High Strain Rate Consolidation and Forming of Armstrong and HDH Titanium Powder
and Sheet Material

THESIS

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Abstract

The high cost of titanium currently limits its use to value-added application, primarily in the aerospace and defense industries. Due to the excellent strength-to-weight ratio and corrosion properties of titanium, there is significant interest in lowering the cost of titanium to make it accessible to other markets such as the automotive, transportation and chemical processing industries. The recently developed Armstrong process has created a low cost source of commercially pure and alloyed titanium powders, but current production techniques are inadequate for utilizing these powders to create components at an industrial scale.

In many applications, HSR forming techniques have been used to achieve formability beyond that which can be done by Quasistatic forming techniques. This study was performed to explore the use HSR forming techniques in the consolidation of titanium powders and the production of titanium PM components, in an effort to lower the cost of titanium components and open their availability to other industries. The primary methods utilized in this study were Electromagnetic forming techniques, involving the discharge of a capacitor bank through a driving coil to induce current in a closely coupled workpiece resulting in a strong opposing Lorentz force between them.

For the consolidation of titanium powders, copper tubes were filled with titanium powder and compacted by both solid and disposable coils. Roll compacted sheets were compacted utilizing a Uniform Pressure Actuator, Electromagnetic Press and an
Electronically Driven Expanding Plasma. The UPA uses a driving coil to launch a copper sheet in a planar manner to push a titanium sheet sample on to a flat die. The EM Press involves repeatedly striking a sample with an electromagnetically repelled aluminum flyer with a flat tool steel impactor attached. EDEP involves discharging a capacitor bank through an aluminum foil, causing it to burst into a plasma that expands and compacts the sheet.

The UPA was also shown to be capable of simultaneously forming and consolidating roll compacted sheet, both to densities that have not been achieved in green consolidated sheets and shapes which have not yet been attained in green or sintered material by any available Quasistatic technique. Milled titanium powder was also consolidated, showing increased density upon sintering relative to Quasistatic consolidated materials with the same green density.
Dedication

This document is dedicated to my family and close friends who have supported me in my pursuit of a graduate degree.
Acknowledgments

I would like to thank my advisor, Dr. Glenn Daehn, for providing me with the opportunity to pursue this research and degree. I also would like to thank my research group, especially Geoff Taber, Huimin Wang and Jason Johnson, along with Kathy Babusci, for giving their time and input throughout the course of research.

I thank the Department of Energy and Oak Ridge National Laboratory for their support and funding this research. In particular, I thank Yukinori Yamamoto, Wei Chen, Jim Kiggans and Bill Peter for providing me with information, support and materials.

In addition, I would like to thank Gregg Fenton of Applied Research Associates for his help with aspects of the data analysis.
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Fields of Study

Major Field: Materials Science and Engineering
Table of Contents

Abstract ................................................................................................................................................... ii
Dedication ........................................................................................................................................ iv
Acknowledgments .............................................................................................................................. v
Vita ................................................................................................................................................... vi
Fields of Study .................................................................................................................................. vi
Table of Contents .............................................................................................................................. vii
List of Tables ..................................................................................................................................... xi
List of Figures ................................................................................................................................... xii
Chapter 1: Introduction ...................................................................................................................... 1
Chapter 2: Titanium Powder Consolidation ...................................................................................... 9
  2.1 Equipment and Methods ............................................................................................................. 13
    2.1.1 Coils ................................................................................................................................... 13
    2.1.2 Capacitor Bank, Rogowski Coil and Voltage Divider ....................................................... 17
    2.1.3 Photon Doppler Velocimeter .............................................................................................. 18
    2.1.4 Tubes .................................................................................................................................. 23
    2.1.5 Mandrels ............................................................................................................................ 24
3.4.6 EM Press Effectiveness .................................................................................. 104

3.5 Conclusions ........................................................................................................... 104

Chapter 4: Conclusions ............................................................................................... 106

Chapter 5: Recommendations ..................................................................................... 108

List of Acronyms ......................................................................................................... 110

References .................................................................................................................. 111

Appendix A: Data for Tube Consolidation Samples ................................................. 114

Appendix B: Data for UPA Flat Sheet Compaction Samples ..................................... 122

Appendix C: Data for EDEP Samples ....................................................................... 133
List of Tables

Table 1: Rise time to peak current of solid coil direct powder consolidations ............... 39
Table 2: Matrix of HSR sheet tests ........................................................................................ 55
Table 3: Wall angles and depths of the channel die channels ........................................... 70
Table 4: Micrographs and densities of received materials (ORNL) ................................... 74
Table 5: Charge energy, velocity, kinetic energy and density of flyer driven CPARM samples ........................................................................................................................................................................ 76
Table 6: Charge energy, velocity, kinetic energy and density of driven 64ARM samples .................................................................................................................................................. 78
Table 7: Charge energy, velocity, kinetic energy and density of impacted CPARM samples ............................................................................................................................................... 80
Table 8: Charge energy, velocity, kinetic energy and density of impacted 64ARM samples ............................................................................................................................................... 84
Table 9: Channel formed sample results and images .......................................................... 93
List of Figures

Figure 1: Matrix of HSR powder consolidation tests ............................................................ 7
Figure 2: Matrix of roll compacted sheet tests................................................................. 8
Figure 3: Test matrix of HSR powder consolidations ....................................................... 13
Figure 4: The machined solid driving coil ....................................................................... 14
Figure 5: A section view of the solid coil model .............................................................. 15
Figure 6: Dyneema fiber wrapped and finished solid driving coil with leads attached.... 16
Figure 7: A disposable coil ............................................................................................. 17
Figure 8: Maxwell Magneform 16kJ Capacitor Bank (13) ............................................. 18
Figure 9: PDV data processing diagram .......................................................................... 20
Figure 10: PDV arrangement for a disposable coil experiment ....................................... 21
Figure 11: Annulus with mirror for solid coil compaction PDV ....................................... 22
Figure 12: An image of the periscopic arrangement with the compaction tube and annulus placed next to the coil ................................................................. 23
Figure 13: Tubes utilized for HSR consolidation methods ............................................. 24
Figure 14: Mandrels utilized for HSR consolidation experiments ................................. 26
Figure 15: A schematic of a solid coil direct powder consolidation ............................... 28
Figure 16: Sample tubes both pre and post compaction ............................................... 29
Figure 17: A schematic of the offset tube arrangement .................................................. 30
Figure 18: A disposable coil sample, prior to powder loading, with the driving tube removed............................................................................................................................. 31

Figure 19: An assembled disposable coil sample .................................................................................................................................................................................. 32

Figure 20: Secondary electron images of CP-Ti Armstrong powder (a and b), and HDH (c) powders (15) .................................................................................................................................................................................. 35

Figure 21: SE SEM images of Armstrong Ti-64 powder. (a) and (b): as-received powder; (c) and (d): 1-hr milled powder (16) .................................................................................................................................................................................. 36

Figure 22: The velocity and current traces for direct solid coil compaction of Armstrong CP-Ti powder at 8kJ .................................................................................................................................................................................. 38

Figure 23: A graph of Charge Energy versus Peak Primary Current of HDH and Armstrong solid coil direct consolidations ........................................................................................................................................................................... 39

Figure 24: Charge energy versus pre and post sintered density of solid coil direct compacts .................................................................................................................................................................................. 40

Figure 25: Micrographs and density gradients of HDH and Armstrong CP-Ti direct compaction 8kJ samples provided by ORNL ........................................................................................................................................................................... 41

Figure 26: A disposable coil offset sample using the small mandrel compacted at 5.12kJ alongside an uncompacted tube ........................................................................................................................................................................... 42

Figure 27: Tube velocity, coil velocity, primary electrical current and voltage traces for a 20% charge energy disposable coil offset compaction ........................................................................................................................................................................... 44

Figure 28: A graph of the charge energy against the peak electrical current and rise times of all disposable coil consolidated samples. ........................................................................................................................................................................... 45
Figure 29: Charge energy versus density of disposable coil compacted Armstrong Ti-6Al-4V samples
............................................................................................................................................. 45

Figure 30: QS and HSR green compacted and sintered pressure-density data provided by ORNL
.................................................................................................................................................. 47

Figure 31: HSR disposable coil offset consolidation density data compared to pressed and sintered densities samples of Armstrong Ti-6Al-4V powders (17) .............................................. 49

Figure 32: Tube compaction samples both (a) before and (b) after sintering ....................... 50

Figure 33: A schematic view of the Uniform Pressure Actuator (18) ........................................ 57

Figure 34: Unloaded uniform pressure actuator ................................................................. 58

Figure 35: Flat die for UPA with PDV port ......................................................................... 59

Figure 36: A typical dogbone-shaped EDEP foil ............................................................... 61

Figure 37: An EDEP sample in the test chamber ............................................................... 62

Figure 38: A schematic of the EM Press coil and flyer .................................................... 63

Figure 39: EM Press Coil assembly .................................................................................. 64

Figure 40: The EM Press bushing, post and flyer assembly section view, with adjustable UHMW bushing on the right ................................................................. 65

Figure 41: Charge energy against velocity of Revision 1 and Revision 2 EM Press flyers
.................................................................................................................................................. 66

Figure 42: EM Press with the second revision flyer ......................................................... 66

Figure 43: The MTS Universal Testing System used for the QS compactions of green roll compacted sheets ........................................................................................................... 68

Figure 44: A QS sheet sample in the MTS machine .......................................................... 69
Figure 59: Burst current density vs. density of EDEP samples ........................................ 89

Figure 60: Number of strokes versus percent fraction density of EM Press compacted samples .................................................................................................................................................. 90

Figure 61: Pressure vs density of QS compacted sheet samples ....................................... 91

Figure 62: Micrographs of a channel formed sample showing (A) a cracked wall and (B) a well formed wall .................................................................................................................................................. 94

Figure 63: A macroscopic image of a well formed wall (left) and a cracked wall (right) 94

Figure 64: Charge energy versus density of CPARM and 64ARM UPA compacted flat sheet samples ..................................................................................................................................................

Figure 65: Velocity as compared to green density of CPARM and 64ARM driven and impacted samples ..................................................................................................................................................

Figure 66: Kinetic energy per unit area as compared to green density of CPARM and 64ARM driven and impacted samples ..................................................................................................................................................

Figure 67: Charge energy versus density chart of combined UPA and EDEP samples 103
Chapter 1: Introduction

Due to the high cost of raw materials and processing, the use of titanium in many applications outside of the aerospace and defense industries is cost prohibitive. The very high strength-to-weight ratio and excellent corrosion properties when utilized in other applications could have huge implications involving energy efficiency, corrosion properties, and durability (1). Some applications of titanium in the automotive, defense and chemical processing sectors have been explored in recent decades with excellent results, however the current cost of up to $50/lb in some cases has limited its use to only the most high-end, value-added applications.

Previous uses of titanium in automotive applications have included engine and powertrain components. For many years racing engines have been built with titanium valves to increase the engine output. There is also significant potential for the use of titanium for weight reduction. The use of a titanium exhaust system on the 2001 Chevrolet Corvette reduced the mass of the exhaust system by 41% to 11.7kg when compared to the previous steel version (2). It also had the benefit of better corrosion properties. These kind of mass reductions translate to fuel savings and cost savings over the lifetime of the vehicle.
The potential for significant fuel and cost savings in other kinds of vehicles has also been of recent interest. In a 1997 study of titanium armor applications, it was estimated that titanium armor could provide a 30-40% weight reduction when compared to steel rolled homogeneous armor while maintaining vehicle survivability (3). While this would contribute significantly to fuel saving in a variety of defense applications, there is also the potential for significant improvements in vehicle durability due to the reduced load on vehicle components leading to reduced maintenance costs. Durability improvements and fuel savings due to weight reduction could also prove beneficial in many non-armor applications such as long-haul trucking and rail transportation, where the cost of fuel consumption and maintenance over the lifetime of the vehicle often exceeds the initial cost. There is also long-term potential for ultra lightweight titanium-based vehicles, replacing many large fundamental steel or aluminum components with better suited titanium ones.

