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COMPRESSIVE STRENGTH, PLASTIC FLOW PROPERTIES, AND
SURFACE FRICTIONAL EFFECTS OF 1100, 3003 AND 6061 ALUMINUM ALLOYS

BY

GARY WAYNE PINKERTON

B.S.M.E., United States Naval Academy, 1991

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Nuclear Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1993

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MASTER

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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

THE GRADUATE COLLEGE

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GARY WAYNE PINKERTON

ENTITLED COMPRESSIVE STRENGTH, PLASTIC FLOW PROPERTIES, AND

SURFACE FRICTIONAL EFFECTS OF 1100, 3003 AND 6061 ALUMINUM ALLOYS

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF MASTER OF SCIENCE

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ABSTRACT

The purpose of this study is to find aluminum alloys that are effective for use as wire vacuum seals in the 800MeV particle accelerator located at the Louis Anderson Meson Physics Facility (LAMPF) in Los Alamos, NM. Three alloys, Al 1100, Al 3003, and Al 6061, are investigated under uniaxial compression to determine stresses for a given height reduction from 0 to 70 percent, and to find plastic flow and surface interaction effects. Right-circular cylindrical specimens are compressed on-end (cylindrically) and radially (for modeling as compressed wire).

Aluminum 1100 and 3003 alloys are compared for length to diameter ratios of 1 and 2 for both compression types, and are then compared to results of radial compression of annealed small diameter Al 1100 wire currently used at LAMPF. The specimens are also compressed between three different platen surfaces, polished steel, etched steel, and aluminum 6061-T6, to determine effects of friction. The Al 3003 alloy exhibits 20 to 25% lower stresses at all height reductions than Al 1100 for both cylindrical and radial compression.

Al 6061 cylinders of 2 diameters (3.175mm and 6.35mm) are tested with 2 heat treatments, H-Temper and Solution Annealed, under identical conditions to those used with Al 1100 and Al 3003 above. The purpose of these tests is to determine the applicability of Al 6061 as a replacement for the highly activating stainless steel beam line vacuum housing. The results show that Al 6061 is approximately 3 to 4 times

as strong as the seal material in compression, but that some surface deformation occurs which suggests that the alloy may not be sufficiently rigid for this purpose.

Varying test parameters on the three alloys gave the following results: specimens with smaller length to diameter ratios have 10 to 20 percent higher stresses in compression to 70% height reduction. Aluminum to aluminum surface galling is visible on the platens after most compression tests. Deformation of the platens occurs in a few cases where the seal alloys are compressed to 70%, and in all cases for compression of Al 6061 specimens. Aluminum platens cause the highest stresses up to 40% compression, where rough (etched) steel platens take over.

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1. INTRODUCTION

Metal wire and flat rings have been used extensively in the vacuum industry as atmospheric seals. Rubber seals are too porous and degrade much too quickly to be effective in an ultra-high vacuum environments where radiation damage is also a factor, such as in the LAMPF proton storage ring. Metal seals eliminate this difficulty, but can still provide problems because of poor compressive flow characteristics. Since the seal material must be significantly softer than the vacuum chamber itself, metals such as copper, aluminum, gold and iridium are commonly chosen for this application. The seals are prepared from fully annealed alloys to ensure uniform flow when clamped between the chamber surfaces.

The particle accelerator at the Los Alamos Meson Physics Facility (LAMPF) operates at a vacuum of approximately 10^{-10} to 10^{-12} MPa (10^{-6} to 10^{-8} Torr), with the proton storage ring at the end of the beam line operating at 10^{-12} to 10^{-13} MPa (10^{-8} to 10^{-9} Torr). Rubber and polymer seals are good only down to approximately 10^{-10} MPa (10^{-6} Torr), and are insufficient for use in a high radiation environment. Figure 1.1 shows the layout of the accelerator at LAMPF, and Figure 1.2 gives a view of the radio-frequency accelerator section of the beam line. Metal seals are required in all chamber section joints and at portals used for servicing, observation, instrumentation and experimentation. Since the facility accelerates charged particles (H^+ , H^- and polarized H^-) to $0.84c$ (or eighty-four percent of the speed of light) with an energy of 800MeV, there are significant radiation damage effects to consider. In a recent paper addressing this subject, Sommer [2] listed the following as major concerns: "Strength,

ductility, rupture lifetime, and cyclic fatigue lifetime are all changed, generally in an adverse way. Volumetric swelling and stress-induced radiation-enhanced creep lead to dimensional changes that often cause difficulty." [2] Thus, a seal material must be chosen for both plastic-flow properties and irradiation characteristics.

Figure 1.1: The Los Alamos Meson Physics Facility located in Los Alamos, New Mexico. [1]

Figure 1.2: The third stage of the LAMPF accelerator. It is located 9 meters underground and is 731 meters long. The inset to the right is a cut-away view of one section of this stage. [1]

Aluminum 1100 alloy wire is currently used at LAMPF because of its low strength, high ductility, and low activation relative to stainless steels (transmutants decay rapidly after beam shut-down). This application works fine with the aluminum seals between the original 304L stainless steel chamber pieces. However, aluminum alloys produce much lower dose rates than steel does in the short period after beam

shut-down as a result of the difference in irradiation-induced transmutants. Figure 1.3 shows the dose rate as a function of time after irradiation for these two metals. After only 3 days, the aluminum dose rate is an order of magnitude lower than the steel. For this reason, the facility is in the process of replacing the highly activating stainless steel with aluminum 6061-T6 sections. Operation during the past two years with test sections of this alloy have presented difficulties in consistently achieving secure aluminum to aluminum vacuum seals.

Figure 1.3: Dose rate as a function of decay time for equal volumes of aluminum alloy 6061 and stainless steel alloy 304L. NOTE: These curves are for equal, short-term doses where ^{22}Na is **not** saturated in the Al; Allowing the 2 metals to achieve equilibrium under irradiation would cause the aluminum curve to increase to within a factor of 2 of the stainless steel curve. [3]

The experiments of this study were performed to determine the cause of the inability to routinely achieve proper aluminum to aluminum sealing between the Al 6061 vacuum housing sections. Unlike tensile testing which is standardized with well established procedures, compression testing is still very loosely defined in terms of both testing methods and interpolation of results. In the American Society of Testing and Materials (ASTM) Definitions of Terms Relating to Methods of Mechanical Testing (E 6), compressive strength is arbitrarily defined as the "degree of distortion which is regarded as indicating complete failure of the material." [4] There is no standard measure (like the 0.2% offset yield stress in tension tests) to use in comparing different materials. Factors such as friction, cracking and density changes (all of which are discussed in Section 2) greatly affect compressive stress vs. strain data as measured experimentally. Thus, the results are extremely dependent on the method of compression (i.e. rate of the test, and type of compressing surfaces). Therefore, the experiments described here were designed to closely model the actual application of aluminum seals between flat steel and aluminum chamber material, and to determine the effects of changing geometric parameters such as length and height of the specimens on stress for a given height reduction.

1.1 OBJECTIVES

Experiments were performed to determine the differences in the plastic flow characteristics and compressive stress levels of soft aluminum alloys compressed between steel and Al 6061-T6 surfaces. The application was for large (25 to 50%)

compression levels which could be performed without extreme conditions in time and temperature. Thus, a series of room temperature and quasi-static compression tests were performed with the following objectives:

1. To determine the effects of friction from both polished and rough steel surfaces and the effects of Al-Al galling from compression with Al 6061-T6 surfaces.
2. To compare the stress versus reduction in height for cylindrical specimens compressed on-end and radially. Cylindrical compression (on-end) was performed for comparison with previous results and wire-type (radial) compression was performed to more closely model the application.
3. To determine the effects of various length to diameter ratios on compressive stress and hardness distributions.
4. To compare the plastic-flow properties of two possible seal materials (Al 1100 and Al 3003) and of 6061 for use as the chamber material.
5. To determine the effects of grain size and orientation on compressive strength and hardness.
6. To determine the effects of various heat treatments on the resistance to compressive deformation of Al 6061.

2. BACKGROUND

The properties of metals undergoing plastic flow are determined by several factors acting in unison. In tension experiments, the main elements that affect the alloy's strength are: the effects on the microstructure from any heat treatment or cold working, the presence of stress intensifiers or cracks, density changes, and the rate at which the experiment is performed. In compression experiments, surface friction effects, barreling, and roll-over of the material from the sides to the load-carrying surfaces must also be accounted for. A few experiments have been performed to attempt to isolate the effects of these factors on the strength and flow characteristics of metals. These experiments and their results are discussed on the following pages.

2.1 ONE-DIMENSIONAL EXPERIMENTS

One-dimensional, or uniaxial, testing is the most common type used to determine compressive plastic flow properties of metals. Uniaxial compression assumes radial symmetry in the plane perpendicular to the testing direction, making it ideal for compressing homogenous, cylindrical specimens. Figure 2.1 shows a typical specimen along with the geometry for cylindrical compression. This type of testing is easily performed using the same screw-drive or hydraulically actuated linear-motion machines used in tension experiments. Figure 2.2 shows a typical hydraulic testing system of this type used to investigate constant strain rate uniaxial compression. [5]

Figure 2.1: Specimen and geometry for cylindrical compression ($L/D=2$).

Figure 2.2: Hydraulic test stand with recorders and digital processor. [5]

The simplicities of one dimensional testing are offset by numerous problems associated with friction at the compressing surfaces. Friction between the testing machine and the specimen prevents deformation at the surface and therefore causes uneven plastic flow (*Friction* in compression experiments will be discussed further in Section 2.3). As the specimen is compressed, it spreads out near the equatorial plane, or barrels, which allows the force to be distributed over a larger area. This means that using the original area to calculate stress results in extremely high values. One method of accounting for barreling is to calculate an instantaneous average area. [4] This method approximates the experimental situation by assuming that the specimen retains a constant volume. By also assuming expansion without barreling, an instantaneous load carrying area can be calculated by converting each reduction in height into a corresponding increased radius, as shown below:

$$V = \text{constant} = \pi r_o^2 h_o = \pi r^2 h^2 \quad (2.1)$$

where r_o and r are initial and final radii, and h_o and h are initial and final specimen heights, respectively. At any given reduced height, h :

$$\text{Stress} = \frac{P}{\pi r^2} = \frac{Ph}{V} \quad \text{where } P = \text{Recorded load} \quad (2.2)$$

Thus, substituting Equation 2.1 into Equation 2.2 gives an expression for stress in terms of measured quantities, P , h , r_o , and h_o . Namely,

$$\text{Stress} = \frac{Ph}{\pi r_o^2 h_o} . \quad (2.3)$$

As barreling becomes significant, material from the sides of the specimen rolls over onto the compressing surfaces, providing a slightly larger load carrying area. This also increases the surface area of the specimen at the interface with the platens which in turn effects the frictional forces. As compression continues, the L/D ratio decreases and the amount of roll-over increases until the specimen can no longer spread freely through barreling and roll-over. Figure 2.3 shows a specimen that has been compressed to 70% of its original height. Note that past approximately 40% the stress increases dramatically. This transition is a function of L/D and will be discussed later in this report.

Figure 2.3: Experimental average axial stress and height reduction for $L/D=1$, 12.7mm dia. specimens of aluminum alloy Al 7075-T6 (upper solid curve) and Al 6061-T651 (lower broken curve). [4]

2.1.1 COMPRESSED SPECIMEN GEOMETRY

The geometry of a cylindrical specimen compressed uniaxially can be compared to its original shape to help characterize how the plastic flow propagated during the test. The amount of deformation that occurs is highly dependent on the position of the material in the undeformed billet. Figure 2.4 shows a steel specimen that has been cut longitudinally along its diameter. Figure 2.5 is a computer generation of the same

specimen obtained from HEMP, a finite difference computer code developed at Lawrence Livermore National Laboratory. [6]

Figure 2.4: Experimental cross-section of HRC 40 4340 steel specimen. [7]

EXPERIMENT VS THEORY*		
	TEST	HEMP
D ₁	.79	.78
D ₂	1.02	1.00
D ₃	1.22	1.23
H	0.65	0.64

* VALUES IN CENTIMETERS

Figure 2.5: Theoretical compression obtained by using HEMP. [7]

Note in Figure 2.5 the two diameters, D_1 and D_2 . D_1 represents the diameter of the original specimen, and D_2 is the diameter of the compressed specimen including the extra surface area caused by roll-over of the cylindrical surface onto the platen surface. Just inside D_1 there is a conical region (emphasized by the horizontal lines in Figure 2.5) which represents a relatively undeformed portion of the specimen that was directly under the platens during compression. This region is bounded in the figure by dotted lines which represent belts of high shear deformation. At the very center of the specimen, the material is placed in extreme axial compression. Finally, the top and bottom most sections of these two figures are the barreled surfaces where the billet is

subjected to large tensile hoop stresses. [7] As this region expands radially, it forces the material near the surface to spread out to meet the increased circumference. Figure 2.6 is a set of photographs corresponding to the microstructure of the billet in Figure 2.4 which shows the relative grain boundary sizes of the dead zone, the compressed specimen center, and the barrelled surface.

