, causing a small amount of melt on both. The stud is then pressed to the plate and the current stopped, allowing cooling and solidification of the melt. The arc and the forcing of the stud to the plate usually creates splatter that is necessary for the ejection of surface contaminants that may adversely affect the weld. Stud welding has not been investigated for space applications. Though an inert gas is commonly used, it may not be necessary in a vacuum. The arc may be started by direct contact of the nib to the plate. The arc is of such a short duration that the melting of the nib may create the medium for the arc to sustain itself before the stud and plate are forced together. The splatter ejected from the joint might cause a projectile hazard, however. Friction welding may be used as a substitution for stud welding.

All of the gas-shielded arc welding methods have a contamination hazard associated with them because of the quantities of gas required and the fumes and splatter from the arc-weld itself. The gas is the major consumable and does
not directly add to the weld. The other consumable, the filler metal, does.

2.5.4. Solid State Welding

There are two major types of solid state welding that may be applicable to welding in space: (1) flash butt welding, and (2) friction welding. Both are advantageous in that they are energy efficient, non-contaminating, and use little, if any, consumables. Solid state welding does not require the presence of a liquid state of the metal, though there may be a brief period when some surfaces become molten, as in the case of friction welding.

Flash butt welding is the forcing of two workpieces together, usually sheets or thin plates, following a high heat input to soften the metal so that it will deform plastically. High forces are required to expel contaminants from between the two joining surfaces. Friction welding uses the relative rotation of two workpieces to create friction that heats the interface. The two workpieces are forced together, making a weld. The two methods differ in that flash butt welding requires an external source of heat and usually very high forces, and is performed on sheets or plates. In friction welding, usually at least one of the workpieces is circular. No external heat source is required, only a mechanism to rotate one workpiece relative to the other. Friction welding can be used as a substitute for stud welding.
Vacuum appears to have little effect on flash butt welding of aluminum alloys [Kuchuk-Yatsenko et al., 1991] and may enhance friction welding of aluminum alloys [Guza, 1988 and Jacoby, 1991]. Though not yet investigated, it is presumed that microgravity has little or no effect on either flash butt welding or friction welding.

2.5.5. Brazing

Brazing is a well established technology on earth and is typically used for tubular welds or pipe fittings. The technique has been demonstrated in space aboard Skylab. Vacuum enhances brazing by removing gases from the joint as the braze material flows between the workpieces. Microgravity enhances brazing because capillary action does not have to overcome gravity to fill a joint. Brazing is relatively efficient due to the low melting temperatures of the braze material and produces little contamination. A disadvantage of brazing is its relative weak strength compared to welded joints [Revitt, 1987].

2.5.6. Resistance Welding

Resistance welding is widely used in industry for fabrication of objects made of sheet metal that have lap joints, such as automobile bodies. Resistance welding is easily automated and does not require precise fitup. It does require fairly high currents and a moderate external pressure on the sheets to ensure good sheet-to-sheet contact. Resistance welds are typically spot welds and the joints
formed are not usually airtight. Resistance welding is probably little affected by either vacuum or microgravity.

The current required to make the weld is proportional to the electrical conductivity of the material being welded. Aluminum, being highly conductive, requires high current. On the space station, with its limited power supply, some method of storing energy would probably be required for resistance welding. Some sort of capacitor discharge could be used, but the discharge might damage sensitive nearby equipment.

2.6. Summary of Welding Techniques

Table 2.1 shows the issues concerning the possible techniques for welding in space.
<table>
<thead>
<tr>
<th>Issue</th>
<th>Brazing</th>
<th>Resistance welding</th>
<th>Laser welding</th>
<th>Electron beam welding</th>
<th>GTAW</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROCESS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IVA</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>EVA</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Quality</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Low</td>
<td>Medium</td>
<td>Very low</td>
<td>Very high</td>
<td>High</td>
</tr>
<tr>
<td>Versatility</td>
<td>Limited</td>
<td>Medium</td>
<td>Moderate</td>
<td>Limited to EVA</td>
<td>Very high</td>
</tr>
<tr>
<td>Automation</td>
<td>Possible</td>
<td>Limited</td>
<td>Generally</td>
<td>Generally</td>
<td>Possible</td>
</tr>
<tr>
<td>Radiation (penetrating)</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Personnel shielding for X-ray</td>
<td>None</td>
</tr>
<tr>
<td>Radiation (optical)</td>
<td>None</td>
<td>None</td>
<td>Eye protection req'd</td>
<td>No</td>
<td>Eye protection req'd</td>
</tr>
<tr>
<td>Inspectability</td>
<td>Poor</td>
<td>Poor</td>
<td>Component dependent</td>
<td>Component dependent</td>
<td>Component dependent</td>
</tr>
<tr>
<td>Other advantages</td>
<td>Demonstrated on orbit</td>
<td></td>
<td></td>
<td>Fit-up tolerant</td>
<td>Process control possible</td>
</tr>
<tr>
<td>Other disadvantages</td>
<td>Two-side access req'd</td>
<td>Manipulation Limited Fit-up constraints</td>
<td>Vacuum req'd</td>
<td>Magnetic deflection</td>
<td>Inert gas required</td>
</tr>
</tbody>
</table>

Table 2.1. Welding Techniques and Issues [from Watson and Dickinson, 1988].
2.7. Welding Applications

There are many applications for welding in space, both IVA and EVA. Some of the more important are:

**Repair of Tubing.** Fluid lines are vital to the life support systems aboard the space station. During the thirty-year service life of the space station, it is possible that a fluid line will have to be replaced, either due to damage or due to corrosion. Orbital tube welders have been designed for use in space, though none have yet been tested by performing actual welds [Anderson, 1991]. One problem with tube welding in space is that the pressure both inside and outside of the tube must be the same or the weld puddle will be blown away from the joint.

**Repair of Skin of Habitat.** The skin of the habitat may be punctured by a micrometeoriod, the space shuttle during docking maneuvers, or an out-of-control robotic arm. Any puncture would have to be repaired to ensure the survival of the space station and her crew. Such repairs may take the form of patches that cover the hole or tear that are welded or bolted in place. If a habitat was de-pressurized, the repair would probably have to be conducted from the outside of the habitat. Current generation space suits
emit gases and do not tolerate gas buildup that might occur if the weld took place in an enclosed space, such as the inside of a depressurized module.

**Repair of Truss Structure.** The truss is the main structural member of the space station. Repair of the truss may include orbital tube welding or some other technique. If the truss was damaged, some cutting may have to be performed, and methods would have to be developed that would perform a clean cut without loss of cutting debris.

**Construction of Space Vehicles or Their Parts.** For missions to other planets, vehicles may be so large that they will necessarily be constructed in space. The space station then becomes the construction, outfitting and launching point for the mission. Depending on the ease of space construction, it may be cost effective to transport materials to space for construction or assembly rather than to construct items on earth and then launch them into orbit or beyond. One of the structures that is envisioned for a mission to Mars is a large aero-brake. With present technology, such a
structure could not be assembled on earth and launched into space.

**Repair of Satellites.** One of the missions of the space station will be the repair and maintenance of satellites. Such repair and maintenance may require welding. Repair of a satellite could save millions of dollars over the development, construction and launch of a new satellite.

**Addition Of Equipment To Satellites and Space Station.** Additional equipment would likely require new foundations for mounting. Because of the stresses that a foundation is expected to withstand, foundations are usually welded.
CHAPTER 3. THEORETICAL CONSIDERATIONS OF FRICTION

The following discussion covers the theory of friction of metals relevant to friction welding. An understanding of the theory of friction is necessary for an understanding of friction welding and the effects of vacuum and contaminant layers.

3.1. Brief History of Friction Theories

Three theories have been proposed for the phenomenon of friction: (1) the Roughness Theory, (2) the Adhesion Theory and (3) the Delamination Theory. (The term “delamination theory” is used by the author of this thesis; the friction model explained by Suh and Sin [1981] and other references was simply called “a more realistic model of friction”).

Roughness Theory proposes that friction is due to the interlocking of mechanical protuberances [Rabinowicz, 1965]. The belief in this theory was held by most scientists and engineers until the 1920’s. Around 1920 the adhesion theory was developed, proposing that adjoining surfaces bond, or adhere, thus creating friction. A major problem with this theory was that the frictional force created by adhesion should be proportional to the area of contact, something not borne out in experimental results. Bowden and Tabor [1942] determined that the real area of contact is considerably smaller than the apparent area of contact, and that the real
area of contact is proportional to the load. This discovery solved the major problem with adhesion theory. Delamination theory was proposed in the late 1970’s and 1980’s. This theory states that plowing by wear particles is the predominant mechanism of wear (and friction), though plowing by asperities and adhesion may be important in certain circumstances.

The three theories are not mutually exclusive, but components of each are applicable in different situations relevant to friction welding.

3.2. Adhesion Theory

Proponents of the roughness theory believed that a smooth surface was a frictionless surface. Experiments have shown that very smooth (atomically smooth) surfaces can have very high values of friction coefficients because the real area of contact approaches the apparent area. In adhesion theory, the adhesive forces between adjoining asperities (high points on a surface) cause the friction.

3.2.1. Area of Contact

When two surfaces come in contact, one material being harder than the other, high stresses are developed at the points of contact. If we assume (1) the two surfaces have a similar roughness, (2) the asperities deform elastically, and (3) Poisson’s ratio for both materials is 0.3, then the asperities of both materials have a radius of curvature $r$,
and the area of contact of the two asperities, $A_r$, is given by Hertz’s equation:

$$A_r = 2.9 \left[ L \left( \frac{1}{E_1} + \frac{1}{E_2} \right) \right]^{\frac{2}{3}}$$

(3.1)

where $L$ is the load, $E_1$ and $E_2$ are the moduli of elasticity for the two materials [Tabor, 1951]. If the stresses exceed the penetration hardness of the material, the area of contact is given by:

$$A_r = \frac{L}{p}$$

(3.2)

where $p$ is the penetration hardness of the softer material [Rabinowicz, 1965].