In the chemical processing industry, the excellent corrosion resistance and strength properties make titanium the ideal choice for some applications. One potential application is heat exchangers for use with seawater. The past use of copper in heat exchangers suffers from dissolution over time which can contaminate water that flows through the facility. Titanium would provide an ideal alternative, but due to the significant cost associated with its use stainless steel remains the current choice for these applications (4).

Today, a majority of titanium is produced using the Kroll process. The Kroll process involves reducing TiCl$_4$ in liquid magnesium, resulting in titanium and
magnesium chloride. This process is done in individual batches which must be held at a temperature of 800-900°C for a number of days. At the conclusion of the Kroll process the titanium is in a sponge form which requires much purification and further Hydride-Dehydride processing to create a powder (8). In the Hydride-Dehydride process, the titanium is exposed to a high pressure hydrogen environment held at an elevated temperature to cause hydrogen embrittlement. The embrittled titanium sponge is then broken apart and the hydrogen is removed in a vacuum environment before the powder is ready for use (9). This substantial amount of processing results in a very expensive powder.

The Armstrong process, recently developed by International Titanium Powder LLC (ITP) holds a host of advantages which ultimately lead to a much less expensive product. The Armstrong process utilizes TiCl$_4$ vapor deposited into a continuous sodium stream for a reduction reaction, resulting in titanium and sodium chloride. The first advantage of the process is that it is a continuous production process, resulting in lower costs and a much shorter production time. In addition, the reaction takes place at a much lower temperature, contributing to a reduction in energy required. The resulting material is commercially pure titanium in powder form requiring little additional processing. For some applications, ball milling is performed to increase the tap density of the powder. Titanium alloys can be produced simply by adding other metal vapors into the sodium stream along with the TiCl$_4$ vapor. These factors all lead to a significantly lower production cost for the raw powder material, estimated to be about $5/lb (10).
There is a significant difference between the morphologies of the Armstrong and Kroll-derived HDH powders. The new Armstrong powders have a very irregular, flaky morphology an irregular size distribution and contain much internal porosity. HDH powders have a much more uniform, more spherical morphology and a more uniform size distribution. A comparison of these powders can be seen in Figure 21. HDH powders do have a substantially higher tap density, being around 50%, where Armstrong powders, even after ball milling, can only achieve about 30% tap density. In addition to having vastly different morphologies, the low cost also enables the potential for PM techniques to replace more expensive melt processing techniques that contribute to a significant portion of the cost of a titanium component (5).

Most current and common titanium production techniques involve melting Kroll titanium sponge. As simple melting and casting of titanium in air yields numerous impurities, advanced and costly techniques such as Vacuum Arc Remelt (VAR), Electron-Beam Melting, and Plasma Arc Single Melt Processing are required. VAR involves utilizing an electrode created from air-melted titanium to strike an electrical arc, slowly melting the titanium electrode. The process takes numerous hours, but ultimately produces a more pure ingot (1). Electron-Beam Melted materials require systems with multiple high-output electron beams in a vacuum system where feedstock is melted by one set of beams into a hearth, while an additional set of beams is used to heat material for refining and casting (11). Plasma Arc Single Melt Processing, utilizing a similar process to that of Vacuum Arc Remelting, involves using a plasma arc struck with various gases and particular environments to cast titanium material. The difficulty with
all of these techniques is the substantial amount of energy and cost involved with melting titanium in the kind of environment required limit impurities. As such, non-melt powder metallurgy techniques have been sought as a means of reducing processing costs while also utilizing a lower cost source of base material, that being Armstrong powders.

Recent work at Oak Ridge National Laboratory has explored many PM processes for use with Armstrong titanium powder. Vacuum Hot Pressing was shown to produce commercial grade titanium products, but is not likely to be commercially feasible due to the high costs associated with it. Extrusion techniques using pre-heated sealed canisters of pressed powder have produced >99% theoretical density samples, showing potential for the use of this technique in the production of some sizes of bar stock. Fully consolidated samples have also been produced by a technique called Pneumatic Isostatic Forging (PIF). The process, used by Ametek for a number of years on other metal powders, involves first cold pressing samples into a net shape. These samples are then preheated and sealed in a vessel for Cold Isostatic Pressing (CIP). While in this pressurized vessel, a high pressure argon atmosphere is applied for a short duration, effectively forging the sample. This method has shown potential in the production of various net-shape parts and small sheets. A fourth method utilized for consolidation of these powders has been Roll Compaction. Raw powder material is fed into counter-rotating rollers, producing continuous sheets of green densities of up to 67%. This method shows much potential for sheet applications as the cost associated with it is very low, however, higher densities are required in order to use these sheets for commercial applications (5). These non-melt techniques have shown that it is not only possible to
fully consolidate these low-cost titanium powders, but that some existing techniques can be applied to titanium powders. However, there are still size limitations and concerns with processing costs restricting widespread use of these materials. Due to the vast potential of a low-cost source of titanium, further investigation into additional methods was warranted. As such, this study of High Strain Rate (HSR) techniques for powder consolidation and compaction was initiated.

Previous work in HSR powder consolidation has involved the use of gas guns, explosives and electrohydraulic compaction techniques. It was seen that samples in which the compaction velocity exceeded the speed of sound in the powder, a very significant increase in density was seen due to the existence of a shockwave. This shockwave resulted in high localized pressures and some interparticle melting. It has also been seen that HSR consolidation techniques that do not create a shockwave still benefit from increased densities due to localized heating causing enhanced interparticle bonding (12). Also, surprisingly, HSR equipment can be much lighter and easier to implement than conventional pressing equipment. It was with these factors in mind that this study was performed.

In Chapter 2, the HSR consolidation of both HDH and Armstrong titanium powders was explored. Two methods were utilized, both involving the placement of titanium powder in a copper tube and radially compacting the tube by electromagnetic means. In the first method, Solid Coil Direct Consolidation, a copper tube containing a mandrel was filled with titanium powder and compacted by means of a solid machined copper coil connected to a capacitor bank. The second method, Disposable Coil Offset
Consolidation, utilized a copper tube containing an offset column of titanium powder containing a mandrel, a wrapped in a one-time use disposable coil made of copper wire connected to a capacitor bank. In this arrangement, the copper tube is given space to accelerate prior to striking the titanium powder, creating higher impact velocities. For experiments performed by both methods, the current of the driving coil was recorded along with the radial velocity of the tube, and in some cases the voltage of the system and velocity of the disposable coil were recorded as well. A test matrix for these experiments is shown in Figure 1.

![Figure 1: Matrix of HSR powder consolidation tests](image)

Chapter 3 explores the potential of HSR forming and compaction techniques when applied green-state roll compacted sheets provided by ORNL. An Electromagnetic Uniform Pressure Actuator (UPA) was used to propel a copper sheet in two different arrangements, both to drive and impact roll compacted titanium sheet material onto a flat die. Electrically Driven Expanding Plasma (EDEP) was also utilized as a means of driving titanium sheet material onto a flat die. Recent work has also produced an
electromagnetically driven press which was used to repeatedly strike a titanium sample and compact it further with each hit. In addition, the UPA was used to drive green and sintered sheet samples over a channel die of varying wall angles to determine if forming of these sheets was possible at HSR.

For all of these methods, green state roll compacted Armstrong powder CP-Ti and Ti-6Al-4V sheets were used, with the addition of various sintered Armstrong and HDH CP-Ti sheets for the forming experiments using the channel die. A matrix of the tests performed with the state of the materials used for each of the test methods is shown in Figure 2.

<table>
<thead>
<tr>
<th></th>
<th>UPA</th>
<th>EDEP</th>
<th>EM Press</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Die</td>
<td>Green Roll Compacted Sheet</td>
<td>Green Roll Compacted Sheet</td>
<td>Green Roll Compacted Sheet</td>
</tr>
<tr>
<td>Channel Die</td>
<td>Green and Sintered Roll Compacted Sheet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Matrix of roll compacted sheet tests
Chapter 2: Titanium Powder Consolidation

Current industrial-scale production methods for titanium powder involve the use of powder derived from the Kroll process (5). The Kroll process involves reducing TiCl$_4$ in liquid magnesium, resulting in titanium and magnesium chloride. This process is done in individual batches which must be held at a temperature of 800-900°C for a number of days. At the conclusion of the Kroll process, the titanium is in a sponge form, which requires much purification and further Hydride-Dehydride processing to create a powder (8). The Hydride-Dehydride process involves exposing the sponge to a high pressure hydrogen environment held at an elevated temperature to cause hydrogen embrittlement of the titanium. The embrittled titanium sponge is then broken apart and the hydrogen is removed in a vacuum environment before the powder is ready for use (9). This substantial amount of processing results in a very expensive powder.

The Armstrong process, recently developed by International Titanium Powder LLC (ITP) utilizes TiCl$_4$ vapor deposited into a continuous sodium stream for a reduction reaction, resulting in titanium and sodium chloride. The first advantage of the process is that it is a continuous production process, resulting in lower costs and a much shorter production time. In addition, the reaction takes place at a much lower temperature, further contributing to a reduction due to the lower amount of energy required to maintain the reaction. The resulting material is commercially pure titanium in powder form.
requiring little additional processing. In some applications, ball milling is performed to increase the tap density of the powder. Titanium alloys can be produced simply by depositing other metal vapors into the sodium stream along with the TiCl$_4$ vapor. These factors all lead to a significantly lower production cost for the raw powder material (10). Further descriptions of both the HDH and Armstrong processes are in Section 2.2. However, a reduction in raw material costs is only a portion of the high cost of titanium products. Current processing techniques contribute to a significant portion of the cost associated with titanium usage (5).

Most current and common titanium production techniques involve melting the material. As simple melting and casting of titanium in air yields numerous impurities, advanced techniques such as Vacuum Arc Remelt (VAR), Electron-Beam Melting, and Plasma Arc Single Melt Processing are required. VAR involves utilizing an electrode created from air-melted titanium to strike an electrical arc, slowly melting the titanium electrode. The process takes numerous hours, but ultimately produces a more pure ingot (1). Electron-Beam Melted materials require systems with multiple high-output electron beams in a vacuum system where feedstock is melted by one set of beams into a hearth, while an additional set of beams is used to heat material for refining and casting (11). Plasma Arc Single Melt Processing, utilizing a similar process to that of Vacuum Arc Remelting, involves using a plasma arc struck with various gases and particular environments to cast titanium material. The difficulty with all of these techniques is the substantial amount of energy and cost involved with melting titanium in the kind of environment required to limit impurities. Non-melt powder metallurgy techniques have
been sought as a means of reducing processing costs while also utilizing a lower cost source of base material, that being Armstrong powders.

Recent work at Oak Ridge National Laboratory has explored many PM techniques for use with the new Armstrong titanium powder. Vacuum Hot Pressing was shown to produce commercial grade titanium products, but is not likely to be commercially feasible due to the high costs associated with it. Extrusion techniques using pre-heated sealed canisters of pressed powder have produced >99% theoretical density samples, showing potential for the use of this technique in the production of some sizes of bar stock. Fully consolidated samples have also been produced by a technique called Pneumatic Isostatic Forging (PIF). The process, used by Ametek for a number of years, involves first cold pressing samples into a net shape. These samples are then preheated and sealed in a vessel for Cold Isostatic Pressing (CIP). While in this pressurized vessel, a high pressure argon atmosphere is applied for a short duration, effectively forging the sample. This method has shown potential in the production of various net-shape parts and small sheets. A fourth method utilized for consolidation of these powders has been Roll Compaction. Raw powder material is fed into counter-rotating rollers, producing continuous sheets of green densities of up to 67%. This method shows much potential for sheet applications as the cost associated with it is very low (5). These non-melt techniques have shown that it is possibly, in some cases, to consolidate these low-cost titanium powders, but that some existing techniques can be applied to titanium powders. However, there are still size limitations and concerns with processing costs restricting widespread use of these materials. Due to the vast potential of
a low-cost source of titanium, further investigation into additional methods was warranted. As such, this study of High Strain Rate (HSR) techniques for powder consolidation and compaction was initiated.

