

# **DEVELOPMENT OF 1000-TON COMBUSTION DRIVEN COMPACTION PRESS FOR MATERIALS DEVELOPMENT AND PROCESSING**

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*Paper Presented and Published in the Conference Proceedings at the 2007 MPIF/APMI International Conference on Powder Metallurgy & Particulate Materials, (PowderMet2007), held in Denver, Colorado, May 13-16, 2007.*

## **ABSTRACT**

The following presents the technological development aspects and materials processing efforts of UTRON's 1000 ton Combustion Driven Compaction (CDC) press. The 1000 ton press program has evolved from an earlier program in which a 300 ton press was manufactured and tested [10]. This "scaled-up" version of the CDC process has allowed larger surface area parts to be manufactured at the uniquely higher CDC compaction pressures (e.g., up to 150 tsi). Process advantages of this higher compaction pressure include: significantly higher green part densities, net shaping ability, improved material properties, and reduced part shrinkage. The primary focus for this effort has been to demonstrate the proof of concept and applicability of the CDC process for materials component manufacturing. To this end, results of the geometrical, physical, and materials properties of select CDC parts made with the 1000 ton press are presented. The parts were produced using commercially available copper, niobium, and rhenium-based alloy powders, and are given as a function of process parameters and select optimal sintering conditions. These components were near net shape or net shape quality at compaction pressures ranging from 50 tsi to 144 tsi. Upon inspection, the components exhibited higher part densities and improved properties when compared to conventional P/M pressing techniques. While a broad range of micro and nano materials can be compacted using the CDC process [8-13], this effort will address only those cases discussed above.

## **INTRODUCTION**

In recent years, combustion driven compaction (CDC) has emerged as a favorable method of powder consolidation. Much like traditional P/M processing, the CDC process has the ability to compact powder materials of varying sizes and morphologies; including micro and nano structured powder materials. However, when pressed using the CDC process, the resultant components have been shown to obtain much higher densities, both in green and sintered conditions, than are possible with traditional P/M pressing techniques [1-3, 14-16]. One clear advantage in the CDC process is the pressing force employed: traditional pressing can achieve up to 55 tsi on the powder during consolidation, whereas the CDC process can deliver up to 150 tsi on the powder. Some advantages of this process are reduced part shrinkage, improved mechanical durability, minimal grain growth (depending on the material system), and near net shape or net shape attributes in high performance components.

The CDC process, which utilizes controlled combustion and unique rapid compaction (e.g., milliseconds) in the loading cycle, has been developed and successfully applied to compact a variety of

geometries. In addition, single and multi-layered functional gradient materials (FGM) have been successfully pressed. The list of other materials that have been pressed using the CDC process include: ferrous and non-ferrous materials such as copper, niobium, ceramics, and particulate nanocomposite materials. The resultant components of which have shown high densities, improved mechanical, high temperature strength/ductility, and electrical properties, as well as improved thermo-physical and magnetic properties. Additionally, the CDC process offers competitive economic manufacturing advantages through reduction of sintering and post processing times [8, 9-13].

### **Applications of CDC Technology [8-13, 17]**

Applications for the CDC technology have been demonstrated and / or are in development for fabricating high density components with unique materials. A few advantages offered from the CDC process are a cost-effective near net shape manufacturing process and reduced material waste. These advantages can be directly shown in the bottom line cost of high value components. To date, UTRON has consolidated powders to form the following products: x-ray anode targets, laser optical mirror substrates / heat sinks, RF microwave components for normal and superconducting accelerators, high storage capacity fuel cell / battery electrodes (advanced thermoelectrics for next generation applications), and high temperature rocket nozzle components. In addition, the CDC press has been used to consolidate powders to form high performance, light-weight armors, high density engine parts, advanced magnetic nanocomposites, and various bearing and gear parts. These examples show the versatility of the CDC process and the wide range of products possible to be manufactured for the energy, defense, and commercial industries.

### **Comparison of Select Powder Processing Technologies**

Several powder metallurgy shaping and consolidation technologies exist today, each with its own advantages and disadvantages to process variety of engineering materials including nanostructured materials[1-7, 13-16]. Table 1 provides some of the process advantages and limitations of various powder consolidation and part manufacturing technologies, as obtained from the reviews of manufacturing technologies in the literature. As evident, every method's effectiveness is reliant upon function of the form. For example, complex geometry parts with internal passages and undercut features have been better served by forging technologies rather than conventional pressing by mechanical or hydraulic presses. Similarly, gears and bushings produced in large quantities lend themselves toward high-speed consolidation operations, such as conventional pressing or high energy compaction, rather than cold isostatic pressing or triaxial compaction.

Another important consideration in choosing the most suitable technology revolves around post-processing. While every circumstance differs with varying powder systems, post processing can easily be kept to a minimum by selecting the correct consolidation method. One example is the amount of additional machining required after compacting and sintering. With the use of cold or hot isostatic pressing, bi-level or multi-level parts with complex contours require a significant amount of machining after consolidation to achieve the final product. Conversely, with conventional pressing or high energy compaction a near-net shaped part can easily be obtained that requires very little post-sintering machining. Similarly, when porosity is of concern, forging operations are used rather than conventional mechanical or hydraulic pressing.