Figure 2.6: Photographs of a compressed cylindrical Cu specimen showing large undeformed grains directly under the platen (dead zone) (*left*), compressed grains at the specimen center (*center figure*) and non-uniform, compressed grains of the rolled-over sides (*right*). [8]

2.1.2 HARDNESS OF THE COMPRESSED SPECIMEN

Hardness testing of deformed specimens is commonly performed to help judge the extent to which inhomogeneities have developed during compression. The resulting data can be used to map out the relative sizes of dead zones, roll-over areas, and other deformed regions of the microstructure discussed in Section 2.1.1. Dadras *et al.* [8] took Knoop micro-hardness measurements on copper specimens that had been cut longitudinally as in Figure 2.4. Figure 2.7 shows the variation in these micro-hardness values for high friction compression (see discussion on this experiment in Section 2.3). The values shown are displayed in ratios of local hardness numbers to the hardness of the undeformed billet. Note the low values of 1.00 and 1.17 associated with the dead zone (conical region of Figure 2.5), and of 1.03 on the barreled surface. The axially compressed central region discussed in Section 2.1.1 is also visible in the lower left corner of Figure 2.7 with a hardness ratio of 1.65. Hartley *et al.* [9] received similar results from micro-hardness tests of this type performed on commercially pure aluminum.

Figure 2.7: Distribution of Knoop hardness on right upper-1/4 section cut from a Cu specimen. Numbers are ratios of local hardness to the hardness of the undeformed billet. [8]

2.2 TWO-DIMENSIONAL EXPERIMENTS

Two-dimensional compression has been used extensively in the past as an accurate means of measuring plastic strain behavior of metals. [10,11,12] Biaxial testing eliminates the problems associated with unconstrained barreling present in the one-dimensional case discussed in Section 2.1. It also limits the specimen to expansion in one direction which leads to more straightforward calculations of strain (i.e. plane strain). In 1946, Bridgman [10] introduced a two-dimensional compression machine designed to provide accurate experimental results to compare with the Prandtl-Reuss classical theory of plasticity. His test machine used two hydraulic presses to apply load in two of the principal directions. Bridgman used continuous pressure control on one of the presses which allowed him to keep the strain at zero in that direction. The second

press was moved at a fixed speed to achieve a constant strain-rate under compression. Strain and load (calculated from a change in pressure on calibrated Bourdon gages) were recorded for the third principal direction.

Bell [11] developed a modified apparatus in 1983 that was based on Bridgman's two-dimensional experiments. This apparatus, shown in Figure 2.8, replaces Bridgman's moving hydraulic press with a dead-weight steel loading block. The block is moved by a common hydraulic or screw-actuated testing machine. It is constrained in one direction by tight fitting steel walls that, like Bridgman's machine, reduce the test to biaxial strain. The advantages of this apparatus are simplicity, accuracy, and the ability to measure stress and strain, simultaneously, in two principal directions.

Figure 2.8: 2-D compression apparatus designed for total constraint in direction 2 and reduced-friction motion along 1 & 3. [12]

The loads applied in direction 1 are read directly from a load-cell on the testing machine, and direction 1 strain is measured with a clip gage (clip gage 1 in Figure 2.7). Holes drilled in the steel frame allow another clip gage to measure strain in direction 3. [12] Figure 2.9 shows the path of applied load, and the directions in which stress and strain are measured for a typical rectangular specimen used in 2-dimensional compression.

Figure 2.9: Example of a rectangular specimen used in 2-dimensional compression tests.

2.3 EFFECTS OF FRICTION

Surface friction between the specimen and the compressing platen represents the largest single obstacle to the establishment of standards for testing metals in compression. Numerous approaches to solving this problem have been taken with little success in being able either to predict (and then account for it in calculations), or to overcome all the effects of friction. One method of dealing with this problem is to account for frictional effects by using data from specimens of varied geometry to extrapolate a *zero-friction* flow strength. [5] This method was first used by Cook and Larke [13], who experimented with specimens of various length to diameter (L/D) ratios. They noticed, while performing uniaxial compression on copper alloys, that frictional effects are less on thin (high L/D ratio) cylinders than on short (low L/D ratio) ones. To account for this friction input, they obtained data for a series of L/D ratios, plotted these as stress vs. L/D , and extrapolated a *zero-friction* flow strength.

Another process used to take care of surface friction is to decrease it to a negligible level by placing some form of lubrication between the surfaces. This approach was taken by Dadras *et al.* [8] in their experiments by using Teflon_® wafers to separate the cylindrical copper specimens from the compressing platens. Figure 2.10 shows the very small barreling that occurred with the use of Teflon_® compared to compression under high friction surfaces.

Figure 2.10: Barreling caused from polished and Teflon_® coated platens (*left*), and from platens coated with abrasive foil (*right*). [8]

Various types of oils and greases are also used to reduce the effects of friction to negligible levels. In their experiments with the two-dimensional compression apparatus shown in Figure 2.8, Khan and Wang [12] used small amounts of grease to decrease friction. They had previously tried using Teflon_® alone, but friction from fixed surfaces in two directions remained significant. From their results obtained from using both grease and Teflon_®, they concluded that "the specimen can undergo fairly large compressive strain without significant barreling so that the deformation is kept uniform." [12] However, there is no conclusive data which shows that the compressive stresses obtained in either of these experiments is adequately void of frictional effects. Since there is no true *zero-friction* condition for comparison, the cases using lubrication (petroleum or Teflon_® wafers) are still, at best, acceptable approximations.

The type and condition of platens used in both uniaxial and biaxial compression

also play a large role in determining the effects of surface friction on total stress.

Dadras and Thomas [8] performed a series of experiments in which stresses in copper billets were recorded under compression from two very different surfaces. First, the billets were tested with highly polished tungsten carbide platens with thin Teflon[®] sheets as added lubricant (coefficient of friction, $\mu=0.1$). For the second set of experiments they used sandblasted sheets of copper that had been sprayed with fine abrasives ($\mu=1$) between the platen and the copper billets. Photographs showing the degree of barreling from these two surfaces were shown in Figure 2.9. The load vs. displacement curves for these experiments on 28.6mm long specimens is shown in Figure 2.11. Notice that the *rough* surface causes higher loads at low height reductions, but at height reductions greater than 40%, the *polished* surface recorded higher loads. At small height reductions, the abrasives provided an uneven surface that resisted the easy deformation that should occur at the surface under relatively low loading. Under high loading, the large surface area between the smooth platen and the billet presented a situation for supporting extreme loads without yielding. As support for this, note in Figure 2.12 that, in a clean environment, highly polished metals have much higher friction factors than rough surfaces. In contrast, the small, sharp abrasives on the copper foil acted to cause high, localized stresses which led to greater yielding (represented as larger height reduction) at significantly lower loads.

Figure 2.11: Experimental and theoretical Load vs. Displacement curves for low and high friction compression of specimens in Fig. 2.9. [8]

TABLE 2.1
Coefficients of Friction for Common Materials. [14]

Material	μ
Perfectly clean metals in vacuum	Seizure $\mu > 5$
Clean metals in air	0.8-2
Clean metals in wet air	0.5-1.5
Steel on dry bearing metals (e.g. lead, bronze)	0.1-0.5
Steel on ceramics (e.g. sapphire, diamond, ice)	0.1-0.5
Ceramics on ceramics (e.g. carbides on carbides)	0.05-0.5
Polymers on polymers	0.05-1.0
Metals and ceramics on polymers (PE, PTFE, PVC)	0.04-0.5
Boundary lubrication of metals	0.05-0.2
High-temperature lubricants (MoS_2 , graphite)	0.05-0.2
Hydrodynamic lubrication	0.001-0.005

The effects of platens are also extremely material dependent. In several situations with commonly used metals (although it was not the case at large height reductions in the results of Figure 2.11), smooth surfaces between metals of differing hardness represent a very low friction situation. The smooth surface of the harder material allows very easy flow of the softer material during yielding. However, smooth surfaces between metals of similar hardnesses can cause extremely high friction situations. Two aluminum materials held in contact under a load are prone to galling, often severe enough to destroy the surfaces when sliding over each other under small normal forces. When alloys of aluminum are tested in compression and forced to flow

under high normal forces, very high stress situations are created, as is shown in the experimental results that follow.

2.4 CRACK FORMATION

Surface cracking of metals in compression can be severe under large height reductions, especially in cylindrical billets where material on the equatorial surface is placed in tension as the specimen spreads out. These cracks are reported in most studies of uniaxial compression, but very little is known about the effects they have on strength. A series of tests on aluminum alloys placed in compression was performed by Papirno, Mescall, and Hansen. [4] The goal of these tests was to determine the effects of cracks that develop on the barreled surface on the yield strength and plastic flow characteristics of Al 7075 and Al 6061-T651 alloys. The experiments were performed on right circular cylinders with L/D ratios of 1 and 2. The samples were loaded axially in a 267kN capacity screw-actuated Weidemann-Baldwin (W-B) testing machine. They were compressed at a rate of approximately 1.5×10^{-5} m/s (1mm/min) to final reductions in height of 15 to 80 percent.

Surface deformation in the Al 6061-T651 specimens was observable at 5 to 7 percent reduction in height. At this point of compression, small surface wrinkles appear on the barreled surface. These wrinkles, commonly called the "orange peel effect," increase in size as compression continues, and extend from the bottom to the top surface at approximately 45 degrees to the vertical axis. As shown in Figure 2.12,

shear forces turn these wrinkles into micro-cracks at height reductions greater than 70%. The $L/D = 1$ specimen was compressed 65% with a maximum stress of 673MPa and showed no visible cracks. The stress in the $L/D = 2$ specimen is approximately 75% of that shown for the $L/D = 1$ specimen, yet it showed many large cracks when viewed under a microscope. This led Papirno *et al.* to the conclusion that for Al 6061-T651, "crack formation in compression is influenced more by deformation than by axial stress." [4]

Figure 2.12: Compressed aluminum alloy Al 6061-T651, cylindrical specimens, Dia=12.7mm. *TOP*: $L/D=1$, Height Reduction=65%. *BOTTOM*: $L/D=2$, Height Reduction=70%. [4]

Cracks appeared in the Al 7075-T6 cylinders at approximately the same 5 to 7 percent reduction in height that was observed with the 6061 samples. However, as Figure 2.13 shows, the surface deformation is much larger than was seen in the 6061 specimen with several large cracks visible. This alloy has a 0.2% offset yield stress of 634MPa which is approximately twice that of Al 6061-T651. [14] Yet, Figure 2.3 shows that the final stresses are approximately equal for the two alloys. Thus Mescall hypothesized that extensive cracks in the 7075 alloy decreased the load carrying capabilities of the specimen, while the 6061 stayed virtually intact.

Figure 2.13: Compressed aluminum alloy Al 7075-T6, cylindrical specimens, Dia.=12.7mm. *TOP*: L/D=1, Height Reduction=67%. *BOTTOM*: L/D=2, Height Reduction=72%. [4]

In a companion paper to that of Mescall *et al.* mentioned previously, the effects of fracture during compression are compared to similar cracks in tension specimens. The following is an excerpt from the paper that describes the vast difference in these two crack types:

Fracture at either the equatorial surface or along internal conical surfaces does not necessarily signal the end of the load carrying capacity in the upset test. In fact, the fractured specimens continue to support an increasing load, in marked contrast to the tension test, where the load drops sharply shortly after fracture is nucleated in the interior. [7]

2.5 EFFECTS OF GRAIN SIZE

The effects of grain size on plastic flow properties and compressive strength is also dependent on the type of metal tested. In ductile metals, small grains allow easier flow and thus lower compressive yield strength. In contrast, large grain sizes in brittle metals promote surface cracks that also reduce the strength required for compressive yielding.

The effects of grain size on strength of Al 7075 and Al 6061 alloys was investigated by Papirno *et al.* in the paper discussed previously. Grain size measurements were taken on both alloys to help identify the difference in crack formation. The 7075 aluminum had larger grains with an average size of 264 μ m. This was nearly twice the size of the 143 μ m grains of the 6061 alloy. With this information, they made the conclusion that visible cracks and "surface wrinkling (are) the result of

intergranular slip and the larger 7075 surface deformation is related to its larger grain size." [4] Thus, for a given amount of compression, the 6061 alloy had more useful load carrying area left.

2.6 STRAIN RATE AND CREEP SENSITIVITY

Specimen dependence on loading history and strain rate is seldom considered significant in compression experiments. However, in applications requiring high impact loads or extended periods of compressive loading these areas could become a significant factor in design. Lenard [15] designed a set of experiments to test two aluminum alloys under single and multistage uniaxial compression. The chemical composition by weight percent is given in Table 2.2. Lenard used the hydraulic testing machine shown in Figure 2.2 to compress axi-symmetric specimens at constant strain rates ranging from 0.2 to 70sec^{-1} . The first alloy (Al-4.48Mg) was tested at strain rates of 0.2 and 10.5sec^{-1} . Identical specimens were then tested in two stages beginning at a rate of 25sec^{-1} to a strain of 0.25, interrupted for 100ms, and then strained at 0.7sec^{-1} to a strain of 70 percent. The results of these tests are shown in Figure 2.14. From this, Lenard determined that the alloy was independent of effects from rate of compression, loading history, and creep during the interrupt period.

TABLE 2.2
Chemical Composition by wt% of Aluminum Alloys used by Lenard. [15]

	Cu	Fe	Mg	Mn	Ni	Si	Ti	Zn	Al
Al + Mg	.003	.003	4.84	.001	.001	.003	.001	-	rest
Al + Mg + Si	.002	.002	1.00	.001	.001	0.64	.001	.001	rest

Figure 2.14: One and Two-Stage test results for Al-4.84Mg. [15]

The addition of silicon and the reduction in magnesium content gave Lenard's second alloy (Al-1Mg-0.64Si) lower strength and higher rate sensitivity. The results of these experiments (see Figure 2.15 below) show that increasing the strain rate from 1 to 50sec^{-1} raises the strength at low strains by 10 percent. [15] Finally, he performed a six stage test on the Al-Mg-Si alloy which gave the discontinuous curve shown in Figure 2.16 and is presented as further support for the conclusion of rate dependence given above. Thus, for these two aluminum alloys, rate dependence was relatively small, and only occurred for high strain rates at low true strains.