Previous work in HSR powder consolidation has involved the use of gas guns, explosives and electrohydraulic compaction techniques. It was seen that samples in which the compaction velocity exceeded the speed of sound in the powder, a very significant increase in density was seen due to the presence of a shockwave. This shockwave resulted in high localized pressures and some interparticle melting. It has also been seen that HSR consolidation techniques that do not involve a shockwave still benefit from increased densities due to localized heating causing enhanced interparticle bonding (12). However, in previous work, sample cracking and spalling has often hindered the use of HSR processing techniques. This study was performed with the intent of exploring the potential advantages of HSR techniques when applied to new low-cost titanium products.

In this study, both HDH and Armstrong titanium powders were consolidated at HSR. Two methods were utilized, both involving the placement of titanium powder in a copper tube and radially compacting the tube by electromagnetic means. In the first method, Solid Coil Direct Consolidation, a copper tube containing a mandrel was filled with titanium powder and compacted by means of a solid machined copper coil connected to a capacitor bank. The second method, Disposable Coil Offset Consolidation, utilized a copper tube containing an offset column of titanium powder containing a mandrel, all wrapped in a one-time use disposable coil made of copper wire.
connected to a capacitor bank. In this arrangement, the copper tube is given space to accelerate prior to striking the titanium powder, creating higher impact velocities. For these experiments the current of the driving coil was recorded along with the radial velocity of the tube, and in some cases the system voltage and velocity of the disposable coil were recorded as well. A test matrix for these experiments is shown in Figure 3, while further details of these methods are in Section 2.1. The results of these experiments, followed by a discussion of the results and a list of the conclusions reached are in Sections 2.3, 2.4 and 2.5 respectively.

![Test matrix of HSR powder consolidations](image)

**Figure 3:** Test matrix of HSR powder consolidations

### 2.1 Equipment and Methods

#### 2.1.1 Coils

Titanium powder consolidation tests were performed using two similar axisymmetric experimental setups. Identical copper tubing was used as the driver in both variants, with one of the primary differences between the two methods being the different
driving coil. The first method utilized a solid coil machined from a copper rod, while the second method used disposable coil made of wrapped copper wire.

The solid coil was made of Alloy 18150 copper machined into a coil as shown in Figure 4. The coil had 13 turns that were .25” wide on the inside face with a .125” gap between each turn, making the pitch .375”. A trapezoidal shape, shown in the model in Figure 5, was used for the section of the coil with a .125” length for the smaller parallel-side dimension on the outer edge of the coil. The coil had an inside diameter of 1.375” and an outside diameter of 2.375”. A plastic insulating sleeve was fit tightly on the inside of the coil to prevent electrical arcing to the workpiece during forming operations. In order to withstand the substantial outward radial force associated with compacting a tube in this type of coil, the entire coil assembly was wrapped in Dyneema® Fiber and encased in epoxy. The finished coil is shown in Figure 6.

Figure 4: The machined solid driving coil
Figure 5: A section view of the solid coil model
The disposable coils utilized by the second compaction method are a simple and inexpensive alternative to solid machined coils, though they are consumed with each test. They also offer the advantage of a higher current density, due to the ability to allow a greatly reduced coil pitch. Insulated .010” commercial copper magnet wire was tightly
hand-wrapped around a portion of the tube being utilized for testing. The coils had 6
turns and contained a .010” gap created by a piece of G-10 wedged between the third and
fourth turns to allow for measurements of the tube velocity to be taken during the event.
For some experiments, retro-reflective tape was placed on the third turn of the coil to
allow for observation of the velocity of the coil as it was repelled during the compaction
event. Figure 7 shows one of these disposable coils removed from the compaction tube.

![Figure 7: A disposable coil](image)

2.1.2 Capacitor Bank, Rogowski Coil and Voltage Divider

All of the electromagnetically driven experiments were conducted utilizing a 16kJ
Maxwell Magneform 8 capacitor bank, shown in Figure 8. The total capacitance of the
bank is 426 µF, with a maximum charge voltage of 8.66 kV. The typical rise time to the
peak current upon discharge is around 15-30 µs, varying significantly with coil geometry.
A Rocoil brand FG-1823 Rogowski coil set to 100kA/V and 10,000:1 voltage divider
were connected to an oscilloscope and used to record the discharge current and voltage in real time. The data acquisition rate for all channels was 5GS/s with a window of 500 µs and a pretrigger recording of 100 µs worth of data. Triggering occurred on a rise of greater than 180 mV on the current trace channel, indicating a primary electrical current of 18,000 A.

Figure 8: Maxwell Magneform 16kJ Capacitor Bank (13)

2.1.3 Photon Doppler Velocimeter
The Photon Doppler Velocimeter (PDV) was used to track the velocity of various moving surfaces throughout the course of testing. Recently developed at Lawrence Livermore National Laboratory, the PDV utilizes a fiber optic laser and high speed oscilloscope to determine the velocity of a moving surface (12). A laser probe is used to focus the laser beam on the desired surface. The movement of the surface causes a Doppler shift in the reflected beam which is then combined with an unshifted reference beam. As shown in Figure 9, the frequency of the resultant beam represents only the Doppler shift and can be used to calculate the velocity of the surface. The PDV can provide multiple channels of data with very high spatial and temporal resolution. It is also exceptionally versatile due to its ability to utilize inexpensive probes of various beam shapes and focal lengths (14).
The diagram illustrates the process of PDV data processing. The light, both shifted and unshifted, is directed towards the fiber optic lens, resulting in mixed light being emitted. The intensity graph shows the characteristic pattern of the system over time.

Figure 9: PDV data processing diagram

One limitation of the PDV is that, due to its reliance upon the resultant beam comprised of the shifted and unshifted beam, it is not able to show a negative velocity to indicate a direction of travel either towards or away from the probe. As such, all velocities will be shown in the positive range. This did not present an issue, as in electromagnetically driven experiments the initial direction of travel of the workpiece is always away from the coil.

In these particular consolidation arrangements, novel methods were required to attain velocity measurements without risking damage to probes or driving coils. For
samples compacted with a disposable coil, a viewport with a polycarbonate sheet was used to protect the PDV probes from the potential hazard of debris that results when a coil expands during the course of testing. Careful alignment of the test sample, viewport and PDV probes allowed for the velocity of the center of the compacting sample to be observed as well as the coil turn immediately adjacent to the center of the sample. This arrangement is shown in Figure 10.

![Figure 10: PDV arrangement for a disposable coil experiment](image)

A more elaborate arrangement was required to allow for a beam to be focused on the moving tube during tests utilizing the solid coil. Previous iterations of solid coils
utilized a port drilled through the epoxy casing between coil windings to allow for velocity measurements to be taken, however, these ports proved to be the cause of critical failure of the coils. As such, a periscope system was used to allow the PDV beam to reach the central portion of the sample. As is shown in Figure 11, a thin annulus of plastic was machined to fit between the insulating lining of the coil and the test sample. A 1mm mirror with a 45° angle was glued on the annulus and the annulus was placed at the centered on the sample, which in turn was centered in the coil. This arrangement allowed for the PDV beam to be directed from outside of the coil at one end along parallel to the sample in the small gap between the sample and lining, off the angled mirror and on to the center of the sample. An example of this periscopic PDV arrangement with the sample tube placed next to the coil is shown in Figure 12.

Figure 11: Annulus with mirror for solid coil compaction PDV
2.1.4 Tubes

All experiments utilized driving tubes of the same material and radial dimensions. The tubes were Alloy 122 Copper with an Outside Diameter (OD) of 1.125” and Wall Thickness (WT) of .035”. For solid coil experiments, a tube length of 8” was used to
accommodate reusable end plugs that sat outside of the compacted region. For disposable coils, 4” lengths of tubing could be utilized as the coil length and resulting compacted region was smaller. All copper tubing was annealed at 550°C for 30 minutes shortly before testing to aid in forming ability as well and assure uniformity of material properties across the all samples.

For disposable coil offset experiments, a powder sleeve was used to accommodate an offset between the copper tube and the material to allow for further acceleration prior to the flyer tube impacting the powder. The sleeve had an OD of .97” and a WT of .020”. Figure 13 features the two lengths of copper tube utilized as well as the sleeve material.

![Figure 13: Tubes utilized for HSR consolidation methods](image)

2.1.5 Mandrels
Three different mandrels were utilized to displace material to effectively increase the compaction pressure during testing. Solid coil experiments utilized a stainless steel tapered pin with a threaded end. The minimum and maximum outside diameters were .386” and .490” respectively. The mandrel was 5-11/16” long with a 5” tapered length. The remaining threaded section was outside of the compacted region and was used to assist in removal of the pin. Disposable coil experiments utilized 3” long mandrels cut from hardened stainless steel rod stock. The small mandrel size was .625” in diameter while the large mandrel was .75”. All of the mandrels used in testing are show in Figure 14.
2.1.6 Solid coil direct consolidation method

The first series of tests ran utilized the solid machined coil as a driver and the 8” long copper driving tube. The tapered mandrel was centered inside the driving tube.
about the tapered region within the tube by installing a test plug inside the tube at the proper location. CP-Ti powder of either the HDH or Armstrong morphologies were added to the tube and manually tapped to their tap density before installing a second test plug to seal the tube. Initial densities were measured by taking the mass of the empty and full test samples and dividing by the known volume.

The plastic annulus with the angled mirror to allow for periscopic beam alignment with the PDV was centered on the sample before being placed inside of the driving coil attached to the capacitor bank. The samples were centered vertically within the coil placing one end of the sample on an adjustable height table and moved by means of adjusting the table and measuring its placement with a set of calipers. PDV system was then aimed off of the angled mirror and on to the tube prior to running the experiment. Figure 15 shows a schematic of what occurs upon discharge of the capacitor bank. The primary electrical current discharged through the coil induces an opposing current in the tube. Both the primary and induced electrical currents have opposing magnetic fields resulting in a repulsive Lorentz force that compacts the tube, resulting in the consolidation of the powder contained inside.
Figure 15: A schematic of a solid coil direct powder consolidation

Following the experiment, density measurements were taken by measuring the diameter of the sample at the center using calipers to .0005” accuracy and multiplying the initial density by the ratio of the cross sectional area of the sample before and after the experiment, assuming conservation of mass of the copper tube. Figure 16 compares a compacted sample to a noncompacted tube. These samples were then sent to Oak Ridge National Laboratory where they were removed from the tubes and sintered prior to being mounted for optical microscopy. ImageJ analysis software was used to determine the sintered density of the samples.
Figure 16: Sample tubes both pre and post compaction

2.1.7 Disposable coil offset consolidation method
After the results of the solid coil results were gathered, it was decided to attempt to achieve higher densities for subsequent tests by making two modifications to the test arrangement. The first change was to switch from a solid coil to a disposable coil with a greatly reduced pitch. The reduced pitch increases the current density in the tube, resulting in a higher force. The second change was to contain the titanium in a plastic tube within the copper tube with a reduced diameter. This 1.2mm offset allowed the tube to accelerate prior to impacting the titanium powder at high velocity. Figure 17 features a schematic of cross sectional view of this arrangement. Mandrels of .625” and .75” were utilized for these experiments. Nylon end plugs with an O-ring, shown in Figure 18, were designed to maintain the axial alignment of the copper tube, mandrel and titanium column while also sealing powder in the plastic tube.

Figure 17: A schematic of the offset tube arrangement
Samples were assembled in a manner similar to those for direct consolidation. The plastic tube and mandrel were aligned by placing one end of each in one of the end plugs. Titanium powder was added and manually tapped dense before the copper tube was then added and the second end plug was placed on the other end. Densities were calculated by measuring the mass of the empty and full sample and dividing by the known fill volume of the sample. Samples were then given a single wrap of 2” wide
Kapton electrically insulating tape about the center to prevent electrical arcing to the tube during the test. A small square hole was cut in the Kapton tape to allow for PDV measurements of the tube surface to be taken. The hand-wrapped 6 turn coil was then placed over the sample with the gap in the windings aligned over the hole in the tape prior to being taped in place. A small piece of retro-reflective tape was placed on the coil winding adjacent to the gap to allow for the velocity of the repelled coil to be observed. Figure 19 shows a prepared sample prior to it being attached to the capacitor bank.