<b>Table 1. Comparison of Existing Consolidation Technologies [2, 4-7, 14-15]</b>		
<i>Method</i>	<i>Advantages</i>	<i>Disadvantages</i>
Conventional Mechanical Pressing	<ul style="list-style-type: none"> <li>- High production rates</li> <li>- High degree of repeatability</li> </ul>	<ul style="list-style-type: none"> <li>- Low green density parts</li> <li>- Considerable post-processing</li> <li>- High initial set-up costs</li> <li>- High shock loading to powder</li> </ul>
Conventional Hydraulic Pressing	<ul style="list-style-type: none"> <li>- High production rates</li> <li>- High degree of repeatability</li> </ul>	<ul style="list-style-type: none"> <li>- Low green density parts</li> <li>- Considerable post-processing</li> <li>- High initial set-up costs</li> </ul>
Forging	<ul style="list-style-type: none"> <li>- Fully dense parts</li> <li>- Negligible porosity</li> <li>- Near net shape</li> <li>- High mechanical strength</li> <li>- High fracture toughness</li> </ul>	<ul style="list-style-type: none"> <li>- Low production rates</li> <li>- Requires dual process (pre-form)</li> <li>- Higher production costs</li> </ul>
Powder Injection Molding (PIM)	<ul style="list-style-type: none"> <li>- High production rates</li> <li>- High degree of repeatability</li> <li>- Near net shape</li> <li>- Low porosity</li> <li>- High strength</li> <li>- High toughness</li> </ul>	<ul style="list-style-type: none"> <li>- Lengthy debinding at post-production</li> <li>- Costly for larger parts</li> <li>- Expensive smaller powders used</li> </ul>
Cold Isostatic Pressing (CIP)	<ul style="list-style-type: none"> <li>- No friction between powder &amp; die</li> <li>- More uniform density distribution</li> <li>- Ability for complex part geometries</li> <li>- Lower initial costs than conventional</li> </ul>	<ul style="list-style-type: none"> <li>- Very slow production rates</li> <li>- Less accurate green part dimensions</li> <li>- Considerable post-processing</li> </ul>
Triaxial Compaction	<ul style="list-style-type: none"> <li>- No friction between powder &amp; die</li> <li>- More uniform density distribution</li> <li>- Higher densities than CIP pressing</li> <li>- Ability for complex part geometries</li> </ul>	<ul style="list-style-type: none"> <li>- Very slow production rates</li> <li>- Less accurate green part dimensions</li> <li>- Considerable post-processing</li> </ul>
Hydropulsing / High Velocity Compaction (HVC)	<ul style="list-style-type: none"> <li>- High production rates</li> <li>- High degree of repeatability</li> <li>- Near net shape</li> <li>- Low porosity</li> <li>- High strength</li> <li>- High toughness</li> </ul>	<ul style="list-style-type: none"> <li>- Shock wave densification limited to metal alloys - excludes ceramics</li> </ul>

Table 1 shows select processing and property attributes and characteristics between existing, commercially available consolidation technologies[2, 4-7]. Listed in the table are some of the advantages and disadvantages of these processes. It is important to note that the table is a generic reference to these

technologies and that each can retain different characteristics for different powder systems. Nonetheless, on the whole, it is easy to see that depending upon the specific properties of the P/M part required a specific method of consolidation can be chosen to efficiently achieve the goal. For example, if the part required is large and needs to be very strong, forging is a much better solution than conventional pressing. Conversely, if a large number of small, low porosity parts are necessary, conventional pressing or High Velocity Compaction (HVC) technologies would be the obvious choice. In light of the commercially available low pressure powder compaction technologies and high velocity compaction technologies [4-5], the technological needs for developing higher density parts still are still growing posing challenges and we have presented the results of the emerging patented Combustion Driven Compaction technology [9] as one of the most competitive and economically viable high density part manufacturing methods.

**Combustion Driven Compaction Technology**

One of the newest and most promising technologies is high pressure Combustion Driven Compaction (CDC). [9] The CDC process resembles conventional pressing in that an upper and lower punch are used to consolidate a powder through a compressive motion. It uses, however, a gas-based mixture combusted under pressure as the driving force rather than a mechanical wheel or hydraulic cylinder. The high energy force of the driving piston allows for much higher compaction forces on the consolidating powder; as high as 150 tsi (tons per square inch) compared to a conventional standard of approximately < 50-55 tsi. The high compaction forces result in significantly higher “green” part densities as well as near net-shaped parts. The result is a decrease in the overall amount of post-processing – sintering is kept at a minimum as well as additional machining. Overall, the benefits can easily be seen in both reduced production times and costs.

Combustion Driven Compaction (CDC) technology could soon join the list of commercially available consolidation technologies [14-16] to produce higher density, higher performance CDC P/M parts in a production scale. Such development work is in progress. For several years the CDC technology has been tested and compared to these other processes utilizing UTRON’s 300 ton CDC press. It has been found that the high energy compaction consistently yields higher green part densities for a wide range of materials when compacting at pressures above the conventional pressing limits of 50 tsi [9-13] In fact, the process routinely yields much higher part densities both before and after sintering with improved properties [10-13] on a spectrum of high density CDC parts using various powder materials. This includes both micro as well as nanostructured high density components of metallic, ceramic and composite materials for various applications.

**TECHNOLOGICAL DEVELOPMENT OF 1000 TON CDC PRESS**

Currently, As a follow-up of the earlier 300 Ton CDC Press (Fig. 1a) development and successful use, a 1000 ton CDC press (Fig. 1b) is being assembled and tested for both actual part fabrication (Table 3, Figs. 6-8) and materials evaluation (Figs. 9-13). We used materials such as copper, niobium (coarse and fine grit size powders) and refractory rhenium based alloys and obtained higher green part densities.