Surfaces with a few high points will have a very low real area to apparent area of contact ratio, while very smooth surfaces will have a high ratio.

### 3.2.2. Friction Coefficient

As the asperities of the two materials adhere together, the asperity of the softer material begins to shear when the shear stress in the asperity reaches its shear strength. Then the friction coefficient $f$ is given by:

$$f = \frac{s}{p}$$

(3.3)

where $s$ is the resistance to plastic flow in shear of the softer material. As the asperity of the softer material shears, a particle is formed of the softer material. Usually the particle adheres to the harder material.
For a rough surface, there is a roughness contribution to the friction coefficient. A hard asperity of a rough surface may plow into the surface of the softer material. In this case, an idealized asperity may be thought of as a cone as shown in Figure 3.1.

\[
\Delta L
\]
\[\theta \]
\[\Delta F \]
\[2r \]

Figure 3.1. Schematic Diagram of a Cone-Shaped Asperity [after Rabinowicz, 1965].

The groove swept out by the asperity is \(r^2 \tan \theta\). The frictional force, \(F\), is then:

\[
F = \pi r^2 s + r^2 \tan \theta \cdot p
\]

and the normal force, \(L\), is:

\[
L = \pi r^2 p
\]

and the friction coefficient, \(f\), is then (both adhesion and plowing):

\[
f = \frac{s}{p} + \frac{\tan \theta}{\pi}
\]

In adhesion theory, the plowing term is large when \(\tan \theta\) is 0.2 or larger. For ordinary surfaces, \(\tan \theta\) is approximately 0.05 or less [Avient et al, 1960].
3.2.3. Energy of Adhesion

The surface energy of a material, $\gamma$, is a function of the bonds of the material at and near the surface. Experiments have shown that the penetration hardness of a metal is related to the surface energy:

$$\gamma \propto p^{\frac{1}{3}}$$  \hspace{1cm} (3.7)

For a deforming solid, the work required to extend or increase its surface area is a function of the surface energy. For a simple tensile test, the work required to elongate the specimen’s surface, $E_s$, is [Rabinowicz, 1965]:

$$E_s = \gamma \left[ 2\pi r \left( 1 - \frac{x}{2l} \right) (1 - x) - 2\pi r l \right]$$  \hspace{1cm} (3.8)

$$\equiv \pi r x \gamma$$

The surface energy of a material is closely related to the notion of compatibility of a pair of materials. Compatibility is a measure of the mutual solubility of the materials or the ability to form intermetallic compounds which may lead to high energies of adhesion and high friction. The energy of adhesion of two materials is related to the surface energies of the materials by:

$$W_{ab} = \gamma_a + \gamma_b - \gamma_{ab}$$  \hspace{1cm} (3.9)

where $\gamma_{ab}$ is the interfacial surface energy of the two materials. $\gamma_{ab}$ is, then, a measure of compatibility. For most materials, the energy of adhesion becomes:
\[ a \text{ and } b \text{ identical } \quad W_{ab} = 2\gamma_a \]
\[ a \text{ and } b \text{ compatible } \quad W_{ab} = \frac{3}{4}(\gamma_a + \gamma_b) \quad (3.10) \]
\[ a \text{ and } b \text{ incompatible } \quad W_{ab} = \frac{1}{2}(\gamma_a + \gamma_b) \]

High values of \( W_{ab} \) indicate high friction. A matrix of the compatibility of several pairs of materials is shown in Figure 3.2.

Rabinowicz's compatibility chart for various metal combinations derived from binary diagrams of the respective elements in terms of preferred antifriction surfaces: 
- \( \bullet \): Two liquid phases, solid solution less than 0.1% solubility (lowest adhesion); 
- \( \circ \): Two liquid phases, solid solution greater than 0.1%, or one liquid phase, solid solution less than 0.1% solubility (next lowest adhesion); 
- \( \ast \): One liquid phase, solid solution between 0.1 and 1% solubility (higher adhesion); 
- \( \ast \circ \): One liquid phase, solid solution over 1% higher adhesion. Blank boxes indicate insufficient information.

Figure 3.2. Compatibility of Metals [from Rabinowicz, 1971].

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3.2.4. Surface Contaminants

Metal surfaces normally are covered by a variety of films or layers of contaminants such as an oxide layer, an adsorbed layer (usually water vapor and oxygen), and a greasy or oily film. The outer layer of the metal itself may be work hardened. A schematic of these layers is shown in Figure 3.3.

![Figure 3.3. Surface Films On a Metal (not to scale) [from Rabinowicz, 1965].](image)

Surface contaminants can have a marked effect on the surface energy and thus greatly effect the friction of the surface. Generally, any contaminant reduces the friction, acting as a lubricant. In most instances involving friction of metals without the presence of intentional lubrication, the contaminating layers tend to wear off, at least partially. Metal surfaces generally have initial friction coefficients of 0.1 to 0.3 when slid together. As the contaminants wear off, the coefficient of friction rises. In some cases, notably when two like or similar metals are slid against each other, the friction coefficient may become quite high (around 0.9 to 2.0). In other cases, such as dissimilar
metals or like metals with contaminating films, the coefficient of friction is usually lower (0.3 to 0.7).

In some environments it is possible to determine the friction coefficient for metals with surfaces free of contaminating films. Such surfaces are usually obtained in a vacuum (better than $10^{-7}$ torr) with the surface being machined or the surface layers chemically removed. The coefficient of friction under these circumstances can be very high, with values of 5 to 200 being common (moderate sliding speeds) [Rabinowicz, 1965]. Softer metals show more severe friction behavior under these circumstances than do harder metals. An examination of the metal surfaces following such severe friction show a very high real to apparent area of contact ratio.

3.2.5. Temperature

Nearly all the energy expended in friction is dissipated as heat generated at the interface and the surrounding shearing material. The actual area of contact as two surfaces slide past one another is much smaller than the apparent area, and the temperature at the actual points of contact may be higher than that of surrounding material. The temperature at the junctions is called the “flash temperature”. The points of contact adhere, shear and fracture, and new junctions are created, so the locations of the junctions change their position [Rabinowicz, 1965]. The temperature rise at the junctions can be calculated for some simple geometries. For example, if one assumes a circular junction...
of radius $2r$ and moderate sliding velocity, the steady-state temperature rise due to friction is:

$$\theta_m = \frac{fLv}{4Jr(k_1 + k_2)} \quad (3.11)$$

where $J$ is the mechanical equivalent of heat and $k_1$ and $k_2$ are the thermal conductivities of the materials. As shown above, the force $L$ can be determined by the plastic deformation of the softer material, and the expression for temperature becomes:

$$\theta_m = \frac{9400f \nu}{J(k_1 + k_2)} \quad (3.12)$$

At high sliding velocities the temperature is:

$$\theta = \frac{fL\nu}{3.6J\left(\rho_1 \cdot c_1 \cdot r^3k_1\right)^{1/2}} \quad (3.13)$$

where $\rho_1c_1$ is the volumetric specific heat of the smaller slider on the larger surface.

The temperature greatly affects the shear strength and the penetration hardness of a material, and thus affects the coefficient of friction. Generally, as the temperature of a material undergoing friction increases, the material softens. As a material’s temperature increases from room temperature to more elevated temperatures, the friction coefficient increases until the material reaches a “tacky” state. Further increase in temperature reduces the friction as the material at the junctions may actually melt. The material at the tacky state, able to undergo considerable shearing, further
accelerates the increase in temperature, so the tacky state is unstable.

### 3.2.6. Adhesive Wear

In the adhesion theory of friction, adhesive wear is the most common form of wear, but the wear particles formed do not account for a large portion of the friction between two sliding surfaces. Of the proponents of adhesion theory, some feel that wear particles occur very infrequently as a junction is broken, say 0.01% to 5% of the time [Rabinowicz, 1965], while other believe that a junction rarely breaks along its original interface, thus almost always creating a wear particle [Bikerman, 1962]. In adhesive theory, though the wear particles are not considered of major importance to the friction, they are of major importance to the wear of the materials.

A wear particle will be formed if the adhesive force at a junction interface is greater than the force required to break the softer material at some other nearby plane, such as along a grain boundary. Wear particles have been measured microscopically and range from 10 to 500 μ, with a typical lengths between 10 μ and 100 μ [Rabinowicz, 1953]. These wear particles may tend to adhere to the opposite surface from which they came, resulting in a transfer of material from one surface to another. In some cases the material may not adhere to either surface and eventually be removed from between the two surfaces. The average wear particle diameter d for loose particle formation is approximately:
\[ d = 60,000 \frac{W_{ab}}{p} \]  

(3.14)

and for tightly held particles (particles adhered to one surface), the diameter is:

\[ d = 24,000 \frac{\gamma_a}{p} \]  

(3.15)

Wear particles for clean uncontaminated surfaces tend to be larger than for unclean surfaces. The cleanliness of a surface, as explained above, is often a function of the distance slid, thus the diameter of wear particles tends to increase with distance slid (or with time).

For moderate sliding speeds, wear coefficients \( k \) have been empirically determined and have application in the form:

\[ V = \frac{kLx}{3p} \]  

(3.16)

where \( V \) is the volume of material removed or transferred and \( x \) is the sliding distance. Values for \( k \) are generally on the order of \( 10^{-3} \).

3.3. Delamination Theory

In contrast to adhesion theory, delamination theory states that the friction caused by the plowing by particles is more important than adhesion or the plowing by hard asperities, though each of these processes is important under certain circumstances [Suh, 1986]. Friction in this model is comprised of three components, friction due to asperity deformation \( f_d \), friction due to adhesion \( f_a \), and friction due
to plowing of asperities and/or wear particles $f_p$. The coefficient of friction is then:

$$ f = f_d + f_a + f_p \quad (3.17) $$

For two surfaces in contact and initially at rest, as relative motion takes place between the two, the causes of friction undergoes a change based on the distance slid. Such relation is termed the “genesis of friction” [Suh and Sin, 1981].