Figure 19: An assembled disposable coil sampled
The sample was then attached to the capacitor bank and the PDV beams were focused on the tube and windings. Figure 10 shows a test sample attached to the capacitor bank with the PDV in place. The experiment was then run with the electrical current, voltage and two velocity measurements recorded. Following the experiments density measurements were taken by measuring the diameter of the sample at the center using calipers to .0005” accuracy and multiplying the initial density by the ratio of the cross sectional area of the sample before and after the experiment, assuming conservation of mass of the copper tube.

2.2 Materials

Oak Ridge National Laboratory provided 3 types of powder for consolidation in this study. For solid coil direct compaction, Hydride-Dehydride (HDH) and Armstrong CP-Ti powders were used, while for the disposable coil offset compactions experiments, Armstrong Ti-6Al-4V powders were used.

2.2.1 HDH CP-Ti powder

HDH powders are currently the most widely used types of powders for titanium PM applications (5). These powders are actually derived from the Kroll process for titanium production. In the Kroll process, TiCl₄ is reduced in retort filled with liquid magnesium held at 800°-900°C over a period of a few days. The magnesium reduction
reaction with the TiCl$_4$ produces titanium as well as MgCl$_2$. The reaction produces a titanium sponge with many impurities resulting from unreacted magnesium and MgCl$_2$ and must undergo further processing to remove them. At this point, a pure titanium sponge remains (8). In order to refine this sponge into a powder, it must under Hydride-Dehydride processing. The material is subject to a heated, high pressure hydrogen environment to force hydrogen into the sponge and cause embrittlement of the titanium. The sponge can then be broken apart into a powder before being heated and put in a vacuum to remove the hydrogen, resulting in a pure titanium powder (9).

The resulting powder is of a large, round morphology as shown below in Figure 20(c). The observed tap density of the provided HDH CP-Ti powder provided by ORNL was 48-51% of theoretical density.

2.2.2 Armstrong CP-Ti and Ti-6Al-4V

Armstrong titanium powder is a product of International Titanium Powder LLC. In the Armstrong process, TiCl$_4$ vapor is fed into a continuous stream of molten sodium. The sodium reduces the TiCl$_4$ vapor producing titanium and NaCl. The NaCl and titanium are then filtered from the stream. The NaCl is processed in a manner that allows for the sodium to be returned to the cycle. This process holds the advantages of going straight from TiCl$_4$ to a usable powder in one operation, occurring at a much lower temperature, operating continuously as opposed to batch processing, and it also allows for production of homogeneous alloys as other reactants can be fed in with the TiCl$_4$ (10).
This study utilized both CP-Ti and Ti-6Al-4V powders produced by the Armstrong process.

The resulting Armstrong powders direct from the process are typically about 3-7% of theoretical density. This low density is not suitable for many applications, so often the material is ball milled prior to being utilized in a PM application. The powders used in this study were ball milled to achieve tap densities of 30-32% theoretical for both the CP-Ti and Ti-6Al-4V materials. Figure 20 (a) and (b) show Armstrong CP-Ti material, while Figure 21 shows Armstrong Ti-6Al-4V particles both before and after ball milling at various length scales (15).

![Secondary electron images of CP-Ti Armstrong powder (a and b), and HDH (c) powders (15)](image)

Figure 20: Secondary electron images of CP-Ti Armstrong powder (a and b), and HDH (c) powders (15)
When consolidating powders at HSR, a number of factors contribute to how effectively it can be done when compared to QS methods. HSR techniques benefit from irregular powder morphologies. When compared to a more spherical morphology, the irregular morphology contains more stress concentrators to aid in deformation of the
powder, resulting in increased densities. In this manner, Armstrong powders should benefit from HSR consolidation when compared to HDH powders. Another set of factors influencing HSR consolidation is the size and regularity of the powder particles. Powders with a broader size distribution that is not at either extreme of size have the potential for greater particle interaction. In the case of HSR consolidation, particle interaction can result in localized heating which can enhance interparticle bonding during compaction. In this manner, Armstrong powders should also show further benefit from HSR consolidation when compared to HDH powders. Another primary contributing factor is the initial density of the powder. A higher initial density helps facilitate the transmission of energy through the powder more effectively. Even ball milled Armstrong powder, with a tap density of around 30%, is substantially less dense than HDH powders at 50%, making them less suitable in this regard (10).

2.3 Results

2.3.1 Solid coil direct compaction results

An example of the velocity and current data acquired for a solid coil tube compaction is shown below in Figure 22. It can be seen that the peak primary current of 42 kA occurs at 30.5 μs. Data from all of the samples is featured in Appendix A. Shortly after the current begins to rise, the copper tube yields and begins to drive inwards onto the powder. The tube continues compacting the material until the material begins to
reach the limit of consolidation. Throughout this time period there is still a significant Lorentz force being applied to the tube as there is still a significant primary current. This makes a simplified analysis of the compaction pressure by means of observing the deceleration of the tube difficult. The compaction pressure can be obtained by means of more complex models, but that is not within the scope of this document, and will likely be the subject of future publications. Figure 23 shows the charge energy of the capacitor against the peak primary current for all of the sample, with Table 1 showing the rise time from the time of capacitor discharge to the peak primary current. It can be seen that the rise time is nearly constant, while the peak electrical current steadily increases with an increase in Charge Energy.

Figure 22: The velocity and current traces for direct solid coil compaction of Armstrong CP-Ti powder at 8kJ
Figure 23: A graph of Charge Energy versus Peak Primary Current of HDH and Armstrong solid coil direct consolidations

Table 1: Rise time to peak current of solid coil direct powder consolidations

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>Current Rise Time (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HDH</td>
</tr>
<tr>
<td>6</td>
<td>30.5</td>
</tr>
<tr>
<td>8</td>
<td>30.9</td>
</tr>
<tr>
<td>10</td>
<td>30.5</td>
</tr>
<tr>
<td>12</td>
<td>30.9</td>
</tr>
</tbody>
</table>

A graph showing charge energy versus density of each HDH and Armstrong CP-Ti sample is shown in Figure 24. All of the measurements were taken at the center portion of the mandrel and tube, where the mandrel diameter is .438”. The tap densities of both materials are shown by the horizontal lines on the chart. The chart also features...
data provided by ORNL from the samples after a 1 hr sintering operation at 1300°C in argon.

Figure 24: Charge energy versus pre and post sintered density of solid coil direct compacts

After samples were sintered at ORNL, they were also sectioned and mounted for optical micrographs. Figure 25, provided by ORNL, shows the density gradient observed in both HDH and Armstrong CP-Ti samples compacted at 8kJ.
Figure 25: Micrographs and density gradients of HDH and Armstrong CP-Ti direct compaction 8kJ samples provided by ORNL

2.3.2 Disposable coil offset compaction results
For this series of tests, ORNL provided Armstrong Ti-6Al-4V powder for compaction. Figure 26 above shows a sample after compaction alongside an uncompacted tube. The typical data set with tube velocity, coil velocity, primary electrical current and voltage traces from the 3.2kJ sample using the smaller .625” mandrel is shown below in Figure 27. Figure 28 shows a graph of the charge energy against both the peak primary electrical current and the rise time from the time of discharge to that peak. When compared to the solid coil consolidations, it can be seen that the rise times are much shorter and the peak currents much higher. As can be seen from the tube velocity data, the tube accelerates to just over 100 m/s prior to impacting the powder column. Taking the integral of the tube velocity up to the point of impact, the offset distance of 1.2 mm can be accounted for. Following impact, the tube then
proceeds to compact the powder until it completes deceleration at around 38 µs. It can be seen that throughout the compaction event the coil is still accelerating away from the tube, showing that there is still an active Lorentz force between the tube and coil. Because there is still an active force being applied to the tube, simple pressure analysis based on tube deceleration alone would be inaccurate. More complex modeling to account for the active force as well as the tube momentum is possible, and will likely be the subject of future work. The density data for the disposable coil offset compactions on both the large and small mandrel samples is shown in Figure 29.
Figure 27: Tube velocity, coil velocity, primary electrical current and voltage traces for a 20% charge energy disposable coil offset compaction
Figure 28: A graph of the charge energy against the peak electrical current and rise times of all disposable coil consolidated samples.

Figure 29: Charge energy versus density of disposable coil compacted Armstrong Ti-6Al-4V samples
2.4 Discussion

2.4.1 A comparison of HSR and QS consolidation

Much recent work regarding QS consolidation of Armstrong and HDH titanium powder by pressing and sintering has been performed at Oak Ridge National Laboratory (14) (16). Figure 30, provided by ORNL, features QS green pressed and sintered densities compared to compaction pressures from recent data for both Armstrong and HDH CP-Ti powders alongside the HSR data from this study and previously shown in Figure 24. Pressed samples were pressed in a .5” diameter uniaxial double-action die. Densities for these samples were calculated from the mass and volume of the samples following pressing (16).
Figure 30: QS and HSR green compacted and sintered pressure-density data provided by ORNL

In regards to the Armstrong CP-Ti powder, HSR consolidation is seen to both be effective at consolidation and also allow for enhanced sinterability when compared to quasi-statically consolidated samples of the same green density. The lowest energy 6kJ HSR compacted sample can be seen to match the green density of a 10 ksi compacted QS sample, about 45% theoretical density. The advantage in sinterability is seen when following the green dotted lines in Figure 30. While the 10 ksi QS sample sinters to a density of 62%, the HSR consolidated sample of the same green density sinters to 72% of theoretical density. This advantage in sinterability with Armstrong samples can be seen through the full range of data. Following the blue dotted lines in the figure, it can be seen that the 12kJ Armstrong compacted sample has green density of 62%, comparable to that of a QS sample compacted at approximately 28 ksi. Where a 28ksi sample would be
expected to reach a sintered density of approximately 77%, the HSR compacted sample sintered to a density of 83%, equivalent to what one would expect of a sintered sample consolidated at 48 ksi.

A similar analysis of the sinterability of QS and HSR consolidated HDH powder samples shown in Figure 30 reveals that HSR samples are actually less effectively sintered than their QS counterparts. HDH samples consolidated quasi-statically saw an increase in density upon sintering of 12-15%, where samples consolidated at HSR only increased by 7-10%. Also from this data, the necessity to increase the compaction pressure was seen, leading to the change to a disposable coil and offset consolidation method for subsequent testing in order to determine if high enough green densities could be achieved at HSR to exceed the sintered densities that could be attained by pressing and sintering.

For these tests, ORNL was able to provide Armstrong Ti-6Al-4V powders. While sintering and subsequent analysis of these samples is in process and will likely be included in future publications, the initial compaction data featured in Figure 29 above is compared to data pressed and sintered samples of the same material from a recent ORNL study in Figure 31 (17).
By following the blue dotted lines across the figure, it can be seen that the lowest green density test sample, performed at a charge energy of 2.24 kJ with the smaller mandrel, achieved a density of 55% theoretical density, comparable to a sample pressed at 40 ksi. The highest green density achieved by a HSR disposable coil offset consolidation was 74% at a charge energy of 7.04 kJ. This density was beyond what was attained by traditional pressing means. It can also be seen in the QS press and sinter data that the Armstrong Ti-6Al-4V powders show excellent sinterability characteristics, with increases in density from 25-40%. Results from the sintering of samples consolidated at HSR for this study are not available at this time, but there is much potential for higher sintered densities due to the higher green densities attained with HSR methods along with the potential for increased sinterability in the same manner that was observed in CP-Ti Armstrong samples consolidated at HSR.
2.4.2 Near-net-shape applications

In exploring the potential to reduce the cost of titanium components, there are other routes to consider aside from simply a reduction in cost of the raw materials or consolidation techniques. By achieving near net shapes in production, it is possible to reduce machining costs and thereby the final cost of the product. Due to the mandrel-based arrangement utilized for these high strain rate consolidation tests, there is potential for some net shapes. The most apparent of these shapes would be tubes or nozzles, as determined by the use of either straight rod or tapered mandrels. Figure 32, provided by ORNL, shows solid coil direct compaction samples, both HDH and Armstrong, before and after sintering. It can be seen that test samples retain their shape following sintering.

