Materials Behavior and Manufacturing Aspects of High Pressure Combustion Driven Compaction P/M Components

Karthik Nagarathnam, Donald Trostle, Dave Kruczynski, and Dennis Massey

UTRON Inc.
(www.utroninc.com)
8506 Wellington Road, Suite 200
Manassas, VA 20109

Paper Presented at the 2004 International Conference on Powder Metallurgy & Particulate Materials(PM^{2}TEC-2004) to be held in Chicago, IL, June 13-17, 2004.

ABSTRACT

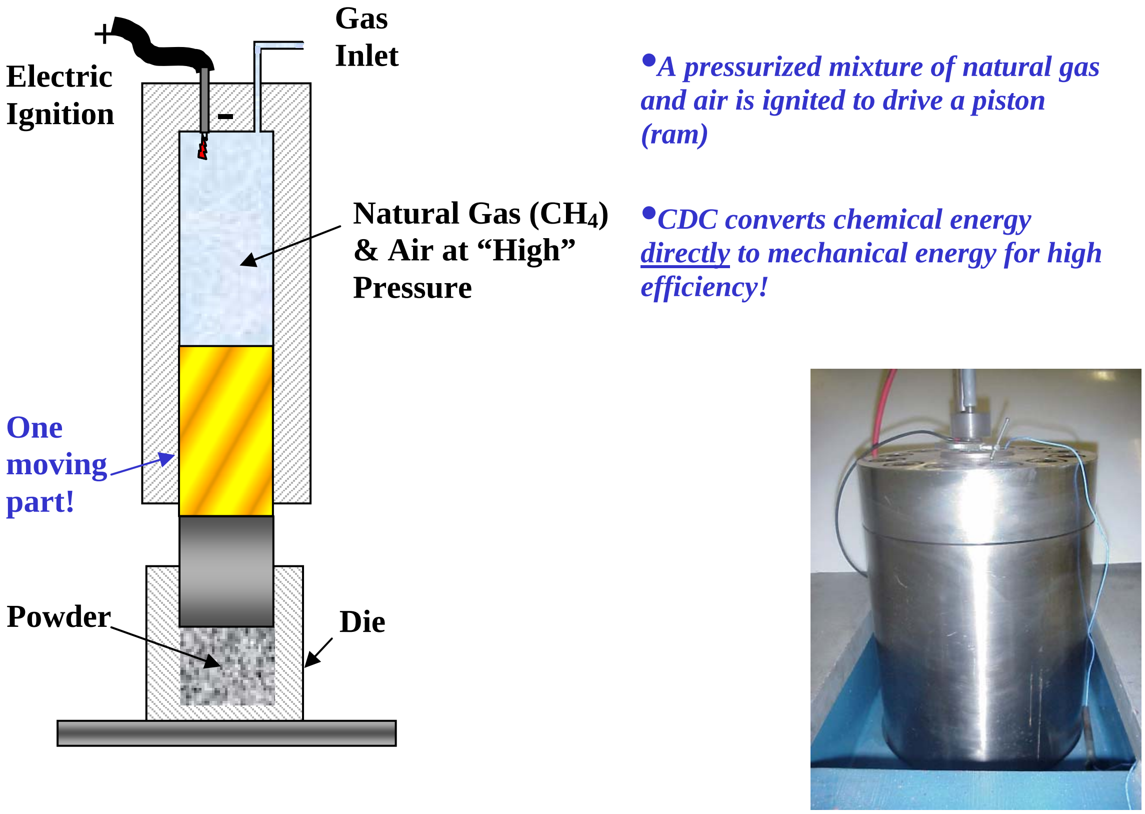
This paper provides an overview of materials behavior and manufacturing aspects of P/M parts fabricated by high pressure Combustion Driven Compaction (CDC) at UTRON.[24-29] This unique compaction method has several advantages such as net-shaping, improved surface finish/quality, amenability to simple or complex geometries, suitability for single or multilayered materials, reduced processing time (e.g., ms) compared to traditional rapid prototyping techniques, little or no post-machining, and improved process flexibility. Select results of CDC processed Aluminum alloys, Stainless Steel 316L (SS316L), Copper and dissimilar combination of SS316L/Copper under optimum process conditions will be presented and discussed. The structure/property characteristics include microstructures, surface roughness/quality and mechanical properties. The potential commercial uses [1-37] of high pressure compaction CDC technology include a wide range of applications such as vacuum seals [15], x-ray targets, cryogenic parts, accelerator/RF microwave components [18-27, 31, 34-36], computer hard disk drive accessories such as read/write heads, engine parts such as valves/valve seats, pushrods, high temperature nozzle liner parts/heat sinks, electrical/electromagnetic parts such as contacts/commutator rings/brushes, tooling inserts, advanced magnets [37], high performance gears, bearings, welding electrodes, and wear/corrosion resistant tribological components.

INTRODUCTION

The Combustion Driven Compaction has several process advantages such as high pressure compaction (>50 tsi up to 150 tsi), compactness, net shaping, reduced process time (e.g., milliseconds), improved density of the parts with unique CDC loading cycle, amenability to make simple to complex parts, suitability for micro/nano powder consolidation, potential for composite/functional gradient materials (FGM) fabrication, improved high performance properties (e.g., net shaping, superior surface finish, mechanical properties), less or no post-machining/grinding needs and scalability to larger sizes.

1.1 Background on the Combustion Driven Compaction (CDC) Process

The CDC Process [15, 24-29] shown in Fig.1 utilizes the controlled release of energy from combustion of natural gas and air to compact powders. In operation the following steps occur: 1) The chamber is filled to high pressure with a mixture of natural gas and air; 2) As the chamber is being filled the piston or ram is allowed to move down pre-compressing and removing entrapped air from the powder and 3) The gas supply is closed and an ignition stimulus is applied causing the pressure in the chamber to rise dramatically, further compressing the metal powder to its final net shape. The CDC process is based on utilizing the direct conversion of chemical energy to produce compaction. The process inherently includes a pre-compaction step preparing the powder for the final compaction load.