### 3.3.1. Genesis of Friction

The six stages of friction as a function of distance slid are shown in Figure 3.4.

![Figure 3.4. Schematic of the Six Stages of Friction](from Suh and Sin, 1981).

---

**Stage I.** The early stage of friction is due largely to the plowing of surface asperities. Adhesion is relatively insignificant because of the contaminated nature of the surface.
Stage II. The friction increases due to an increase in adhesion. For lubricated surfaces, stage I may persist and stage II may be absent.

Stage III. The steep increase in the slope of the friction coefficient is due to a rapid increase in the size of wear particles which results in higher wear rates. Some of these wear particles are trapped between the surfaces and the increase in friction is due to plowing. The friction is greatest for surfaces of near equal hardness because the particles will penetrate into both surfaces and cause plowing in both surfaces. An increase in the amount of clean surface area also increases the friction due to adhesion. There is some plowing by asperities.

Stage IV. The coefficient of friction reaches a constant at the number of wear particles trapped between the surfaces reaches a constant. The friction due to adhesion also reaches a constant. There is some plowing by asperities.

Stage V. Stages V and VI generally occur only when one of the materials is harder than the other. In this stage, the asperities of the harder surface are gradually worn down. Plowing by wear particles decreases because the particles cannot anchor into the hard polished surface.

Stage VI. This stage is reached when the hard surface is polished to its maximum extent and acquires a mirror finish. The surface still contains some “potholes” which become anchor points for more wear particles caused by delamination, which results in some friction.
3.3.2. Components of Friction

There are three components to the coefficient of friction, that due to asperity deformation, to adhesion, and to plowing. Some models have been developed for each.

3.3.2.1. Asperity Deformation Component of Coefficient of Friction

Figure 3.5 shows two asperities interacting. This was modeled using a geometrically compatible slip-line field as shown in Figure 3.6. Analysis of this model shows that the coefficient of friction due to asperity deformation is dependent on the angle of the asperity $\theta'$. The results of the analysis are shown in Figure 3.7. As can be seen, the coefficient of friction varies from about 0.4 to about 1.0 for asperity angles of 0 to 45°. This component of friction is a major contributor to the static coefficient of friction.

Figure 3.5. Two Interacting Surface Asperities [from Suh and Sin, 1981].
Figure 3.6. Asperities Modeled by Geometrically Compatible Slip-line Field [from Suh and Sin, 1981].

Figure 3.7. Slip-line Field Solution For Friction Due To Asperities [from Suh and Sin, 1981].
3.3.2.2. Adhesion Component of Coefficient of Friction

The adhesion force is due to the welding together of two adjoining surfaces, or the force generated when atoms of two surfaces are brought close enough for interatomic action without welding. This component of friction is negligible at the onset of sliding, likely due to the presence of surface contaminants [Suh, 1986]. A slip-line field model was used to analyze the adhesive component of friction as shown in Figure 3.8.

![Figure 3.8. Slip-line Field For Adhesion Component](from Suh and Sin, 1981).

From the model, Challen and Oxley [1979] derived the following for the adhesion component of the coefficient of friction:

$$ f_a = \frac{A \sin \alpha + \cos(\cos^{-1} \mu - \alpha)}{A \cos \alpha + \sin(\cos^{-1} \mu - \alpha)} $$  

(3.18)

where \( A = 1 + \frac{\pi}{2} + \cos^{-1} \mu - 2\alpha - 2\sin^{-1}\frac{\sin \alpha}{\sqrt{1-\mu}}, \mu \) is the strength of the adhesion of the softer material and \( \alpha \) is the
slope of the harder asperity. As $\mu$ varies from 0 to 1, $f_a$ varies from about 0 to 0.4.

3.3.2.3. Flowing Component of the Coefficient of Friction

This component arises due to the penetration of one or both surfaces by a hard asperity or by a wear particle. These asperities or particles gouge a groove in the surfaces. Figure 3.9 shows an idealized model of a wear particle penetrating one or both adjoining surfaces.

Figure 3.9. Surface - Wear Particle Interaction
[from Suh and Sin, 1981].

Sin et al. [1979] found the solution for this model of the plowing component of the coefficient of friction:

- 64 -
According to this model the plowing component of the coefficient of friction varies from 0 to 1.

Plowing not only increases friction, but increases delamination wear and creates more wear particles, which increases the friction, delamination wear, and creates yet more wear particles.

3.3.3. Wear in Delamination Theory

The delamination theory of wear describes the events that could lead to the formation of wear particles and loose wear sheets [Suh, 1986]. The events occur sequentially or independently if preexisting subsurface cracks are present. The events are [from Suh, 1986]:

1. Normal and tangential loads are transmitted to a surface by the contact points as two surfaces come together. Asperities of the softer material are easily deformed and fractured, causing wear particles. Asperities of the harder surface are removed, also, but at a slower rate.

2. The surface traction caused by hard asperities causes plastic deformation of the softer surface. This traction is applied repeatedly as hard asperities move over a point on the surface, causing an incremental plastic
deformation per cycle that accumulates with repeated loading.

3. As the cyclic loading continues, subsurface cracks nucleate below the surface.

4. Once cracks exist, either from cyclic loading or from the presence of preexisting cracks, continued loading causes the cracks to propagate, eventually to join nearby cracks.

5. The cracks finally shear to the surface, creating long thin wear sheets.

3.3.4. Validity of Delamination Model

Experiments were conducted by Suh [1986] in which a copper pin was slid on two different copper places - one plate was flat and the other modulated as shown in Figure 3.10.

![Figure 3.10. Micrographs of Copper Plates [from Suh, 1986].](image)
The theory behind the modulated plate is that once a wear particle forms, it falls into one of the low spots on the modulated plates before it has a chance to increase the friction due to plowing. On the flat plate, the wear particles have no where to go and hence get anchored into one or both surfaces, causing plowing. The results of these experiments are shown in Figure 3.11.

![Figure 3.11. Coefficient of Friction vs. Sliding Distance [from Suh, 1986].](image)

Though not conducted using an aluminum pin on an aluminum plate, the like metals of the copper experiment are as compatible as aluminum would be and the trend should be the same.
CHAPTER 4. THEORETICAL CONSIDERATIONS OF
FRICION WELDING

4.1. General Description of Friction Welding

Friction welding is a type of pressure welding in which workpieces are plastically deformed such that they are joined together without general melting of the material. Heat is introduced into the process to increase the plastic deformation by friction between the workpieces. In pressure welding, workpieces are forced together without the addition of heat, usually requiring much larger forces to cause the required plastic deformation to form a quality joint. Figure 4.1 shows possible variations of the friction welding process for the butt welding of rods.

Figure 4.1. Principle Variations of Friction Welding [from Vill', 1962].

Since the pieces to be welded cause the heat, friction welding introduces heat only where the heat is necessary, in contrast to most other types of welding.
4.2. Factors Affecting Friction Welding

Much of the early theoretical work in the area of friction welding was done by Vill' in the Soviet Union. Much of the following material comes from Vill' [1962].

Of the many factors affecting sliding friction in general, those of importance to friction welding are:

1. The relative speed of motion of the friction surfaces.
2. The temperature of the friction surfaces.
3. The nature of the material and presence of surface films.
4. The magnitude of the normal pressure force.
5. The rigidity and elasticity of the friction surfaces.

It is possible, in the preparation of workpieces or in the actual friction welding process, to directly alter the first four factors in the above list, and by altering the first four, it is possible to influence the fifth.

4.3. The Effects of Temperature and Relative Speed of Surfaces

The energy utilized in overcoming the friction forces during the friction welding process is at first transformed into heat at the surface of the workpieces, at the points of contact. The temperature at these points may be quite high
and of short duration. The temperatures at these points may drop very quickly due to dissipation of heat to the surrounding material. During the initial period of the welding process, the average temperature of the workpieces will increase.

Generally, mechanical properties of a material are temperature dependent. The mechanical strength of a material is usually a negative function of the temperature. The mechanical properties of the workpieces are then dependent on the temperature and also upon the gradient of the temperature. A positive temperature gradient, where the temperature increases toward the surface of the material, should lead to surface failure. A negative gradient should lead to a subsurface failure and may be important in the phenomena of seizure.

Early theoretical work assumed that the coefficient of friction $f$ remained nearly constant throughout the friction welding process. The early investigators knew that this was an over simplification and experiments have shown that the following equations, based on this simplification, are not useful in practice; however the results of their work is valid to a first approximation and gives some insight into the theory of friction welding. Assuming a constant $f$, the heat liberated during friction welding follows a parabolic distribution as shown in Figure 4.2.
Again, to a first approximation, the moment of forces $M$ acting on the entire friction surface is:

$$M = \frac{2}{3} \pi pfR^3$$  \hspace{1cm} (4.1)

The corresponding power $N$ is:

$$N = \frac{2}{3} \pi pfnR^3$$  \hspace{1cm} (4.2)

where $p$ is the unit pressure and $n$ is the relative rotative speed. Then, the moment and the heat liberated (corresponding to the power) is proportional to both the relative rotative speed and the unit pressure.

Experiments conducted by Vill' show that the moment during friction welding follows a typical pattern as shown in Figure 4.3. (It should be noted that the experiments done by
Vill' used a direct drive rather than an inertial welding method.

![Diagram of M and n Curves](image)

Figure 4.3. Typical Moment $M$ and Speed $n$ Curves for Friction Welding [from Vill', 1962].