Figure 2.15: One and Three-Stage test results for Al-1Mg-0.64Si. [15]

Figure 2.16: Six stage compression of Al-1Mg-0.64Si. [15]

3. EXPERIMENTAL PROCEDURE

The emphasis in these experiments was on comparing the plastic flow properties of different aluminum alloys. Monitoring three-dimensional stress vs. strain characteristics was not a primary goal, and thus the uniaxial compression method (described in Section 2.1) was chosen to maximize simplicity in testing and to minimize friction effects. As described in the introduction, application to vacuum seals calls for room temperature, quasi-static, uninterrupted compression. The testing method closely models these conditions through a constant, rate-controlled compression of 1mm/min. Thus, the qualities of rate-dependent compression and the effects of creep in multistage compression were not investigated in these experiments.

3.1 ALLOYS STUDIED

Three aluminum alloys of varied strength, heat treatment and composition were tested in compression. Two of these alloys, Al 1100 and Al 3003, were examined for use as soft metal seals in the Los Alamos accelerator beam line. The third alloy, Al 6061, was tested to determine its strength properties for application as the main beam line vacuum housing, and to serve as a comparison to the similar uniaxial compression experiments by Papirno *et al.* [4]. In the tensile test data in Table 3.2, Al 1100 is listed with approximately 85% of the strength of Al 3003. However, since both alloys have values significantly lower than the yield strength of Al 6061, the important issue is how each of these ductile alloys flows after loading past the elastic limit. Table 3.1

gives the elemental constituents of each alloy studied, and Table 3.2 gives the corresponding tension test results.

TABLE 3.1. Chemical Composition Limits of Wrought Al Alloys. [16]¹

ALLOY	Si/Fe	Cu	Mg	Mn	Cr	Zn	Ti	Other ²	Al(Min.)
1100	1.02 ³	.05-.2	.05	...	...	.10	...	.15	99.00
3003	.6/.7	.05-.2	1-1.5	...	...	.1	...	.15	Remainder
6061	.5/.7	.15-.4	.15	1.0	.35	.25	.15	.15	Remainder

1. Composition is in maximum wt% unless shown as a range.
2. **Other** refers to total percent of other components in percent.
3. Total of Si + Fe is a maximum of 1% by weight.

TABLE 3.2. Tensile Properties of Aluminum Alloys (Units=MPa). [17]

ALLOY	HEAT TREATMENT	YIELD STRENGTH	TENSILE STRENGTH
1100	NONE	35	90
3003	NONE	40	110
6061	S (Soln. Annealed)	210	280
6061	O - TEMPER	245	295
6061	H - TEMPER	300-340	380-415

3.2 MATERIALS PREPARATION

The aluminum alloys described in Section 3.1 were available in three forms: rod (various sizes), wire, and flat-rolled plate. Table 3.3 shows the initial form and the final testing geometry of each alloy.

TABLE 3.3. Initial and Tested Forms of the Aluminum Specimens

ALLOY	INITIAL FORM	INITIAL SIZE(mm)	FINAL CYLINDER TEST DIMENSIONS(mm) ¹
AL 1100	WIRE	1.27 (dia)	1.27 (dia), 6.35 (long)
	WIRE	1.60 (dia)	1.60 (dia), 6.35 (long)
	PLATE ²	6.35 thick, 1% stretch	6.35 (dia), 6.35 (long) 6.35 (dia), 12.7 (long)
AL 3003	PLATE ²	6.35 thick, 1.5% stretch	6.35 (dia), 6.35 (long) 6.35 (dia), 12.7 (long)
AL 6061	ROD	3.17 (dia)	3.17 (dia), 6.35 (long)
<i>Initial T6 treatment</i>	ROD	6.35 (dia)	6.35 (dia), 6.35 (long) 6.35 (dia), 12.7 (long)
	ROD	12.7 (dia)	12.7 (dia), 12.7 (long) ³

1. Final dimensions correct to +/- .01mm.

2. Plate was stretched to straighten (after rolling); length and width varied.

3. These were inserted between the steel platens and specimens for the Al on Al tests.

3.2.1 CUTTING THE SPECIMENS

a) **6061**: The Al 6061-T6 rods were cut initially with a metal band saw. The specimens were then placed on a metal lathe and machined into right-circular

cylinders with the dimensions shown in Table 3.3.

b) **1100 (wire)**: The 1.27mm and 1.60mm diameter wire samples were cut from standard commercial spools with wire-cutters to arbitrary lengths of approximately 20mm. Since the platen surfaces measure 12.7mm in diameter, the excess length of wire at the ends was enough to ensure that no work-hardening of the compressed portion occurred during cutting. This excess length was left on the specimens (which were compressed only radially, not cylindrically) and was not a factor in the experiment.

c) **1100 & 3003 (plate)**: Right-circular cylindrical specimens of Al 1100 and Al 3003 alloys were cut from 6.35mm (1/4") flat plates provided by Anderson [18] of Reynolds Aluminum. To best simulate both commercially-drawn wire, and the purchased 6061-T6 rod, the orientation of grain boundaries had to be determined in the plates. Three samples were taken from each plate and were set in epoxy for polishing and grain boundary etching. Each sample represented a different face (A,B or C) of the plate as shown in Figure 3.1. The samples were polished on a metal polishing wheel using an aqueous solution containing 0.3 μ m aluminum particles followed by a solution containing 0.05 μ m particles. After polishing, the samples were etched using electrolysis in a solution of Barker's Etch (see Appendix A for explanation of Barker's Etch and the etching process). The specimens were then rinsed in ethanol and viewed under a

microscope using a magenta polarizing filter. Figures 3.2 through 3.7 are photographs of these grain boundaries.

Figure 3.1: Plate aluminum, 12.7mm thick, that was etched on faces A, B, and C to determine relative grain boundary sizes and orientation.

Figures 3.2: Grain boundaries of Al 1100 6.35mm thick plate taken from plane A of Figure 3.1. Grains are slightly elongated along direction B, denoting an increase in length during rolling.

Figure 3.3: Grain boundaries of Al 1100 6.35mm thick plate taken from plane B of Figure 3.1. Grains are extremely elongated horizontally which is the direction corresponding to the length of the plate.

Figure 3.4: Grain boundaries of Al 1100 6.35mm thick plate taken from plane C of Figure 3.1. Grains are elongated in this direction which corresponds to a slight increase in width on rolling. **NOTE:** Markings visible in the upper right corner are scratches caused by the cathode while etching.

Figures 3.5: Grain boundaries of Al 3003 6.35mm thick plate taken from plane A of Figure 3.1. Grains are slightly elongated along direction B denoting an increase in length during rolling.

Figure 3.6: Grain boundaries of Al 3003 6.35mm thick plate taken from plane B of Figure 3.1. Grains are extremely elongated in this direction corresponding to the length of the plate.

Figure 3.7: Grain boundaries of Al 3003 6.35mm thick plate taken from plane C of Figure 3.1. Grains are elongated in this direction which corresponds to a slight increase in width on rolling.

Notice that the grains in Figures 3.2 and 3.5 (representing side A, or the top, flat surface of the plates) have large, uniform grains, while the grains in planes B and C are greatly elongated from the rolling process (Figures 3.3, 3.4, 3.6 & 3.7). These large grains are a result of the elongation that occurs during rolling in directions B and C which cause the view of these grains to expand in both directions in plane A. This information dictated that the best solution was to cut the plate along its length so that it corresponded to the length of the specimen. This orientation offered the best simulation of a rod (which would be extremely elongated as observed in plane B). It should be recognized, however, that a true rod would be uniformly elongated in plane A as well as plane B of Figure 3.1.

Several long rectangles were cut in the direction of the arrows in Figure 3.1 from each plate. These rectangles were milled to 6.35mm (1/4") on a side and were then placed in a lathe and turned down into long cylinders of 6.35mm diameter. At this point, the pieces cut from the plates had been reduced to 6.35mm diameter rods and the process described above for cutting and shaping the Al 6061 samples was repeated.

3.2.2 HEAT TREATMENT

Al 1100 and Al 3003 alloys do not form significant precipitates when heat treated. However, the strength and ductility properties of Al 6061 are highly dependent on the history of heat treatment imposed on the alloy. The 6061 test specimens were

purchased as rods with T6-temper for increased strength. To determine the effect of different heat treatments on the compressive behavior, the specimens were given H and O tempers, after first being placed in a furnace and restored to a solution annealed state. This process is described below.

1. **Encapsulation:** The 6061 cylindrical specimens were encapsulated in groups of 4 to 6 under a vacuum of 737mm of mercury in 6mm (1/8" dia. specimens) and 8mm (1/4" dia. specimens) quartz tubing. Several small pieces of titanium sponge were added to prevent any left-over air in the tubes from oxidizing the specimens. Next, the tube was partially closed with approximately 20mm of room above the samples, and was then evacuated. The tube was held in this state for 1 minute, after which it was back-filled with argon to atmospheric pressure to flush out all remaining air. Evacuation and back-filling was repeated 4 times. After pulling the vacuum the 4th time, the tube was partially back-filled to only 254mm of mercury and then sealed with an acetylene torch.

2. **Solution Annealing:** 2/3 of the tubes containing the Al 6061 specimens were placed on ceramic blocks in a cold furnace. They were then heated with a ramp rate of 93°C per hour. Upon reaching 532°C, the capsules were held at a constant temperature for 1.5 hours and then quenched, individually, in ice-water. To facilitate rapid quench, each tube was broken with pliers as it entered the ice-water bath.

3. **O-Temper:** The furnace was preheated to 413°C. The remaining 1/3 of the encapsulated specimens (not annealed) were placed in the furnace for 2.5 hours. The furnace was then turned off to allow slow cooling of the capsules. The tubes remained in the furnace until they returned to room temperature.

4. **H-Temper:** Half of the specimens that had been annealed were again encapsulated and placed in a cold oven. The oven was heated quickly (approximately 1°C/sec) to 160°C and held for 18 hours. The oven was then turned off, and the samples were removed and allowed to air cool.

5. **Summary of Al 6061 Heat Treatment:**

Group 1- (22 total specimens) Solution Annealed

Group 2- (22 total specimens) O-Tempered

Group 3- (22 total specimens) H-Tempered

3.3 TEST MACHINE

The machine used to perform these experiments was a MODEL 850A hydraulically-actuated INSTRON test stand, identical in layout to the system used by Lenard that was shown in Figure 2.2. Load was measured with a 10MTon MTS load cell located on the top (stationary) ram. Specimens were compressed vertically through movement of the lower ram. An INSTRON MODEL 8500 hydraulic control unit and digital to analog converter was used to link the test stand to an Apple Macintosh computer. The computer recorded displacement (up to 510 points) and load.

3.4 TESTING SPECIFICATIONS

Two types of compression geometry, cylindrical and wire, were used in these experiments. In both cases, the load was applied with a single ramp rate of $1.67 \times 10^{-5} \text{ m/s}$ (1mm/min). Specimens were compressed to height reductions of both 40 and 70 percent. Height eduction is defined as:

$$\text{Height Reduction} = \frac{(\text{Initial Height} - \text{Final Height})}{\text{Initial Height}} \times 100\%$$

3.4.1 CYLINDRICAL COMPRESSION

Compression of the cylindrical specimens on-end was performed for two reasons: Calculation of instantaneous area was much easier than in wire compression, and similar previous experiments could be referenced for comparison of results. The following comparisons were made (see Table 3.4):

1. **Alloy comparison:** The five different specimens, Al 1100, 3003, 6061-SA(solution annealed), 6061-O and 6061-H were compared for strength vs. reduction in height.
2. **Compression Amount:** Each specimen type was compressed to a height reduction of 40%, and then an identical specimen was compressed to a height reduction of 70%. The two curves were compared for agreement to 40% compression.
3. **Length/Diameter Ratio:** The effect of L/D ratios on compressive strength was investigated by compressing L/D specimens of 1:1 and 2:1 6.35mm diameter cylinders. #.17mm diameter cylinders were also tested with L/D=2 for Al 6061.

4. **Platen Type:** Specimens including all variations of conditions 1 through 3 (previous page) were compressed between three types of platens to determine the effects of friction with the platen on compressive strength and ability of the specimen to flow in compression: polished 304L stainless steel, rough 304L stainless steel, and Al 6061-T6. Rough steel platens were created by filing the surface of stainless steel platens in a two-directional cross pattern to a depth of approximately 1mm and a spacing between peaks on the surface of 0.11mm.

5. **Repetition:** Each experiment was performed twice to determine accuracy of the recorded load vs. displacement data.

Table 3.4: Summary of Cylindrical Compression Tests.