- *A pressurized mixture of natural gas and air is ignited to drive a piston (ram)*
- *CDC converts chemical energy <u>directly</u> to mechanical energy for high efficiency!*

Fig. 1 Schematic and Equipment of the Combustion Driven Compaction Process

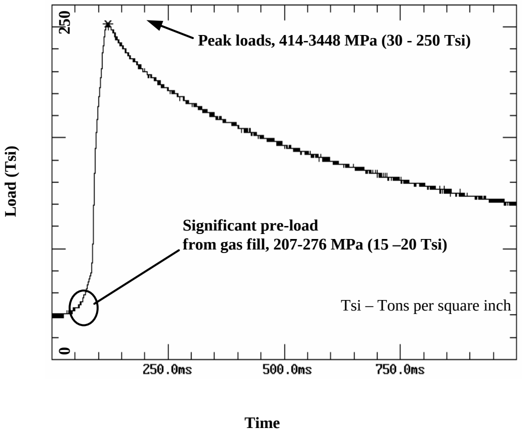


Fig. 2 Typical CDC Compaction Load

The CDC process can provide standard or very high compaction tonnages resulting in high-density parts with improved properties. In addition to the unique loading/high tonnage the CDC process occurs over a relatively short time frame (a few hundred milliseconds) as shown in Fig. 2.

Our CDC press is not much larger than a phone booth and has one moving part unlike a mechanical or hydraulic press which is typically two or more building floors tall and has many moving parts and/or complex hydraulics. Figs. 3 and 4 illustrate this compactness of CDC press with a traditional press.

Size of UTRON's CDC 400 Ton Press

Conventional 400 Ton Press

Fig. 3 Compactness of CDC Press (left) & Fig. 4 Compared with a Traditional Press (right)

1.2 CDC Loading Cycle

As the compaction load to a powder metal is raised the compact density and properties improve. If the powder is compressed too rapidly, shock propagation in some materials can cause internal cracks and separations (over-pressing). Unlike other Forging or explosive Forming, CDC loading rate is much more gentle and highly controlled which provides unique advantages to compact crack-sensitive materials such as brittle materials or composites. The CDC press achieves high density while avoiding shock propagation and defects in the compact with its two-stage, fast but gentle, load cycle. In addition, the load sequence of CDC allows large tonnage loads to be applied without damage to the press or die components. The initial gas fill sequence aligns the ram and die components while applying sufficient load to pre-compress the powder and remove entrapped air. When the fill gas is ignited the ram rapidly presses down but without slamming into the tooling or powder. In other words the process although fast and powerful, is smooth and continuous. The CDC process routinely operates at compaction loads of 2069 MPa (150-Tsi) and above. This is in sharp contrast to conventional compaction processes, which generally are limited to 690 MPa (50-Tsi).[7-14,30, 32-33]. Currently used 300-ton press has operated for over several years indicating the part making ability with longer die life of more than 500 cycles as of the writing of this paper. To date there has been no indication of any damage or wear of carbide dies and hardened tool steel punches when operated routinely at 2069 MPa (150 Tsi).

1.3 CDC Press Scaling

As previously mentioned, since the CDC press directly converts chemical energy into compaction energy it is very energy efficient and capable of producing enormous compaction loads. To date three presses of increasing size have been constructed and operated, 10, 30, and 300 ton. Scaling from one size to the next has been relatively straightforward. Since the process works more or less like a piston in an automobile, although at much higher pressures, the loads that can be produced are a direct function of the combustion pressure and the area of the ram (piston).

It is possible then to scale a CDC press to very high tonnages without increasing the size of the press itself dramatically. As an example a 3000 ton CDC press would only be about 2.75 m high, 1.92 m wide, and 1.28 m deep (9ft x 6ft x 4 ft). The relatively diminutive size of a CDC press will allow powder metal part making to be performed in almost any industrial or commercial building with access to bottled or piped natural gas. Pits and multi-story buildings will not be needed, and the presses can be moved with standard forklifts. This relative portability will allow, for instance, powder metal presses to be incorporated into “machining centers” as needed and then moved to other centers or sites generally without special equipment.

1.4 Material Properties of CDC Parts

As a general rule, as the compressive load applied to a metal powder is raised, the part properties improve. However, if the powder is compressed too rapidly or violently, shock propagation in the material can cause internal cracks and separations. The CDC avoids these problems with its two-stage moderately fast load cycle. In addition, the load application of the CDC allows large tonnage loads to be applied without damage to the press or die components. When standard mechanical/hydraulic presses attempt to compact metal powders to high densities they typically break tooling and/or induce cracking in the parts. Controlled rates of loading are therefore highly desirable and important for compacting various combinations of materials.

In general, CDC compacted green parts (Tables I and IV) possessed significantly higher green densities at CDC pressures of above 50 tsi which is usually the threshold limit offered by traditional powder metallurgical pressing methods. Figures 5-9 shows some of the variety of CDC processed materials to date (Materials processed include Pure metals: Cu, Al, Mo, Ta and Fe; Alloys: 316 SS, 410SS, FL-4400, FLN2-4405 and 737SH; Layered and Mixed: Al/Ti, SS/Mo, Cu/Ta, Al/Alumina, SS/Ta, FL-4400/Cu, FL-4400/Al, Fl-4400/Ti, FL-4400/Ta), aluminum nitride, in various shapes and geometries including the multi-layered parts made of steel/copper, copper/stainless steel/niobium, AlN, and nanocomposite magnetic materials such as FeNi-SiO2. The latter material compacted with CDC high pressure loading with much higher density had relatively superior magnetic permeability as high as 16 at the tested frequencies of up to 100 MHz.[37]

Traditional pressing technology [12] is generally limited to 50 tons per square inch (tsi) or less. The CDC process routinely operates at compaction loads in the 150-tsi range and above, making a huge difference in the final quality of the compacted part both in the green (unsintered state) and in the sintered state. Some of the encouraging results of UTRON's CDC processed materials for potential accelerator components for Department of Energy (DOE) applications are presented in Fig. 7. It is apparent from the results of CDC properties and surface finish data that the high pressure CDC process produces far superior compacted parts. For accelerator applications [15, 24-27, 34-36], our high pressure compaction technology has ample potential to produce several near net shape components of copper, niobium, stainless steels, dissimilar material combinations such as copper/stainless steels or copper/molybdenum and ceramic composites such as Cu/AlN, SiC with fine surface finishes after pressing or with a very minimal amount of post processing/sintering. Our potential capability to upgrade to higher tonnages will be further beneficial for densifying larger single/multilayered complex parts.