**Table 2. Representative CDC Part Geometries at Varying Press Loads**

Tsi	Part Area sq. in.	Square (in. per side)	Solid Cylinder (in. OD)	Hollow Cylinder 1" wall (in. OD)	Hollow Cylinder 1/2" wall (in. OD)	Hollow Cylinder 1" ID (in. OD)	Hollow Cylinder 3" ID (in. OD)
150	6.67	2.58	2.91	3.12	4.75	3.08	4.18
100	10	3.16	3.57	4.18	6.86	3.71	4.66
50	20	4.47	5.05	7.36	13.23	5.14	5.87

This 1000 Ton press has the capability to press a part up to 150 tsi with a maximum solid pressing area of 6.67 in<sup>2</sup>. The pressing areas can be increased if the part requires suitable lower compaction pressures of <150 tsi. While the part geometries could be an infinite combination of dimensions, the given area yields a maximum possible solid cylindrical diameter of 2.9 in. Hollow geometries with much larger outer diameter OD and suitable ID can also be pressed (e.g., 5 inch OD; 4.07 inch ID and 0.465 inch thickness to get 6.66 square inches of pressing area at 150 tsi). With the existing stroke lengths, we can press parts of >0.25 inch thickness to ~3 to 4 inch heights, depending on the fill ratio of the powder material. Based on common P/M part geometries, this will be beneficial for a wide range of products.

The 1000 ton CDC press is intended for R&D scale production of larger scale simple to complex geometry components than those possible with our current 300 Ton CDC press. Select part dimensions of square, solid cylinder and hollow cylinder geometries that can be pressed at 50, 100 and 150 tsi are provided in Table 2 as a partial list for illustration purposes and other geometries can also be developed depending on the customer needs for various scientific and industrial applications. In addition, An initiative is in place currently to produce a fully automated machine which will be capable of production rates equivalent to current technologies.



**Fig1. a) 300 Ton (left) & b) 1000 Ton (right)-Combustion Driven Compaction-CDC Presses**

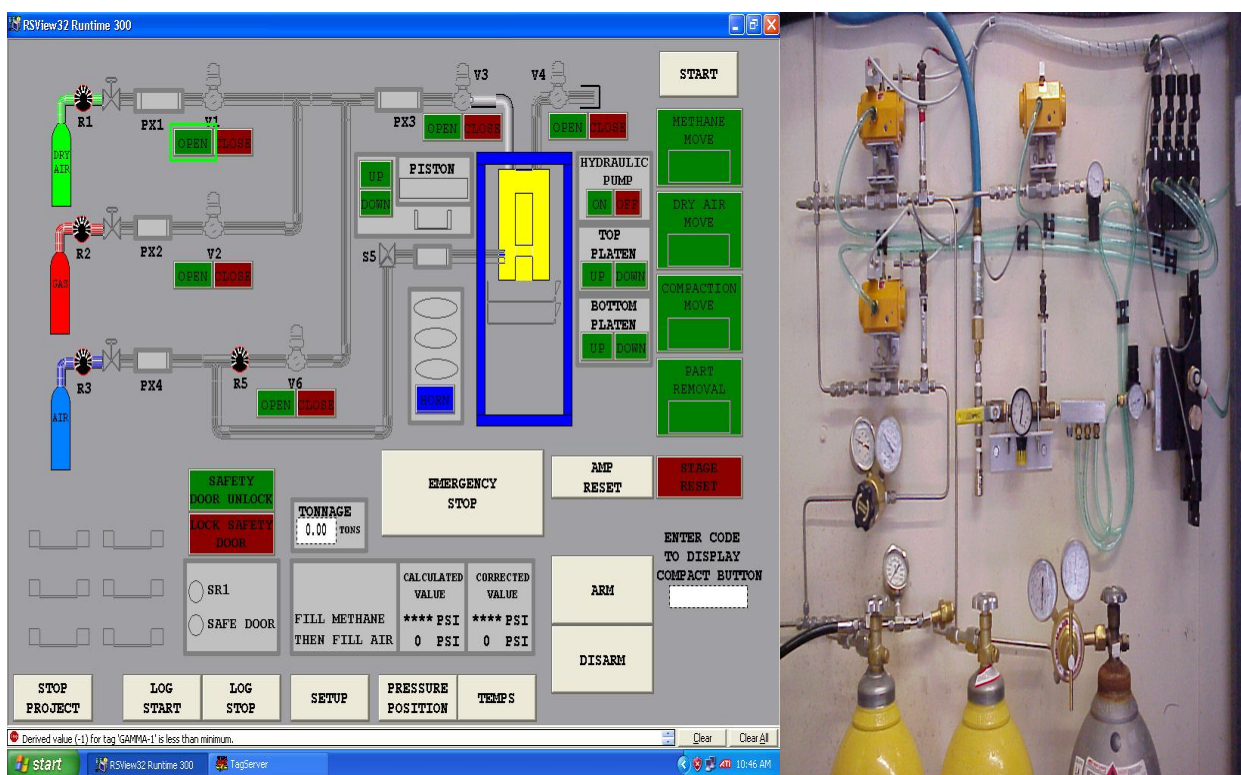
UTRON's 1000 ton CDC press development began in early 2005 with the intentions of pressing larger, multi-level parts. From a known size and area of intended part production, the required compaction energy was calculated. Next, hardware sizing was determined and a design concept created. Early on in the design process finite element modeling was used to determine component sizing based on acceptable safety factors. Throughout the design and re-design process, these models were updated for accuracy. After the structural elements of the press had been determined, ancillary systems had to be developed for fluid management, ignition systems, data acquisition, and safety regulations. These systems are unique to this project due to the unique nature of the CDC process.

Much like commercially available conventional presses, the CDC press also has a very extensive control and data acquisition center (Fig. 2). The touch-screen control center allows the operator to independently jog through the entire pressing cycle. While there are several manual functions to this cycle, a fully automated upgrade can be installed with minimal effort. In addition, an automated data acquisition system is active throughout the cycle collecting various performance data. This information is fed back directly into the controller for use in improving efficiency. Thus the program can become more efficient with each successive cycle and powder system.

One advantage in the press development is UTRON's test facility and fabrication shop in West Virginia. With the exception of the top chamber plate and the base plate, all of the necessary press components were fabricated internally. While the machining was done in West Virginia, the assembly has been erected in the Manassas, Virginia facility. It is in this location that all of the testing procedures have been carried out, select feasibility results obtained (this paper) and been in progress for further fine tuning and scientific understanding/press operating characterization using CDC experimentation.