![Figure 32: Tube compaction samples both (a) before and (b) after sintering](image)

2.5 Conclusions
1. High Strain Rate consolidation by means of a solid coil, direct compaction or a
disposable coil, offset compaction is a potentially effective means of
consolidating Armstrong titanium powders. In some instances, Armstrong
titanium powders compacted at HSR can yield higher densities than what can be
achieved by a standard pressing operation.

2. Armstrong CP-Ti powders consolidated at HSR show better sintering
characteristics than samples consolidated by cold pressing.

3. Near net-shape PM tube or nozzle components can potentially be produced by
means of HSR solid coil direct tube consolidation or disposable coil offset tube consolidation.
Chapter 3: Sheet Consolidation and Forming

Industrial-scale production methods for titanium involve the use of powder derived from the Kroll process (5). The Kroll process involves reducing TiCl$_4$ in liquid magnesium, resulting in titanium and magnesium chloride. This process is performed in individual batches which must be held at a temperature of 800-900°C for a number of days. At the conclusion of the Kroll process, the titanium is in a sponge form, which requires much purification and further Hydride-Dehydride processing to create a powder (8).

The Armstrong process, recently developed by International Titanium Powder LLC (ITP) utilizes TiCl$_4$ vapor deposited into a continuous sodium stream for a reduction reaction, resulting in titanium and sodium chloride. The first advantage of the process is that it is a continuous production process, resulting in lower costs and a much shorter production time. In addition, the reaction takes place at a much lower temperature, further contributing to reduction. The resulting material is commercially pure titanium in powder form requiring little additional processing. In some applications, ball milling is performed to increase the tap density of the powder. Titanium alloys can be produced simply by depositing other metal vapors into the sodium stream along with the TiCl$_4$ vapor. These factors all lead to a significantly lower production cost for the raw powder material (10). Further descriptions of both the HDH and Armstrong processes are in
Section 2.2. Raw material costs only account for a portion of the high cost of titanium products. Current processing techniques contribute to a significant portion of the cost associated with the use of titanium. As such, new consolidation technique are also being explored (5).

Most current and common titanium production techniques involve melting the material. As simple melting and casting of titanium in air yields numerous impurities, advanced techniques such as Vacuum Arc Remelt (VAR), Electron-Beam Melting, and Plasma Arc Single Melt Processing are required. The difficulty with all of these techniques is the substantial amount of energy and cost involved with melting titanium in the kind of environment required limit impurities. The development of low cost powders has sparked interest in non-melt powder metallurgy techniques aimed at reducing processing costs while taking advantage of cheaper raw material.

Recent work at Oak Ridge National Laboratory has explored many PM techniques for use with the new Armstrong titanium powder. Vacuum Hot Pressing was shown to produce commercial grade titanium products, but is not likely to be commercially feasible due to the high costs associated with it. Extrusion techniques using pre-heated sealed canisters of pressed powder have produced >99% theoretical density samples, showing potential for the use of this technique in the production of some sizes of bar stock. Fully consolidated samples have also been produced by a technique called Pneumatic Isostatic Forging (PIF). The process, used by Ametek for a number of years on other metal powders, involves first cold pressing samples into a net shape, CIP of the sample, then applying a high pressure argon atmosphere is for a short duration,
effectively forging the sample. This method has shown potential for the production of various net-shape parts and small sheets. The fourth method utilized, and the one of interest for this study, was Roll Compaction. Raw powder material was fed into counter-rotating rollers, producing continuous sheets of green densities of up to 67%. This method shows very much promise as the cost associated with it is very low (5).

There are still two challenges that must be addressed before these sheets could be adopted for commercial use. First, the samples must attain densities closer to that of theoretical. ORNL has pursued further compaction of these samples by series of processing steps involving sintering, cold rolling, sintering again, cold rolling again, and annealing. Densities greater than 90% theoretical are possible, but the substantial amount of processing makes this unfeasible for production applications. Further information on the consolidation of roll compacted sheets and the resulting materials is in Section 3.2. The second challenge is that these sheet materials have proven difficult to form without cracking or brittle failure.

This chapter explores the potential of high strain rate techniques when applied to green-state and sintered roll compacted sheets provided by ORNL. Various compaction and forming methods were used. An Electromagnetic Uniform Pressure Actuator (UPA) was used to propel a copper sheet in two different arrangements, both to drive and impact roll compacted titanium sheet material onto a flat die. Electrically Driven Expanding Plasma (EDEP) was also utilized as a means of driving titanium sheet material onto a flat die. Recent work has also produced an electromagnetically driven press which was used to repeatedly strike a titanium sample and compact it further with each hit. In addition,
the UPA was used to drive various green and sintered sheet samples over a channel die of varying wall angles to determine if forming of these sheets was possible at HSR. A matrix of these tests is shown below in Table 2. Further explanation of all of these test methods is in Section 3.1, followed by experimental results, discussion and conclusions in Sections 3.3, 3.4 and 3.5 respectively.

Table 2: Matrix of HSR sheet tests

<table>
<thead>
<tr>
<th>Flat Die</th>
<th>UPA</th>
<th>EDEP</th>
<th>EM Press</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Roll Compacted Sheet</td>
<td>Green Roll Compacted Sheet</td>
<td>Green Roll Compacted Sheet</td>
<td></td>
</tr>
<tr>
<td>Channel Die</td>
<td>Green and Sintered Roll Compacted Sheet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.1 Equipment and Methods

3.1.1 Capacitor Bank with Rogowski Coil and Voltage Divider

The capacitor bank and accompanying data acquisition tools and parameters are the same as those utilized for experiments in Chapter 2. See section 2.1.2 for a full description.
An explanation of the Photon Doppler Velocimeter system is featured in section 2.1.3, however the probe placement for these experiments differed. For these planar experiments, a small port shaped to accommodate a collimator probe was cut in the center of the die. This arrangement allowed for the front of the sample to be observed as it traveled towards the die. Observation of the deceleration of the sheet as it struck the die was not possible in this arrangement, as the material that strikes the PDV port extrudes into the port, giving an inaccurate reading following the impact. However, the velocity at impact can be seen from the data. An arrangement where observation of the impact from the back of the sample was impossible as placement of a port through the UPA housing and driving coil is not feasible.

3.1.3 Uniform Pressure Actuator

The Uniform Pressure Actuator (UPA) is a tool used to drive metal sheets in a planar manner at high velocities (17) (11). An 11 turn copper driving coil closely coupled to but insulated from an outer C-shaped channel. A thin copper driving sheet is placed across the open surface of the C-shaped channel, completing the outer circuit. The foil is pressed in place only along the portion of the surface in contact with the face of the C-shaped conductive outer channel as is illustrated in Figure 33. By fixing only the edges of the copper sheet, the remainder of the sheet is capable of free motion. Upon discharge of the capacitor bank, the primary current traveling through the driving coil
induces an opposing secondary current in the outer circuit created by the C-shaped channel. The resulting Lorentz force drives the copper sheet away (18). By this method, a driver sheet can be accelerated to velocities in excess of 200 m/s over a distance of a few millimeters. Figure 34 shows the UPA with a vacuum system attached. The primary coil can be seen in the center of the UPA, while the face of the outer channel can be seen on both sides of the coil.

Figure 33: A schematic view of the Uniform Pressure Actuator (18)
In this particular application of the UPA, 1.65” by 4” titanium sheet samples were either placed upon a copper driver sheet and driven into a die fixed 3mm from the coil or affixed to the die and impacted by the moving driver sheet. The driver sheets were 3” by 4” and cut from sheet stock of .010” thick Alloy 110 copper. The flat die, shown in Figure 35, was 3” by 4”. The PDV port in the die allowed for the velocity of the sheet to be observed up to the moment of impact. In the driven arrangement, titanium samples were also propelled over a channel shaped die in order to determine the maximum fraction of theoretical density that could be attained in a flat sheet as well as the formability and amount of strain that could attained by the sheets prior to failure. All forming samples were tested at the most effective charge energy for compaction, that being 4.48 kJ.
3.1.4 Electrically Driven Expanding Plasma

An additional means of driving planar samples at high velocity involves utilizing Electrically Driven Expanding Plasma (EDEP). A dogbone shaped thin aluminum foil is connected to a capacitor bank on both ends. The capacitor bank is then discharged through the foil. If the discharge rate of the capacitor bank is fast enough, the foil with vaporize in the narrowest section, causing a rapid expansion that drives the sample. There is also additional electromagnetic drive that results from induced eddy currents in
the material as well as an additional chemical expansion caused by the oxidation of the vaporized aluminum (19).

In the compaction of titanium sheet, dogbone shaped aluminum foils with widths of .5” or 1” and thicknesses of .002” or .003” with a narrowed section length of 2.5” were attached to the leads of the capacitor bank. An example of a typical foil is shown in Figure 36. The central portion of the foil was taped with Kapton to provide electrical insulation from the steel backing block. A titanium sheet measuring the length of the narrowed section and being .5” wider than the foil being used is then centered atop the foil. Thin plastic was then placed around the edges of the sheet to help contain the plasma and achieve a higher compaction pressure. Finally, a flat steel top block was added and bolted in place to act as a flat die. Figure 37 shows a sample mounted in the testing chamber just prior to testing.
Figure 36: A typical dogbone-shaped EDEP foil
3.1.5 Electromagnetically Driven Press

The third tool used to further compact green state rolled titanium sheets was an EM press that was recently developed by Dr. Glenn Daehn’s research group at The Ohio State University. The EM press utilizes a 4 turn planar primary copper coil with a 6.5” outside diameter closely coupled to an aluminum flyer assembly of the same diameter that slides in a bushing arrangement. The coil and flyer assembly is shown in schematic
form in Figure 38. A pulse from the capacitor bank through the primary coil induces an opposing current in the aluminum flyer, resulting in strong Lorentz force that accelerates the flyer assembly away.

Figure 38: A schematic of the EM Press coil and flyer

The coil assembly consisted of G10 layers and a copper coil with leads attached. The coil was waterjet cut from Alloy 18150 copper sheet. It was placed within a G10 negative, also waterjet cut to accommodate the complex shape. A section view of the model of this coil assembly with the leads is shown in Figure 39. The bushing arrangement, shown in Figure 40, utilizes Ultra High Molecular Weight Polyethylene for bushings. Two of the adjacent bushings are backed by brass plates with screws behind them. In this manner, the bushings restrict motion of the tool to translation along the
central axis. In addition, the two backed sides can be adjusted to compensate for wear of the bushings over time as the tool is used. In Figure 40 the flyer assembly can also be seen. The aluminum flyer is bolted to the tool post which slides in the bushing arrangement and has a stroke distance of up to 3/8”. The tool post has an alignment pattern and hole on the end to allow for interchangeable tooling to be utilized, including adapters to accommodate industry standard punch and die equipment. A retraction spring is used to return the tool to its initial position after each stroke. The full EM Press is shown in Figure 42.

Figure 39: EM Press Coil assembly
For these tests, two different flyers were utilized. The first flyer was a flat, low-mass plate with excess material removed for mass reduction. This assembly had a mass of .91 kg and could be propelled a peak velocity of up to 28.5 m/s. This is the flyer featured in the assembly shown in Figure 40. This flyer proved too weak and ultimately failed due to issues involving fatigue and deformation of the flyer upon impact at higher energies. As a result, a more robust second revision of the flyer was created and used for further testing. This new flyer included support ribs, resulting in a higher mass of 1.47 kg and a lower maximum velocity of 13.2 m/s. Velocities of both revisions of the flyer at the tested energies are shown in Figure 41. The second revision flyer can be seen in Figure 42.
Figure 41: Charge energy against velocity of Revision 1 and Revision 2 EM Press flyers

Figure 42: EM Press with the second revision flyer
The EM press is of rapidly repeated strokes, limited only by the cycle time of the capacitor bank and cooling limitations of the coil. For the application of compacting rolled titanium sheets, a flat tool steel attachment with a 1.5” square face was attached to the flyer assembly. A flat steel backing block was used as a die. A scribed 1” square of material struck at incremented charge energies of .96kJ and 1.28kJ for the first flyer revision and 1.28kJ and 1.92kJ for the second. Each sample was struck 20 times at the same energy. Thickness measurements were taken with a ball micrometer after strokes 1, 3, 5, 10 and 20 to observe the results throughout the process.