Fig. 5 Net-Shape Quality of CDC Processed Samples(e.g., Dogbones, Cylinders, Rings, & Gears)

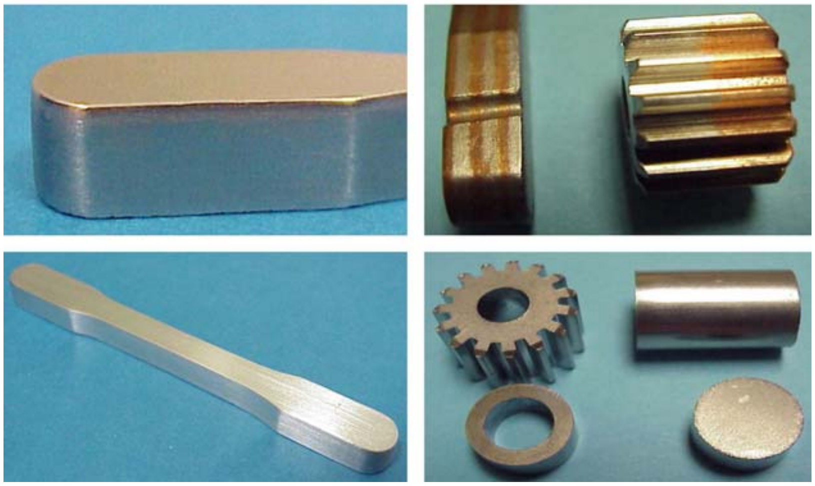


Fig.6 Variety of a) Cu-Based Multi-Layered Materials (Top Row); b) Aluminum, Ferrous Alloys and Refractory Materials (Bottom Row) Compacted by CDC High Pressure Compaction

The final dimensions of a compacted component can be closely controlled by the die design, particularly when the part is compacted to near full wrought material density. When using carbide dies, dimensions perpendicular to the applied load can be held to very close tolerances, which are basically those of the die itself. Although not all our current dies were designed for high tolerances, We nevertheless obtain dimensional variations of only a few tens of microns perpendicular to the pressing direction. Dimensional stability in the direction parallel to the compaction load is largely controlled by the amount of powder used and its even distribution before pressing. If this is done carefully, dimensions parallel to the compaction direction can also be controlled, but to what degree remains to be shown.

A trial sample of layered copper/steel was tested by bonding a bar to the copper with epoxy and then pulling the sample until the materials separated. The material was tested in the green state and failed with a load of 536 psi. This single case points to the ability of these layered compacts to sustain some mechanical load directly after pressing without sintering.

Additional Properties of CDC Processed Materials

Material	Load (tsi)	Density (g/cc)	Roughness (microns)	Hardness (kg/mm^2)
Al-Mg Alloys	**52**	**2.632**	**0.2-0.6**	**39 - 47 (Green & Sintered)**
Low Carbon Steel	**154**	**7.59**	**0.1936**	**85 -100 (Sintered)**
Austenitic Stainless	**150**	**7.537**	**0.1698**	**200 (Green)**
Copper	**150**	**8.718**	**0.1695**	**100 (green)**

Process	% Scrap
Machining	**10-60**
Forging	**20-25**
Forming	**10-25**
Extrusion	**15**
Casting	**10**
Powder	***5***

Combustion Driven Compaction

Fig. 7 % Scrap vs Manufacturing Process, CDC Copper & Stainless Steel Rings and Select Material Properties

We have demonstrated the successful fabrication feasibility of fully dense a) SS316L, b) double layers of SS316L/Copper, and c) Multiple layers of Cu/SS316L/Niobium with submicron surface finishes and good bonding. (Fig. 8). Some of these metal powders were compacted around the perimeter of a preformed/metallized alumina ceramic and high-pressure compaction was done without cracking the sample @ 60 tsi compaction pressure. We have also shown (Fig. 9) the fabrication potential and technical feasibility for net-shape quality, well-bonded and crack-free AlN ceramic and Copper/AlN composites by high pressure CDC compaction up to 100 tsi. The powders used for fabricating these composite materials were relatively finer(-625 mesh). The typical part size is about 0.5 inch diameter using our existing die/punch assembly. These results highlight our process's potential for the development of functional gradient composite materials (FGM).

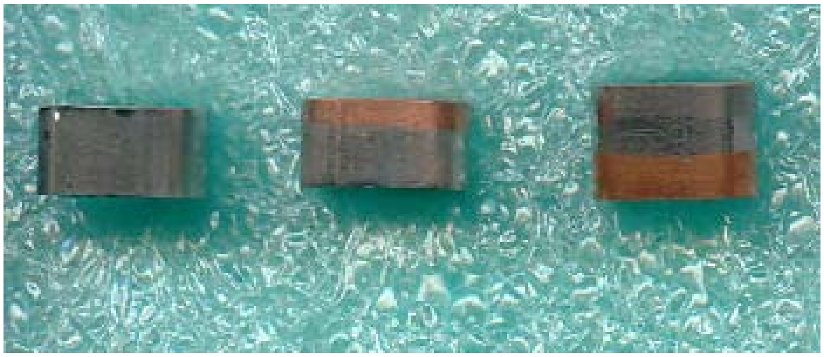


Fig. 8 Multilayer CDC cylindrical slugs of SS, SS/Cu, and Cu/SS/Nb.[15,24-26]

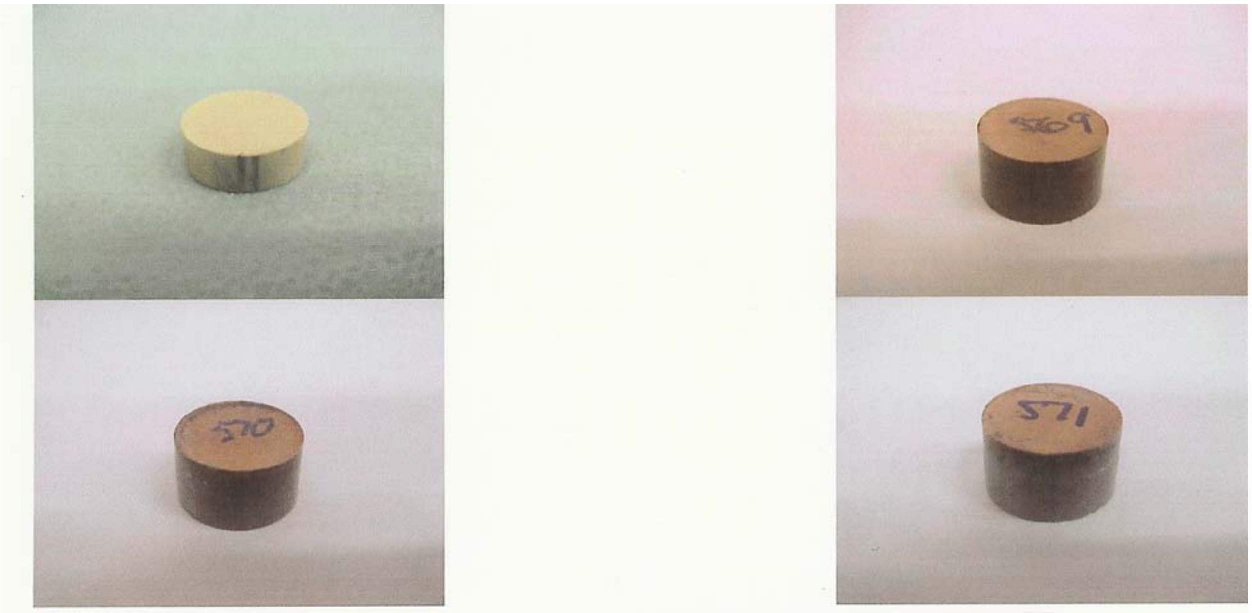


Fig. 9. Net Shape Fabrication Potential for Aluminum Nitride and Cu/AlN Ceramic Composite Cylinders (0.5 inch Diameter) [27]

These preliminary results provide the anticipated potential benefit, scientific basis, and significant needs for further evaluation and exploration of this unique CDC materials fabrication method.