### 1000 Ton CDC Press Hardware and Assembly

The 1000 ton CDC Press designed and developed by UTRON team has been assembled and present at UTRON's Headquarters in Manassas, VA. The various system components include the Main Press Frame (Fig. 1) with supporting sub-structures such as columns, top platen and lower platen, pedestal assembly for mounting the tool assembly, and control systems such as PLC Control), data detection sensors such as pressure probes, temperature measurements, chemical source supply cylinders and flow control valve hardware, (Fig. 2) high voltage/high pressure electrical ignition system, and data acquisition systems.

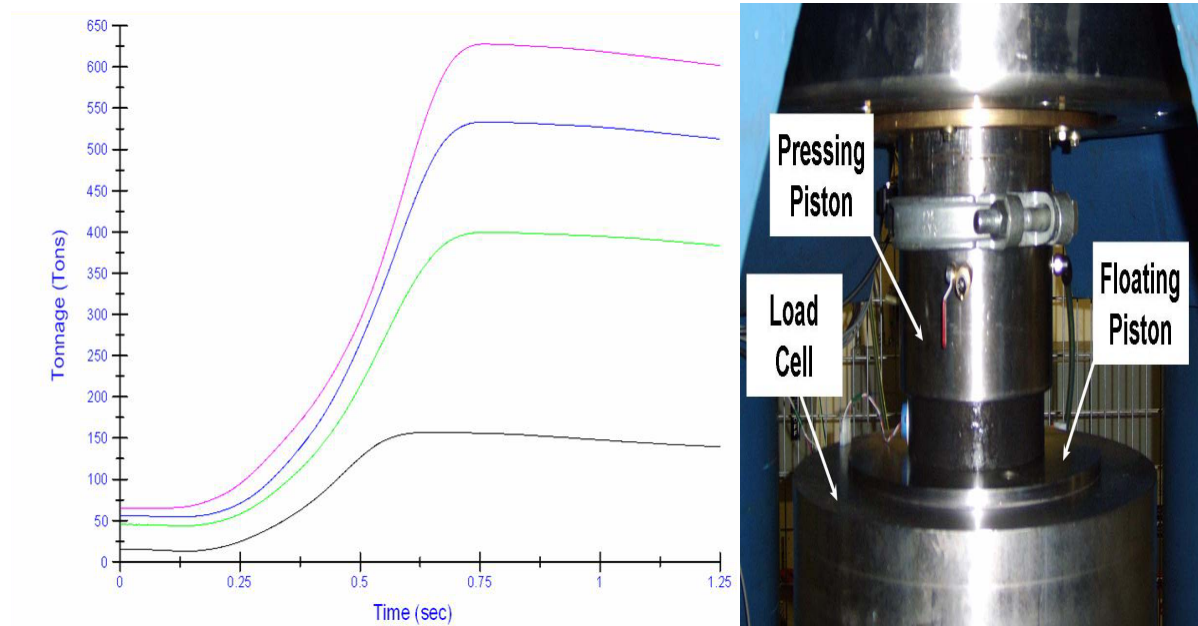


**Fig. 2 a PLC Control (left side) and 2b) Chemical Supply/Flow Control Hardware (right side) for the 1000 Ton CDC Press**

### Load Cycle Characterization

In an effort to characterize the loading cycle of the UTRON 1000 ton press, preliminary calibration tests at constant combustion volume were performed to measure the pressing force (tonnage) as a function of time. This was accomplished through the use of a specially designed load cell (shown in Fig. 3b). The load cell was positioned axially below the pressing piston and the press was run normally at varying tonnages. The load cell consists of a pressure chamber, a floating piston, and a ballistic pressure probe. As the CDC process propagates, the pressing piston loads the floating piston which pressurizes the load cell pressure chamber. A ballistic pressure probe then records the pressure change at a rate of 100 KHz. A high speed data acquisition system then records the pressure change over a two second period. Figure 3a shows a few of the resulting curves.

From the load versus time graph, it is clear to see that the CDC process yields a smooth load cycle varying from the lower pre-load to the maximum applied tonnage over a time of milliseconds. Due to the high preloads characteristic of the CDC process, progressively higher tonnage curves begin at progressively higher preloads. Therefore, the curves have higher starting values on the graph. By comparison, the curves show a consistent load cycle over the given time period. This results in a smooth loading cycle to the powder metal in the die. Additionally, the repeatability of the CDC process through varying tonnages is apparent.



**Fig. 3 a) Tonnage vs Time Characterization and b) the Experimental Setup Used**

Some of the operating characteristics of the 1000 Ton CDC press were obtained using controlled combustion volume and hydraulically measured load acting on trial steel tubes without any tooling in place. These data include load versus time plots as measured using load cell sensors. The results provide the preliminary attributes to operate the scaled up version of this 1000 Ton press within the design limit maximum of 1000 Ton rated capacity and we continue to evaluate and refine our press operating strategies.

## EXPERIMENTAL RESULTS OF CDC POWDER COMPACTION

The powder materials that have been compacted using 1000 Ton CDC press include copper, niobium and rhenium based refractory alloys to demonstrate the CDC pressable characteristics resulting in much higher green densities. The geometries that have been fabricated (Fig. 4 shows the tooling assemblies) are 2 inch diameter disks (copper and niobium), complex shaped part for Next Generation Linear Collider (NLC) using and hollow cylinders (refractory Rhenium based material). The selection of experimental materials is based on the technological importance of materials such as Copper and Niobium [12-13] for their applications for normal and superconducting characteristics/attributes for RF/Superconducting accelerator applications and rhenium and other refractory materials are excellent for high temperature applications [17].