TEST TYPE	COMPARISONS MADE (2 REPETITIONS EACH)
Alloy Type	Al 1100, 3003, 6061-SA, 6061-H
Hgt. Reduction	40%, 70%
L/D Ratio	1:1, 2:1 (includes 2:1 for 6061 3.17mm dia.)
Platen Type	Polished 304L SS, Rough (etched) SS, Al 6061-T6

3.4.2 WIRE COMPRESSION

Wire-type (or radial) compression was performed to better model the plastic flow conditions of wire seals. The cylindrical specimens were compressed radially to compare with cylindrical compression. Then, the two variations (1.27mm and 1.60mm diameter) of Al 1100 wire specimens were tested under identical conditions for comparison with results from the larger diameter (rod) specimens. The following parameters were compared in wire compression (see Table 3.5):

1. **Alloy Comparison:** Same as above.
2. **Compression Amount:** Same as above.
3. **Length to Diameter Ratios:** Same as above. NOTE: In radial compression, height=diameter. So, the initial height of the specimen is equal for $L/D = 1$ and 2. The surface area touching the platen (not the initial space between platens) varies with L/D .
4. **Plate Type:** Specimens of each type in parameters 1-3 were compressed between the following two platens: polished steel and Al 6061-T6. Rough steel platens were also used in compressing the Al 1100 wire samples (discussed in #6 below).
5. **Repetitions:** Same as above.
6. **Testing of Wire Samples:** Al 1100 wire was tested in the two diameters listed above. The wires were longer than the platen diameter so that an undamaged length of 12.70mm was compressed to height reductions of 40% and 70%. Four repetitions of each variation were tested.

Table 3.5: Summary of Wire (Radial) Compression Tests.

TEST TYPE	COMPARISONS MADE (2 REPETITIONS EACH)
Alloy Type	Al 1100, 3003, 6061-SA, 6061-H
Hgt. Reduction	40%, 70%
L/D Ratio	1:1, 2:1 (includes 2:1 for 6061 3.17mm dia.)
Platen Type	Polished SS, Al 6061-T6; Rough SS for Al 1100 small dia. wire only
Small Dia. Wire	Al 1100: 1.27 & 1.60mm dia. wire vs. 6.35 & 3.17mm dia. samples

3.5 POST-COMPRESSION HARDNESS TESTING

Micro-hardness testing was performed on the following specimens, after compression, to test the effects of changing the test parameters on localized hardness values. These tests are described in Table 3.6. Tests 2, 4, 5 and 6 are variations of test 1 (test 3 is a variation of test 2) with the changes shown in the COMMENTS column on the right:

Table 3.6: Micro-hardness Tests Performed on 1/8-specimen Sections.

No.	Alloy	Dia(mm)	L/D	Percent Compressed	Type of Compression	Comments
1	Al 1100	6.35	2	70	Cylindrical	Used as Control Specimen
2	Al 1100	6.35	1	70	Cylindrical	L/D Effects
3	Al 1100	6.35	1	40	Cylindrical	Compression Amt. Effects
4	Al 1100	6.35	2	70	Wire	Compare Wire vs. Cyl.
5	Al 3003	6.35	2	70	Cylindrical	Al 1100 vs. Al 3003
6	Al 6061-H	6.35	2	70	Cylindrical	Al 1100 vs. Al 6061-H

A Vicker's imprinting diamond was used for the hardness measurements. The diagonals of the indentation were measured and an average of the two was used to determine imprinted area (and thus hardness). Figure 3.8 shows how each specimen was sectioned for hardness testing. Finally, micro-hardness testing was performed on an Al 6061-T6 platen to determine the stresses imposed from the compression of the Al 6061-H specimen described under #1 above. Hardness measurements were taken at 45 points over the surface that was in contact with the specimen during compression. The top 2mm of the surface was removed and the surface was polished prior to hardness

testing. This was necessary because the platen had been indented approximately 2mm during compression.

Figure 3.8: Vertical cross-section showing crossed lines that denote cuts made on 1/2 of a compressed sample (cut to give the vertical cross-section shown above) to get the 1/8-specimen section shown to the right that was used for micro-hardness analysis.

4. RESULTS

The results contained in this section consist of three separate areas:

1. cylindrical compression data.
2. radial (wire) compression data.
3. post-compression micro-hardness results.

During the compression tests, the INSTRON equipment recorded load vs. displacement data. The load values were converted to stress using an area factor that was characteristic of the deformation observed during the test. To help interpret the recorded data, the resulting stress vs. height reduction curves (instead of the original load vs. displacement curves) are included in Section 4.2 and Section 4.3. The equations for calculating area from Section 5.1 and Section 5.2 can be used to retrieve load values registered during the test from these curves, and the equation that defines height reduction in terms of displacement and initial height (shown in Section 3.4) can be used to obtain original displacement values.

4.1 SPECIMEN REPETITION

One hundred and twelve test specimens were required to apply every test condition shown in Section 3.4. The calculation of this total is presented in Table 4.1.

Table 4.1: Calculation of Total Number of Compression Tests Completed.

Test Type	Alloys	% Compressed	L/D	Platen	Total
Cylindrical	5	2	2	3	60
Radial	5	2	2	2	40
Wire (Al 1100)	1	2	2	3	12
TOTAL:					112

Repetitions were completed for each of the 112 cases to determine the validity of the results. Two repetitions were performed for each of the 100 combined cylindrical and radial tests. Four repetitions were performed for each case of the two types of Al 1100 wire. Thus, a total of 248 specimens were tested. Figure 4.1 and Figure 4.2 display the curves for two repetitions for cylindrically compressed and radially compressed Al 1100 alloy specimens, respectively. In nearly all cases (with the exception of cases where the platens failed), the data was reproducible to within $\pm 5\%$. In a few of the cases using only two repetitions, greater differences occurred. For these specimens, curves from 40 and 70 percent were compared. As will be discussed later in Section 5, this effectively doubled the amount of repetitions, and the abnormal curve was identified and subsequently discarded.

Figure 4.1: Stress vs. height reduction for two Al 1100 cylinders compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, L/D=1, Compression=70%. (units in mm)

Figure 4.2: Stress vs. height reduction for two Al 1100 cylinders compressed with polished steel platens. Radially compressed. Diameter=6.35, $L/D=1$, Compression=40%. (units in mm)

4.2 CYLINDRICAL COMPRESSION RESULTS

Compression of 120 right-circular cylinders was performed to meet the test parameters described in Section 4.1 (60 cases were outlined in Section 4.1 with two repetitions per case). Half of these cylinders were compressed to 40%, and the other half were compressed to 70%. It will be shown in Section 5 that a high degree of accuracy exists between 40 and 70% curves (assuming all other parameters are held constant). Therefore, only plots showing the full 70% reduction in height are shown. Figures 4.3 through 4.30 give the stress (figured from *average area stress* described in Sections 2.1 and 5.1) associated with reductions in height to 70% for cylindrical compression with each of the three platen types. Table 4.1 lists these specimens by platen type and includes stresses for height reductions of both 30 and 60% (stresses were read directly from the curves that follow).

NOTE: A few specimens were compressed where the computer failed to record the load vs. displacement data. There are no results available for these tests, and they will be listed in the tables with stress=NONE. For cylindrical compression to 70%, the unusable samples include:

1. Al 6061-S with Dia.=6.35mm, L/D=2, compressed with Al 6061-T6 platens.
2. Al 6061-S with Dia.=3.18mm, L/D=2, compressed with rough steel.

To allow for easy comparison between graphs, all plots shown in the next two sections (4 & 5) will be plotted from 0-70% height reduction and from either 0-350MPa (for 1100 and 3003 alloys) or 0-700MPa (for 6061 alloy).

TABLE 4.1
SUMMARY OF CYLINDRICAL COMPRESSION RESULTS

FIGURE #	ALLOY	DIAM.(mm)	L/D	STRESS: 30% (MPa)	STRESS: 60% (MPa)
PLATEN:	POLISHED STEEL				
4.3	1100	6.35	1	192	255
4.4	1100	6.35	2	188	228
4.5	3003	6.35	1	155	200
4.6	3003	6.35	2	142	155
4.7	6061-H	6.35	1	430	460*
4.8	6061-H	6.35	2	395	330
4.9	6061-H	3.175	2	392	410
4.10	6061-S	6.35	1	380	445
4.11	6061-S	6.35	2	345	380
4.12	6061-S	3.175	2	335	370
PLATEN:	AL 6061-T6				
4.13	1100	6.35	1	208	265
4.14	1100	6.35	2	198	235
4.15	3003	6.35	1	165	225
4.16	3003	6.35	2	158	195
4.17	6061-H	6.35	1	470	470*
4.18	6061-H	6.35	2	420	458*
4.19	6061-H	3.175	2	430	475
4.20	6061-S	6.35	1	425	435*
NONE	6061-S	6.35	2	NONE	NONE
4.21	6061-S	3.175	2	338	410*
PLATEN:	ROUGH STEEL				
4.23	1100	6.35	1	215	290
4.24	1100	6.35	2	196	235
4.25	3003	6.35	1	160	217
4.26	3003	6.35	2	158	200
4.27	6061-H	6.35	1	460	585*
4.28	6061-H	6.35	2	414	476
4.22	6061-H	3.175	2	420	460
4.29	6061-S	6.35	1	395	485*
4.30	6061-S	6.35	2	355	420
NONE	6061-S	3.175	2	NONE	NONE

* 60% Stress values are abnormally low due to platen failure.

Figure 4.3: Stress vs. height reduction for aluminum 1100 cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.4: Stress vs. height reduction for aluminum 1100 cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.5: Stress vs. height reduction for aluminum 3003 cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.6: Stress vs. height reduction for aluminum 3003 cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.7: Stress vs. height reduction for Al 6061-H cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.8: Stress vs. height reduction for Al 6061-H cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.9: Stress vs. height reduction for Al 6061-H cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=3.175, Length=6.35, Compression=70%. (units in mm)

Figure 4.10: Stress vs. height reduction for Al 6061-S cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.11: Stress vs. height reduction for Al 6061-S cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.12: Stress vs. height reduction for Al 6061-S cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=3.175, Length=6.35, Compression=70%. (units in mm)

Figure 4.13: Stress vs. height reduction for Al 1100 cylinder compressed with aluminum 6061 platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.14: Stress vs. height reduction for Al 1100 cylinder compressed with aluminum 6061 platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.15: Stress vs. height reduction for Al 3003 cylinder compressed with aluminum 6061 platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.16: Stress vs. height reduction for Al 3003 cylinder compressed with aluminum 6061 platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.17: Stress vs. height reduction for Al 6061-H cylinder compressed with Al 6061 platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.18: Stress vs. height reduction for Al 6061-H cylinder compressed with Al 6061 platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.19: Stress vs. height reduction for Al 6061-H cylinder compressed with Al 6061 platens. Cylindrically compressed. Diameter=3.175, Length=6.35, Compression=70%. (units in mm)

Figure 4.20: Stress vs. height reduction for Al 6061-S cylinder compressed with Al 6061 platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.21: Stress vs. height reduction for Al 6061-S cylinder compressed with Al 6061 platens. Cylindrically compressed. Diameter=3.175, Length=6.35, Compression=70%. (units in mm)

Figure 4.22: Stress vs. height reduction for Al 6061-H cylinder compressed with rough steel platens. Cylindrically compressed. Diameter=3.175, Length=6.35, Compression=70%. (units in mm)

Figure 4.23: Stress vs. height reduction for Al 1100 cylinder compressed with rough steel platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.24: Stress vs. height reduction for Al 1100 cylinder compressed with rough steel platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.25: Stress vs. height reduction for Al 3003 cylinder compressed with rough steel platens.
Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.26: Stress vs. height reduction for Al 3003 cylinder compressed with rough steel platens.
Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.27: Stress vs. height reduction for Al 6061-H cylinder compressed with rough steel platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.28: Stress vs. height reduction for Al 6061-H cylinder compressed with rough steel platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.29: Stress vs. height reduction for Al 6061-S cylinder compressed with rough steel platens. Cylindrically compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.30: Stress vs. height reduction for Al 6061-S cylinder compressed with rough steel platens. Cylindrically compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

4.3 WIRE (RADIAL) COMPRESSION RESULTS

Radial compression was performed on two different types of specimens: specimens identical to those used in Section 4.2 for cylindrical compression, and commercially produced Al 1100 wire of diameters 0.127mm and 0.165mm.

4.3.1 WIRE COMPRESSION OF CYLINDERS

Eighty right-circular cylinders identical to those of Section 4.2 were compressed radially to obtain the goals described in Section 3.4 (40 cases were outlined in Section 4.1 with two repetitions per case). Specimens were compressed to both 40 and 70 percent as in the previous section, and again only plots showing the full 70% reduction in height are shown. Figures 4.31 through 4.48 give the stress (figured from *average mean stress* described in Section 5.2) associated with reductions in height to 70% for wire (radial) compression with two platen types: polished steel and Al 6061-T6. Similar to Table 4.1, Table 4.2 lists these specimens by platen type and includes stresses for height reductions of both 30 and 60 percent.

NOTE: For wire compression to 70%, the unusable samples include:

1. Al 6061-S with Dia.=3.18mm, L/D=2, compressed with Al 6061-T6 platens.
2. Al 6061-S with Dia.=3.18mm, L/D=2, compressed with polished steel.