APPLICATIONS

The anticipated applications of CDC technology for net-shape fabrication include high performance engine parts such as valves/valve seats, connecting rods, gears, brake parts, bushing, spring retainers, washers, roller bearings, pump parts, x-ray targets, sputtering targets, ammunitions, heat sinks/shields/nozzle parts, electrical contact brushes for motors/generators, commutator rings, nuclear plasma components, electromagnetic devices, vacuum seals, welding electrodes, microwave components, microelectronic interconnects/thermal management systems, permanent/superconducting magnets and wear/corrosion/high temperature parts.

KEY RESULTS AND DISCUSSIONS

Select results of experimental conditions and properties of CDC processed Aluminum alloys (Figs.10-12, Table I-III), Stainless Steel 316L and Copper/SS316L (Tables IV-VI and Figs. 13-14) are presented. CDC processing was successfully used to fabricate simpler Al-3Mg alloy samples with theoretically close density, minimal/no porosity, fine surface finish, relatively finer microstructures (Fig. 12) and improved mechanical properties (Table II and III) similar to those of annealed materials [8,9,13, 15-17] for potential vacuum seal applications [15]. The key R&D findings are as follows: 1) The key process parameters such as CDC pressure (Fig. 10 and Table I), powder size, lubricant type and sintering parameters such as (temperature and sintering media) (Table II and were found to influence part quality and properties and needed careful optimization; The density of CDC Al was close to the wrought Al-alloy (Fig. 11) 2) NDT X-ray examination of the CDC processed dogbone samples revealed the absence of any noticeable porosity within the measurable resolution of the x-rays and the 0.25 inch sample thickness; 3)

The average surface roughness (R_a) of CDC Al-3Mg green samples @ CDC pressure of 30 tsi was significantly reduced - by factors of 6.5 to 10 from submicrons to nanometer levels by intelligent process control of die wall lubricant (R_a using Silicone Lube: 0.0742 microns and for Stearate Lube: 0.7495 microns; 4) The sintering treatments @ 600°C included vacuum and nitrogen for varying times of 60, 15 and 30 mins, respectively, which enhanced the mechanical properties such as microhardness (from 30 to 45 VHN-kgf/mm^2) and strengths which are comparable to annealed Al and Al-Mg (e.g., 5454) alloys. The properties and thermal response behavior compared to wrought materials were influenced possibly due to the alloying element variations of additional elements Mn, Fe, Si, Zn, Cu, and Ti.

Fig. 10 As Compacted CDC-Green Al-3Mg Samples; Lubricant: Zinc Stearate Samples:A: #362 (30tsi);B: #364 (50tsi);C: #371 (150tsi)

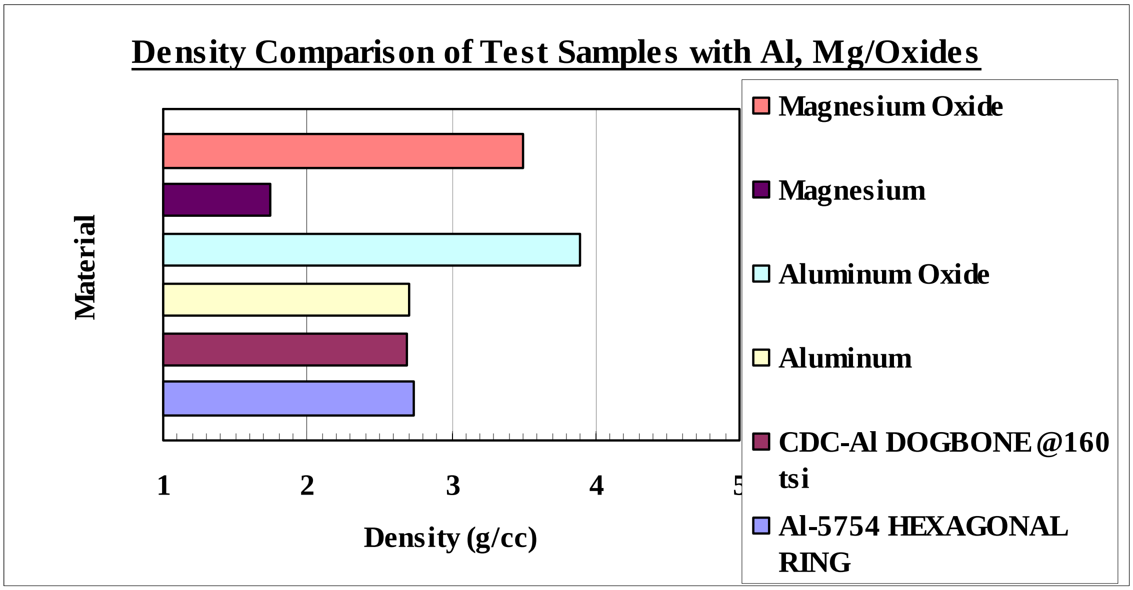


Fig. 11. Density Comparison of CDC Processed Al and Mg Lightweight Alloys

Table I. CDC Process Conditions and Green Densities of Al-3Mg Pre-Blended Alloy[15]

Sample#	CDC Pressure (tsi)	Die-wall Lubricant	Green Density (g/cc)	% Theoretical Density
362, 365	30.4	Zinc Stearate	2.6065	97.52
366	30.4	Zinc Stearate	2.6056	97.59
364, 367	51.6	Zinc Stearate	2.6333	98.62
368	51.6	Zinc Stearate	2.6320	98.57
369	146.8	Zinc Stearate	2.6295	98.48
370, 371	151.1	Zinc Stearate	2.6288	98.46
372	29.7	Dow SILICONE 557	2.6066	97.62