3.1.6 Quasistatic Compaction

To offer a comparison to more traditional QS consolidation methods, scribed 1” square green roll compacted sheet samples were compressed using the MTS Universal Testing System shown in Figure 43. As shown in Figure 44, samples were placed between steel blocks and subjected to a maximum pressure of 510 MPa in increments of 86 MPa. To aid in indicating scale, the red arrow in both Figure 43 and Figure 44 point to the same cylinder attached to the crosshead of the machine. The test plan involving individual tests at various pressures as opposed to a single test generating a real-time pressure-density relationship was chosen due to the thin sample size relative to the substantial displacement of the load frame at these pressures. In addition, 1 cm square samples of each material were compacted at 1.67 GPa and 3.28 GPa to show what observe what results at extreme pressures.
Figure 43: The MTS Universal Testing System used for the QS compactions of green roll compacted sheets
3.1.7 Channel Die

To determine the formability of various titanium sheets, a hardened tool steel die with four channels of varying wall angles was created. Each wall of each channel is of a different angle of 19° to 40° and each channel is also of a progressively greater depth from .02” to .1”. The radii on the top and bottom edges of the channels are all .06”. An image of the die is shown in Figure 45, while parameters for each wall of each channel are featured in Table 3 and a schematic of a channel with dimensions noted is featured in Figure 46.
Figure 45: The channel die

Table 3: Wall angles and depths of the channel die channels

<table>
<thead>
<tr>
<th>Side</th>
<th>Depth (in)</th>
<th>Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td>31</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>0.4</td>
<td>19</td>
</tr>
</tbody>
</table>
Figure 46: Schematic of a channel on the channel die

3.1.8 Data Analysis

Data analysis was performed by a variety of means based upon the test being performed. Where velocity data was taken, Matlab was utilized to process the raw data into a velocity trace and correlate the data with the Electrical Current and Voltage data. All densities stated in this document are a percentage of theoretical density unless otherwise noted. Densities of larger sheet samples compacted with either the UPA or EDEP method were taken by comparative thickness measurements from the known initial density taken by ball micrometer to an accuracy of .0001” at 4 locations about the center of the sheet. In many of these cases, the density was also attained by optical microscopy to verify the accuracy of thickness-based measurements. Samples were polished to .3 micron with alpha alumina and a polishing cloth to achieve a suitable image so that densities could be obtained utilizing ImageJ analysis software.

For the samples consolidated quasistatically or utilizing the EM press, the small 1” sample size gave rise to the need to calculate the change in density in a different manner to compensate for the way in which the material would flow as it was compacted.
Samples were scribed to allow for the changes in density to be determined by calculating the volumetric change of a unit cell within the sheet.

3.2 Materials

Oak Ridge National Laboratory provided various roll compacted samples for compaction and forming. Both green and sintered titanium samples were utilized for forming while only green materials were compacted in flat form.

3.2.1 Presintered Roll Compacted Sheet

Presintered (green) roll compacted sheets of Armstrong based CP-Ti and Ti-6Al-4V were provided by ORNL with initial densities of 67% and 63% respectively. These materials were labeled CPARM and 64ARM. As the material is in a “green” compacted state, it is brittle to the extent that cannot be formed by traditional techniques. Micrographs of these materials are shown in the first column of Table 4. In addition, a green sample of CPARM sheet that was first compacted electromagnetically on a flat die with the UPA was then utilized in a forming operation to determine if obtaining a higher green density had an effect on formability.

3.2.2 Sintered Roll Compacted Sheet
Sintered samples as well as samples that were sintered, further cold rolled and again sintered samples were provided and utilized for formability comparisons. For ease of reference, sintered samples will be referred to as “A” condition while sintered, further roll compacted and again sintered samples will be referred to as the “B” condition. CPARM sheets were provided in both the A and B conditions. In addition, a thicker Armstrong CP-Ti sheet, type CPARM-2, was provided in the A and B processed conditions as well as a Hydride-Dehydride (HDH) powder morphology sheet, CPHDH, in both A and B conditions. The HDH sheets, produced from powder derived from titanium sponge resulting from the Kroll process, can be seen to have much larger particles and a very different distribution of porosity (5). Table 4 features a more concise presentation of the provided materials including micrographs, with column 2 showing samples in condition A and column 3 showing samples in condition B.
Table 4: Micrographs and densities of received materials (ORNL)

<table>
<thead>
<tr>
<th>Material</th>
<th>As Rolled</th>
<th>1100°C/1hr (A Condition)</th>
<th>1100°C/1hr+33%CW+1100°C/1hr (B Condition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPARM</td>
<td>thickness</td>
<td>.0181&quot; 66.7%</td>
<td>.014&quot; 73.6%</td>
</tr>
<tr>
<td>Image</td>
<td>density</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPARM-2</td>
<td>thickness</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Image</td>
<td>density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64ARM</td>
<td>thickness</td>
<td>.0131&quot; 63.0%</td>
<td>N/A</td>
</tr>
<tr>
<td>Image</td>
<td>density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPHDH</td>
<td>thickness</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Image</td>
<td>density</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.3 Results

3.3.1 Flyer Driven Compaction of CPARM and 64ARM sheets with the UPA

CPARM roll compacted sheets were driven at velocities of 103 m/s to 192 m/s prior to impacting the die. The sheets were driven by an annealed .010” thick Alloy 110 copper sheet. A capacitor bank charge energy of 4.48 kJ provided the highest percentage of theoretical density when compacted, that being 98%. An optical micrograph of this sample is shown in Figure 47. It can be seen that most of the porosity has been removed from the sample, with the remaining pores being so isolated as to likely eliminate any interconnected porosity upon sintering. Table 5 features the charge energy, kinetic energy per unit area of the flyer and sheet together, impact velocity and final density of each sample. Figure 47 plots sample charge energies against their densities and velocities. The kinetic energy per unit area of each sample was calculated to include the mass of the moving titanium and copper sheets.
Table 5: Charge energy, velocity, kinetic energy and density of flyer driven CPARM samples

<table>
<thead>
<tr>
<th>Charge Energy (kJ)</th>
<th>Velocity (m/s)</th>
<th>Kinetic Energy (J/cm²)</th>
<th>Density (% Theoretical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.56</td>
<td>103</td>
<td>1.74</td>
<td>83.1%</td>
</tr>
<tr>
<td>3.20</td>
<td>127</td>
<td>2.63</td>
<td>93.7%</td>
</tr>
<tr>
<td>3.84</td>
<td>141</td>
<td>3.25</td>
<td>98.6%</td>
</tr>
<tr>
<td>4.48</td>
<td>136</td>
<td>3.03</td>
<td>99.7%</td>
</tr>
<tr>
<td>5.12</td>
<td>145</td>
<td>3.44</td>
<td>98.3%</td>
</tr>
<tr>
<td>5.76</td>
<td>176*</td>
<td>5.07</td>
<td>94.7%</td>
</tr>
</tbody>
</table>

*Insufficient velocity data replaced with similarly driven sample of other chemistry

Figure 47: A graph of the charge energy against the density and velocity of UPA driven CPARM samples

Velocity data of Semi-transparent points was insufficient and substituted for that of the sample of same drive mode of the other sample chemistry.
Figure 48: Optical micrograph of a UPA driven CPARM sheet sample compacted at 4.48kJ

64ARM roll compacted sheets under the same test conditions were driven at velocities from 101 m/s to 176 m/s. Again, a capacitor bank charge energy of 4.48 kJ gave the highest percentage of theoretical density, that being 88%. Table 6 features the charge and kinetic energy per unit area of the flyer and sheet sample, impact velocity and the resulting final density. Figure 49 plots sample charge energies against their densities and velocities. An optical micrograph of 64ARM material consolidated to 79.7% dense is shown in Figure 50.
Table 6: Charge energy, velocity, kinetic energy and density of driven 64ARM samples

<table>
<thead>
<tr>
<th>Charge Energy (kJ)</th>
<th>Velocity (m/s)</th>
<th>Kinetic Energy (J/cm²)</th>
<th>Density (% Theoretical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.56</td>
<td>101</td>
<td>1.81</td>
<td>73.1%</td>
</tr>
<tr>
<td>3.20</td>
<td>118</td>
<td>2.48</td>
<td>77.7%</td>
</tr>
<tr>
<td>3.84</td>
<td>141</td>
<td>3.55</td>
<td>81.5%</td>
</tr>
<tr>
<td>4.48</td>
<td>136*</td>
<td>3.30</td>
<td>87.9%</td>
</tr>
<tr>
<td>5.12</td>
<td>152</td>
<td>4.13</td>
<td>81.3%</td>
</tr>
<tr>
<td>5.76</td>
<td>176</td>
<td>5.53</td>
<td>79.8%</td>
</tr>
</tbody>
</table>

*Insufficient velocity data replaced with similarly driven sample of other chemistry

Figure 49: A graph of the charge energy against the density and velocity of UPA driven 64ARM samples

Velocity data of Semi-transparent points was insufficient and substituted for that of the sample of same drive mode of the other sample chemistry
3.3.2 Flyer Impacted Compaction of CPARM and 64ARM sheets with the UPA

CPARM sheets impacted on a flat die by the copper flyer were struck at velocities from 116 m/s to 183 m/s achieving a maximum percentage of theoretical density of 97% when consolidated at the maximum attainable energy of 5.76 kJ. Table 7 shows the charge energy, kinetic energy of the moving flyer per unit area, impact velocity and the final density of each sample. Figure 51 plots sample charge energies against their densities and velocities. Figure 52 shows an optical micrograph of the most densely consolidated impacted sample, 97%. Figure 53 shows the data collected from a UPA
sheet compaction, that being the primary current, voltage and velocity of the flyer sheet.

The acceleration of the sheet begins at around the 6.5 µs mark, and it can be seen impacting the die at about 27.5 µs.

Table 7: Charge energy, velocity, kinetic energy and density of impacted CPARM samples

<table>
<thead>
<tr>
<th>Charge Energy (kJ)</th>
<th>Velocity (m/s)</th>
<th>Kinetic Energy (J/cm²)</th>
<th>Density (% Theoretical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.56</td>
<td>116</td>
<td>1.53</td>
<td>84.4%</td>
</tr>
<tr>
<td>3.20</td>
<td>143</td>
<td>2.33</td>
<td>89.9%</td>
</tr>
<tr>
<td>3.84</td>
<td>173</td>
<td>3.38</td>
<td>85.8%</td>
</tr>
<tr>
<td>4.48</td>
<td>166</td>
<td>3.14</td>
<td>90.2%</td>
</tr>
<tr>
<td>5.12</td>
<td>180*</td>
<td>3.67</td>
<td>89.6%</td>
</tr>
<tr>
<td>5.76</td>
<td>188</td>
<td>4.03</td>
<td>97.1%</td>
</tr>
</tbody>
</table>

*Insufficient velocity data replaced with similarly driven sample of other chemistry
Figure 51: A graph of the charge energy against the density and velocity of UPA impacted CPARM samples.
Figure 52: Optical micrograph of an impacted CPARM sheet sample
Figure 53: The primary current, voltage and flyer velocity trace from the CPARM 3.84kJ flyer impacted UPA compaction

64ARM roll compacted sheets under the same test conditions were struck at velocities from 116 m/s to 183 m/s. In this set of tests, a capacitor bank charge energy of 5.76 kJ gave the highest percentage of theoretical density, that being 81.3%. Table 8 features the charge and kinetic energy per unit area of the flyer and sheet sample with the resulting final density. Figure 54 plots sample charge energies against their densities and velocities. An optical micrograph of impact consolidated 64ARM material at 81.3% theoretical density is shown in Figure 55.
Table 8: Charge energy, velocity, kinetic energy and density of impacted 64ARM samples

<table>
<thead>
<tr>
<th>Charge Energy (kJ)</th>
<th>Velocity (m/s)</th>
<th>Kinetic Energy (J/cm²)</th>
<th>Density (% Theoretical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.56</td>
<td>116</td>
<td>1.53</td>
<td>71.9%</td>
</tr>
<tr>
<td>3.20</td>
<td>120</td>
<td>1.64</td>
<td>72.3%</td>
</tr>
<tr>
<td>3.84</td>
<td>173*</td>
<td>3.38</td>
<td>76.4%</td>
</tr>
<tr>
<td>4.48</td>
<td>156</td>
<td>2.75</td>
<td>79.9%</td>
</tr>
<tr>
<td>5.12</td>
<td>180</td>
<td>3.67</td>
<td>78.6%</td>
</tr>
<tr>
<td>5.76</td>
<td>183</td>
<td>3.80</td>
<td>81.3%</td>
</tr>
</tbody>
</table>

*Insufficient velocity data replaced with similarly driven sample of other chemistry.