TABLE 4.2
SUMMARY OF RADIAL COMPRESSION RESULTS

FIGURE #	ALLOY	DIAM.(mm)	L/D	STRESS: 30% (MPa)	STRESS: 30% (MPa)
PLATEN:	POLISHED STEEL				
4.31	1100	6.35	1	142	225
4.32	1100	6.35	2	140	192
4.33	3003	6.35	1	122	195
4.34	3003	6.35	2	112	158
4.35	6061-H	6.35	1	365	498
4.36	6061-H	6.35	2	345	460*
4.39	6061-H	3.175	2	355	538*
4.37	6061-S	6.35	1	330	495
4.38	6061-S	6.35	2	295	395*
NONE	6061-S	3.175	2	NONE	NONE
PLATEN:	AL 6061-T6				
4.41	1100	6.35	1	160	235
4.42	1100	6.35	2	130	150*
4.43	3003	6.35	1	128	205
4.44	3003	6.35	2	110	160
4.45	6061-H	6.35	1	390	550*
4.46	6061-H	6.35	2	415	360*
4.40	6061-H	3.175	2	445	660
4.47	6061-S	6.35	1	475	595*
4.48	6061-S	6.35	2	380	375*
NONE	6061-S	3.175	2	NONE	NONE

* 60% Stress values are abnormally low due to platen failure.

Figure 4.31: Stress vs. height reduction for Al 1100 cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.32: Stress vs. height reduction for Al 1100 cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.33: Stress vs. height reduction for Al 3003 cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.34: Stress vs. height reduction for Al 3003 cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.35: Stress vs. height reduction for an Al 6061-H cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.36: Stress vs. height reduction for an Al 6061-H cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.37: Stress vs. height reduction for an Al 6061-S cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.38: Stress vs. height reduction for an Al 6061-S cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.39: Stress vs. height reduction for an Al 6061-H cylinder compressed with polished steel platens. Wire (radially) compressed. Diameter=3.175, Length=6.35, Compression=70%. (units in mm)

Figure 4.40: Stress vs. height reduction for an Al 6061-H cylinder compressed with Al 6061-T6 platens. Wire (radially) compressed. Diameter=3.175, Length=6.35, Compression=70%. (units in mm)

Figure 4.41: Stress vs. height reduction for an Al 1100 cylinder compressed with aluminum 6061 platens. Wire (radially) compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.42: Stress vs. height reduction for an Al 1100 cylinder compressed with aluminum 6061 platens. Wire (radially) compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.43: Stress vs. height reduction for an Al 3003 cylinder compressed with aluminum 6061 platens. Wire (radially) compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.44: Stress vs. height reduction for an Al 3003 cylinder compressed with aluminum 6061 platens. Wire (radially) compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.45: Stress vs. height reduction for an Al 6061-H cylinder compressed with Al 6061-T6 platens. Wire (radially) compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.46: Stress vs. height reduction for an Al 6061-H cylinder compressed with Al 6061-T6 platens. Wire (radially) compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

Figure 4.47: Stress vs. height reduction for an Al 6061-S cylinder compressed with Al 6061-T6 platens. Wire (radially) compressed. Diameter=6.35, Length=6.35, Compression=70%. (units in mm)

Figure 4.48: Stress vs. height reduction for an Al 6061-S cylinder compressed with Al 6061-T6 platens. Wire (radially) compressed. Diameter=6.35, Length=12.7, Compression=70%. (units in mm)

4.3.2 WIRE COMPRESSION OF AL 1100 WIRE

Twenty-four 12.7mm long wire samples were compressed for each of the two diameters (12 different cases as outlined in Section 4.1 with four repetitions per case). Specimens were compressed to both 40 and 70% as in the previous section, and again only plots showing the full 70% reduction in height are shown. Figures 4.49 through 4.54 give the stress (figured from *average mean stress* described in Section 5.2) associated with reductions in height to 70% for wire (radial) compression with three platen types: polished steel, Al 6061-T6 and rough steel. Table 4.3 lists these specimens by platen type and includes stresses for height reductions of both 30 and 60%.

TABLE 4.3
SUMMARY OF RADIAL COMPRESSION OF 1100 WIRE RESULTS
(Dimensions: sizes=mm, stress=MPa)

FIGURE #	PLATEN TYPE	DIAM.	LENGTH	STRESS:30% COMP	STRESS:60% COMP
4.49	POLISHED STEEL	.165	12.7	90	210
4.50	POLISHED STEEL	.127	12.7	100	215
4.51	AL 6061-T6	.165	12.7	142	220
4.52	AL 6061-T6	.127	12.7	154	240
4.53	ROUGH STEEL	.165	12.7	130	265
4.54	ROUGH STEEL	.127	12.7	132	280

Figure 4.49: Stress vs. height reduction for aluminum 1100 wire compressed with polished steel platens. Wire (radially) compressed. Diameter=.165, Length=12.7, Compression=70%. (units in mm)

Figure 4.50: Stress vs. height reduction for aluminum 1100 wire compressed with polished steel platens. Wire (radially) compressed. Diameter=.127, Length=12.7, Compression=70%. (units in mm)

Figure 4.51: Stress vs. height reduction for aluminum 1100 wire compressed with aluminum 6061 platens. Wire (radially) compressed. Diameter=.165, Length=12.7, Compression=70%. (units in mm)

Figure 4.52: Stress vs. height reduction for aluminum 1100 wire compressed with aluminum 6061 platens. Wire (radially) compressed. Diameter=.127, Length=12.7, Compression=70%. (units in mm)

Figure 4.53: Stress vs. height reduction for aluminum 1100 wire compressed with rough steel platens. Wire (radially) compressed. Diameter=.165, Length=12.7, Compression=70%. (units in mm)

Figure 4.54: Stress vs. height reduction for aluminum 1100 wire compressed with rough steel platens. Wire (radially) compressed. Diameter=.127, Length=12.7, Compression=70%. (units in mm)

4.4 MICRO-HARDNESS RESULTS

Micro-hardness tests were performed on the 1/8-specimen sections (shown in Figure 3.8) of the 6 specimens and the aluminum platen listed in Section 3.4. Thirty-five to fifty indentations were made on each surface and compared to similar indentations made on undeformed specimens. Figures 4.55 through 4.60 show these 1/8-specimen sections with general contour lines drawn to divide the sample into areas of similar hardness ratios. Figure 4.61 is of the aluminum platen with concentric circles showing the relative hardnesses. The numbers shown represent a ratio of local hardness over hardness of the initial, undeformed specimen.

Figure 4.55: Hardness ratios for Al 1100 1/8-specimen cross-section.
D=6.35mm, L/D=2, Cylindrical compression=70%.

Figure 4.56: Hardness ratios for Al 1100 1/8-specimen cross-section.
D=6.35mm, L/D=1, Cylindrical compression=70%.

Figure 4.57: Hardness ratios for Al 1100 1/8-specimen cross-section.
D=6.35mm, L/D=1, Cylindrical compression=40%.

Figure 4.58: Hardness ratios for Al 1100 1/8-specimen cross-section.
D=6.35mm, L/D=2, Wire compression=70%.

Figure 4.59: Hardness ratios for Al 3003 1/8-specimen cross-section.
D=6.35mm, L/D=2, Cylindrical compression=70%.

Figure 4.60: Hardness ratios for Al 6061 1/8-specimen cross-section.
 $D=6.35\text{mm}$, $L/D=2$, Cylindrical compression=70%.

Figure 4.61: Hardness ratios for the aluminum platen used to compress the specimen shown in Figure 4.55 above. Dimensions in mm.

5. DISCUSSION

The test results given in Section 4 are compared to determine the following aspects of aluminum alloys in compression:

1. Determine the precision between cylindrical compression results and previous work referenced in Section 2.
2. Determine the differences in flow characteristics between cylindrical and wire compression geometries.
3. Determine relative characteristics of the different alloys in strength and localized hardness.
4. Determine the effects of wire size and L/D ratio.

5.1 AREA CALCULATION FOR CYLINDRICAL COMPRESSION

Area calculation for cylindrical geometry must take into account the increase in load carrying area due to barreling and side-surface roll-over. The method used to find stress in the graphs of Section 4.2 was the same that Papirno *et al.* [4] used in the aluminum compression experiments discussed in Section 2. Recall from Section 2.1 that this method approximates the experimental situation by assuming that the specimen retains a constant volume and its right-circular cylindrical shape (thus it assumes no significant barreling occurs). These assumptions led to Equation (2.3) that was capable of determining area for a given height reduction and initial diameter. Equation (2.3) is rewritten as:

$$Stress = \frac{Ph}{\pi r_o^2 h_o} \quad (2.3)$$

5.1.1 COMPARISON TO PREVIOUS WORK

The results from Section 4.2 for cylindrical compression agree very closely with identical experiments by Papirno *et al.* [4]. Figure 5.1 is a graph of stress vs. height reduction for Al 6061-T651 (slightly higher strength than 6061-H) taken from Papirno's results. Included in this figure are Papirno's results for $L/D=1$ and $L/D=2$. Figure 5.2 shows the data from Section 4.2 for Al 6061-H plotted on the same scale. The curves display the same trends and are nearly identical up to 60% compression, at which point platen failure invalidates the data for $L/D=1$ in Figure 5.2. The predictability of these results provides a standard for comparison of the wire compression results of the next section.

Figure 5.1: Stress vs. Height Reduction for 12.7mm diameter aluminum alloy Al 6061-T651 with $L/D=1$ (upper solid curve) and $L/D=2$ (lower broken curve). [4]

Figure 5.2: Stress vs. Height Reduction for 6.35mm diameter Al 6061-H alloy with $L/D=1$ and $L/D=2$.

5.2 AREA CALCULATION FOR RADIAL COMPRESSION

The cylindrical specimens and the Al 1100 wire samples that were radially-compressed require an area calculation much different than the *average area* calculation used in the previous section. The length of these specimens is taken as either 12.7mm (1/2in.) or 6.35mm (1/4in.) and is considered constant throughout compression.

However, the width varies as a function of radial distance from the center. Figure 5.3 shows a typical cylindrical specimen with the initial height, h_o , and Length, L , depicted

for radial compression. In this configuration, the width initially equals 0 at the top & bottom and is a maximum (equal to the diameter) at $h_0/2$. Applying these two extremes in width gives the smallest stress at the centroid and the largest stress (approaching infinity at *height reduction*=0) at the surface. Therefore, all deformation should occur at the surface.

Figure 5.3: A right-circular cylindrical specimen oriented for radial compression.

Friction with the compressing platens prohibited deformation from occurring exclusively at the surface. Figure 5.4 shows that the *surface area stress* (deformation is considered to occur only at the surface in this stress calculation) for wire compression is too high at large height reductions due to greatly increased friction (excessive stress at very low height reductions is a result of the load carrying area approaching 0 at zero height reduction and will be discussed later in this section). As a result, stress had to be calculated with the assumption that significant plastic deformation occurs remotely

from the surface. This was accounted for by using the *mean specimen area* calculation that is described in the remainder of this section.

The area calculation for radially-compressed specimens is based, like the *average area* calculation for cylindrically compressed specimens, on the assumption that volume is held constant. As the specimens are compressed, the height decreases, and the width increases as a result of barreling and roll-over of side-surface material onto the platen surface. By approximating this situation with a constant volume change, the material removed from the top and bottom surfaces is assumed to be replaced in an even thickness along the two sides. In Figure 5.5, A_2 and A_3 represent the area removed from the compressed surfaces and the area added to the sides, respectively. Note that A_3 lies in an arc concentric to the original outer surface. Thus, each value of load for a given height reduction recorded by the testing machine must be divided by the surface area specific to that instant in time. Note in part (b) of Figure 5.5 that at any given compression, the ratio of the current surface area to the surface area not including barreling and roll-over is $(2 \cdot x_1 \cdot L)/(2 \cdot x \cdot L)$, or just x_1/x . Table 5.1 defines the variables used in this section and references them to appropriate figures.

Figure 5.4: Radial stress calculated from Surface Area Stress and Cylindrical stress calculated from Average Area Stress. $D=6.35$, $L/D=1$, Compression=70%. (units in mm)

Figure 5.5: End view of a specimen compressed radially from an initial height $h_0=D$ to a new height, h . (a) The inner circle represents the original specimen. The outer circle shows the bound of the rolled-over material making up the edge of the slant-hashed figure, or the newly compressed specimen. (b) One-half of part (a) showing A_3 , the area added due to barreling and roll-over.

TABLE 5.1
Variables Used For Instantaneous Wire Area Calculation

VARIABLE	DESCRIPTION	REF. FIGURE #
A_o	Area of original specimen defined by radius r_o	5.3,5.5
A_2	Area compressed from top/bottom surface	5.5(a)
A_3	Area added to left/right side	5.5(b)
A_R	Area of ring between circles of radius r & r_o	5.5(a)
A_T	Area of triangle defined by side x and $\angle\theta$	5.6
A_{T3}	Area of small triangles above & below A_3	5.7
A_w	Area of wedge from A_o defined by $\angle\theta$	5.6
h	Current height of specimen	5.5
h_o	Original height of specimen	5.3
L	Length of specimen	5.3
r	Radius of current outer circle	5.5,5.6,5.7
r_o	Radius of original specimen	5.3,5.5,5.6
θ	Angle between vertical and radial to end of x (point A)	5.6
θ_1	Compliment of θ	5.7,5.8
θ_2	Angle between vertical and radial to end of x_1 (point C)	5.7,5.8
x	Half-width of platen surface without considering A_3	5.6
x_1	Half-width of surface including A_3 ($= x + \text{distance AC}$)	5.6

The variables needed to calculate instantaneous areas for this geometry are the width of the platen surface (x_1), the radius at the centroid (r), and the length (L). As explained above, L is constant, and x_1 and r are dependent on the amount of height reduction. A_2 and A_3 must first be obtained for each instantaneous height reduction. These values are used to solve a set of simultaneous equations for the surface half-

width, x , and the radius, r .

