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CRADA Final Report for CRADA Number Y-1292-0078

MACHINING AND INSPECTION OF STRUCTURAL CERAMIC COMPONENTS

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ABSTRACT

This document is the final report of the Cooperative Research and Development Agreement (CRADA) between Lockheed Martin Energy Systems, Inc. (Energy Systems) and the Coors Ceramics Company (Coors). The purpose of this CRADA was to develop advanced technology and manufacturing practices for machining and inspecting ceramic components. Specific CRADA objectives were accomplished through the completion of six projects at four separate Coors' facilities. The projects included the development of an analytical model to simulate the mechanics of a powder rolling process, development and testing of a microwave-based system for measuring the density of conveyed ceramic material, and the development and testing of four machine vision inspection systems. This CRADA benefited the U.S. Department of Energy (DOE) activities associated with advanced heat engines, enhanced critical manufacturing skills within the DOE complex for fabricating precision, high quality workpieces from difficult-to-machine materials, and enabled U.S industry to maintain a position of leadership in the structural ceramics field.

INTRODUCTION

Lockheed Martin Energy Systems, Inc. (Energy Systems) and the Coors Ceramics Company (Coors) negotiated a Cooperative Research and Development Agreement (CRADA) to develop advanced technology and manufacturing practices for machining and inspecting ceramic components. The goal of this CRADA was to examine existing ceramic machining and inspection processes, develop the necessary interface for accessing Department of Energy (DOE) precision manufacturing technology and materials characterization expertise, and apply this dual-use technology in a mutually beneficial manner. This project was supported by the Cost-Effective Machining of Ceramics (CEMOC) Program that is jointly sponsored by the DOE offices of Defense Programs (DP), Energy Efficiency and Renewable Energy (EE), and Energy Research (ER). The CEMOC project supports DOE technical needs in manufacturing hard materials and also enables U.S. industry to maintain a position of leadership in the ceramics field.

Present ceramic component manufacturing methods are often time consuming, labor intensive and prone to introduce damage to the workpieces. Other quality limitations are imposed by the lack of in-process feedback and the overall variability of the machining and inspection processes. This CRADA addressed these manufacturing needs through specific objectives which included improving the accuracy and consistency of critical workpiece dimensions on ceramic components and increased process understanding through process modeling and analysis. The parts exhibited a range of shapes and dimensional tolerance requirements. This provided an opportunity to develop the necessary complete systems approach on simpler configurations before proceeding to the more complex product requirements associated with high-priority industrial applications.

The CRADA objectives were accomplished through the completion of six individual projects at four separate Coors' facilities. The first three CRADA projects were completed at the Coors Ceramics Company in Grand Junction, Colorado. These three projects involved developing an analytical model to simulate the mechanics of the powder rolling process, development and testing of a new microwave inspection technique to nondestructively measure the density of green state ceramic material as it is formed by the roll compaction process, and the development, installation and testing of an automated machine vision system to inspect parts for critical defects and measure part geometry. A fourth CRADA project was completed at the Golden Technologies Company (Coors subsidiary) in Golden, Colorado. This project involved the development of a fast and accurate vision system for measuring the dimensions of cylindrical ceramic blanks used to manufacture engine components. A fifth project was completed at Golden Photon, Inc., a Coors subsidiary that manufactures photovoltaic panels. This project consisted of developing a prototype vision system for the dimensional inspection of critical features that directly affect product performance. The sixth CRADA project was completed at the Coors Electronic Package Company in Chattanooga, Tennessee, a manufacturer of ceramic substrate carriers used for mounting integrated circuit electronic packages. This project consisted of developing and building a machine vision system to inspect the ceramic substrate carriers for printing defects. These six completed CRADA projects are described in further detail in the following section of this document.