Table 3 provides the experimental conditions used and the properties of the produced CDC parts. Figs 6-8 show the CDC compacted part geometries using 1000 ton press indicating the potential for both simple and complex part geometry fabrication using large scale part geometries and relatively higher suitable compacting pressures for obtaining optimum part fabrication conditions and properties similar to those obtained using 300 Ton CDC press. The parts have not only higher green densities but also have exhibited better surface finishes with sub-micron quality and improved mechanical strength even in green state (e.g.,  $R_B$  hardness K5-Cu: 58.5-61.5; K8-Nb: 87.5 -92) and after suitable sintering (K-14 Rhenium Alloy Material:  $R_B$ : 90.5-93.5 ). CDC-Copper and Niobium for accelerator applications have showed excellent responses under optimal process conditions using 300 Ton CDC press previously.[13] In this paper, we are showing similar trends in terms of pressing and properties with good similarity. Results also bring out the CDC pressability and unique advantage of higher pressure consolidation of fine as well as coarse powders (e.g., Nb) resulting in much higher part densities compared to conventional means. Figs 9-13 provide the representative microstructures obtained in CDC compaction after pressing (Fig. 9 for copper and Figs. 10-12 for niobium) and after sintering (Fig. 13, for Refractory Rhenium-based material). CDC Rhenium-based materials [Patent Pending-[17]] under optimal processing conditions has resulted in much higher sintered densities (e.g., 97-98+ % of Theoretical Values comparable to HIPed parts) with better manufacturing advantages of minimal number of processing steps, less processing time, minimal grain growth, mechanical high temperature properties and cost-effective competitiveness.

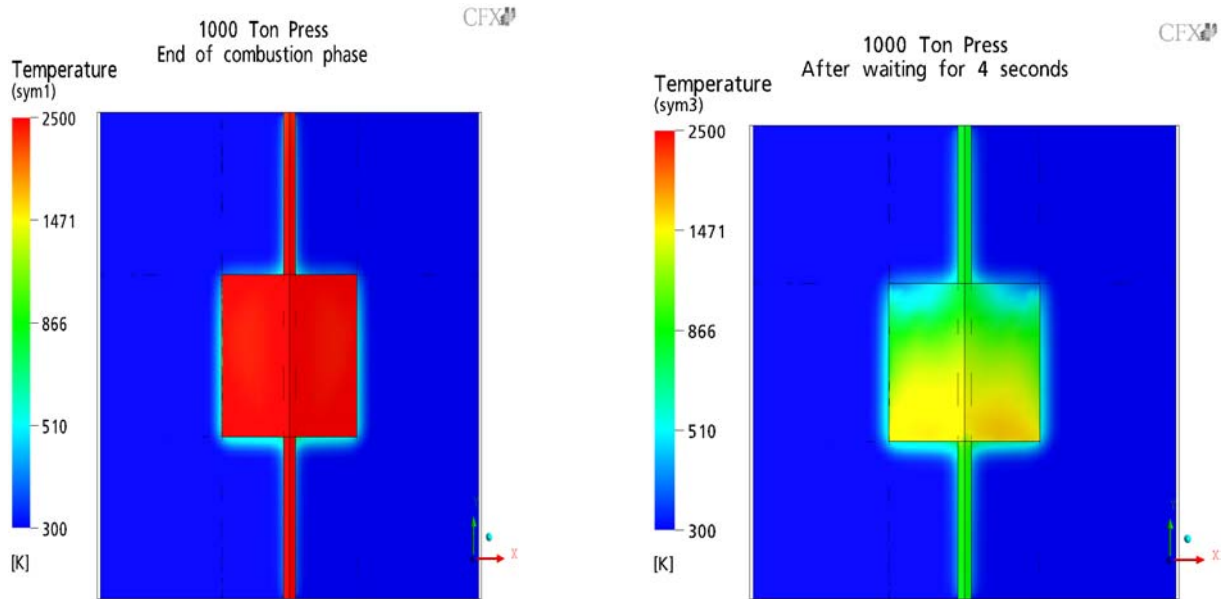


**Fig. 4 Tooling Assembly Setup for Fabricating the NLC Copper Disks (shown in Fig 7) and Hollow Cylinders (shown in Fig. 8) CDC Press Operating Characteristics:**



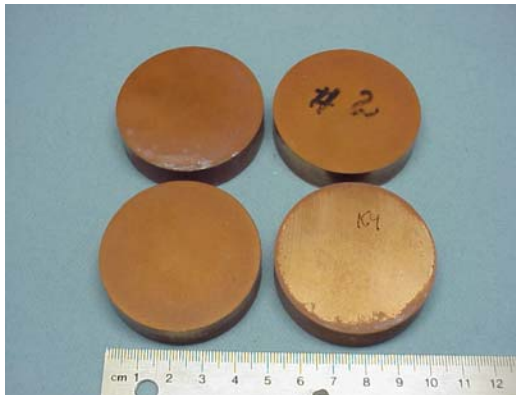
## Combustion Related Computational Fluid Dynamics (CFD) Calculations for the 1000 Ton Press Development

We have performed CFD calculations of the flow inside the 1000 ton press, including heat transfer through the combustion wall chamber. The code used is ANSYS-CFX. The geometry is simplified with respect to the real press, but the parameters of the calculation are those of the real press. The model chamber is axisymmetric, with an outlet above and an inlet below (Fig. 5a). The temperature of the gas after all methane is burned is about 2500 K. However, the wall temperature stays below 1000 K, because of the protection provided by the gas boundary layers. This remains true as long as no valve is open. If the valve is opened immediately after burning to release the hot gas, the wall in the vicinity of the valve can become very hot (2000 K) due to the blowing off of the boundary layers by the flow. But if one waits 4 to 5 seconds before opening, most of the heat is transferred to the walls, and then it is safe to release the gas. The wall temperature will remain below 1000 K. Of the total energy provided by the chemical reactions, some of the energy goes into heating the walls. In the case of continuous operation, this heat must be extracted in 4 to 5 seconds with an active cooling system. Figure 5a shows a vertical cut of the chamber and wall after the methane combustion is over. Figure 5b shows the press after waiting for 4 seconds. The gas temperature has decreased considerably.