The initial peak in moment is due to the increased static friction relative to kinematic friction. As the oxide and other contaminating films are breached, the exposed metal surfaces seize (adhere). The seizing surfaces are deformed and are broken apart. As more metal becomes exposed due to the deformation of the surface, the seizures and the breaking of bonds becomes more frequent, resulting in a temperature rise. The decrease from the peak moment shown in Figure 4.3, occurring simultaneously with a temperature increase, can occur for two reasons:

1. A reduction in the metal strength, requiring less power to destroy the seizure connection;

2. An appearance of liquid metal on the friction surfaces acting as a lubricant (computed temperatures of surfaces of low carbon steel by
Vill' [1962] show the temperature can reach the melting point; aluminum, with its lower melting point, should also be reached).

Away from the interface, the isothermal lines become more linear in the rod (perpendicular to the rod axis) and more hemispherical in the plate or bulk material (neglecting boundary effects). If the bar is assumed to be of infinite length and heat transfer to the surrounding atmosphere is neglected, the heat input can be assumed to be from a heat source of constant power, uniformly distributed over the faying surface. In this case, the temperature distribution $T$ in the rod, away from the faying surface, can be expressed as [from Vavilov and Voinov, 1964]:

$$T(x, t) = \frac{q_2 \sqrt{t}}{\sqrt{\pi \lambda c \gamma}} \text{erfc} \frac{x}{2\sqrt{at}}$$  \hspace{1cm} (4.3)

where $q_2$ is the specific thermal power of the heat source, $\lambda$ is the coefficient of thermal conductivity, $c\gamma$ is the volumetric heat capacity, $a$ is the coefficient of thermal diffusivity, $t$ is the time, and erfc is the complimentary error function. If one assumes that $T(0, t) = T_k$ and the heating time is $t_k$, then:

$$t_k q_2^2 = \pi \lambda c \gamma T_k^2 = \text{constant}$$  \hspace{1cm} (4.4)

At the beginning of the weld, the workpieces are being "ground in" and the temperature of the faying surfaces does not alter greatly from the initial temperature. As the contaminating surface layers are broken up and dispersed or
expelled from the interface, adhesive bonding begins to take place. Continued relative motion between the workpieces breaks the bonds, releasing the energy as heat, causing a temperature rise. Following the break up of the contaminating layers, the rate of heat input from the broken bonds reaches a nearly constant level [Vavilov and Voinov, 1964]. Thus, at the initial stages of the friction weld, the temperature does not increase greatly, but following the break up of the surface layer and exposing bare metal, the temperature does greatly increase.

4.4. The Effects of Axial Pressure

In friction welding, the quality of the weld is measured by the upset, the amount material forced out from between the workpieces during the weld. The amount of upset and the power generated during heating is highly affected by the specific pressure. A high specific pressure creates more uniform heat on the faying surfaces and results in a higher quality weld. The higher the specific pressure, the higher the maximal moment and the earlier the generation of heat [Vavilov and Voinov, 1964].

The friction welding process can incorporate either a steady axial pressure or a staged pressure cycle. The steady pressure cycle is simpler and easier to apply, while the staged pressure cycle evens out the temperature distribution and the power input into the weld is better utilized. Commercial friction welding processes, usually being direct drive rather than inertial, often use a staged pressure cycle.
in which the pressure is increased at the end of the cycle as the rotation of the rod is stopped. With a staged pressure cycle, it is critical that the pressure be stepped at specific points in the heat input cycle, corresponding to the rotation speed of the rod. In a direct drive system, the rod rotation is directly controlled. In an inertial system, only the initial rotation speed is controlled - the rotation of the rod during the weld is determined by the friction between the workpieces, and thus determining the amount of a pressure step and the time of application is much more difficult.

4.5. The Effects of External Atmosphere and Surface Contamination

Many friction experiments have been conducted in different atmospheres and in vacuum. The atmospheres serve principally to retain the films on the friction surfaces [Vavilov and Voinov, 1964]. As shown in Figure 4.4, the lack of oxygen in the surrounding atmosphere tends to increase the amount of wear observed.
Sliding speed

Relationship of wear (by weight) to sliding speed during friction between grade 45 steel and grade 45 steel in different gases. Specific pressure 10 kg/cm² (0.98 MN/m²).

Figure 4.4. Relationship of Wear to Sliding Speed in Different Atmospheres [from Vavilov and Voinov, 1964].

Typical friction experiments involve pin and disk apparatus or some other mechanism where the pin slides over a given point on the disk intermittently. Some time elapses between subsequent passes of the pin on a specific location on the disk, allowing time for atmospheric gases to interact with the metal surface. Most metals readily form oxides that
tend to prevent bonding and thus reduce the coefficient of friction. During friction welding, the atmosphere can react with the surface only during the initial period. As the workpieces are forced together, the atmosphere is expelled from the interface. Because the atmosphere is expelled during friction welding, no reaction between the faying surface and the atmosphere can take place.

When aluminum slides upon aluminum, as in the case of friction welding, it is actually the contaminant layers that are sliding upon one another, at least initially (see Figure 3.3).

In a vacuum environment, some of the contaminants on the surface can be expected to volatilize at least partially, especially the greasy and adsorbed gas layers. However, the oxide layer can be expected to remain.

The adsorbed surface layer and greasy films tend to decrease the surface interaction, decreasing friction. During sliding friction, oxide layers tend to be broken up and the surface energies of the materials approach that of metals without oxide layers [Rabinowicz, 1964]. If a contaminant is present, the surface energies approach that of the contaminant, typically very low, resulting in a very low coefficient of friction. When grease-free surfaces are slid against one another, the friction can be:

- Severe - high frictional coefficient (usually 2.0 to 0.9), usually due to asperities or large particles (diameters of approximately 50 μm)
transferred from one surface to another. These particles usually have irregularly shaped sides. Severe behavior occurs when the materials are the same or when the two metals interact to form alloys (are compatible) (aluminum oxides tend to not form alloys, compared to elemental aluminum).

- Mild - low friction coefficients (0.7 to 0.3), usually a large number of fine lines due to asperities, small particles (diameters of less than 25 μ).

When metals are slid past one another in high vacua (the surfaces being machined to remove the oxide surface contamination) severe friction may occur. This is particularly true of softer metals, such as aluminum. Continued sliding in a vacuum makes the real area of contact grow inordinately large, causing very high values of friction, some with values of 5 to 200 [Rabinowicz, 1964]. If two like materials are slid past one another, wear of the two surfaces takes place. Particles from one surface may be transferred to the other. As a particle is transferred from one surface to the other, the surface of contact moves in the opposite direction as the direction of transfer. The net motion of the surface of contact is in the direction of the weaker material. If the two surfaces are of the same material, the weaker material may be that which has the
higher temperature. The creation of wear particles is a random phenomena.

The minimum load required to obtain wear particles may be calculated from the equations below [Rabinowicz, 1964]. The minimum particle diameter $d_{\text{min}}$ is:

$$d_{\text{min}} = 20,000 \frac{\mu_{\text{ab}}}{p}$$  \hspace{1cm} (4.5)

and the minimum load $L_{\text{min}}$ is:

$$L_{\text{min}} = \pi \times 10^8 \frac{\mu_{\text{ab}}^2}{p}$$  \hspace{1cm} (4.6)

Surface energy data for metallic elements and non-metals are given in Tables 4.1 and 4.2. The hardness of a material also affects its friction characteristics. Softer materials tend to have high coefficients of friction [Suh, 1986].
Table 4.1. Properties of Metallic Elements

<table>
<thead>
<tr>
<th>Metal</th>
<th>Melting Temp. °C</th>
<th>Young's Modulus E 10^11 dyne/cm²</th>
<th>Yield Strength 80 10^3 dyne/cm²</th>
<th>Hardness p kg/mm²</th>
<th>Surface Energy erg/cm²</th>
<th>γ/γ⁻⁻² cm</th>
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<tbody>
<tr>
<td>Aluminum</td>
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<td>0.83</td>
<td>1.1</td>
<td>27</td>
<td>900</td>
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<td>150</td>
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<td>7</td>
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<td>45</td>
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<td>0.72</td>
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<td>820</td>
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<tr>
<td>Silver</td>
<td>951</td>
<td>0.78</td>
<td>2.0</td>
<td>80</td>
<td>920</td>
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<tr>
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<td>0.90</td>
<td>3.5</td>
<td>80</td>
<td>920</td>
<td>12</td>
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<tr>
<td>Tantalum</td>
<td>2996</td>
<td>0.90</td>
<td>3.5</td>
<td>80</td>
<td>920</td>
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<tr>
<td>Terbium</td>
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<td>0.38</td>
<td>2.0</td>
<td>80</td>
<td>920</td>
<td>12</td>
</tr>
<tr>
<td>Tellurium</td>
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<td>0.38</td>
<td>0.9</td>
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<td>60</td>
<td>12</td>
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<tr>
<td>Tungsten</td>
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<td>1.5</td>
<td>37</td>
<td>400</td>
<td>12</td>
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<tr>
<td>Thallium</td>
<td>1545</td>
<td>1.4</td>
<td>1.5</td>
<td>37</td>
<td>400</td>
<td>12</td>
</tr>
<tr>
<td>Thallium</td>
<td>1545</td>
<td>1.4</td>
<td>1.5</td>
<td>37</td>
<td>400</td>
<td>12</td>
</tr>
<tr>
<td>Thorium</td>
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<td>1.89</td>
<td>2.0</td>
<td>435</td>
<td>2300</td>
<td>12</td>
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<tr>
<td>Vanadium</td>
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<td>8.4</td>
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</tr>
</tbody>
</table>

Sources of Data:
Hardness: Main sources as above.
Surface Energy: A number of data were taken from D. Tabor, The Hardness of Metals, Oxford, 1951.
Surface Energy: Some data were taken from other publications.
Surface Energy: Some data were taken from other publications.

Table 4.1. Properties of Metallic Elements [from Rabinowicz, 1964].