In addition to the completed projects listed above, two smaller CRADA tasks were initiated. In February 1993 a task was initiated to improve the machining and inspection of semiconductor polishing plates. The machining tests were conducted at Energy Systems using a Moore diamond turning machine that was converted to a grinder. Preliminary work was also completed to develop a prototype economical inspection system. This CRADA task was terminated in March 1994 because of nonrepeatable errors in machine fixturing caused by converting the Moore diamond turning machine into a grinder. The second task, initiated in April 1993, involved developing models to simulate the processes that produce beverage valves and can tooling sets. These parts have tight tolerances and manufacturing requirements similar to those required for heat engine components such as valves, valve guides, cam roller followers, etc. The results of the simulation models, presented to Coors management in October 1993, identified critical choke points in the manufacturing processes. Energy Systems also developed coordinate measuring machine inspection programs and measurement techniques to inspect tooling products and assisted Coors in establishing their in-house measurement capability.

There appears to be commercial potential in working with Coors to extend the capabilities of the vision inspection systems. This will be pursued under a work for others agreement. No inventions were made or reported as part of this CRADA.

INDIVIDUAL CRADA PROJECTS

1. Roll-Compaction Process Modeling (Grand Junction, CO)

The Coors Ceramics Company in Grand Junction, Colorado manufactures a variety of plate-type ceramic structures such as electronic substrates. It is recognized that a key element in obtaining a cost-effective process for producing ceramic workpieces is the minimization of work performed on the parts after the sintering stage. A critical aspect in the process improvement effort is the development of a reliable process model for the entire ceramic component manufacturing operation. In October 1992, a CRADA task was initiated to develop such a process model.

Alumina substrates were chosen for the initial modeling activities because they have a relatively simple shape and the finish machining activities are limited to laser scribing and drilling. In addition, the roll compaction process has been thoroughly studied by Coors and there are a relatively small number of parameters to be characterized. The objective of this project was to develop a process model that combines information from in-process sensors with a knowledge base obtained from experienced roll press operators to generate the appropriate control signals. The goal was a control system that reduces the process variability while improving the product quality as measured by workpiece density and shrinkage. Energy Systems provided the modeling expertise and Coors preformed the operations testing required to develop, validate and optimize the model.

The development of an initial process model was completed in May 1993. Because some materials properties data required to drive the model were not readily unavailable, the model was used primarily for parametric studies to evaluate the relative influence of the various system parameters. The results of the parametric studies were used to identify the two process parameters having the most influence on the density and thickness of the ceramic part.

This CRADA project resulted in the development and testing of an analytical model that simulates the mechanics of the powder rolling process for making green ceramic tape. As accurate information on material properties becomes available, the model can be used to gain a better understanding of the roll compaction process resulting in better process control and increased product quality. A limited-distribution final technical project report has been issued to Coors.

2. Green-State Density Measurements (Grand Junction, CO)

The Coors Ceramics Company in Grand Junction, Colorado manufactures a variety of plate-type ceramic structures used in industry. The three major process steps in the manufacturing process are powder blending, roll compaction, and sintering. The dimensional control of the final product is affected by numerous variables in the manufacturing process including the density of the green-state ceramic produced by the roll compaction process. In October 1992, Energy System and Coors initiated a CRADA project to develop a microwave-based density measurement system. The initial goal of this task was to provide an accurate, automatic, in-process product density measurement system to replace the manual punch technique used by Coors in the roll-compaction operations. A longer term objective was to link the product measurements made on the green ceramic to the dimensional quality measurements collected with the Machine Vision Inspection System. This would enable the automatic monitoring and control of the critical process parameters and lead to a significant reduction in the manufacturing cost and an increase in product quality.

Preliminary tests, performed at Energy Systems, indicated that microwave transmission measurements would provide real-time product density data for the green-state ceramic fabrication process. A prototype green density measurement system was developed by Energy Systems and installed on a production line in Grand Junction in December 1993 for extensive testing. The first series of tests demonstrated that the microwave system accurately emulated the manual punch technique used by Coors. Based on these encouraging results, a second series of experiments was conducted to determine if the measured density of the green state ceramic material could be used to predict shrinkage of the sintered substrates. The results of these experiments showed that both the conventional density measurement process used by Coors and the microwave-based system provided similar results. Neither technique provided an accurate prediction of part shrinkage. This demonstrated that substrate density measurements alone do not provide sufficient information to accurately estimate the shrinkage of the final product.