**Fig. 5. CFD Calculations of thermal history a) after combustion is completed b) after 4 seconds**

Table 3. Experimental Combustion Driven Compaction Conditions and Properties									
Run#	Type of Powder Material Compacted	Peak Combustion Load: (tons)	Applied Combustion Load Pressure (tsi)	Green Density (g/cc)	Percent of Theory	Die Geometry:	Inner Dia, ID (in)	Outer Dia, OD (in)	Thickness or Height or Length (in)
K1	Copper Mix1	78.4	25.0	8.3955	93.70	Cylinder		2.0045	0.4975
K2	Copper Mix 1	152.0	48.4	8.5473	95.39	Cylinder		2.0035	0.507
K3	Copper Mix 1			8.6868	96.95	Cylinder		2.002	0.501
K4	Copper Mix 1	243.7	77.6	8.6516	96.56	Cylinder		2.0045	0.4915
K5	Copper Mix 2	229.7	73.1	8.1907	91.41	Cylinder		2.0105	0.5285
K6	Nb -80/+200	346.8	110.4	8.4112	98.15	Cylinder		2.006	0.494
K7	Nb -80/+200	309.7	98.6	8.4112	98.15	Cylinder		2.006	0.49
K8	Nb -325 mesh	452.7	144.2	8.3651	97.61	Cylinder		2.007	0.496
K10	Copper Mix 2	180.7	42.2	8.006	89.35	NLC-Complex Shape Disk	0.4265	2.455	0.4314
K11	Copper Mix 2	253.0	59.1	8.1625	91.10	NLC-Complex Shape Disk	0.428	2.4575	0.4396
K13	Refractory Rhenium Alloy	136.6	83.2	11.0293	81.58	Hollow Cylinder	0.477	1.5282	1.3365
K14	Refractory Rhenium Alloy	180.1	109.7	11.7122	86.63	Hollow Cylinder	0.476	1.5293	1.256
K15	Refractory Rhenium Alloy	163.4	99.5	11.2881	83.49	Hollow Cylinder	0.476	1.5307	1.3025

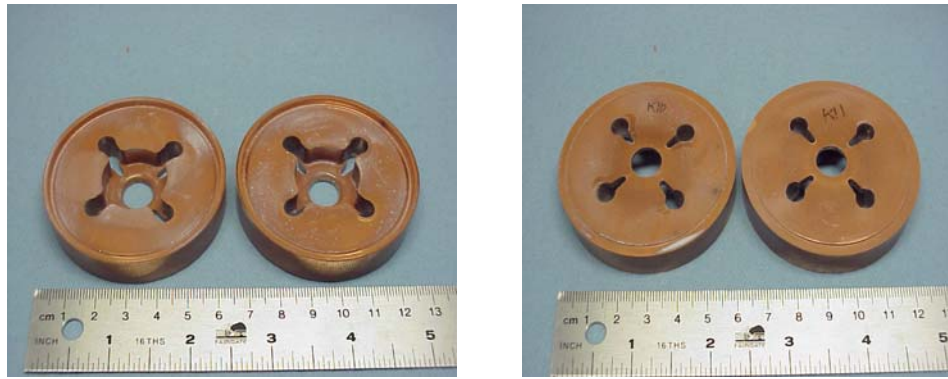


a



b

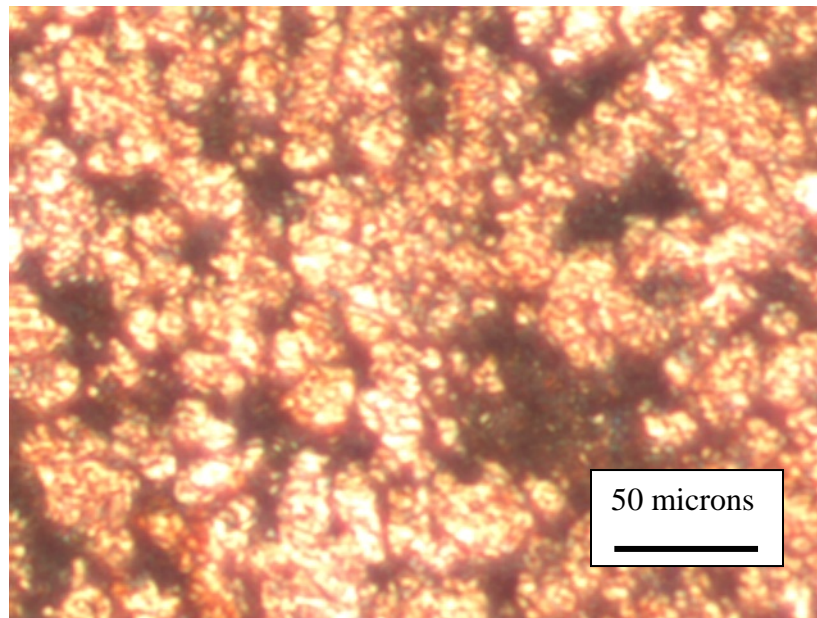
Fig. 6 CDC Compacted a) Copper and b) Niobium Disks (2 inch diameter) Pressed Using 1000 ton CDC Press