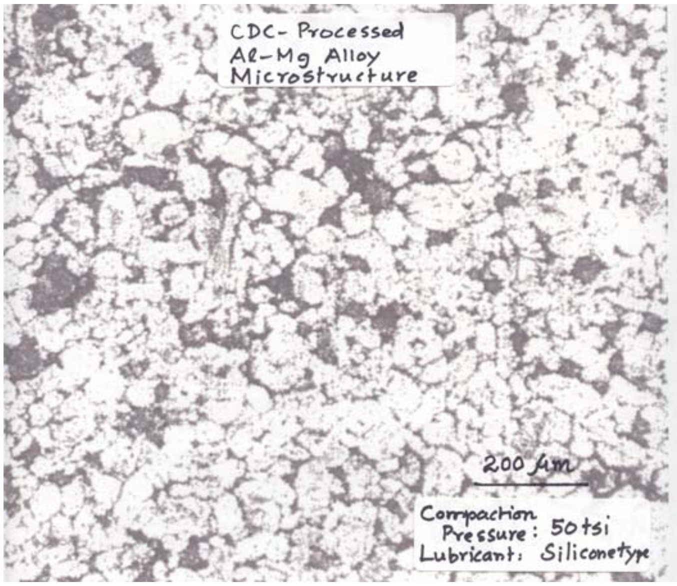


Fig. 12 Microstructure of CDC Processed Al-3Mg (Pre-Blended Powder Alloy)

Table II. Effect of Sintering on Microhardness(VHN) values (kg_f/mm^2) as listed for Green/ Sintered Samples and Surface Roughness of CDC processed Al-3Mg Alloy [15]

Sample ID # and Process Conditions	Green State	Vacuum Sintered@ 70*10-3 torr 600 deg C, 1 hr	Nitrogen Sintered 600 deg C, 15 mins	Surface Roughness (Ra-Average and RMS values in microns)
362 (30 tsi)	29.93			Ra: 0.7495; RMS:1
364 (50 tsi)	34.40			Ra: 0.1942; RMS: 0.2714
371 (150 tsi)	30.04			Ra: 1 ; RMS: 2
365 (30 tsi)			43.606	
367(50 tsi)			30.644	
370 (150 tsi)			39.288	
372 (30tsi and Silicone Lube)			41.341	Ra: 0.0742; RMS: 0.1049 (Sample # 373) with NANO SURFACE FINISH
366 (30 tsi)		44.274		Ra: 5.2 to 5.62; RMS: 6.24 to 7.7 after sintering
368 (51.6 tsi)		47.393		
369 (146.8 tsi)		43.942		

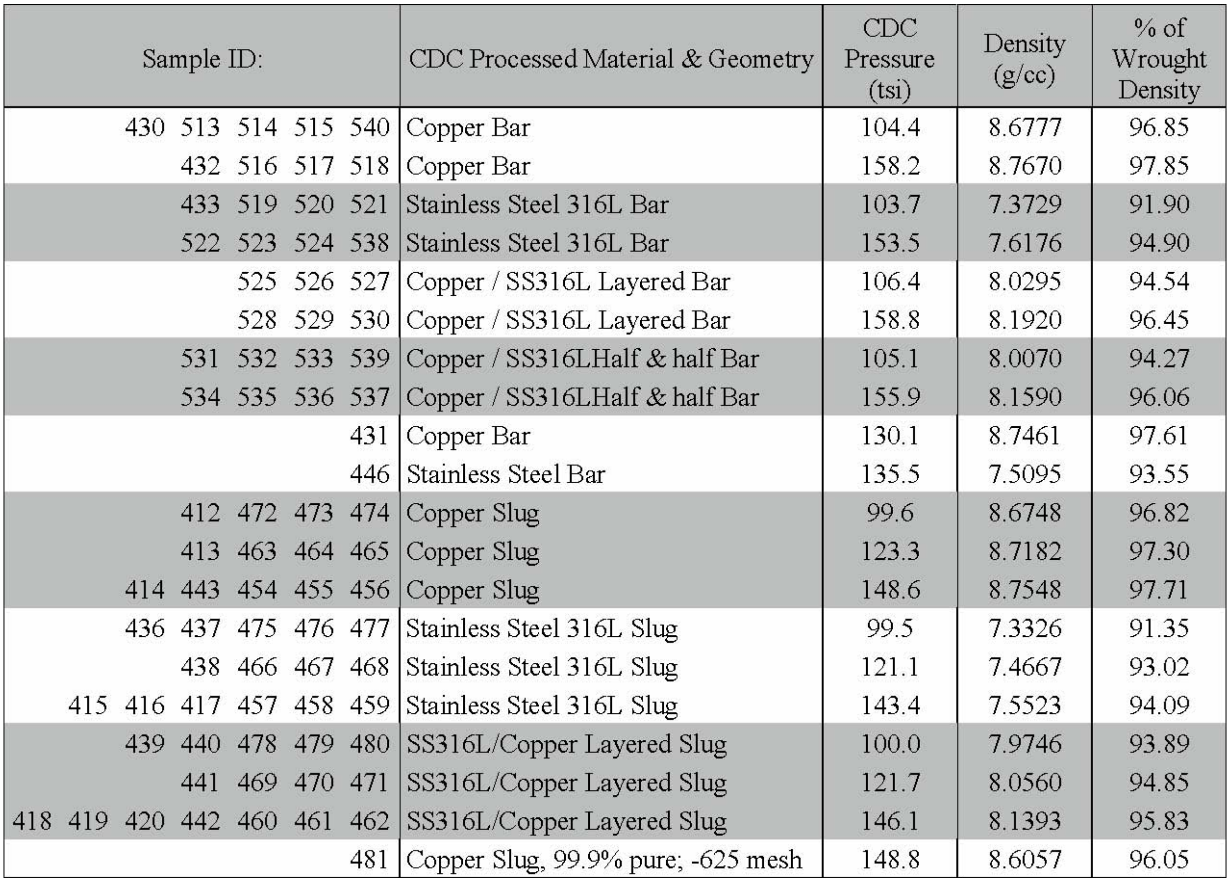
Table III. Mechanical Properties of Nitrogen Sintered CDC Al-3Mg Alloys 600 deg C; 30 mins (Zn Stearate Die Wall Lube) [15]

Sample ID#(CDC Pressure)	#362(30 tsi)	#364 (50 tsi)	#371(140 tsi)
Thickness(in)	0.2648	0.2494	0.2536
Width (in)	0.2325	0.2354	0.2361
Area(sq. inch)	0.06157	0.05871	0.05987
Yield Load, lbs	567	538	581
UTS Load, lbs	851	932	923
Yield Strength, psi	9200	9200	9700
UTS, psi	13800	15900	15400
Elongation, % in 1 inch	2.5	3.3	3.3
Modulus of Elasticity ($X 10^6$ psi)	9.0	6.3	7.3

The CDC processed SS316L, Copper and Dissimilar Cu/SS316L parts of tensile dogbones (MPIF Standard No. 10 with 3.5 inch length and 0.25 inch thickness bars) and cylindrical slugs (0.5 inch diameter) revealed higher densities (Tables IV and V), fine surface finish (Tables V and VI) and improved mechanical hardness (Table V), and strength/ductility (Table VI) properties under optimum sintering conditions. Representative results are presented in tables IV to VI and Figs. 13 and 14.