Subsequent discussions between Coors and Energy System led to the conclusion that there are other parameters that complicate the relationship between green state density and fired part shrinkage. Additional efforts on the microwave density system were curtailed until a better understanding of the roll-compaction process is formulated.

This CRADA project resulted in the development and delivery of a nondestructive microwave-based density measurement system that accurately emulates the destructive punch technique currently being used. A limited-distribution final technical project report has been issued to Coors.

3. Machine Vision Inspection System (Grand Junction, CO)

The Coors Electronics Products Division in Grand Junction, Colorado produces flat ceramic substrates for commercial and defense applications. The ceramic components typically require extensive inspection operations for the detection of possible surface defects and for dimensional certification. The verification of dimensional integrity is performed on a small sampling of a product batch using traditional gauging equipment (calipers, micrometers, etc.). Characterization of surface quality, e.g., the presence of impurities, chips, blisters, pits, etc., is tediously performed visually by several inspectors using a variety of hand motions, lighting angles, and part orientations. In October 1992, Coors initiated a CRADA project with Energy Systems to develop an automated machine vision system capable of performing the necessary inspection tasks and integrate it into the production line for real-time process certification and control. Energy Systems was responsible for developing and testing the vision system component and Coors was responsible for the design, construction, and installation of an automated parts handling system.

This CRADA project involved a two-phase effort: the first, a proof-of-principle demonstration and the second, an implementation of a working system to be placed into production. A bench top prototype system was developed and demonstrated to Coors' management in April 1993. The initial prototype system was capable of detecting defects such as surface contamination but could not reliably detect other defect types. Further improvements were made in the prototype system and extensive testing on production parts demonstrated that the system was capable of surface defect detection and dimensional inspection and that the system output compared favorably with independent measurement techniques. In July 1993, Coors management decided to proceed with the second phase of the project and organized a design team to develop a specification for the automatic parts handling system.

In December 1993, the Coors design team completed a conceptual design for the automated parts handling equipment and initiated procurement of the necessary hardware. In the original design concept, a parts handling robot was designed that relied on vacuum conveyer belts to move and position the parts beneath the cameras. It soon became apparent that the materials used for fabricating conveyer belts would easily be seen behind the part and would invalidate the inspection information. A new design was proposed and implemented by Coors that utilizes a fixture to hold each part during the time that it is being imaged by the cameras.

In November 1994, the parts handling system was installed and integrated with the vision hardware and software and extensive testing was begun to evaluate the systems capability for defect detection. Early in the testing, it became apparent that "good" parts were being rejected because of dust contamination on the parts during inspection. As anticipated, the vision system could not distinguish dust particles from actual part defects such as pits and cracks. At the time of the conceptual design, it was thought that dust could easily be removed by directing an air stream across the surface of the parts. Early attempts to do this using a series of commercial air knives and fabricated manifolds equipped with air nozzles were only partially effective. In September 1995, a new parts loading system incorporating a "tacky roller" cleaning unit designed and fabricated by Coors was installed. Unfortunately, this new loader assembly failed to adequately remove dust and debris from the parts. An electrostatic method was evaluated and was also unsuccessful. A vacuum brushing technique was evaluated and appeared to remove all the dust from a part. This technique was not adopted due to its cost and the concern by Coors that dust could not be removed and kept off parts in the production floor environment.

In March 1996, increased emphasis was placed on using the machine vision system for dimensional characterization and studies were conducted to determine the system's capability to perform dimensional measurements. The results of these studies showed that the system was very repeatable at any particular inspection station but that there was a station-to-station systematic error induced by each fixture's position relative to the camera. Because of these promising results, Energy Systems and Coors worked together to install a laser structured lighting system that measures each part's position (distance) relative to the camera. Energy Systems modified the vision software to use the laser system distance measurements to dynamically correct the dimensional measurements. In August 1996, the results from a measurement capability showed that the modified system could make dimensional measurement with sufficient precision and accuracy to meet Coor's requirements.