The area of wedge A_w , defined by the angle θ , is computed. From Figure 5.6,

$$A_w = \left(\frac{\theta}{360} \right) \pi (r_o)^2 \quad (5.1)$$

where θ is defined as

$$\theta = \cos^{-1} \left(\frac{h/2}{r_o} \right) \quad (5.2)$$

Figure 5.6: View of Figure 5.5(b) blown-up to show the hashed wedge and triangle that are defined by the radial extending to point A. These two are used to calculate the area removed from a compressed specimen, A_2 , shown in Figure 5.5(a)

Next, the area of triangle A_T , shown in Figure 5.6 and defined by sides $(h/2)$, x , and r_o , is found by using the equation for the area of a right triangle ($A_T = 1/2$ base x height).

By the Pythagorean theorem,

$$x = \sqrt{(r_o)^2 - \left(\frac{h}{2}\right)^2} \quad (5.3)$$

so that the area is written

$$A_T = \left(\frac{h}{4}\right) \sqrt{(r_o)^2 - \left(\frac{h}{2}\right)^2} \quad (5.4)$$

Then, A_2 is just 2 times the area in wedge A_w that is **not** included in triangle A_T :

$$A_2 = 2(A_w - A_T) \quad (5.5)$$

Recall the assumption that $A_3 = A_2$. A_3 must now be redefined in terms of the unknown outer radius, r , to find the specimen's new half-width, x_j . Figure 5.7 is the upper half of Figure 5.6 redrawn with imaginary triangle ABC that encompasses A_{T3} added for clarity. The area below this triangle and inside the concentric arcs is $1/2$ of A_3 , or $1/2$ the area added to the specimen sides. This area can then be expressed as

$$A_3 = 2 \left[\left(\frac{\theta_1}{360} \right) A_R - A_{T3} \right], \quad \text{where } \theta_1 = 90 - \theta \quad (5.6)$$

and A_R is defined as

$$A_R = \pi(r^2 - r_0^2). \quad (5.7)$$

Figure 5.7: Blow-up of the area below the hashed triangle in Figure 5.6. Note that triangle ABC is not a physical part of the specimen, but is included for geometrical calculation of A_j .

Now, approximate the arcs AD and BC in Figure 5.7 as straight lines so that box $ABCD$ (which is enlarged and redrawn in Figure 5.8) is simply a trapezoid with (side AB) = (side CD). Then

$$\overline{AB} = \overline{CD} = r - r_0. \quad (5.8)$$

and

$$\overline{BE} = \overline{AB} \sin(\theta_1). \quad (5.9)$$

Figure 5.8: Box $ABCD$ from Figure 5.7. The solid lines between points A & D and B & C show the trapezoidal approximation that is made from the actual dotted lines adjacent to them.

Referring to Figure 5.7, note that θ_2 can be written as

$$\theta_2 = \sin^{-1} \frac{(h/2)}{r} \quad (5.10)$$

which gives for side AD ,

$$\overline{AD} = \frac{(\theta_1 - \theta_2)}{360} 2\pi r_0 \quad (5.11)$$

and for side BC ,

$$\overline{BC} = \frac{(\theta_1 - \theta_2)}{360} 2\pi r. \quad (5.12)$$

Using the Law of Sines, the dimensions of the rest of the trapezoid in Figure 5.8 can be determined. First, consider the relation:

$$\angle CAD = \sin^{-1} \left(\overline{CD} \left(\frac{\sin(\theta_2)}{\overline{AD}} \right) \right). \quad (5.13)$$

From this result,

$$\angle CDA = 180 - \theta_2 - \angle CAD. \quad (5.14)$$

Since $\angle CDA$ is known, side AC can be found by again using the Law of Sines:

$$\overline{AC} = \sin(\angle CDA) \left[\frac{\overline{AD}}{\sin(\theta_2)} \right] \quad (5.15)$$

Thus, the area of the small triangle, T_3 , (located in the outer ring above A_3) is just

$$A_{T_3} = \frac{1}{2} (\overline{AC}) (\overline{BE}). \quad (5.16)$$

Finally, x_1 is written:

$$x_1 = \overline{AC} + x. \quad (5.17)$$

Equations 5.6 through 5.17 are now solved exactly for the 12 unknown variables: A_R , A_{T3} , r , θ_2 , x_1 , $\angle CDA$, $\angle CAD$, and (sides): AB , AC , AD , BC , and BE . The variables of importance for calculating instantaneous area are r and x_1 . Since the cross-sectional area was non-uniform throughout the specimen, the stress was calculated in three places: at the platen surface, at the centroid, and at the median (one half the distance from the surface to the centroid). First, the stress at the surface was calculated by dividing the load recorded for a given height reduction by the surface area, A_s :

$$A_s = 2[\overline{AC} + x]L \quad (5.18)$$

Stress was also calculated at the centroid to determine the effect of this significantly greater cross-sectional area:

$$A_c = [2r]L \quad (5.19)$$

Extreme surface friction at large height reductions, and the problem of the stress approaching infinity at the beginning of compression (where $h_o = h$), made the use of A_s in Equation 5.17 unacceptable at both compression extremes (Min: 0%, Max: greater than 60%). This was shown earlier in Figure 5.4 where stress (calculated from A_s) vs. height reduction for an Al 6061-H specimen was plotted against the cylindrically

compressed result for the same specimen. The geometric calculation of r includes the assumption that the sides grew in concentric circles to the original specimen. Since the stresses are much smaller at the centroid, this steady increase in r did not occur in experimentation until barreling became a factor at large height reductions. The model predicted stress reductions from an increase in radius at even moderate height reductions (>20%). Thus, stress at the surface was more accurate for moderate height reductions, while stress at the centroid worked better at both minimum and maximum compression. Therefore, a mean area, A_M , was used which combined areas A_S and A_C to best represent the experimental compression test:

$$A_M = [r + x_1] \cdot L \quad (5.20)$$

5.3 COMPARISON OF CYLINDRICAL AND WIRE COMPRESSION

Stress vs. height reduction curves of wire compression obtained by using the *mean area* calculation of Equation (5.20) are similar in shape to curves from the cylindrically compressed specimens. Up to 40% height reduction radially compressed specimens have stresses of 70 to 80 percent of those of identical specimens compressed cylindrically. At this point, the curves from radial compression increased in slope and by 70% height reduction they are at 90 to 95 percent of the stresses from cylindrical compression. Figure 5.9 shows these relationships by plotting the curve for *average area stress* vs. height reduction for a cylindrically compressed Al 1100 specimen with $L/D=1$ alongside the *mean area stress* vs. height reduction for wire compression of an identical specimen. This graph is followed by Figure 5.10 which shows the same curves for $L/D=2$.

The goal of these experiments was to establish relationships between different alloys. Since the application is for radial (wire) compression, it was important to determine if results from cylindrical compression were characteristic of what physically occurred in compression of the vacuum seals. However, it was not essential to derive an area calculation for wire compression that allowed results to exactly repeat cylindrical compression results like those shown in Figures 5.1 and 5.2. A difference in magnitude between the two curves in Figures 5.9 and 5.10 is not as significant as a difference in slope. Greatly differing slopes from these two tests would indicate that either plastic deformations in cylindrical and radial compression are not dependent upon the same parameters (L/D , friction, rate of compression, etc.), or the *mean area stress* calculation of Section 5.2 is not valid.

The micro-hardness cross-sections in Figures 4.55 through 4.58 (discussed further in

Section 5.10) suggest that the *mean area stress* calculation derived in Section 5.2 overestimates the amount of load carrying surface at small height reductions (Note that the stress for wire compression is much lower for wire compression than for cylindrical compression at low height reductions in Figures 5.9 and 5.10, which is a result of assuming too large of an initial load carrying area). Figures 4.55 to 4.57 (micro-hardness contours for cylindrical compression of Al 1100) show a hardness that is dependent on vertical position (i.e. the low stress dead zone at the top, moderate stresses in the middle and high compressive stresses at the bottom). Figure 4.58 (wire compressed specimen) shows a greater dependence on horizontal position with the largest stresses on the left (representing the horizontal center of the uncompressed specimen). This suggests that a majority of the load for wire compression is concentrated at the horizontal center of the specimen, with the sides only being loaded at large height reductions.

One possible method for improving on the load carrying area calculation for wire compression is to represent the specimens as a series of vertical cylinders of varying height stacked next to each other. These small cylinders would vary initially (moving horizontally out from the specimen center) from a height equal to the specimen diameter to a height approaching zero (at both outer edges of the uncompressed specimen). This method would give higher stresses at the beginning of compression since only a few of the cylinders (the tallest ones located at the center) would be in contact with the platens. As the specimen was compressed further, the load carrying area would increase as more cylinders came in contact with the platens. So, as seen in Figure 4.58, the horizontal center of the specimen (left side of Figure 4.58) would see the largest compressive stress, while the material on the edges

would experience very little compression.

Barrelling of the small cylinders may make this approach to radial area calculation also an oversimplified solution. The tendency for cylinders to spread radially as a result of surface friction with the platens (discussed in Section 2) must be accounted for in the analysis. Barrelling of this magnitude should create hoop stresses at the outer surfaces that would result in large horizontal expansion and cracking, all effects that were not observed in the wire compressions of this study.

Figure 5.9: Stress vs height reduction for Al 1100 cylinders compressed with polished steel platens. Cylindrically & Radially compressed. $D=6.35$, $L/D=1$, Compression=70%. (units in mm)

Figure 5.10: Stress vs. height reduction for Al 1100 cylinders compression with polished steel platens. Cylindrically and Radially compressed. $D=6.35$, $L/D=2$, Compression=70%. (units in mm)

5.4 COMPARISON OF DIFFERENT ALLOYS

The emphasis of this section is to compare the relative strengths of Al 1100 and Al 3003 to help determine the better alloy for use as a vacuum seal. Hardness considerations and specifics on plastic flow characteristics that help to explain the experimental results that will be shown in the next section will be held for discussion in Section 5.10. It should be noted that along with determining the better seal, it is important to determine relative strengths of the seal material to Al 6061, a possible chamber material. Therefore, comparisons will also be made between the different 6061 heat treatments and between all of the tested alloys, Al 1100, 3003, and 6061.

5.4.1 Al 1100 VS. Al 3003

Comparisons were drawn between Al 1100 and Al 3003 for both cylindrical and radial compression for all three platen types and for both $L/D=1$ & $L/D=2$. In every case, Al 1100 exhibited greater stresses for the same height reduction than those recorded for compression of Al 3003. Figure 5.11 ($L/D=1$) and Figure 5.12 ($L/D=2$) show this result for cylindrical compression to a reduction in height of 70%. Figure 5.13 ($L/D=1$) and Figure 5.14 ($L/D=2$) give similar results for radial compression. In each case, the two curves are nearly parallel with Al 1100 having 20 to 25% higher strength than Al 3003.

5.4.2 Al 6061-H VS. Al 6061-S

Al 6061 was tested between all three of the platen types during cylindrical compression, and it was tested between both aluminum and polished steel in radial compression. However, a majority of the aluminum platens failed during tests that continued to a height reduction of 70%. Thus means that only the polished steel platens were successfully used in both cylindrical and radial compression. For this reason, the following discussion will be limited to results of Al 6061 compression by polished steel platens.

Al 6061 with H-tempering exhibited the highest stresses in all specimen geometries for the three heat treatments tested. O-tempered specimens had stresses slightly above those of the solution annealed (SA) specimens, but well below the stresses of the H-tempered 6061 samples. For this reason, curves for the O-tempered specimens were omitted, and the analysis that follows was based on the minimum and maximum stress cases of H-temper and SA, respectively. Figure 5.15 shows the stress vs. strain data for cylindrical compression of Al 6061 alloy in both heat treatments, and with $L/D = 2$. These curves show the H-temper version approximately 15% higher than the solution annealed case. Figure 5.16 shows these curves for an identical specimen that has been compressed radially. Note in this case that the curves are plotted only to 60% height reduction. The curves dropped off radically past this point because of failed (bent) steel platens. Figure 5.17 is another radial compression case with $L/D=2$. In this plot the specimen initial diameter is 3.175mm, or half the diameter of the specimen used for Figure 5.16. Again, the recorded stresses for H-temper are approximately 15% higher, but in this case both stresses are considerably higher than seen in the previous figure (this diameter effect will be discussed in Section 5.7).

5.4.3 SEAL ALLOYS VS. CHAMBER MATERIAL

Figure 5.18 combines Figures 5.14 and 5.15 to show the relative compressive strengths of Al 6061-H to Al 1100 and Al 3003. All three curves follow plastic deformation curves (past 25% height reduction) with approximately the same slope. The difference comes in the first 10% compression where the Al 6061-H specimen has an extremely high yield strength. The overall compressive strength of the Al 6061 alloy is approximately double that of the other two metals. However, it was very common during testing for an Al 1100 or Al 3003 specimen to deform the Al 6061-T6 platen surface (this will be discussed further in Section 5.9 on Platen Failure). Thus, these results suggest that Al 6061-T6, unlike the current stainless steel chamber, is definitely not invulnerable to deformation by the wire seals.