Figure 54: A graph of the charge energy against the density and velocity of UPA impacted 64ARM samples

Velocity data of Semi-transparent points was insufficient and substituted for that of the sample of same drive mode of the other sample chemistry.
3.3.3 Electrically Driven Expanding Plasma Consolidation

Various foil thicknesses and widths were attempted in order to increase the compacted area while maintaining the high levels of compaction that were observed. Both CPARM and 64ARM green titanium sheets were compacted to their full theoretical densities. Micrographs of these 64ARM and CPARM samples are shown in Figure 56.
Figure 57 shows the electrical current and voltage trace for the experiment for a typical EDEP experiment. It can be seen that the foil burst at 10 µs. Figure 58 shows the charge energy versus density for all samples consolidated with EDEP labeled with their foil geometries. It can be seen that near fully dense samples were only achieved when samples were compacted with .5” wide foils. Another metric by which we measure the potential of an EDEP foil is by burst current density, the current per cross sectional area at the time the foil burst. The burst current density is an indicator of how much potential energy is available when the foil turns into plasma. Figure 59 shows the burst current density versus density for all of the EDEP Samples. It can be seen that the narrower .5” foils which are capable of producing near fully dense samples also show a significantly higher BCD, related to the smaller sample cross section.

Figure 56: Micrographs of 4kJ .002”x.5” foil a) 64ARM and b) CPARM samples
Figure 57: Electrical current and voltage traces for the 6.4kJ EDEP 64ARM sample compacted by a .003”x1” foil
Figure 58: Charge energy vs. density of EDEP samples
3.3.4 EM Press Compaction

The EM Press compacted 1” square samples of CPARM material to a maximum density of 97.7% at .96kJ charge energy for each stroke of 20 strokes with the lighter .96 kg first flyer revision. 64ARM material was compacted to a maximum density of 88.5% at 1.28kJ charge energy for each stroke, also using the .96 kg first flyer revision. The densification of all EM Press samples based upon the number of strokes can be seen in Figure 60. It can be seen that the lighter, first revision press is more effective at...
compacting samples than the more massive 1.47 kg second revision flyer assembly, even though the lighter press was operated at a much lower energy.

Figure 60: Number of strokes versus percent fraction density of EM Press compacted samples

3.3.5 Quasistatic Compaction

Both CPARM and 64ARM sheet samples appeared to be continuously achieving greater percentages of theoretical density up to the maximum pressure that could be achieved by the test system. At 510 MPa, CPARM material was compacted to 85.5% theoretical density, while 64ARM material was compacted to 84.9% of its theoretical...
density. Figure 61 shows the QS compaction pressure against the density obtained. Not shown on this chart are two additional smaller samples of each material compacted on the same machine. 1 cm square samples of both CPARM and 64ARM were compacted at pressures of 1.67 GPa and 3.28 GPa. Both CPARM and 64ARM achieved full density at 1.67 GPa.

![Figure 61: Pressure vs density of QS compacted sheet samples](image)

3.3.6 UPA Driven Channel Forming of Various Sheet Materials
Forming samples were driven on to the channel die with the UPA by a .010” annealed Alloy 110 copper sheet at a charge energy of 4.48kJ. This charge energy and copper driver arrangement is identical to that which was the most effective at compacting flat sheets, achieving a velocity of 136 m/s.

In this arrangement, green state sheets were successfully formed and compacted at the same time. A 64ARM sheet was formed with a wall angle 37° at a depth of .10”. This method proved nearly as effective at forming the CPARM material, achieving a maximum wall angle of 34° at a depth of .08”. A green sample of CPARM that was first flat compacted with the UPA to near full density prior to this forming operation was compacted to a wall angle of 25°. Lesser success in forming was seen with the sintered CPARM-A sample as well as the sintered, further cold rolled and again sintered CPARM-B sample, both achieving a wall angle of 19°. The remaining thicker CPARM-2 and CPHDH samples in both the A and B processed conditions failed to form. Table 9 shows all of the formed samples noting the maximum wall angles achieved and the failure modes of the material. A macroscopic view of a typical channel failure, wall cracks, can be seen more easily in Figure 63, where the right wall shows cracks while the left does not. Figure 62 features micrographs these same two walls.
Table 9: Channel formed sample results and images

<table>
<thead>
<tr>
<th></th>
<th>As Rolled</th>
<th>1100C/1hr (A Condition)</th>
<th>1100C/1hr+33%CW+1100C/1hr (B Condition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPARM Image</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Max Angle (°)</td>
<td>34</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Notes</td>
<td>Failure by Cracking on Wall</td>
<td>Failure by Cracking on Wall</td>
<td>Failure by Cracking on Wall</td>
</tr>
<tr>
<td>HSR-Compacted CPARM Image</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Max Angle (°)</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Notes</td>
<td>Failure by Cracking on Wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPARM-2 Image</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>Max Angle (°)</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Notes</td>
<td>Failure by Cracking on Wall</td>
<td>Failure by Tearing along Radii</td>
<td></td>
</tr>
<tr>
<td>64ARM Image</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>Max Angle (°)</td>
<td>37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Notes</td>
<td>Failure by Cracking on Wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPiDH Image</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
<tr>
<td>Max Angle (°)</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Notes</td>
<td>Failure by Cracking in Channel Center, Failure to Form</td>
<td>Failure by Cracking in Channel Center, Failure to Form</td>
<td></td>
</tr>
</tbody>
</table>
Figure 62: Micrographs of a channel formed sample showing (A) a cracked wall and (B) a well formed wall

Figure 63: A macroscopic image of a well formed wall (left) and a cracked wall (right)

3.4 Discussion
3.4.1 A comparison of HSR compaction and QS

Utilizing HSR forming techniques, it is possible to near full density in CPARM material by a variety of techniques while still in the green state. Techniques utilizing the UPA are capable of full density in CPARM and 88% density in 64ARM over a moderately sized area with a small input energy. EDEP is capable of achieving near full density in both CPARM and 64ARM over a smaller area and showing some local variations in density. The EM Press was able to achieve fully dense CPARM and 89% dense 64ARM over a small area as well. Achieving near fully dense CPARM and 64ARM samples with QS compaction was possible, but only at impractical pressures around 1.6 GPa, and this being on a much smaller sample than that which was compacted in the UPA experiments. HSR techniques were also able to achieve theoretical densities with the 64ARM material over small areas, and also achieve a similar densities to the maximum QS compaction density over a much larger areas.

HSR techniques are very effective at achieving high green densities overall when compared to QS techniques. In order to achieve densities greater than 90% with CP-Ti powder material quasistatically it takes a cold rolling operation, a sintering operation, another cold rolling operation, followed by a final sintering operation, whereas a single cold rolling operation followed by a HSR operation can achieve a higher density even greater than 90%. The reduced number of processing steps, particularly sintering operations, could offer a cost advantage. One advantage that QS techniques maintain is
the size of the sheets they can produce. Researchers at ORNL have utilized roll compaction to produce sheets many inches wide and feet long. The current state of HSR flat compaction technology has a size limitation of a few square inches processed individually. However, the size of individually processed samples could likely be scaled up, and with some investment it might be possible to develop a technique of creating continuous sheets of HSR compacted material by performing pulsed power compactions incrementally along a sheet.

3.4.2 Simultaneous Forming and Compaction

Forming attempts with a titanium sheet driven by a flyer utilizing the UPA were able to achieve depths of up to .10” as well as angles of up to 37° on the green state 64ARM roll compacted material. CPARM material was formed at 34° at a depth of .08”. While these depths and angles were limited to green materials, some limited formability was also seen with sintered CPARM samples as well, achieving wall angles of 19°. QS forming attempts at ORNL have yet form roll compacted titanium sheets. This is very significant in its own right, however there is also the added advantage of simultaneous compaction. Green roll compacted samples were compacted to densities similar to those seen that were compacted on a flat die in the same arrangement. As these materials have not effectively been formed and are difficult to compact to densities greater than 90%, the fact that HSR techniques have shown to both compact them to these densities and form them in a single, low-cost operation shows significant promise for UPA sheet forming.
3.4.3 A Comparison of Driven and Impacted UPA Compactions

Both the driven and impacted methods of compacting flat sheets with the UPA are effective, however the driven methodology offers some advantages. Foremost, it offers higher densities over the range of charge energies tested, as shown in Figure 64. Figure 64 combines all of the charge energy and density data previously shown. It can be seen that these densities also correlate with higher impact velocities as shown in Figure 65 and with higher kinetic energies per unit area as shown in Figure 66. Figure 65 combines all of the previously shown velocity data. The idea that a driven titanium sample would achieve a higher density may be counterintuitive as adding titanium to the moving mass should reduce the amount of acceleration. There are a few possible explanations for why this occurs. The slight increase in moving mass may be slowing the acceleration but allowing the impact to occur closer to the peak current. Electrical Current is one of the primary factors contributing to the Lorentz force. Even though the material is no longer as closely coupled to the primary coil, there is much potential for a high force at impact which could account for the densities. This can be seen in Figure 53, where the sample impacts near the peak primary current. The sheet continued to accelerates up to the moment of impact, verifying that there is still force applied up to that moment. Ultimately, the impact velocities of driven and impacted samples were not significantly different. Another possible explanation for this could be difficulties in preparing the flyer impacted sheet experiments.
Figure 64: Charge energy versus density of CPARM and 64ARM UPA compacted flat sheet samples
Figure 65: Velocity as compared to green density of CPARM and 64ARM driven and impacted samples

Velocity data of semi-transparent points was insufficient and was substituted for that of the sample of same drive mode of the other sample chemistry.
During testing, UPA experiments launch the flyer upwards. In order to fix titanium sheet samples on the die, tape was used at the edges of the sample. It is possible that the center of the sheets were sagging and not entirely flush with the die, causing inconsistencies in test results and reducing densities due to the sheet being struck and subsequently pushed into the die at a much lower velocity. The potential for this to occur with an impacted sample does indicate an advantage of the driven method, a simpler test arrangement.
Another key difference is the potential material choices and dies that can be utilized with either method. A driven sample can readily be formed into a shaped die, but due to the fact the material is being accelerated with the flyer, reduced formability might be seen in thicker or more massive samples. The impacted method would allow these more massive samples to be struck at a HSR, but the reduced velocity due to the inelastic collision between the flyer and sample would not likely allow for these samples to be formed effectively.

### 3.4.4 Driven UPA peak effectiveness at 4.48kJ

The highest densities achieved with the UPA in both the CPARM and 64ARM materials were at a charge energy of 4.48kJ with the driven method. Many attempts were made to find a clear reason for this that could be explained with the test data, but none were conclusive. Attempts included calculating the kinetic energy from the known mass and velocity and correlating the die impact velocity and density, as well as correlating the difference in time between the peak current and die impact with the density. Likely, it is a combination of factors contributing to this.