For SS316L and Cu & Cu/SS316L samples (Fig. 13), the optimum sintering conditions were 1200 deg C; 2 hrs (Fig. 13) and 1000 degC; 30 mins, respectively. The Scanning Electron Micrograph (SEM) of green and sintered SS316L samples revealed polycrystalline matrix grains in the microstructures (Fig. 14a and b) and Xray Diffraction indicated the presence of mainly face-centered cubic fcc-gamma phase (lattice parameter of 3.60 Angstroms) typical of austentic stainless steel 316L.

Table IV. Experimental Conditions of CDC Processed Green Copper and Stainless Steel 316L Samples [25, 27]



Sample ID:	CDC Processed Material & Geometry	CDC Pressure (tsi)	Density (g/cc)	% of Wrought Density
430 513 514 515 540	Copper Bar	104.4	8.6777	96.85
432 516 517 518	Copper Bar	158.2	8.7670	97.85
433 519 520 521	Stainless Steel 316L Bar	103.7	7.3729	91.90
522 523 524 538	Stainless Steel 316L Bar	153.5	7.6176	94.90
525 526 527	Copper / SS316L Layered Bar	106.4	8.0295	94.54
528 529 530	Copper / SS316L Layered Bar	158.8	8.1920	96.45
531 532 533 539	Copper / SS316LHalf & half Bar	105.1	8.0070	94.27
534 535 536 537	Copper / SS316LHalf & half Bar	155.9	8.1590	96.06
431	Copper Bar	130.1	8.7461	97.61
446	Stainless Steel Bar	135.5	7.5095	93.55
412 472 473 474	Copper Slug	99.6	8.6748	96.82
413 463 464 465	Copper Slug	123.3	8.7182	97.30
414 443 454 455 456	Copper Slug	148.6	8.7548	97.71
436 437 475 476 477	Stainless Steel 316L Slug	99.5	7.3326	91.35
438 466 467 468	Stainless Steel 316L Slug	121.1	7.4667	93.02
415 416 417 457 458 459	Stainless Steel 316L Slug	143.4	7.5523	94.09
439 440 478 479 480	SS316L/Copper Layered Slug	100.0	7.9746	93.89
441 469 470 471	SS316L/Copper Layered Slug	121.7	8.0560	94.85
418 419 420 442 460 461 462	SS316L/Copper Layered Slug	146.1	8.1393	95.83
481	Copper Slug, 99.9% pure; -625 mesh	148.8	8.6057	96.05

Table V. Effect of CDC Process Parameters on Density, Microhardness and Surface Roughness of Green Samples [25, 27]

Sample ID#	Compaction Pressure (tsi)	Green Density(g/cc)	Micro Hardness (kg_f/mm^2)	Surface Roughness, µm, Average (Ra)
CDC-Cu#412	100	8.642	114.5	0.1343
CDC-Cu#413	125	8.675	104.84	
CDC-Cu#414	150	8.718	114.5	0.1695

Wrought Copper		8.9		
CDC-SS316L#415	150	7.47	203.5	0.1798
CDC-SS316L#416	150	7.57	214.16	
CDC-SS316L#417	150	7.537	211.5	0.1698
Wrought SS		~7.5-8.1		
SS316L/Cu #418	150		Cu= 111.5 ; SS=189.2	
SS316L/Cu #419	150		Cu=102.7 ; SS=219.5	
SS316L/Cu #420	150		Cu=102.7 ; SS=211.6	Cu: 0.3759; SS: 0.2177

Table VI. Mechanical & Surface Roughness Properties of Sintered SS 316L & Cu/SS 316L[25, 27]

Sample	Yield Strength, psi	UTS, psi	% Elongation	Elastic Modulus, x10^6 psi	Average Roughness, microns
520 SS 316L	31, 500	74,000	36	21.9	1.25
538 SS 316L	29, 000	77, 000	43	26.7	2.02
525 Cu/SS316L	22, 100	32, 700	9.2	23.8	

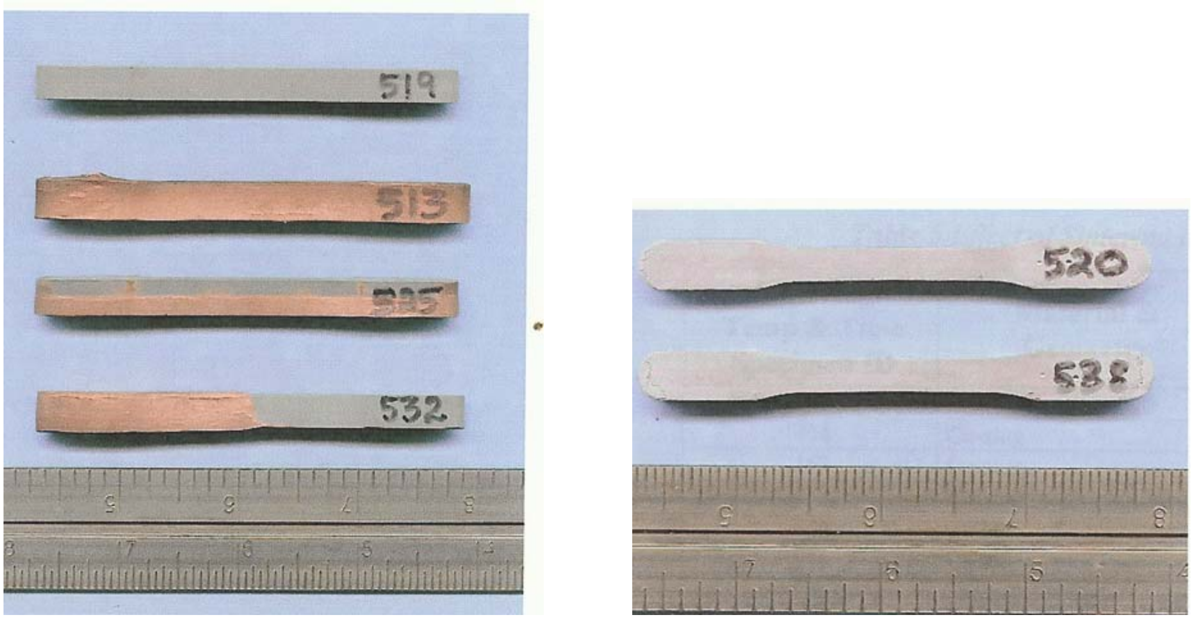


Fig. 13 Digital Images of Vacuum Sintered CDC Tensile Dogbone samples:
a) SS316L, Copper and Cu/SS316L after 1000 degC; 30 min (left); and b) Sintered SS316L; b) SS316L samples after 1200 degC; 2hrs [27]