Figure 5.11: Stress vs. height reduction for Al 1100 & 3003 cylinders with polished steel platens. Cylindrically compressed. Diameter=6.35, $L/D=1$, Compression=70%. (units in mm)

Figure 5.12: Stress vs. height reduction for Al 1100 & 3003 cylinders with polished steel platens. Cylindrically compressed. $D=6.35$, $L/D=2$, Compression=70%. (units in mm)

Figure 5.13: Stress vs. hgt. red. for Al 1100 and Al 3003 with polished steel platens. Radially compressed. $D=6.35$, $L/D=1$, Compression=70%. (units in mm)

Figure 5.14: Stress vs. hgt. red. for Al 1100 and Al 3003 with polished steel platens. Radially compressed. $D=6.35$, $L/D=2$, Compression=70%. (units in mm)

Figure 5.15: Stress vs. Height Reduction for Al 6061 (H temper & Soln. Annealed) cylinders. Cylindrically compressed. $D=6.35$, $L/D=2$, Compression=70%. (units in mm)

Figure 5.16: Stress vs. Height Reduction for Al 6061 (H temper & Soln. Annealed) cylinders. Radially compressed. $D=6.35$, $L/D=2$, Compression=70%. (units in mm)

Figure 5.17: Stress vs. Height Reduction for Al 6061 (H temper & Soln. Annealed) cylinders. Radially compressed. $D=3.175$, $L/D=2$, Compression=70%. (units in mm)

Figure 5.18: Stress vs. Height Reduction for Al 1100, 3003, and 6061-H cylinders.
Cylindrically compressed. $D=6.35$, $L/D=2$, Compression=70%. (units in mm)

5.5 HEIGHT REDUCTION OF 40% VS. 70%

Half of the specimens tested were halted at 40% reduction in height. The purpose of this process was to allow half of the specimens to be examined at some stage prior to the extreme distortion that appears at 70% compression. A hardness analysis was completed on some 40% compressed samples for comparison to identical specimens that were tested to 70%. This will be addressed later in Section 5.10. Here, a comparison between 40 and 70% values acts as a check on the repeatability of the results, similar to the analysis performed in Section 4 using Figures 4.1 and 4.2. Figure 5.19 and Figure 5.20 show radially compressed specimens of Al 1100 and Al 3003 alloys, respectively. These cylinders had a length to diameter ratio of 1 and were compressed under polished steel platens. Both sets of curves show the 70% compression curve to lay almost perfectly over the 40% curve. Figure 5.21 shows similar results when an identical Al 1100 specimen to the one in Figure 5.19 is compressed between Al 6061-T6 platens. These results are typical of both the cylindrical and wire compression results and greatly add to the validity of the results.

Figure 5.19: Stress vs. hgt. red. for Al 1100 cylinders with polished steel platens.
 Radially compressed. $D=6.35$, $L/D=1$, Compression=40% & 70%. (units in mm)

Figure 5.20: Stress vs. hgt. red. for Al 3003 cylinders with polished steel platens.
Radially compressed. $D=6.35$, $L/D=1$, Compression=40% & 70%. (units in mm)

Figure 5.21: Stress vs. hgt. red. for Al 1100 cylinders with Al 6061-T6 platens.
Radially compressed. $D=6.35$, $L/D=1$, Compression=40% & 70%. (units in mm)

5.6 EFFECTS OF LENGTH TO DIAMETER RATIO (L/D)

Length to diameter ratio was shown by Papirno *et al.* [4] in Figure 5.1 to greatly affect compressive stresses at large height reductions. This figure showed a deviation of approximately 10% between the $L/D=1$ and the $L/D=2$ specimens at 40% compression. Figures 5.22 and 5.23 show stresses in Al 1100 and Al 3003 alloys, respectively, for cylindrical compression under polished steel platens. L/D ratios of 1 and 2 are plotted in each of these graphs, and like Figure 5.1, they show the curve for $L/D=1$ to be about 10% larger at 40% height reduction. Figure 5.24 contains the results for a similar Al 6061 specimen. These curves appear to have a larger difference, but with the increased stresses the percent difference between the curves is still around 10 to 12%.

Figure 5.22: Stress vs. height reduction for aluminum 1100 cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, $L/D=1$ & 2, Compression=70%. (units in mm)

Figure 5.23 Stress vs. height reduction for aluminum 3003 cylinder compressed with polished steel platens. Cylindrically compressed. Diameter=6.35, $L/D=1$ & 2, Compression=70%. (units in mm)

Figure 5.24: Stress vs. Height Reduction for Al 6061-S cylinders with polished steel platens. Cylindrically compressed. $D=6.35$, $L/D=1$ and 2, Compression=70%. (units in mm)

5.7 DIAMETER EFFECTS

Specimens in compression are subject to continually increasing effects of friction as the normal force between the platen and specimen grows. In tests where the platens are separated by tall specimens (high L/D), the limitation in movement at the surface is nullified by low stress plastic flow near the specimen center. This situation arises because the material at the center is sufficiently removed from the platen frictional surface to remain relatively unaffected. Yet in nearly all of the specimens used in these experiments, there was a large increase in the slope of Load vs. Displacement past 50 to 60% compression. In similar curves referenced from Papirno *et al.* (Figures 2.3 and 5.1), the slopes are approaching a vertical line at 70% height reduction. Such a drastic increase did not occur in these experiments. Slopes approaching this extreme occurred somewhat in the Al 6061-H specimens compressed with rough steel platens, which will be discussed in the next section.

The characteristic of friction that causes stress to climb exponentially at large height reductions is not solely dependent upon the L/D ratio. In these experiments, specimens of small initial height result in higher stresses than do taller specimens with the same L/D . The radial compression tests clearly illustrated this result. The orientation of specimens during radial compression dictates that L/D (or actually initial height, h_0 , over the diameter, D) will always be 1 (refer to the discussion of Figure 5.3 in Section 5.2). The actual length of the cylinder is irrelevant in determining stress since it is included in the calculation of load-carrying area. Thus, if 2 different diameter wires of the same alloy and heat treatment result in different stresses then variations in stress for a given type of material are not uniquely a function of L/D .

Figures 5.25 and 5.26 show comparisons of 0.165mm and 0.127mm aluminum 1100 wire for compression under polished steel and Al 6061-T6 platens, respectively. These specimens both initially occupy a space between the platens (defined as the length in cylindrical compression) equal to their diameter and are compressed to a platen separation equal to 30% of the two wire's initial diameters. The 0.127mm diameter wire registered higher stress values in every one of the 24 experiments where it was tested under identical conditions with the 0.165mm wire. This same trend can be seen by referring back to the radial compression data for Al 6061 cylinders in Figure 5.16 (diameter = 6.35mm) and Figure 5.17 (diameter = 3.175mm) for L/D=2. In these two cases for H and S-temper alloy 6061, the 3.175mm diameter specimen had stresses 15% higher than the 6.35mm specimen.

The above argument did not, however, hold true for comparison of the Al 1100 wire and the Al 1100 cylinders compressed radially. Figure 5.27 shows that the wire had a considerably lower stress, initially, than the 6.35mm diameter cylinder had. One major factor in this result is that the wire was created for the explicit purpose of uniform compression. It was tested in a completely annealed state. In contrast, the plate was rolled which resulted in greatly elongated grains that were shown in Figures 3.2-3.4. The approximation of cutting the specimens along side B of Figure 3.1 was the best choice available for modeling a rod, but it still left the specimen with an asymmetric crystalline structure that progressed in the test to uneven plastic flow.

Figure 5.25: Stress vs. height reduction for aluminum 1100 wire compressed with polished steel platens. Radially compressed. Diameter=0.165 & 0.127, Length=12.7, Compression=70%. (units in mm)

Figure 5.26: Stress vs. height reduction for aluminum 1100 wire compressed with Al 6061-T6 platens. Radially compressed. $D=0.165$ & 0.127 , Length= 12.7 , Compression= 70% . (units in mm)

Figure 5.27: Stress vs. height reduction for Al 1100 wire and cylinder compressed with Al 6061-T6 platens. Radially compressed. $D = 3.65$ & 0.165 , Length = 6.35 & 12.7 , Comp. = 70% . (units in mm)

5.8 EFFECTS OF DIFFERENT PLATENS

Polished steel, rough (etched) steel, and Al 6061-T6 platens were chosen to simulate low friction, extremely high friction, and aluminum interface galling, respectively. The predicted result was that both rough steel and aluminum platens would cause stresses to be much higher than those obtained from the highly polished steel platens. This did occur in nearly all the specimens, but to a much lower degree than expected. Figures 5.28 and 5.29 show the differences in stress caused by compressing three identical Al 1100 and Al 3003 specimens, respectively. These curves exhibit the general trend observed in the experiments as a whole. The Al 6061-T6 platens caused the highest stress initially (to approximately 20% height reduction), and then leveled off to follow a curve essentially parallel to the polished steel curve. The rough steel curve began identical to the polished steel curve, but quickly increased at 40 to 50% height reduction to stresses above those of the specimen compressed with aluminum platens.

Figures 5.30 and 5.31 show similar curves for radial compression with Al 6061-T6 and polished steel platens. Again, the aluminum platen is slightly (15 to 20%) higher and then tapers down to a slope parallel to the steel curve. Figure 5.32 shows this same trend for Al 6061-S cylinders that are compressed cylindrically. The rough steel platen overrides the aluminum platen's stress level at approximately 40% compression. Neglecting the aluminum platen failure past 55% compression, it again follows the polished steel curve at height reductions greater than 25%.

Figure 5.28: Stress vs. height reduction for aluminum 1100 cylinder compressed with 3 platen types. Cylindrically compressed. Diameter=6.35, L/D=1, Compression=70%. (units in mm)

Figure 5.29: Stress vs. height reduction for aluminum 3003 cylinder compressed with 3 platen types. Cylindrically compressed. Diameter=6.35, $LD=1$, Compression=70%. (units in mm)

Figure 5.30: Stress vs. hgt. red. for Al 1100 cylinders. Platens: Al 6061-T6 & polished steel .
 Radially compressed. Diameter=6.35, L/D=1, Compression=70%. (units in mm)

Figure 5.31: Stress vs. hgt. red. for Al 3003 cylinders. Platens: Al 6061-T6 & polished steel .
Radially compressed. Diameter=6.35, L/D=1, Compression=70%. (units in mm)

Figure 5.32: Stress vs. Height Reduction for Al 6061-S cylinders compressed by 3 platen types. Cylindrically compressed. $D=6.35$, $L/D=2$, Compression=70%. (units in mm)

5.9 PLATEN FAILURE

Al 6061 specimens of both heat treatments reached values of stress greater than 400MPa during compression to 70% height reduction. This stress deformed the Al 6061-T6 platens and in some cases bent or caused surface deformations on the steel platens. Figure 5.33 shows the failure of the aluminum platens at approximately 45% compression of Al 6061 (both H-tempered and solution annealed) specimens. The tangent lines are drawn to show a decrease, or leveling-off of the slope. This signifies platen failure since the trend shown by harder platens (Titanium in Figure 2.3, and SS in Figure 5.35) is for the curve to **increase** in slope after approximately 40% compression.

Aluminum platen failure during radial compression is shown in Figure 5.34. These platens failed at 38% height reduction. Radial compression is unique in that, initially, all the load of compression is carried by one small line along the platen centerline. Theoretically, the stress that causes failure should be independent of area. However, a highly localized load at the beginning of compression can make a slight imprint into the surface which then further opposes spreading of the specimen and the load.

The stainless steel platens were also deformed during the compression experiments. Six steel platens were destroyed either through bending (so that they would not compress specimens in a straight line), or through indentation over a series of compression tests. Figure 5.35 shows this failure for two Al 6061 samples with $L/D=1$ that were compressed cylindrically. At 65%, the slope falls off for these two curves, again revealing deformation of the platens.

Figure 5.33: Failure of Al 6061-T6 platens at 45% compression of Al 6061(H & S temper) cylinders. Cylindrically compressed. Diameter=6.35, $L/D=1$ & 2, Compression=70%. (units in mm)

Figure 5.34: Failure of Al 6061-T6 platens at 38% compression of Al 6061(H & S temper) cylinders. Radially compressed. Diameter=6.35, $L/D=2$, Compression=70%. (units in mm)

Figure 5.35: Failure of stainless steel platens at 65% compression of Al 6061(H & S temper) cylinders. Cylindrically compressed. Diameter=6.35, L/D=1, Compression=70%. (units in mm)

5.10 MICRO-HARDNESS COMPARISONS

The micro-hardness contour plots shown in Figures 4.55 through 4.60 are helpful in explaining the relative strengths obtained from the compression tests displayed in Section 3. The 1/8-specimen samples used for Vicker's hardness testing were cut to allow analysis of the changes in vertical hardness from the platen surface to the specimen center, and for analysis of hardness extending horizontally from the specimen center to the cylindrical (barreled) surface. The purpose of choosing these six specimens and the comparisons that were intended to be made were given in Section 3.5. From these figures, correlations are drawn between the micro-hardness test results and the stress vs. height reduction results obtained from the initial compression tests.

5.10.1 COMPARISON WITH PREVIOUS RESULTS

The results of similar Knoop hardness tests by Dadras *et al.* [8] on Copper compressed specimens were given in Section 2.1.2. In comparing Figure 4.55 (the control specimen for the tests) with Figure 2.7, several similarities are observed. The cone-shaped dead zone is visible in both figures as a wedge of low relative hardness in the upper left corner. Also, an area of extremely high relative hardness is shown at the upper right corner which represents the high stresses caused by rolled-over material compressing against the platen surface. Similarly, there is an area of moderately high stress 2/3 of the way to this upper right section that is a result of higher stresses being endured by the corner of the of the initial right-circular specimen. Low relative hardness (1.3 for Figure 4.55 and 1.03 for Figure 2.7) is present at

the center of the outer barreled surface where the material is placed in tension from large hoop stresses (see Section 2.1.1). Finally, the center of both samples is relatively low in hardness with increasing values near the lower edge, and extremely high values near the lower left corner (the center of the original compressed specimen).