At the time of impact, the sample is still close enough the primary coil to be potentially receiving a significant Lorentz force at the time the material is striking the die. The kinetic energy of the high velocity impact properly balanced with a high Lorentz force at that instant could be what accounts for higher densities at lower charge energies.
This is similar to the idea of following through with a golf or baseball swing to maximize power as opposed to merely striking the ball as fast as possible.

3.4.5 EDEP Effectiveness

EDEP can achieve sample densities that are nearly theoretical full density. Figure 67 places the EDEP sample charge energy and density data from Figure 58 over the UPA sample data shown in Figure 64. It can be seen that EDEP maintains a comparable level of effectiveness when compacting CPARM sheets, but when compared to other 64ARM data in Figure 67, it can be seen that EDEP is much significantly more effective. However, these successes were limited to low width and low thickness foils. After initial test successes with .002” thick by .5” wide foils, both thicker and wider foils were attempted with higher charge energies to compensate for the increased cross sectional area in an attempt to maintain the Burst Current Density. However, as can be seen in Figure 58 and Figure 59, an increase in energy to compensate for the increase in cross sectional area did not yield a higher burst current density or sample density. This is predominantly due to the limited rate of discharge of our capacitor bank. With a larger foil cross section it is possible for more of the discharged electricity to flow through the foil before it bursts, meaning less energy is contained in the foil at the time of burst to be utilized for generating and driving plasma. If the energy could have been put into the foil faster, more potential energy would have been present at the time of burst and the
resulting burst current density would have been higher and possibly sufficient to cause significant amounts of compaction.

Figure 67: Charge energy versus density chart of combined UPA and EDEP samples

An additional disadvantage of EDEP comes from a non-uniform pressure and edge effects. The samples show a significantly higher density near the edges of the foil, which is due to the edges bursting before the central areas of the foil. Density variations illustrating this effect can be observed in Figure 56b.
3.4.6 EM Press Effectiveness

The EM Press, by means of repeated strokes, was able to achieve nearly fully dense CPARM samples and 64ARM samples that were 89% dense. Due to the nature of the tooling, the sample size is limited to a 1” square. A sample of the same size compacted quasistatically in a press required an impractical 1.6 GPa to achieve the same density in CPARM material and over 500 MPa to achieve the same density in 64ARM material. An increase in the compaction area would subsequently lead to a reduced impact pressure, making scaling of this technique difficult. There may be potential to raster across the surface stroke by stroke a number of times to achieve these high densities across a larger area, but this would be a very time consuming process and likely impractical. This may yet be the most effective technique for achieving such significant densities over small areas as strokes can be performed in rapid succession.

3.5 Conclusions

1. HSR techniques are very effective for both further compacting roll compacted Armstrong powder based sheet materials and forming them. The EM Press, UPA and EDEP are capable of achieving near fully dense green samples in CP-Ti Armstrong based sheets. QS roll compaction techniques cannot achieve near full density even with sintering, further roll compacting and sintering operations.
2. The UPA is capable of achieving high green compact densities over samples of a few square inches while simultaneously forming the sheets into channels. QS techniques have not yet proven to be capable of forming roll compacted sheets.

3. EM Press compaction is very effective at achieving high densities after multiple strokes, with significant potential for the production of various smaller titanium components.

4. Driving samples with the UPA over a die is more effective at achieving high densities in roll compacted sheets than samples fixed to a die and impacted. It also has the advantage of being capable of simultaneous forming, which cannot be done in the impacted arrangement.
Chapter 4: Conclusions

1. High Strain Rate consolidation by means of a solid coil, direct compaction or a disposable coil, offset compaction is a potentially effective means of compacting Armstrong titanium powders. In some instances, Armstrong titanium powders compacted at HSR can yield higher densities than what can be achieved by a standard pressing operation.

2. Armstrong CP-Ti powders consolidated at HSR show better sintering characteristics than samples consolidated by standard pressing prior to sintering.

3. Near net-shape PM tube or nozzle components can potentially be produced by means of HSR solid coil direct tube consolidation or disposable coil offset tube consolidation.

4. HSR techniques are very effective for both further compacting roll compacted Armstrong powder based sheet materials and forming them. QS techniques cannot achieve densities as high as those that can be attained by a single HSR operation without multiple rolling and sintering operations.

5. The UPA is capable of achieving high green compact densities over samples of a few square inches while simultaneously forming the sheets into channels. QS techniques have not yet proven to be capable of forming roll compacted sheets.
6. EM Press compaction is very effective at achieving high densities after multiple strokes, with significant potential for the production various smaller titanium components.

7. Driving samples with the UPA over a die is more effective at achieving high densities in roll compacted sheets than samples fixed to a die and impacted. It also has the advantage of being capable of simultaneous forming, which cannot be done in the impacted arrangement.
Chapter 5: Recommendations

1. Further work be done to explore the Pressure-Density relationship of Armstrong titanium powders. This information can likely be derived from data acquired in both Solid Coil Direct Consolidation and Disposable Coil Offset Consolidation. The use of Finite Element Modeling techniques simulating the active Lorentz force being applied throughout the course of the experiment could be utilized to solve for instantaneous compaction pressures.

2. Explore the possibilities of utilizing Solid Coil Direct Consolidation and Disposable Coil Offset Consolidation for net shape forming. Assessing the effectiveness and cost of these techniques for the production of tubes or nozzles could open the doors to low cost components for use in industry.

3. Explore the scalability of the Uniform Pressure Actuator in an effort to achieve larger formed and compacted titanium sheets. Given the substantial demand for low cost titanium sheet material and the reduced processing afforded by forming and compaction in one operation, this could prove a very quick and effective route for utilizing Armstrong titanium powders in industrial applications.

4. Use Finite Element Modeling techniques to better understand how UPA driven sheet samples are compacted and formed. Understanding why samples with lower charge energies and higher moving masses ultimately yield a faster moving
and denser sample when compared to higher energy samples could be of much value in predicting the effectiveness of these methods for particular applications.
List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CIP</td>
<td>Cold Isostatic Pressing</td>
</tr>
<tr>
<td>CP</td>
<td>Commercially Pure</td>
</tr>
<tr>
<td>EDEP</td>
<td>Electrically Driven Expanding Plasma</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
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<tr>
<td>HDH</td>
<td>Hydride-Dehydride</td>
</tr>
<tr>
<td>HIP</td>
<td>Hot Isostatic Pressing</td>
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<tr>
<td>HSR</td>
<td>High Strain Rate</td>
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<tr>
<td>ITP</td>
<td>International Titanium Powder, LLC</td>
</tr>
<tr>
<td>ORNL</td>
<td>Oak Ridge National Laboratory</td>
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<tr>
<td>PDV</td>
<td>Photon Doppler Velocimeter</td>
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<tr>
<td>PIF</td>
<td>Pneumatic Isostatic Forging</td>
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<tr>
<td>PM</td>
<td>Powder Metallurgy</td>
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<tr>
<td>QS</td>
<td>Quasistatic</td>
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<tr>
<td>UPA</td>
<td>Uniform Pressure Actuator</td>
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References


Appendix A: Data for Tube Consolidation Samples

Charge Energy: 6kJ
Powder Type: HDH CP-Ti
Mandrel: Tapered
Mandrel OD where data was taken: .438"
Final Tube OD: 1.061"
Initial Density: 50.7%
Compacted Density: 59.8%
Sintered Density: 65.1%

Appendix A. 1: 6kJ HDH CP-Ti direct coil solid consolidation data
Charge Energy: 8kJ
Powder Type: HDH CP-Ti
Mandrel: Tapered
Mandrel OD where data was taken: .438"
Final Tube OD: 1.050"
Initial Density: 50.2%
Compacted Density: 61.1%
Sintered Density: 69.0%

Appendix A. 2: 8kJ HDH CP-Ti direct coil solid consolidation data
Charge Energy: 10kJ
Powder Type: HDH CP-Ti
Mandrel: Tapered
Mandrel OD where data was taken: .438"
Final Tube OD: 1.030"
Initial Density: 48.6%
Compacted Density: 62.6%
Sintered Density: 67.4%

Appendix A. 3: 10kJ HDH CP-Ti solid coil direct consolidation data
Charge Energy: 12kJ
Powder Type: HDH CP-Ti
Mandrel: Tapered
Mandrel OD where data was taken: .438"
Final Tube OD: 1.028
Initial Density: 50.1%
Compacted Density: 64.9%
Sintered Density: 70.1%

Appendix A. 4: 12kJ HDH CP-Ti solid coil direct consolidation data
Charge Energy: 6kJ
Powder Type: Armstrong CP-Ti
Mandrel Type: Tapered
Mandrel OD where data was taken: .438"
Final Tube OD: .986"
Initial Density: 32.2%
Compacted Density: 47.4%
Sintered Density: 72.3%

Appendix A. 5: 6kJ Armstrong CP-Ti solid coil direct consolidation data
Charge Energy: 8kJ
Powder Type: Armstrong CP-Ti
Mandrel: Tapered
Mandrel OD where data was taken: .438"
Final Tube OD: .946"
Initial Density: 32.3%
Compacted Density: 54.3%
Sintered Density: 73.5%

Appendix A. 6: 8kJ Armstrong CP-Ti solid coil direct consolidation data
Charge Energy: 10kJ
Powder Type: Armstrong CP-Ti
Mandrel: Tapered
Mandrel OD where data was taken: .438"
Final Tube OD: .927”
Initial Density: 32.3%
Compacted Density: 58.2%
Sintered Density: 76.0%

Appendix A.7: 10kJ Armstrong CP-Ti solid coil direct consolidation data
Charge Energy: 12kJ
Powder Type: Armstrong CP-Ti
Mandrel: Tapered
Mandrel OD where data was taken: .438"
Final Tube OD: .902"
Initial Density: 32.7%
Compacted Density: 65.2%
Sintered Density: 82.5%

Appendix A. 8: 12kJ Armstrong CP-Ti solid coil direct consolidation data
Appendix B: Data for UPA Flat Sheet Compaction Samples

Appendix B. 1: 2.56kJ CPARM UPA driven data

Appendix B. 2: 3.2kJ CPARM UPA driven data
Appendix B. 3: 3.84kJ CPARM UPA driven data

Appendix B. 4: 4.48kJ CPARM UPA driven data
Appendix B. 5: 5.12kJ CPARM UPA driven data

Appendix B. 6: 2.56kJ CPARM UPA impacted data
Appendix B. 7: 3.2kJ CPARM UPA impacted data

Appendix B. 8: 3.84kJ CPARM UPA impacted data
Appendix B. 9: 4.48kJ CPARM UPA impacted data

Appendix B. 10: 5.76kJ CPARM UPA impacted data
Appendix B. 11: 2.56kJ 64ARM UPA driven data

Appendix B. 12: 3.2kJ 64ARM UPA driven data
Appendix B. 13: 3.84kJ 64ARM UPA driven data

Appendix B. 14: 4.48kJ 64ARM UPA driven data
Appendix B. 15: 5.12kJ 64ARM UPA driven data

Appendix B. 16: 5.76kJ 64ARM UPA driven data
Appendix B. 17: 2.56kJ 64ARM UPA impacted data

Appendix B. 18: 3.2kJ 64ARM UPA impacted data
Appendix B. 19: 3.84kJ 64ARM UPA impacted data

Appendix B. 20: 4.48kJ 64ARM UPA impacted data
Appendix B. 21: 5.12kJ 64ARM UPA impacted data

Appendix B. 22: 5.76kJ 64ARM UPA impacted data
Appendix C: Data for EDEP Samples

Appendix C. 1: 4kJ EDEP CPARM sample consolidated by a .002"x.5" foil

Appendix C. 2: 6.4kJ EDEP CPARM sample consolidated by a .002"x1" foil
Appendix C. 3: 4 kJ EDEP 64ARM sample consolidated by a .002"x.5" foil

Appendix C. 4: 4.8kJ EDEP 64ARM sample consolidated by a .002"x.5" foil
Appendix C. 5: 6.4kJ EDEP 64ARM sample consolidated by a .003”x1” foil