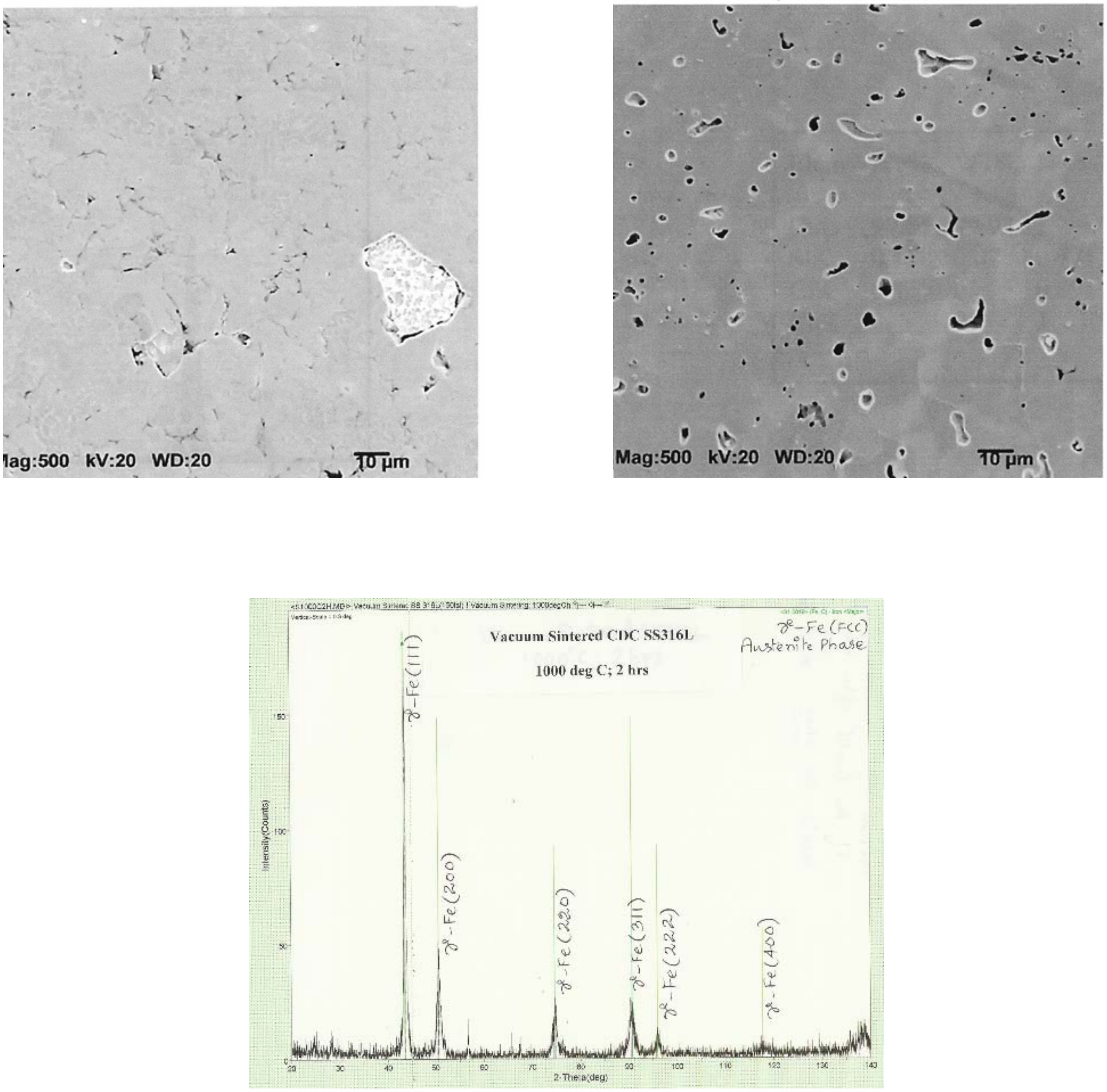


Fig. 14 Representative SEM micrographs of CDC processed a) Green SS316L (sample #468 at 121 tsi) b)Vacuum Sintered SS316L microstructures (Sample#437: 1200 degC; 2 hrs). C) X-ray Diffraction (XRD) of Vacuum Sintered SS316L (1000 degC; 2hrs) [27]

SUMMARY AND CONCLUSIONS

- CDC processing has been used successfully to fabricate dense net-shape parts of select geometries using a variety of materials such as Al-3Mg, SS316L, Copper and Cu/SS316L.
- The produced parts were found to have fine surface finish, improved mechanical properties and net shape attributes by proper control of compaction conditions and sintering optimization.

- The CDC Stainless steel samples showed higher strength and ductility under optimum sintering conditions and relatively little changes in Geometrical Dimensions such as shrinkage or expansion after sintering treatment at 1200 deg C.
- The CDC processed Al-3Mg Alloy revealed the sintered mechanical properties close to the annealed materials following controllable dimensional changes after 600 deg C sintering treatment : % Increase Range in Thickness: 1.96 to 5.2%, % Increase Range in Width: 1.25 to 4 %, and % Increase Range in Length:1.3 to 1.6%.
- Layered Stainless Steel 316L/Copper difficult-to-weld and dissimilar material combinations were successfully bonded in solid-state using CDC process with intermediate mechanical strength properties.
- Preliminary Results are encouraging and Potential applications exist for future efforts.

ACKNOWLEDGMENTS

Support for this R&D work is mostly from the Small Business Innovative Research (SBIR) project awards funded by Innovative Science and Technology Office of the Ballistic Missile Defense Organization (Presently MDA) and U.S. Department of Energy (DOE) and partly from the R&D project from Jefferson Lab.

REFERENCES

[1] I. E. Campisi & L. R. Doolittle from JLAB (Editors), *Proceedings of the Workshop on Microwave-Absorbing Materials for Accelerators*, Continuous Electron Beam Accelerator Facility (JLAB-CEBAF), Newport News, VA, Feb 22-24, 1993, pp. 1-385.