5.10.2 L/D EFFECTS

Figure 4.56 shows hardness results of an 1/8-specimen cut from a compressed Al 1100 cylinder (similar to Figure 4.55) with $L/D=1$. This figure shows the same stress areas present in Figure 4.55, but to a larger extent. The dead zone in the upper left, the high axial compression area in the lower left, the high stress area from side-surface roll-over in the upper right, and the low stress area of the lower right are all clearly defined in Figure 4.56. These areas gave higher relative hardness values than in Figure 4.55. This result is in agreement with the discussion in Section 5.6 which stated that the lower L/D specimen experienced significantly higher stresses.

5.10.3 EFFECTS OF VARYING COMPRESSION

A specimen compressed to only 40% was also analyzed using contours from several Vicker's hardness impressions. This specimen, shown in Figure 4.57, is identical in initial parameters to Figure 4.55. Notice that the two curves again have similar characteristics in the four corners. However, the 40% compressed case shows a much larger "soft center" area. In Figure 4.55, the high relative hardness areas (concentrated in the lower left of Figure 4.57) have moved into the center and into the dead zone region of the upper left.

One factor that is not clear is the cause of the increased hardness area present in the lower middle of each of the three Al 1100 specimens compressed cylindrically (Figure 4.55 through Figure 4.57). Figure 2.7 showed the highest hardness extending approximately 2/3 of the distance from the lower left (the specimen center) towards the barreled surface. Since this is repeated in each of the Al 1100 cylindrically compressed specimens, investigation of the slight (10%) increase in hardness occurring in the lower middle will be neglected.

5.10.4 WIRE VS. CYLINDRICAL COMPRESSION

A radially compressed specimen, identical in initial geometry to the one used to obtain the results shown in Figure 4.55, was cut in similar pieces and hardness tested. The results are shown in Figure 4.58. The dead zone and high axial stress areas that are very distinct on the left side of the cylindrical 1/8-specimen cuts are only slightly visible in Figure 4.58. The right side of Figure 4.58 has much lower hardness contours than those found in the cylindrically compressed specimens. This can be explained by considering the wire compression of the specimen to be cylindrical compression of an extremely barreled specimen. Then as the specimen is compressed and the platen surface grows, the effect is simply exaggerated side-surface roll-over. The material shown at the extreme right is not placed under compression until well into the experiment (50 to 60% height reduction). Thus, a majority of the load is carried at the center (refer to the discussion of wire vs. cylindrical compression in Section 5.3), which results in the unusually high relative hardness measurement of 2.1 that is visible in the lower left of the figure.

5.10.5 Al 3003 VS. Al 1100

Figure 4.59 displays the hardness contours for an Al 3003 alloy sample of identical geometry to the control sample in Figure 4.55. A larger number of contours were drawn on this figure because of the small changes in relative hardness that occurred in comparison to the Al 1100. Two important characteristics of compression of the Al 3003 are visible in this figure that help explain the lower strength values found in Section 5.4. The dead zone area is spread over a majority of the width and extends well into the center of the cut specimen. Also, the concentrated high stress area present at the lower left corner of the Al 1100 figures is of a much lower magnitude in Figure 4.59. Like the dead zone, this area extends well to the right and into the center of the specimen. Thus, the Al 3003 contours show that it compresses with larger, more uniform regions that have hardness ratios significantly lower than those of the Al 1100 specimens.

5.10.6 Al 6061 VS. Al 1100

The contour results of hardness testing of an 1/8-specimen cut of Al 6061-H are shown in Figure 4.60. The four corner regions are visible in this figure as in the previous softer alloys, but the regions of high relative hardness are greatly exaggerated. This result, along with the presence of higher peak hardness ratios (2.3 in the lower left and 2.1 in the upper right), is attributed to the poor plastic flow properties of age-hardened aluminum 6061. The contours of this figure all represent relative hardness ratios well above those of Al 1100 and Al 3003. This agrees with measurements of the compressed specimens that showed much smaller final diameters for Al 6061. Thus, the original assumption of constant volume during

compression is an inaccurate statement for 6061 compressed to this extreme.

5.10.7 ALUMINUM PLATEN HARDNESS

The Al 6061-T6 platen shown in Figure 4.61 was used to compress the specimen shown in Figure 4.55. Observation of the platen following the test showed that it was visibly indented 2-3mm. This thickness was machined from the deformed face to provide a flat surface for hardness testing. The surface was then polished using the aluminum compound described in Section 3.2.1. Again, the values shown are Vicker's hardness values divided by the average of five measurements taken from a similar uncompressed platen. The concentric contour lines were moved approximately 2mm to the right to compensate for the specimen being off-center when the compression test began. Figure 4.61 shows that the greatest hardness existed at the center (approximately the width of the specimen) and decreased as the platen radius increased. The hardness at the outer circumference was unaffected (hardness ratio = 1) by the compressive forces that caused deformation in the center.

6. CONCLUSIONS

Al 3003 cylindrical specimens used in these tests exhibited better qualities than Al 1100 for use as a wire seal for the LAMPF particle accelerator. These specimens were formed from identical Al 3003 and Al 1100 1% strained (during rolling) 6.35mm flat plates. The results of both cylindrical and radial compression showed that Al 3003 had 10 to 20 percent lower average stresses. Subsequent hardness tests proved that the Al 3003 flowed much more evenly and had significantly lower relative hardness values at 70% compression. It should be noted here that the fully annealed Al 1100 wire provided by LAMPF exhibited lower stresses than both the Al 1100 and Al 3003 cylinders did. Also, the 3003 alloy had larger grains which may have assisted compressive flow. If the cylinders had been annealed further, the Al 1100 performance may have similar to the softer Al 3003.

Al 6061 was tested in two heat treatments and was found to have approximately 15% higher strength in the age-hardened H-Temper than in the Solution Annealed state. Al 6061 was also used in a T6-Temper as a compressing platen to test its applicability for use as a primary material in the beam line vacuum housing. Compression of Al 6061 specimens showed visible deformation of the platen surface at 40% and total failure of the platen at 70% for both cylindrical and wire compression. These platens showed only slight signs of surface roughness from compression of the softer alloys (Al 1100 & Al 3003) to a maximum of 70%. However, this surface attack may be excessive enough to prevent LAMPF from achieving a sufficiently high vacuum. This deformation alone (without considering Al-Al galling effects) warrants further testing before replacing the stainless steel beam line with Al 6061.

The geometric calculation of a *mean area stress* for wire compression discussed in

Section 5.2 is sufficiently accurate at modeling cylindrical compression results. The curves of stress vs. height reduction obtained from cylindrical compression reproduced the results of previous work with axial compression of aluminum given in Section 2, and the results of wire compression modeled the cylindrical results in both slope and magnitude within approximately 15%. Wire compression curves followed the trends of cylindrical compression for each change in geometry and testing procedure. Thus, the numerous results of previous one-dimensional axial compression accurately represents the application of radial compression as wire seals.

Specimens were tested in both cylindrical and wire compression for variations in compressive strength and plastic flow properties as a result of changes in L/D ratio, percent height reduction, initial diameter, and type of compressing surface. The following are conclusions made from analyzing final hardness values and stress levels for height reductions from 0 to 70 percent:

1. Specimens with lower Length to Diameter ratios undergo larger compressive stresses and have higher relative hardnesses throughout the specimen resulting in poor, uneven plastic deformation.
2. The rate at which stress rises as a function of percent deformation increases steadily past 40% height reduction and approaches a vertical slope past 70% compression.
3. Two wire specimens with different diameters that are compressed radially will have significantly different stresses for the same height reduction, with the smaller diameter wire having a larger stress.

7. FUTURE WORK

1. Further comparisons need to be made between Al 1100 and Al 3003 alloys to determine the relative compressive characteristics. It appears from these results that Al 3003 flows better under high compressive stresses. However, when the results of radial compression of 1100 fully annealed, small diameter wire and 1100 cylinders (from flat plate) were compared, the lower stresses in the wire suggested that a significant amount of hardening had occurred in the plate. Therefore, these two alloys need to be tested as small diameter, fully annealed wire in radial compression.
2. Microstructural tests are required to determine the effects of interstitials, impurities, and grain size on the compressive flow characteristics of Al 1100 and Al 3003 alloys.
3. Analytical modeling like that performed by Mescall *et al.* [7] for cylindrical compression is required for wire (radial) compression. The goals of this work would be to help compare plastic flow in this configuration with cylindrical compression, and to further test the validity of the *mean area stress* in Section 5.

4. Further information is required on the effects changing the diameter of wire on the resulting stress during radial compression.
5. The complete effects of aluminum-aluminum galling are not known. Further investigation is required to determine the relative effects of using etched platens compared to brightly polished platens.
6. Further investigation of the *small cylinder area* model discussed in Section 5.3 is required to determine its usefulness for wire compression in comparison to the *mean area stress* method.

APPENDIX

Barker's Etch Solution:

Chemical Formula- HBF_4

Commercial Availability (form used)- 48% HBF_4 in H_2O

- Process:
1. Dilute solution to 3% HBF_4 in H_2O .
 2. Pour solution into a glass container and hook leads from a 20V DC power source to the following:

Anode- Stainless Steel
Cathode- Titanium wire

3. Etch aluminum with the following parameters:

Alloy	Time(min)	Current(Amp)	Potential(V)
6061	2	0.5	20
3003	1.5	0.5	20
1100	1.5	0.5	20

4. Rinse specimens in alcohol and view under a 4X-25X microscope using a magenta polarizing filter.

REFERENCES

1. John C. Allred and Beverly Talley, LAMPF (Los Alamos Meson Physics Facility, Los Alamos National Laboratory, Los Alamos, NM, 1987, pp. ii-13.
2. W. F. Sommer, "Radiation Effects Concerns at a Spallation Source," Los Alamos National Laboratory Report, LAUR-901142, Los Alamos, NM, 1990, pp. 8-14.
3. P. D. Ferguson, "Dose Rate Curves for Aluminum Alloy 6061 and Stainless Steel Alloy 304," Internal Memorandum, Group MP-5, Los Alamos National Laboratory, Los Alamos, NM, 1989.
4. R. Papirno, J. Mescall and J. McLaughlin, "Fracture in Axial Compression Tests of Cylinders," Compression Testing of Homogeneous Materials and Composites, ASTM STP 808, Richard Chait and Ralph Papirno, Eds., American Society for Testing and Materials, 1983, pp. 7-23.
5. J. G. Lenard, "Development of an Experimental Facility for Single and Multistage, Constant Strain Rate Compression," ASME Journal of Engineering Materials and Technology, v. 107, 1985, pp. 126-131.
6. M.L. Wilkins, "Calculation of Elastic-plastic Flow," Report UCRL-7322, Revision 1, Lawrence Livermore Laboratory, University of California, Livermore, CA, 1969, pp. 69-131.
7. J. Mescall, R. Papirno and J. McLaughlin, "Stress and Deformation Tests in Metals," Compression Testing of Homogeneous Materials and Composites, ASTM STP 808, Richard Chait and Ralph Papirno, Eds., American Society for Testing and Materials, 1983, pp. 7-23.
8. P. Dadras and J. F. Thomas, Jr., "Deformation Inhomogeneities in Upset Forging," Compression Testing of Homogeneous Materials and Composites, ASTM STP 808, Richard Chait and Ralph Papirno, Eds., American Society for Testing and Materials, 1983, pp. 24-39.
9. P. Hartley, C. E. N. Sturgess and G. W. Rowe, International Journal of Mechanical Sciences, v. 22, 1980, pp. 743-753.
10. Percy W. Bridgman, "Studies of Plastic Flow of Steel, especially in Two-Dimensional Compression," Journal of Applied Physics, v. 17, 1946, pp. 225.

11. James f. Bell, "Plane Stress, Plane Strain, and Pure Shear at Large Finite Strain," International Journal of Plasticity, v. 4, no. 2, 1988, pp. 127-148.
12. A. S. Khan and X. Wang, "An Experimental Study of Large Finite Plastic Deformation in Annealed 1100 Aluminum During Proportional and Nonproportional Biaxial Compression," International Journal of Plasticity, v. 6, no. 4, 1990, pp. 485-504.
13. M. Cook and E. C. Larke, "Resistance of Copper and Copper Alloys to Homogeneous Deformation in Compression," Journal of Institute of Metals, v. 71, 1945, pp. 371-390.
14. M. F. Ashby & D. Jones, ENGINEERING MATERIALS 1: An Introduction to their Properties and Applications, Pergamon Press, New York, 1988, p. 226.
15. J. G. Lenard, "Response of Two Aluminum Alloys to Single and Multistage Compression," ASME Journal of Engineering Materials and Technology, v. 108, pp. 376-377.
16. Aluminum Standards & Data, The Aluminum Association, 3rd Ed., New York, 1972, pp. 33-34.
17. Eric A. Brandes, Ed., "Aluminum and Aluminum Alloys," Smithells Metals Reference Book, Butterworths, Boston, 1983, pp. 22-4-5.
18. Kevin A. Anderson, Reynolds Aluminum Corporation, (Verbal Reference).