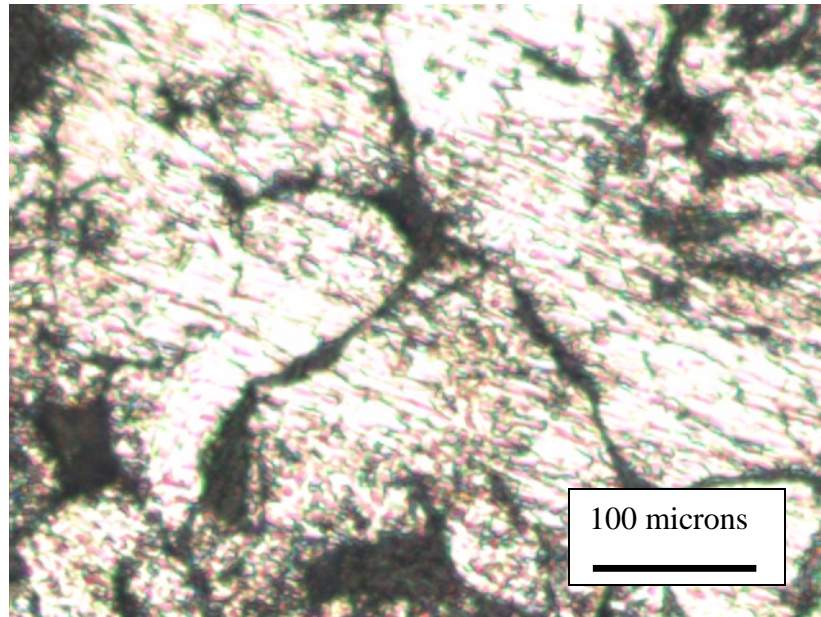
**Fig. 7 Next Generation Linear Collider Copper Disks Using 1000 Ton CDC Press [12-13]**



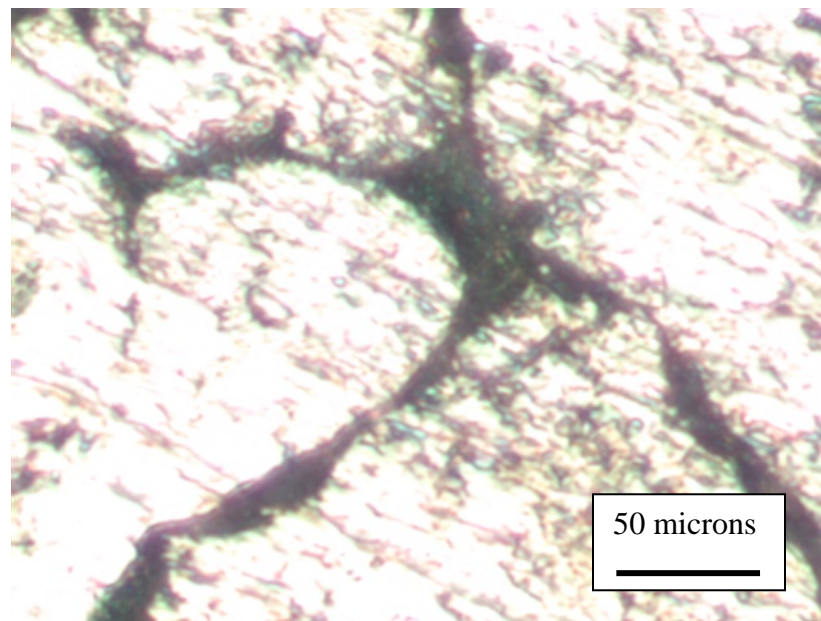
**Fig. 8 CDC Pressed Hollow Refractory Rhenium-Based Alloy Cylinders Pressed using 300 (ID: 1466-1470) & 1000 C Press (ID: K13-K16) [12]**



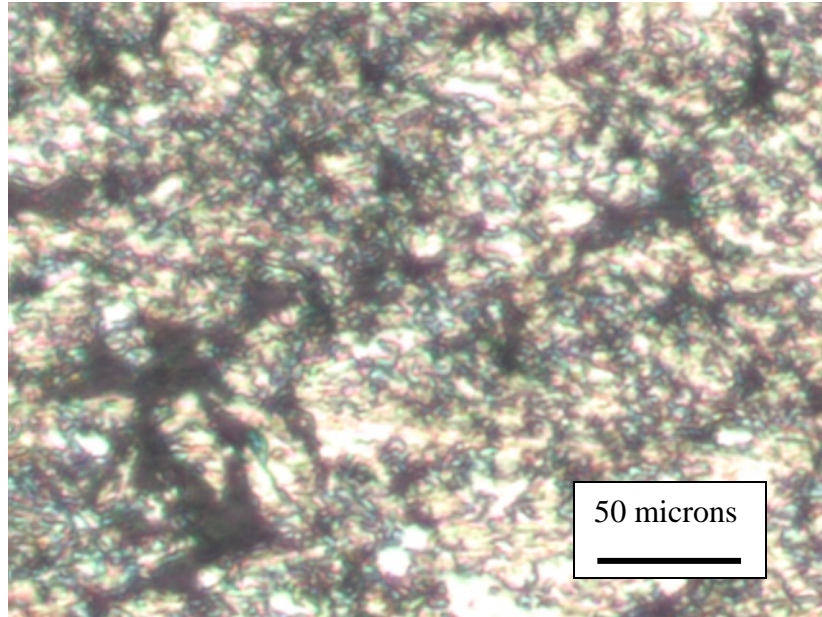
**Fig. 9 As-Pressed Microstructure of Copper (Cu)**