- 80 -
<table>
<thead>
<tr>
<th>Material</th>
<th>Surface Energy $\gamma$, erg/cm²</th>
<th>Hardness $p$, kg/mm²</th>
<th>$\gamma/p, 10^{-8}$ cm²/kg/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgCl</td>
<td>100</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>740</td>
<td>2150</td>
<td>0.34</td>
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<tr>
<td>BaF₂</td>
<td>210</td>
<td></td>
<td></td>
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<tr>
<td>CaCO₃</td>
<td>170</td>
<td>120</td>
<td>1.4</td>
</tr>
<tr>
<td>CaF₂</td>
<td>340</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdO</td>
<td>360</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KCl</td>
<td>85</td>
<td>35</td>
<td>2.4</td>
</tr>
<tr>
<td>LiF</td>
<td>260</td>
<td>100</td>
<td>2.6</td>
</tr>
<tr>
<td>MgO</td>
<td>670</td>
<td>500</td>
<td>1.3</td>
</tr>
<tr>
<td>Mica</td>
<td>250</td>
<td>40</td>
<td>6.2</td>
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<tr>
<td>Si</td>
<td>930</td>
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<td>ThO</td>
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<td></td>
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<tr>
<td>TiC</td>
<td>900</td>
<td>2400</td>
<td>0.38</td>
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<tr>
<td>UC</td>
<td>750</td>
<td></td>
<td></td>
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<tr>
<td>UO₂</td>
<td>415</td>
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<td></td>
</tr>
<tr>
<td>VC</td>
<td>1250</td>
<td>2500</td>
<td>0.50</td>
</tr>
<tr>
<td>ZnO</td>
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<td></td>
</tr>
<tr>
<td>ZrC</td>
<td>600</td>
<td>2100</td>
<td>0.28</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>530</td>
<td>1150</td>
<td>0.46</td>
</tr>
</tbody>
</table>


Table 4.2. Surface Energy Data for Non-Metals [from Rabinowicz, 1964].

### 4.6. Surface Preparation

Films on the surface of a metal fall into two groups: (1) oxide films, which are relatively brittle, and (2) adsorbed surface films of water vapor and possibly organic substances, that are relatively elastic and mobile [Tylecote, 1968].

Abrasion of the surface is the simplest form of surface preparation and the most likely technique that will be used
in space. Machining removes more contaminants and leaves a relatively smooth surface, but requires extra equipment and produces some debris which is to be avoided in space. Among the most common materials for abrasion are a wire brush, steel wool, and sandpaper or emery cloth.

Abrasion of the surface is called "scratch-brushing" and is the most common form of surface preparation [Tylecote, 1968]. Scratch-brushing breaks up the oxide and removes some of the particles. Scratch-brushing increases the surface area by a factor of three over a smooth surface.

Use of a degreasing agent (such as xylol) after scratch-brushing reduces the strength of cold welds in aluminum. Use of trichlorethylene after scratch-brushing adversely affects welds, but the welds can be improved by heating the material to 250 °C in air or 180 °C in a vacuum, volatilizing the degreasing agent. Other degreasing agents can form compounds with the metal surface that may adversely affect the weld. A degreasing agent probably would not be used in the vacuum of space because the agent would volatilize during application [Tylecote, 1968].

The action of preparing the surface by abrasion or scratch-brushing work-hardens the surface. Also, particles of the broken-up oxide, and of the abrasive, become embedded or buried in the surface.
CHAPTER 5. EXPERIMENTAL APPARATUS

5.1. Introduction

In inertial friction welding there are three parameters that can be adjusted to optimize the weld: (1) the moment of inertia of the flywheel, by changing the size of the flywheel, (2) the rotation rate of the flywheel and the stud, and (3) the axial force. In this thesis, the moment of inertia of the flywheel was fixed because of the high cost of making several flywheels and the inability to adequately balance a "stacked plate" flywheel for the high rotation rates required. The experimental apparatus was designed to allow variation of the other two variables, rotation rate and axial force.

The inertial friction welder used for this thesis was originally developed by Guza [1988], as was the bell jar/vacuum chamber that surrounds the welder (the vacuum chamber was not used for this thesis). Some modifications to the system were done to make it more robust, however the essential design remains the same. To reduce construction costs, the welder was designed with off-the-shelf components that are typically used in non-vacuum environments. A diagram of the inertial friction welder is shown in Figure 1.5. The vacuum system is able to attain vacua of $10^{-7}$ torr and greater, however the electric motor, not designed for use in a vacuum, failed in vacua greater than 10 torr. In this
thesis, the vacuum system was not used. As a substitute for vacuum, an argon atmosphere was used to prevent oxidation, as explained below. A schematic of the welder is shown in Figure 5.1. The major components of the apparatus used for this thesis are:

1. A 3-horsepower electric motor with variable speeds to accelerate the flywheel.

2. A flywheel to store the kinetic energy needed to perform the weld. The flywheel is directly connected to the electric motor shaft.

3. A pneumatic piston used to force the plate onto the rotating stud. The motive force is pressurized nitrogen.


5. An airtight dry box to enclose the above items.

6. A switch and solenoid valve assembly that powers the electric motor and the operates the pneumatic piston.

7. Argon to flood the dry box.
5.2. Use of Argon

The main purpose of using vacuum in previous experiments was to prove the technique for possible application in space welding. It was attempted to simulate the environment of space as closely as possible, neglecting the effects of microgravity and temperature extremes. Experiments by Guza [1988] and Jacoby [1991] show that vacuum does not greatly affect the quality of the weld. There is only slight enhancement of welds performed in vacuum over those conducted in air.

To study the effects of the oxide layer, one must be able to abrade the oxide layer in the absence of oxygen and the prepared specimen must be isolated from oxygen until after the inertial weld can be completed. In order to perform such a weld in a vacuum, one would have to develop a method of abrading the surface in the vacuum, and overcome the problems of the electrical motor failure in high vacuum. By
performing the inertial friction weld in an argon atmosphere, the oxygen can be eliminated, preventing oxide formation following abrasion. The argon, being a noble gas, will not react with the aluminum metal to form other compounds. Also, the argon gas can be used as the cooling medium for the electric motor. Since the system is under essentially atmospheric pressure, vacuum effects on the lubricants of bearings are eliminated.

In previous experiments, the specimen was exposed to air for 10 to 20 minutes after surface preparation before a sufficient vacuum was reached to conduct the experiments. The time required for a monolayer of gas one molecule thick to form on a bare metal surface is $10^{-8}$ seconds [Rittenhouse, 1967]. For surfaces that have been scratch-brushed (see Surface Preparation below), the oxide film has reached a large proportion of its limiting thickness after only 15 seconds exposure to air. As shown in Figure 5.2, the oxide limiting thickness for most material is reach after 10 minutes. Even in vacuums as high as $10^{-5}$ torr, there are enough oxygen present to form an oxide layer 50 Å thick, so the presence of an oxide layer must be assumed if the metal surface has been exposed to any oxygen [Tylecote, 1968].
Figure 5.2. Oxidation of Pure Metals at Room Temperature Following Scratch-Brushing [from Tylecote, 1968].

5.3. Electric Motor

An electric motor is used to accelerate the flywheel to the required speed. Depending on the motor, electrical power could be required for as little as 5 seconds or as long as 20 minutes. Because electrical power is disconnected from the motor prior to making the weld, the power of the motor is not a factor in making the weld, only the moment of inertia of the flywheel and the coupled motor armature. The power of the motor determines only the time required to accelerate the flywheel to the required speed. In theory, then, essentially any motor could be used to accelerate the flywheel. For the experiments of Guza [1988] and Jacoby [1991] a series-wound, brush-type motor capable of variable speed was chosen because
of low cost, superior torque, current-carrying capacity, and microprocessor speed control. For this thesis a similar motor was used in order to maintain the same moment of inertia of the armature and the same welding rotation rates as previous work. A 3 horsepower Porter-Cable® Model 7518 Router was selected as the electric motor. The Model 7518 has microprocessor improvements over the Model 518 used by Guza and Jacoby, and is less expensive, but the moment of inertia of the armature is the same. The motor is capable of speeds of 10K, 13K, 16K, 19K and 21K rpm.

5.4. Flywheel

The flywheel is a solid mass of 304 stainless steel that fixes the moment of inertia for the welder. The design of the flywheel is governed by three approximate rules of thumb for the inertial friction welding of aluminum (these rules of thumb were developed by Manufacturing Technology, Inc., Mishawaka, IN, as reported by Guza [1988]):

1. The velocity range necessary for satisfactory welds is 800 to 3,000 sfpm, equivalent to 12,223 to 45,837 rpm for a 0.25 inch diameter stud.

2. The minimum weld energy required can be estimated from:

\[ E (\text{ft} - \text{lbf}) = 15,550 \cdot (D \text{ (in inches)})^{2.5} \]  

(5.1)

where \( E \) is the weld energy and \( D \) is the diameter of the stud.
3. The axial force required can be estimated from:

\[ F \text{ (lbf)} = \frac{1}{2} \cdot (E \text{ (in ft - lbf)}) \]  \hspace{1cm} (5.2)

where \( F \) is the weld force.

The above rules of thumb require that the minimum weld energy is 484.38 ft-lbf.