[2] I. E. Campisi (JLAB), "*Fundamental Power Couplers for Superconducting Cavities*," Research Report/Conf. Paper for the Work Supported by US DOE Contracts Nos. DE-AC05-00OR22725 & DE-AC05-84-ER40150).

[3] C. Adolphsen, J. Cornuelle, T. Lavine, H. Padamsee, and S. Tantawi, *(A Summary of the RF-Technology Working Group-T3)* , October 16, 2001. www.slac.stanford.edu/lc/wkshp/snowmass2001/t3/T3_Group_Report_Long-Version.doc).

[4] S. Tantawi (SLAC, California), *New Concepts in Coupler Structures*, HPC 2002 Workshop Presentation, JLAB, Newport News, VA, October 30-November 1, 2002.

[5] P. Kneisel, "*Development of Seamless Niobium Cavities for Accelerator Applications*", Proceedings of the 1999 Particle Accelerator Conference, NY, pp. 943-945, 1999.

[6] X. Xu, R.S. Callin, W.R. Fowkes, A. Menegat, G.P. Scheiurum, and D. H. Whittum, "*RF Breakdown Studies in X-Band Klystron Cavities*," (http://accelconf.web.cern.ch/accelconf/pac97/papers/pdf/8PO32.PDF).

[7] S. Kalpakjian, "*Competitive Aspects of Manufacturing*," in Manufacturing Engineering and Technology, Third Edition, Addison Wesley Publishing Company, 1995, pp. 1216-1243.

[8] C. G. Goetzel, *Treatise on Powder Metallurgy*, Vol. 2, 1950

[9] W. D. Callister, *Materials Sci. & Engg-An Introduction*, 1985.

[12] G. S. Upadhyaya, " *Sintered Metallic and Ceramic Materials-Preparation, Properties and Applications*," John Wiley & Sons Ltd, pp. 1-670, 2000.

[13] Aluminum Powder Metallurgy, (www.aluminum.org)

[14] Copper and Copper Alloy Powder Metallurgy Database, (www.copper.org/pm/consolidation.html)

[15] D. Kruczynski, F.D. Witherspoon and K. Nagarathnam, "*Combustion Driven Compaction (CDC) Processing of Aluminum and Metal/Ceramic Alloys for JLAB's Accelerator Applications,*" High Power Coupler (HPC 2002) Workshop Industry Participation/Presentation (Dr. Campisi- Co-Organizer) and UTRON/JLAB Project Reports on CD-Power Point Version Submitted to JLAB (Nov 27, 2002) and Fermi Lab (Dec 2002), pp. 1-50.

[16] J. E. Hatch, *Aluminum: Properties and Physical Metallurgy*, p. 209, ASM International, Materials Park, OH, 1984.

[17] M. Pastor et al., Welding Research Supplement, pp. 207-216-s, June 1999.

[18] J. J. Kruzic et al., "*Fracture and Fatigue Behavior at Elevated Temp. of Alumina Bonded with Cu/Nb/Cu Interlayers,*" J. American Ceramic Society, Vol. 85, No. 10, p. 2531-41, 2002.

[19] D. T. Palmer, M. Hill, S. Schwartzkopf, R. H. Siemann and R. Witherspoon, "*Materials Research Related to W-Band Cavity Construction,*" Proc. of 1999 Particle Accelerator Conference, NY, pp. 545-547, 1999.

[20] Conference.kek.jp/SRF2001/pdf/PT024.pdf

[21] http//accelconf.web.cern.ch/AccelConf/e02/PAPERS/THPDO029.pdf

[22] http//www-project.slac.stanford.edu/nlc/components/copper.html

[23] http://www.mpif.org/industry/spch02pub.pdf "*State-of -the-Art North American P/M Industry2002*".

[24] K. Nagarathnam, D. Kruczynski and D. Massey, " *Near Net Shape Manufacturing Using Combustion Driven Compaction,*" UTRON's DOE SBIR Phase I Project Results, Under Contract Number DE-FG02-03ER83816, (7/21/2003-4/20/2004).

[25] UTRON's *DOE SBIR Project Results*, 2002-Present.

[26] K. Nagarathnam, D. Kruczynski and D. Massey, "*Microwave Component Fabrication Using the Fast Combustion Driven Compaction Process*," DOE SBIR Phase II Project, Technical Progress Report #1 (DOE/ER83567-2), pp. 1-57, Under contract number: DE-FG02-02ER83567, February 20, 2004.

[27] D. Witherspoon, K. Nagarathnam and D. Kruczynski, "*Microwave Component Fabrication Using the Fast Combustion Driven Compaction,*" SBIR Phase I Report #DOE/ER/83567-1, Under contract Number: FG02-02ER83567, pp. 1-122, July 2003.

[28] U.S. Patent Application No. 09/902,784, "*Dynamic Consolidation of Powders Using A Pulsed Energy Source*", UTRON Inc.

[29] D.L. Kruczynski, J. M. Ryan, D.S. Trostle, F.D. Witherspoon, D.W. Massey, "*Combustion Driven Compaction,*" *Paper @ 2002 World Cong on Powder Met & Particulate Materials*, June 16-21, 2002, Orlando, Florida.

[30] ASM Specialty Handbook, *Copper and Copper Alloys*, J. R. Davis, ed., pp. 1-591, 2001.

[31] *Handbook of Accelerator Physics and Engineering,* World Scientific Publishing Company, 2nd Printing, 2002.

[32] W. F. Smith, "*Principles of Materials Science & Engg*", Ch 9, pp. 544-545, 1996.

[33] B. Ullrich, "Fabrication of Copper P/M Structural Parts," June Issue of the International Powder Metallurgy, Vol. 39, No. 4, pp. 40-46, 2003.

[34] D. Sun, T. Arkan, E. Borissov, J. Carson, D. Finley, G. Kobliska and G. Romanov, "*Microwave Quality Assurance For R&D on the Next Linear Collider at FermiLab*", Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL, pp. 1198-1200.

[35] Proceedings of LINAC 2002, Gyeongju, Korea, pp. 278-280.

[36] T. Raubenheimer, *JLC/NLC Tech Update*, Arlington Linear Collider Workshop, Arlington, TX, Jan 9, 2003.

[37] Y. Zhao, C. Ni, D. Kruczynski, X. Zhang, and J. Q. Xiao, "*Exchange-Coupled Soft Magnetic FeNi-* SiO_2 *Nanocomposite,*" US-DARPA through Air Force Research Laboratory under Grant No. F33615-01-2-2166. pp. 1-9, (Manuscript Prepared for Publication).