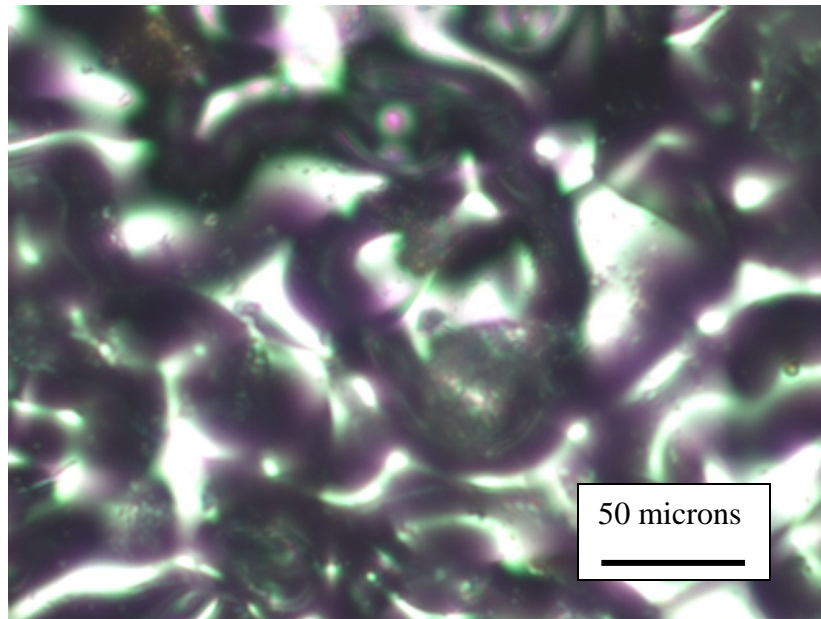
**Fig. 10 As Pressed CDC Niobium-Nb Microstructure at Low Magnification (10X Obj)  
Coarse Grain: (-80 +200 mesh) (10X Obj)**



**Fig. 11 As-Pressed CDC Niobium-Nb Microstructure at higher magnification (20X Obj)  
Coarse Grain:( -80+200 mesh) (20x Obj)**



**Fig. 12 As pressed Microstructure of Niobium-Nb-Fine Mesh (-325 mesh) (Nb)**



**Fig. 13 Sintered Refractory Rhenium-Based Material Microstructure**

## **CONCLUSIONS AND SUMMARY**

- The 1000 Ton CDC Press has been presented together with select results of compaction experimental operating characteristics and materials being compacted to produce select geometries and properties.
- The materials being successfully compacted include Copper, Niobium and Refractory Rhenium-Based Materials.

- The uniqueness of obtaining higher part densities for finer as well as coarser powders using 1000 Ton CDC Press has been demonstrated similar to those results obtained previously for micro as well as nanosized powder materials being processed using the 300 Ton CDC press.
- The produced CDC parts have possessed much higher compacted densities and properties similar to those obtained previously using 300 Ton-CDC press [9-13] than possible by conventional P/M methods depending on the tonnage per square inch and type/size of powder being used indicating the unique advantages of controlled high pressure consolidation.
- These preliminary results are encouraging and form the basis for further materials development, fabricating simple to complex geometries of larger part sizes that can be pressed anywhere for example, from 50 to 150 tsi depending on the application, and to establish the scientific/engineering basis for further development and advancement to production scale CDC pressing technology.

The possible applications for the CDC net-shape program are virtually limitless. Some typical examples as discussed previously are: valves/valve seats, connecting rods, gears, brake parts, bushings, spring retainers, washers, roller bearings, pump parts, x-ray targets, sputtering targets, ammunitions, and heat sinks/shields/nozzle parts. In addition, of growing interest is the use of the CDC technology for soft magnets. Given the ability of the CDC process to achieve very high green densities in nanocomposite systems [8], certain powder systems can be pressed to yield improved magnetic properties with minimal processing steps compared to conventional multi-step methods. Also, as noted by technical reviewers of the PM industry<sup>3</sup>, the automotive industry stands to benefit from higher density parts provided cost-effectiveness can be justified for high performance, competitive high performance materials that can be developed with significant material savings and better performance. Key to their success will be higher fatigue strength parts for use in transmissions, engines, and chassis. Fortunately, the CDC process is scalable, and not limited to only the 1000 ton press. As the customer needs and demands arise, higher tonnage presses with much larger effective pressing areas can be developed to cater to the growing need for larger PM produced parts.

Equally important to the success of high energy compaction is the powder from which the parts are made. The CDC process has proven its worth with powders ranging from pure metals to complex alloy systems. Conversely, the process has also had success with nanocomposite materials<sup>8</sup>. As new and innovative nano-powders become available, testing can proceed with the CDC technology to determine the depth to which material properties can be enhanced.

These examples span not only military or research but also commercial markets. Cost effectiveness together with higher performance and improved properties has become essential component and of significant factor in recent days for governmental as well as commercial product markets in the US and abroad. With the next generation automation processes of the CDC program, large volume production runs will be not only technically feasible but also be economically viable.

## **ACKNOWLEDGMENTS**

We convey our thanks and gratitude to our research sponsors for their support and funding from Small Business Innovation Research (SBIR) programs such as the Department of Energy (DOE) under contract# DE-FG03-03ER83816)/Missile Defense Agency(MDA) sponsors (under contract# HQ0006-05-C-7224) and UTRON's management for some internal R&D funding for this initiative on the 1000 Ton CDC Press Development. We also like to thank our end users/customers, suppliers/vendors for their interest in our CDC compaction technology for their specific product and materials development needs. We are also very grateful to several UTRON's team members who have showed great deal of enthusiasm, teamwork and dedication with the CDC press design and development aspects in this project (e.g., Maurice Meneguzzi , Barry Landers, Chuck Martin, Jeremy Herdman, Mike Ezzo, Machine shop team at

Ashton and Manassas, Chad Eisenhauer, Lester Via, Marco Luna and other support staff at Manassas/Ashton for their outstanding team work and coordination during the various stages of component design, fabrication/machining, testing, materials procurement/development, tooling (Special thanks to Mr. Charles Rose and the team at Bronson and Bratton, Inc) and assembly stages of this technologically challenging and feasible 1000 ton scaled up version of press design and development.

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