The weld energy is related to the moment of inertia \( Wk^2 \) by:

\[ E = \frac{Wk^2 s^2}{5,873} \]  \hspace{1cm} (5.3)

where \( E \) is the weld energy (ft-lbf), \( W \) is the weight of the rotating components (lbf), \( k \) is the radius of gyration (ft) and \( s \) is the speed (rpm). The moment of inertia of the system is the sum of the moments of inertia of the components, namely the flywheel, the shafting, and the motor armature, or:

\[ W_{k_{weld}}^2 = W_{k_{flywheel}}^2 + W_{k_{shafting}}^2 + W_{k_{motor armature}}^2 \]  \hspace{1cm} (5.4)

The moment of inertia of the motor armature and the motor were determined to be [Guza, 1988]:

- \( W_{k_{motor armature}}^2 = 1.030 \times 10^{-3} \text{ lbf - ft}^2 \)
- \( W_{k_{shafting}}^2 = 2.802 \times 10^{-3} \text{ lbf - ft}^2 \)

Assuming only the minimum speed of 12,223 rpm could be obtained, the moment of inertia of the welding system was required to be (from equation 5.3):

\[ W_{k_{weld}}^2 = 1.9062 \times 10^{-2} \text{ lbf - ft}^2 \]

Therefore, the moment of inertia of the flywheel had to be:
\[ W_k^{flywheel} = 1.0962 \times 10^{-2} - 1.030 \times 10^{-3} - 2.802 \times 10^{-3} \]
\[ = 1.523 \times 10^{-2} \text{ lbf} - \text{ft}^2 \]

which equates to a flywheel diameter of 3 inches and a height of 1 inch. A diagram of the flywheel is shown in Figure 5.3.
Figure 5.3. Detail of Flywheel [from Guza, 1988].
5.5. **Pneumatic Piston**

A Enerpac® Hydraulic Cylinder, Model 50, is used to generate the axial force necessary to make the weld. The piston has a stroke of 5/8 inch and an area of 1.00 in\(^2\). The force behind the piston is pressurized nitrogen fed to the assembly via a regulator and a solenoid valve. The regulator can be adjusted between 0 and 200 psi. The nitrogen is stored in a compressed gas bottle.

5.6. **Dry Box**

To determine the effects of aluminum oxide on inertial friction welding, experiments were conducted in argon for the following reasons:

1. An atmosphere of argon prevents the formation of oxide and does not form any other contaminant layers if the argon if free of contaminants (the argon used was labeled as pure).

2. The use of argon allowed the use of a dry box rather than a vacuum chamber. A dry box can be fitted with gloves that allow the manipulation of equipment inside the box without the risk of contamination from the outside atmosphere. In a vacuum, a mechanism that allows this sort of access is extremely expensive. With this access, a plate can be abraded by any of several methods before being loaded into the experimental
apparatus, and the experiments can be conducted without exposure to oxygen.

3. An argon atmosphere allows the use of an electric motor that was not designed for use in a vacuum. The router used as the electric motor is air cooled. In previous experiments, the motor failed in vacua as low as 1 torr, so testing could not be performed in vacua as great as that of space. In an argon atmosphere, the argon gas will cool the motor.

The dry box was constructed of 1/4 inch plexi-glass. Photographs of the dry box and other experimental apparatus are shown in Appendix A.

Before experiments take place, the dry box is flooded with argon at a rate of 50 ft$^3$/hr. Vents located at the top of the box allow the argon to displace the air. Since argon is denser than air (1.78 kg/mm$^3$ for argon, 1.29 kg/mm$^3$ for air), the air will be forced out the top of the dry box. The dry box has a volume of 12 ft$^3$, which should allow for a complete volume change in 14.4 minutes, however the box was purged for 45 minutes to ensure that all air that might be trapped within the box was displaced.

All materials required for the weld - workpieces, surface abrasion equipment, tools for loading the workpieces into the apparatus - are loaded into the dry box before flooding with argon. Once the purge is complete, the
workpieces can be abraded via use of the gloves, and loaded into the apparatus and the experiment performed.

5.7. **Switch and Solenoid Valve**

The three-way switch operates both the electric motor and the solenoid valve. The switch is set up so that power is disconnected from the electric motor before the solenoid valve is opened which forcing the plate onto the stud. This prevents any "direct drive" of the welding machine - only the energy stored in the flywheel-armature is imparted into the weld.

5.8. **Laser Microscope**

Following welding, the welds were subjected to a bend test to determine the weld integrity. The welds were then broken (if the weld did not break during the bend test) so the surfaces could be examined using the Lasertec Corporation 1LM21 Confocal Laser Scanning Microscope, shown in Figure 5.4.
The microscope allows up to 30,000x magnification and accurate surface profiling with Z-scale expansion for surface analysis. For more information in the laser microscope, refer to the operating manual.
CHAPTER 6. EXPERIMENTAL PROCEDURE

6.1. Step-by-Step Procedure

The following is the step-by-step procedure for conducting the experiments. Explanations for some of the steps is given below.

1. Set router speed controller to desired speed. Ensure the inertial welder controller switch is in the "Off" position. Ensure switch on the router is in the "On" position.

2. Place workpieces and material for abrading surface in dry box.

3. Close dry box door and open vents on top of box.

4. Purge dry box with argon for 30 minutes at a rate of 50 ft\(^3\)/hr. Start router and run for 10 seconds (to flush any air that might be trapped in the motor housing). Shut motor off and continue flush for an additional 15 minutes.

5. Close vents on top of box and reduce argon flow to 20 ft\(^3\)/hr (this allows some positive pressure in the dry box to prevent any air from entering the box in the event of a minor leak).
6. Using the dry box gloves, abrade the surface of both the specimen plate and stud.

7. Load plate and stud into the inertial welding apparatus.

8. Set desired axial force on the nitrogen bottle regulator.

9. Place inertial welder controller switch to the “Router” position. The router should accelerate to the desired speed.

10. In one motion, move the inertial welder controller switch from the “Router” position to the “Valve” position. This removes electrical power from the router and opens the solenoid valve. The plate will be forced onto the stud, stopping the flywheel. Measure the time from the opening of the solenoid valve to the time the flywheel stops with a stopwatch.

11. Close valve on the nitrogen bottle. Bleed pressure in the nitrogen line via the bleed valve. The bracket of the inertial welder holding the plate will drop down about 1/8 inch, leaving the plate attached to the stud if sufficient energy was used to make a weld. Move the inertial welder controller switch to the “Off” position.
12. Open the dry box and remove the specimen, taking care not to damage the weld.

13. Place one edge of the plate into a vice and secure it.

14. Slide bend test tube over stud and perform the bend test. The test is successful if the stud bends before the weld breaks. This shows that the weld is stronger than any reasonable force that a stud would be expected to withstand.

15. Continue bending the stud until the stud breaks away from the plate. If necessary, use pliers to break the stud from the plate. Take care not to touch or damage the fracture plane.

16. Using the laser microscope, examine the topography of the fracture site of the plate. Record any features that may indicate the presence of oxide inclusions or type of fracture. Record the location of the fracture plane relative to the undamaged surface of the plate. Calculate the fraction of the fracture surface area that is dimpled.
CHAPTER 7. EXPERIMENTAL RESULTS

7.1. Results of Welding and Bend Test

The materials welded in this thesis were 2219-T87 plate and 2219 stud, the same material to be used in the construction of the space station Freedom.

In the following tables, SW denotes surface preparation with steel wool, SP denotes 400-grit sandpaper, and WB denotes wire brushing. Photographs of some of the workpieces prior to the bend test are shown in Appendix B.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Temp (°F)</th>
<th>Prepa-</th>
<th>Time (sec)</th>
<th>% Dim</th>
<th>Welding Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>78</td>
<td>SW</td>
<td>-</td>
<td>0.00</td>
<td>no weld</td>
</tr>
<tr>
<td>argon</td>
<td>78</td>
<td>SW</td>
<td>-</td>
<td>0.00</td>
<td>no weld</td>
</tr>
<tr>
<td>air</td>
<td>78</td>
<td>none</td>
<td>-</td>
<td>0.00</td>
<td>no weld</td>
</tr>
<tr>
<td>argon</td>
<td>78</td>
<td>none</td>
<td>-</td>
<td>0.00</td>
<td>no weld</td>
</tr>
<tr>
<td>argon</td>
<td>67</td>
<td>WB</td>
<td>2.02</td>
<td>0.00</td>
<td>no weld</td>
</tr>
</tbody>
</table>

Table 7.1. Experimental Results, Axial Force 100 lb, Speed 10K rpm.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Temp (°F)</th>
<th>Prepa-</th>
<th>Time (sec)</th>
<th>% Dim</th>
<th>Welding Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>78</td>
<td>SW</td>
<td>0.72</td>
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<td>20.17</td>
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<td>argon</td>
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<td>none</td>
<td>0.78</td>
<td>16.17</td>
<td>fail</td>
</tr>
</tbody>
</table>

Table 7.2. Experimental Results, Axial Force 125 lb, Speed 10K rpm.
<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp ('F)</th>
<th>Surface Prepa-</th>
<th>Welding Time (sec)</th>
<th>% Dim</th>
<th>Pled Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>78</td>
<td>SW</td>
<td>1.68</td>
<td>0.44</td>
<td>fail</td>
</tr>
<tr>
<td>argon</td>
<td>78</td>
<td>SW</td>
<td>1.62</td>
<td>0.44</td>
<td>fail</td>
</tr>
<tr>
<td>air</td>
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<td>none</td>
<td>1.70</td>
<td>0.44</td>
<td>fail</td>
</tr>
<tr>
<td>argon</td>
<td>78</td>
<td>none</td>
<td>1.65</td>
<td>0.44</td>
<td>fail</td>
</tr>
</tbody>
</table>

Table 7.3. Experimental Results, Axial Force 100 lbf, Speed 13K rpm.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp ('F)</th>
<th>Surface Prepa-</th>
<th>Welding Time (sec)</th>
<th>% Dim</th>
<th>Pled Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>67</td>
<td>SP</td>
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<td>4.00</td>
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<tr>
<td>argon</td>
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<td>2.32</td>
<td>7.11</td>
<td>fail</td>
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</tbody>
</table>

Table 7.4. Experimental Results, Axial Force 125 lbf, Speed 13K rpm.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp ('F)</th>
<th>Surface Prepa-</th>
<th>Welding Time (sec)</th>
<th>% Dim</th>
<th>Pled Bend Test</th>
</tr>
</thead>
<tbody>
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<td>5.17</td>
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</tr>
<tr>
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<td>SW</td>
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<td>1.78</td>
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<tr>
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<td>1.86</td>
<td>1.78</td>
<td>fail</td>
</tr>
<tr>
<td>argon</td>
<td>78</td>
<td>none</td>
<td>1.85</td>
<td>1.78</td>
<td>fail</td>
</tr>
</tbody>
</table>