This CRADA project resulted in the design, development, building, installation, and evaluation of a cost effective state-of-the-art machine vision system capable of inspecting flat ceramic substrates. The system is capable of making dimensional measurements with sufficient accuracy to meet industry requirements and, in the absence of dust contamination, the system is capable of measuring the various surface defects of interest. Limited-distribution final technical project reports have been issued to Coors.

4. Ceramic Blank Measuring System (Golden, CO)

Manufacturing costs of ceramic engine components can be reduced by minimizing the need to remove grind stock to achieve design dimensions. In order to implement process improvements to achieve near net shape forming of ceramic blanks, a fast and accurate dimensional inspection technique is required. In September of 1994, Coor's Golden Technology Company (GTC) decided to investigate the feasibility of using a machine vision inspection gage to characterize cylindrical ceramic blanks as part of their Advanced Ceramic Manufacturing Technology (ACMT) project. In December 1994, Energy Systems and GTC initiated a CRADA project to develop a prototype machine vision measurement system utilizing off-the-shelf computer vision hardware with vision software developed by Energy Systems. The project was referred to as the Ceramic Blank Measuring System (CBMS).

At times, the manufacturing process used by GTC's high volume product line to manufacture injector plungers from zirconium oxide created a green material with out-of-roundness conditions that could not be removed during final shaping procedures. Economical on-line inspection techniques to cull bad product before final shaping was desired to avoid wasted effort and costs. Manual human inspection in the high volume lines was cost prohibitive.

The goal of this CRADA project was to develop an automated machine vision measuring system capable of determining dimensional attributes of injector blanks for in-process control and quality assurance. A potential follow-on to the initial effort was the measurement of other features such as surface quality and edge chips. This project supported both Coors and DOE needs for process monitoring systems for improved manufacturing process control. Energy

Systems responsibilities included the vision system engineering and software development while GTC was responsible for designing and installing a part handling system and conducting engineering and production metrology studies.

The initial version of the machine vision inspection software was developed and successfully installed on the prototype gage at GTC during March 1995 and improved versions were installed in May and August. The initial prototype CBMS provided a straightness measurement of the ceramic blank with manual part handling. Later versions of the CBMS provided automated part handling, measurement of part diameter and the capability to store the inspection results in a data base.

Measurement capability studies were performed to demonstrate that the accuracy and precision of the CBMS were sufficient to meet GTC's needs. The CBMS was used successfully by GTC to characterize ceramic blanks in various process improvement experiments before the ACMT project was closed out in December 1995.

This CRADA project resulted in the development and testing of a fast, accurate, cost-effective, machine-vision-based inspection gage used to dimensionally characterize cylindrical ceramic parts. A limited-distribution final technical project report has been issued to Coors.

5. Photovoltaic Array Measurement System (Golden, CO)

Golden Photon, Inc. (GPI), a subsidiary of Coors, is a manufacturer of thin-film photovoltaic panels and has been developing the process to increase the efficiency, reproducibility and yield of the product. The photovoltaic module has a series of interconnected strips that are created through a sequence of material removal and resist application steps. The dimensional location and width of the interconnection features directly affect the final product quality. Because the use of a commercially available vision inspection system at each process step was cost prohibitive, GPI initiated a CRADA agreement with Energy Systems to develop a cost-effective prototype system that would offer just off-line inspection of the interconnections during manufacturing. This CRADA project was referred to as the photovoltaic array measuring system (PAMS) and was initiated in December 1995.

Because Energy Systems had successfully applied off-the-shelf PC-computer vision hardware and software to other inspection tasks, it was decided to use this approach in developing the prototype inspection system. In addition to system cost, another equally important objective was to develop a system with sufficient measurement precision and accuracy.