Table 7.5. Experimental Results, Axial Force 100 lbf, Speed 16K rpm.
<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp (°F)</th>
<th>Surface Preparation</th>
<th>Welding Time (sec)</th>
<th>% Dimpled Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>67</td>
<td>SP</td>
<td>2.14</td>
<td>7.11 fail</td>
</tr>
<tr>
<td>argon</td>
<td>67</td>
<td>WB</td>
<td>2.36</td>
<td>7.11 fail</td>
</tr>
<tr>
<td>argon</td>
<td>67</td>
<td>none</td>
<td>2.36</td>
<td>11.11 fail</td>
</tr>
<tr>
<td>air</td>
<td>67</td>
<td>SP</td>
<td>2.23</td>
<td>7.11 fail</td>
</tr>
</tbody>
</table>

Table 7.6. Experimental Results, Axial Force 125 lbf, Speed 16K rpm.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp (°F)</th>
<th>Surface Preparation</th>
<th>Welding Time (sec)</th>
<th>% Dimpled Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>78</td>
<td>SW</td>
<td>1.78</td>
<td>32.98 fail</td>
</tr>
<tr>
<td>argon</td>
<td>78</td>
<td>SW</td>
<td>1.72</td>
<td>31.96 fail</td>
</tr>
<tr>
<td>air</td>
<td>78</td>
<td>none</td>
<td>2.22</td>
<td>18.83 fail</td>
</tr>
<tr>
<td>argon</td>
<td>78</td>
<td>none</td>
<td>1.81</td>
<td>4.00 fail</td>
</tr>
</tbody>
</table>

Table 7.7. Experimental Results, Axial Force 100 lbf, Speed 19K rpm.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp (°F)</th>
<th>Surface Preparation</th>
<th>Welding Time (sec)</th>
<th>% Dimpled Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>67</td>
<td>WB</td>
<td>2.48</td>
<td>21.78 fail</td>
</tr>
<tr>
<td>argon</td>
<td>67</td>
<td>none</td>
<td>2.82</td>
<td>16.00 fail</td>
</tr>
</tbody>
</table>

Table 7.8. Experimental Results, Axial Force 125 lbf, Speed 19K rpm.
<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp (°F)</th>
<th>Surface Prep</th>
<th>Welding Time (sec)</th>
<th>% Dim</th>
<th>Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>67</td>
<td>WB</td>
<td>2.94</td>
<td>92.00</td>
<td>pass</td>
</tr>
</tbody>
</table>

Table 7.9. Experimental Results, Axial Force 140 lbf, Speed 19K rpm.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp (°F)</th>
<th>Surface Prep</th>
<th>Welding Time (sec)</th>
<th>% Dim</th>
<th>Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>67</td>
<td>WB</td>
<td>2.25</td>
<td>75.11</td>
<td>pass</td>
</tr>
</tbody>
</table>

Table 7.10. Experimental Results, Axial Force 125 lbf, Speed 21K rpm.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp (°F)</th>
<th>Surface Prep</th>
<th>Welding Time (sec)</th>
<th>% Dim</th>
<th>Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>67</td>
<td>WB</td>
<td>2.26</td>
<td>12.77</td>
<td>fail</td>
</tr>
</tbody>
</table>

Table 7.11. Experimental Results, Axial Force 110 lbf, Speed 21K rpm.

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Room Temp (°F)</th>
<th>Surface Prep</th>
<th>Welding Time (sec)</th>
<th>% Dim</th>
<th>Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>67</td>
<td>WB</td>
<td>2.80</td>
<td>4.00</td>
<td>fail</td>
</tr>
</tbody>
</table>

Table 7.12. Experimental Results, Axial Force 100 lbf, Speed 21K rpm.
7.2. Results of Fracture Surface Examination

Using the laser microscope the surfaces of the fractured welds, following the bend tests, were examined. The fracture site typically showed two types of surfaces, a striated or grooved surface, and a dimpled surface. The dimpled surface was the result of strong bonds that were broken during the bend test. The percent of the total surface area that was dimpled is recorded in the above tables. Micrographs of features of some of the surfaces are shown in Chapter 8 along with a discussion of the features.
CHAPTER 8. DISCUSSION OF RESULTS

8.1. The Effect of Scratch-Brushing As a Surface Preparation

Surface abrasion that takes place in an argon atmosphere breaks up the oxide layer and does not allow it to reform. Particles of the broken up oxide layer remain on the surface, but bare metal is also exposed. A scratch-brushed surface is rougher than the unscratch-brushed surface, especially for rolled material such as the aluminum plates used in this thesis. Under a microscope, surface abrasion had a great affect on the surface as shown in Figures 8.1 and 8.2.

Figure 8.1. Micrograph of Unabraded Surface, Scale: 100 μ = 1 inch.
However, as shown in the results of Chapter 7, abrasion of the surface as a form of surface preparation has little effect on the quality of the weld or the time required to make the weld. It was expected that, because of the high hardness of the oxide layer compared to aluminum alloy, abrasion would greatly improve the quality of the weld. It was expected that the improvement in the weld would be evidenced by reduced welding times (because of greater friction) and an increased fraction of dimpled surface area. The experimental results show that this is not the case for the parameters used in this welding technique.
Typical times for making the weld were on the order of two seconds. During the welding process, it was observed the two surfaces ground together with little flash production and little shortening of the stud for the initial fraction of a second at the start of the weld. Following that initial period, flash production began and accelerated, and the stud shortened quickly. The author believes that it is during this initial stage that the hard oxide layer is broken up and bare metal is exposed. As bare metal adheres to other bare metal on the opposite surface, friction greatly increases. The adhered metal is then sheared, increasing the temperature of the shear plane. Figure 8.3 shows a reasonable sequence of events for inertial friction welding based on these experiments.

![Sequence of Events for Inertial Friction Welding](image)

**Figure 8.3. Sequence of Events for Inertial Friction Welding.**

The breakup of the oxide layer is of such short duration, probably less than 10% of the time to make the weld, that the effect of that length of that time does not greatly affect the weld. It seems likely that scratch-brushing does shorten the length of time of the initial
grinding in period, however the overall effect of this shortening is insignificant to the weld. Because of the short duration of breakup of the oxide layer in inertial welding, any shortening or lengthening of the breakup does not greatly alter the fraction of time of this initial period. The rotational energy of the flywheel at the end of the initial period is nearly the same whether the period is long (though still very short compared to the entire time to make the weld) or short. The much longer latter stage of the weld, the actual making and shearing of the adhesive bonds, has the greater effect.

During the entire welding cycle the speed of the flywheel decreases nearly linearly, as shown in Guza’s [1988] experiments (see Figure 8.4). If the breakup of the oxide layer were prolonged and had a large effect, the deceleration of the flywheel would not be so linear, but behave more as shown in Figure 8.5. However, the experimental results do not show this. Thus, the effect of the time required to break up the oxide layer is small or negligible compared to the time to make the weld. Therefore, abrasion of the surface as a means of surface preparation to break up the oxide layer appears to be an unnecessary step in the welding process. It should be noted that the surfaces were free of other contaminants such as observable oils or greases. A detailed explanation of the mechanism is the oxide layer break up is made below.
VACUUM EXPERIMENT #1
{CLEAN/FLAT/125LBF/19K/1100}

NO LOAD DATA A
WELDING DATA B

TIME (SECONDS)
8.2. The Effect of Room Temperature And/Or Humidity

The experiments were conducted over two periods, one in January/February and the other in April 1992. The welding lab, where the experiments were conducted, was heated during the winter months and the welding lab was maintained at a warm temperature of 78 °F and the relative humidity was low due to the cold outdoor temperatures. During the spring, the heat was turned off allowing the temperature in the lab to drop to 67 °F, and the weather was rainy with the relatively humidity about 90%. Identical experiments conducted during both periods show some difference in weld quality and in the times required to make the weld. As can be seen is the tables of Chapter 7, the welding times and the percentage of the dimpled surface area are less for the welds made in the cooler, more humid environment.

In order to ascertain the effects of relative humidity, four welds were made under identical conditions except that
two plates were exposed to the flame of a propane torch for several minutes before being placed in the dry box while the other two plates were not. During the heating, drops of moisture of the plate surface were observed, which evaporated as the heating was continued. Following heating, the four plates were placed into the dry box and the dry box flooded with argon for the time specified in the Chapter 6. Cooling of the two heated plates took place for the 45 minutes prior to the testing so that all the plates were at the same temperature. The surfaces were all abraded with steel wool, and the welds performed using 125 lbf and 19K rpm. The welds all took the same about of time, 2.51 seconds ±0.14 seconds, and the welds were nearly identical in strength and in fraction of dimpled surface area.

Because of this test, it was assumed that the differences in the tests performed during the two periods was due solely to the temperature difference and not to the relative humidity difference. However, it is possible that an adsorbed water layer was on the surface of all plates, even those that were heated, because the plates were exposed to the moist room air for several minutes prior to being placed in the argon atmosphere. Also, the heat treatment might have altered the surface metallurgy of the aluminum plate so that effects of humidity were masked. And also, exposure of all plates to dry argon for 45 minutes may have evaporated any moisture.
In summary, it appears that friction welding of aluminum is highly sensitive to the ambient temperature, though no investigation into this was conducted since this was not an objective of this thesis. In the environment of space, where the temperature extremes are ±250 °F, the effects of temperature might be pronounced. Though beyond the scope of this thesis, the welding parameters of axial force, flywheel speed and flywheel mass would have to be determined as a function of temperature of the plate, the stud, or a combination of the two.

8.3. The Effects of Axial Pressure and Rotation Rate

Guza [1988] showed that superior welds were made using welding parameters of 125 lbf axial force and 19K rpm. Somewhat higher values were required to produce welds that passed the bend test. Parameters that made welds that passed the bend test are:

<table>
<thead>
<tr>
<th>Axial Pressure (lbf)</th>
<th>Rotation Rate (krpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>19</td>
</tr>
<tr>
<td>125</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 8.1. Welding Parameters Producing Sound Welds.

There are two probable causes for the difference in parameters from those of Guza [1988]:

- 111 -
1. The effects of different ambient temperatures and/or of the two sets of experiments, for the reasons stated above. Guza did not record the ambient temperature or humidity, so there is no way to ascertain this effect.

2. The effect of gas on the welding itself on the welding mechanism. It is possible that any gas present acts as a fluid as it is pressed between the stud and the plate. The author believes that this effect would be negligible.

The effect of the gas on the welding apparatus may have a great effect. The armature of the router has fan blades for moving air through the router housing to cool the motor. In a vacuum the drag due to these blades would be small. In air, the drag may be appreciable. In argon, which is denser than air, the effect would be even greater. Thus, a greater fraction of the energy put into the system went to cool the motor (and not into welding) in these experiments than in Guza’s.

8.4. The Effect of Fraction of Dimpled Surface on Weld Strength

An examination of the fractured surfaces using a laser microscope showed two types of surfaces: (1) a grooved and striated surface, and (2) a dimpled surface. Figure 8.6 shows
both types of surfaces, the grooved segment on the outer portion of the weld, and the dimpled segment on the inner portion. Figure 8.7 show the dimpled portion at greater magnification.

As is well known in fracture mechanics, a dimpled fracture surface occurs in sound material that was stressed beyond its elastic and plastic limit [Broek, 1987]. In friction welding, the fraction of the total weld surface area that is dimpled should be a good indicator of the strength of the weld. The fraction of the dimpled surface for each weld was calculated using a laser microscope and measuring the diameter of the dimpled surface. In most cases the dimpled surface occurred at the center of the welded area, however in some cases there were bands of dimples surface rather than, or in addition to, the central area. The fraction of dimpled surface is shown in Chapter 7 for each weld.

Based on these experiments, welds passed the bend test if the fraction of dimpled surface exceeded 75%, and did not pass the bend test if the fraction was 22% or less. Fractions in between these values did not occur in these experiments.
Figure 8.6. Broken Friction Weld. Welding occurred only at the center of the weld.
Scale: 100 μ = 1 inch.

Figure 8.7. Dimpled Fracture Area,
Scale 400 μ = 1 inch.
8.5. Model of Inertial Friction Welding

8.5.1. Break-Up of the Oxide Layer

It is proposed that the break-up of the oxide layer occurs at the very initial stages of the inertial friction weld. Tylecote [1968] noted that the aluminum oxide layer appears to break up at deformations far below those predicted by the strength of the layer. This is likely due to the difference in ductility of the oxide layer from that of the aluminum alloy below it. Table 8.2 shows the hardness of aluminum and aluminum oxide for various temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Hardness (kg/mm²)</th>
<th>Ratio Al₂O₃/Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Al₂O₃</td>
<td>Al</td>
</tr>
<tr>
<td>20</td>
<td>2000</td>
<td>36.0</td>
</tr>
<tr>
<td>100</td>
<td>1800</td>
<td>31.5</td>
</tr>
<tr>
<td>200</td>
<td>1600</td>
<td>25.0</td>
</tr>
<tr>
<td>300</td>
<td>1500</td>
<td>15.0</td>
</tr>
<tr>
<td>400</td>
<td>1350</td>
<td>6.5</td>
</tr>
<tr>
<td>500</td>
<td>1200</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 8.2. Relative Hardness of Aluminum and Its Oxide [from Tylecote, 1968].

Asperities on one workpiece press into the surface of the other. The relatively ductile base metal compresses somewhat and flows under the stress of the asperity. The brittle oxide layer does not flow but fractures as it bends, as depicted in Figure 8.8. Plowing by the asperities break up the oxide layer in a relatively short period of time.
8.5.2. Shear Plane and the Effects of Temperature Build-Up

As the oxide layer is broken up, some of the hard oxide particles are forced from between the two workpieces to the flash or upset material. Some of the particles are embedded in one of the two surfaces. The exposed uncontaminated metal surfaces adhere to one another, and continued relative motion between the two workpieces shears the adhesive bonds, creating heat.

The material shears along the plane where the shear strength of the material is weakest, which does not remain at the initial interface. The shear strength of a material is a function of temperature. The higher the temperature, the less shear strength. The temperature distribution in the workpieces has been presumed to be parabolic (see Figure 4.2). However, that only accounts for the heat due to the relative speed of the rubbing surfaces. In actuality, the temperature is a function of both the relative speed and the axial load on the surface (see equations 3.11 and 3.13). It has been assumed that the stress distribution beneath the stud is uniform, as depicted in Figure 8.9.
However, due to the triaxial nature of the stress at the center of the stud and the lack of lateral support at the edges, the actual stress distribution is more like that depicted in Figure 8.10.

The major effect of the difference in stress distribution is that the temperature distribution is probably not that shown in Figure 4.2, but is more like that depicted in Figure 8.11.
Figure 8.11. More Reasonable Heat Distribution Under Stud.

As evidence for this, the following is presented:

1. When the two workpieces are at the same temperature at the beginning of the weld, the stud is at a higher temperature at the end of the weld. This is reasonable because of the much smaller mass of the stud compared to the plate, and the much greater area for the heat of friction to diffuse through in the plate compared to the stud.

2. When breaking the studs from the plate following the weld, the fracture plane is always in the stud, not in the plate. The fracture appears to be along the last shear plane of the weld. Because the fracture is always within the stud, the shear plane must migrate from the initial interface into the stud.
3. The fracture surface often has the appearance shown in Figure 8.12.

![Diagram of Plate Following Stud Fracture]

Figure 8.12. Diagram of Plate Following Stud Fracture.

This would be the expected shape for a temperature distribution shown in Figure 8.11.

4. After observing the above results, one experiment was conducted to see if the shear plane could be forced into the plate rather than remain in the stud. A plate was heated with a propane torch immediately prior to welding. Since the shear plane occurs where the temperature is highest, the shear should occur in the plate since it was much higher in temperature than the stud. When the stud was broken away from the plate, the appearance was as shown in Figure 8.13. This shows that the location of fracture is usually along the last shear plane.
8.5.3. Method of Shear Plane Migration

The migration of the shear plane appears to take place because of the transfer of material from the higher temperature surface to the cooler one. In most cases, the higher temperature surface is the stud. The transfer takes place by the creation of wear particles and wear sheets as shown in Figures 8.14 and 8.15.
Figure 8.14. Wear Particle. Particle has a diameter of about 20 μ.

Figure 8.15. Edge of Wear Sheet, Scale: 100 μ = 1 inch.
The wear sheets and particles break off from the stud and become adhered to the plate surface. Following the transfer of many wear sheets and particles, the shear plane migrates from the initial interface into the stud.
CHAPTER 9. CONCLUSIONS

The following are the conclusions of the study of this thesis:

1. Surface preparation in the form of scratch-brushing is of negligible benefit for the pressures and rotation rates used for inertial friction welding in this study.

2. The quality of vacuum does not appear to appreciably alter the quality of the weld for inertial friction welding. Vacuum does seem to affect the welding apparatus, as shown by the failure at high vacuum, and the lack of drag due to loss of cooling air. The atmosphere, either inert (argon) or air does not appear to affect the quality of the weld.

3. Though not thoroughly investigated by this thesis, it appears the quality of the weld is highly dependent on the initial temperature of the workpieces. The higher the initial temperature of the workpieces, the lower the required energy to perform inertial welding.

4. The relative temperature difference between the workpieces appears to affect the weld. If the
initial temperatures of both workpieces are the same, the stud heats up faster than the plate.

5. The location of the weak point in the bond appears to be coincident with the location of the highest temperature reached, which is the location of the last shear plane in the welding process. Fractures of the weld follow the expected last shear planes.

6. The temperature distribution beneath the stud probably does not follow the parabolic distribution previously assumed. The distribution is a function of both the relative velocity and the axial force between the workpieces, both of which are a function of the distance from the center of the weld. The temperature distribution is most likely quadratic.

7. The fraction of dimpled surface area of the entire welded area may be used as an indicator of the quality of the weld. Fractions in excess of approximately 75% are necessary for a welded specimen to pass the bend test.
CHAPTER 10. SUGGESTIONS FOR FURTHER WORK

Based on the results of this study, the following are suggestions for further work:

1. Investigate the effects of ambient temperature on the quality of the weld. Widely varying temperature extremes are to be expected in space, and welds may have to be conducted under a variety temperatures. This thesis appears to show that ambient temperature effects are important.

2. Direct drive friction welding may allow more controlled energy input into the weld. Stepped axial pressure may do the same. The applicability of both of these techniques should be investigated for use in the space environment.
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Vavilov, A. F., and Voinov, V. P., 1964, Friction Welding, Translated from Russian, Moscow.


APPENDIX A. PHOTOGRAPHS OF WELDING APPARATUS

Figure A.1. Inertial Friction Welder in Dry Box.

Figure A.2. Vents at Top of Dry Box.
Figure A.3. Assembly That Holds Plate and Stud.

Figure A.4. Laser Microscope.
APPENDIX B. PHOTOGRAPHS OF SOME FRICTION WELDS

Figure B.1. Weld Produced With Parameters 140 lbf, 19K rpm.

Figure B.2. Weld Produced with Parameters 125 lbf, 21K rpm.
Figure B.3. Weld Produced With Parameters 125 lbf, 10K rpm.

Figure B.4. Weld Produced With Parameters 100 lbf, 16K rpm.