The PAMS software was developed using Visual Basic and commercially available image processing software libraries. The hardware included of a Pentium based PC, a line scan camera, fiber optic lighting, and a precision computer controlled transport system.

A prototype system was completed and tested at Energy Systems in August 1996. The total time to inspect a single scan across the panel width including the 58 interconnections was approximately 40 seconds which meets GPI's requirements. Tests conducted to evaluate the measurement capability of the system demonstrated that PAMS meets or exceeds the design goals. While time constraints prevented the testing of PAMS at GPI, results of the Energy System tests demonstrated that the system can provide the desired speed and measurement capability. Additional software functionality will need to be completed in order to achieve the goal of a just-off-line inspection system and GPI intends to work with Energy Systems through a work for others agreement to achieve this goal.

This CRADA project resulted in the development of a fast, accurate, and cost effective machine vision based system for dimensional inspection of features that directly affect final part quality. A limited-distribution final technical project report has been issued to Coors.

6. Machine Vision Inspection System (Chattanooga, TN)

The Coors Electronic Package Company (CEPC), in Chattanooga, Tennessee, produces ceramic substrate carriers for the mounting of customer-supplied, integrated circuit, electronic packages. Circuits are printed on green tape with a tungsten alloy. Printing defects introduced early in the manufacturing process are currently detected in the finished part after a substantial cost has been incurred. Defect detection in the printed green tape at an early stage in the process would produce significant cost savings and provide insight into defect origin. Defective parts would be removed from further processing and the defect generating process would be corrected. In April 1995, Energy Systems and CEPC initiated a CRADA project to design, develop, build, and install two prototype machine vision inspection systems, one to be positioned after the tungsten printer and the other to be positioned after the dielectric printer.
Energy Systems was responsible for overall system design, software development and testing, and Coors was responsible for procuring and fabricating the mechanical components.

This CRADA project involved a two-phase effort: the first, a proof-of-principle demonstration and the second, an implementation of a working system to be placed into production. A prototype system was developed and successfully demonstrated to Coors in October 1995. Based on the success of the prototype system, Coors decided to proceed with developing a single 2-mil per pixel system capable of running the necessary software of both inspection stations (tungsten and dielectric printing). The 2-mil per pixel resolution system could be upgraded to a 1-mil per pixel system should that later prove to be necessary.

A study of printed parts was performed to determine the sensitivity of the 2-mil per pixel system to voids. The results showed that the system could reasonably be expected to detect, but not classify, 2 mil white printing voids. Coors considered this capability to be sufficient and began acquisition of system components in the spring of 1996.

While some delays were encountered both in the receiving of materials and the fabrication of the parts handling robot, the system was delivered to Energy Systems in July 1996 for system integration. The completed system was returned to Coors in September 1996 for installation into the production line.

This CRADA project resulted in the development of a cost-effective, state-of-the-art, machine vision based system for detecting printing defects on ceramic substrate carriers used for mounting integrated circuit electronic packages. Limited-distribution final technical project reports have been issued to Coors.

CONCLUSIONS

The purpose of this CRADA between Lockheed Martin Energy Systems and the Coors Ceramics Company was to develop advanced technology and manufacturing practices for machining and inspecting ceramic components. Specific objectives included improving the accuracy and consistency of critical workpiece dimensions and increased process understanding through process modeling and analysis.. These objectives were accomplished through the completion of six major projects at four separate Coors' facilities. The projects involved the development of an analytical model to simulate the mechanics of a powder rolling process, development and testing of a microwave based system for measuring the density of conveyed ceramic material, and the development and testing of four state-of-the-art machine vision systems. Based on the work performed during this CRADA, Coors management has indicated a desire to continue funding Energy Systems to complete the machine vision work at two of their facilities. This CRADA benefited the U.S. Department of Energy (DOE) activities associated with advanced heat engines, enhanced critical manufacturing skills within the DOE complex for fabricating precision, high quality workpieces and enabled U.S industry to maintain a position of leadership in the structural ceramics field.

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