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LLNL-TR-738380

Laser Materials Processing Final Report CRADA No. TC-1526-98

J. Crane, C. J. Lehane

September 12, 2017

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Laser Materials Processing

Final Report
CRADA No. TC-1526-98
Date Technical Work Ended: December 31, 2003

Date: February 21, 2007 Revision: 6

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and United Technologies Corporation (UTC).

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B. Project Scope

This CRADA project was a joint effort between Lawrence Livermore National Laboratory (LLNL) and United Technologies Corporation (UTC)/Pratt & Whitney (P&W) to demonstrate process capability for drilling holes in turbine airfoils using LLNL-developed femtosecond laser machining technology. The basis for this development was the ability of femtosecond lasers to drill precision holes in variety of materials with little or no collateral damage. The ultimate objective was to develop a laser machine tool consisting of an extremely advanced femtosecond laser subsystem to be developed by LLNL on a best-effort basis and a drilling station for turbine blades and vanes to be developed by P&W. In addition, P&W was responsible for commercializing the system. The goal of the so called Advanced Laser Drilling (ALD) system was to drill specified complex hole-shapes in turbine blades and vanes with a high degree precision and repeatability and simultaneously capable of very high speed processing.

Accomplishing these goals required two major inventions: (1) a high average power (50 W), high precision, femtosecond laser system with performance significantly beyond the current state-of-art, and (2) the prescription for quickly and reliably drilling highly shaped precision

0.014” diameter holes with minimal heating of the part. In addition, the cost, complexity, reliability and maintainability of the laser machine needed to be commensurate with future industrial applications. At the start of the CRADA, femtosecond lasers were limited to 5-10 W, and were extremely large and complex. Developing a 5-10x higher power, more compact and simple system required significant technology innovation and invention. Also, at that time, all femtosecond material processing was limited to low speeds using 5-10 W lasers. Developing and demonstrating a high-speed process for precision shaped holes required a robust 50 W laser, which did not exist at that time. The success of this project required two major technology advances to occur simultaneously.

This CRADA originally started out as a nine-month project in 1997. There were two amendments to the original statement of work that expanded the scope of the project and extended the expiration date for an additional three years. Five no-cost time extensions were also executed, extending the final expiration date of this project to March 31, 2004. During the course of the CRADA, the project evolved based on LLNL performance and changes in the LLNL technical personnel. In particular, in June 2000 the original PI left LLNL with most of the key project personnel. Given the commitment by LLNL management, a decision by P&W was made to continue the CRADA.

The project consisted of following major phases: (1) material process research and development, (2) high average power femtosecond laser technology research and development, (3) prototype ALD system build and high speed drill demo, and (4) commercialize the ALD system.

Phase 1 - Process Research and Development

The primary goals of this phase were: (1) demonstrate drilling of shaped precision 0.014” diameter holes with a femtosecond laser, with no collateral damage (melting) to the material, and with a high degree of repeatability, (2) demonstrate scalability to shorter drilling times (< sec) with future higher average power laser systems, (3) develop requirements and specifications of the advanced laser subsystem, and (4) develop the requirements and specifications of a drilling station subsystem.

Two existing Ti:Sapphire lasers capable of producing 1-2 Watt average power, 10-20 mJ pulse energy, 100 Hz pulse repetition frequency (PRF), and 0.1-5 picosecond pulse, and a 5-6 Watt average power, 1 mJ pulse energy, 1000 Hz, and 0.1-5 picosecond pulse were utilized. P&W and LLNL worked together to successfully demonstrate that femtosecond lasers could drill shaped 0.014” diameter holes with the required precision and repeatability. Based on this work the high level requirements for the advanced laser to be developed by LLNL were: 50 Watts average power 10 mJ pulse energy, 5 kHz, and a 2 picosecond pulse length. P&W was responsible for designing and building a drilling station capable of securing and moving turbine blades in a vacuum chamber.

Phase 2 - High Average Power Femtosecond Laser Technology Research and Development

The goal of this phase was to develop and invent advanced laser technologies required for a 50 W femtosecond laser. Instead of scaling existing (<10 W) laser technologies to 50 W, P&W found it desirable to develop new patentable technologies. It was also thought that the size, complexity and cost of ownership of existing systems scaled to 50 W might not meet ultimate industrial requirements. The baseline design was a compact but risky system employing a high average power regenerative amplifier, instead of a more conservative larger multi-stage amplifier.

Beginning in 1998 until late 2000 research and development on a variety of laser technologies occurred, which included: (1) new femtosecond laser amplifiers, (2) new mode locked femtosecond oscillator, (3) new high efficiency dielectric gratings, and (4) ultra thin glass phase plates to spatially format the beam at focus. In early 2000, many of the various options had been tested and a baseline design for the ALD system had been completed.

Due to many technical problems associated with the original baseline concept, the design significantly evolved and resulted in a much larger and more complex optical system. However, many of the new or advanced technologies that were required for the laser system were successfully developed. These included high efficiency dielectric gratings, transmission phase plates, and hollow lens duct diode pumped amplifiers. Several of these technologies are currently benefiting the National Ignition Facility Project.

Phase 3 - Prototype ALD System Build and High Speed Drill Demo
The goals of this phase of the project were: (1) build a 50 W femtosecond laser meeting requirements defined in Phase 1, using components invented and developed in Phase 2, (2) use the 50 W laser with LLNL's small drill station to demonstrate drill speed, quality and precision, using test coupons, (3) integrate the 50 W laser with P&W supplied drilling station, and (4) demonstrate high speed, precision drilling with turbine engine blades.

Beginning in October 2000, the build of the ALD laser began and in January 2001, the laser produced 50 W average power, 10 mJ pulse energy, 5 kHz PRF, and 2 picosecond pulse length, meeting laser requirements of average power defined in Phase 1. This performance represented a world record in high average power for a short pulse system. In January and March 2001, drilling experiments at 50 W were initiated and produced unacceptable drill results. The primary root cause was determined to be the very poor beam quality at this high power. The laser was reconfigured to improve performance and in March 2002, the reconfigured laser produced 35 W average power, 7 mJ energy 5 kHz PRF, 2 picosecond pulse width, with excellent pointing stability, near diffraction limited ($M^2 < 1.5$) beam, and an improved beam shape at drill site. This greatly surpassed the precision performance of the previous 50 W laser.

Drilling experiments with the improved system were initiated and it was determined through process experiments that 20-25 W was the maximum power at 5 kHz to produce shaped holes that had reasonable quality. In June 2002, the ALD laser successfully demonstrated short pulse laser drilling of shaped holes. The uniformity and metallurgy of the test holes met Pratt & Whitney's quality requirements, but drill times were too long. However, this was a major milestone demonstrating high average power short pulse material processing with this unique laser system.

Phase 4 - Commercialize the ALD System and Activate at P&W
During this phase P&W was responsible for commercializing the ALD system with LLNL assistance, and LLNL would assist P&W in activating the system at P&W. Between September 2002 and June 2003, P&W concentrated on commercialization of the system and attracting investment partners both within the government and private sectors.

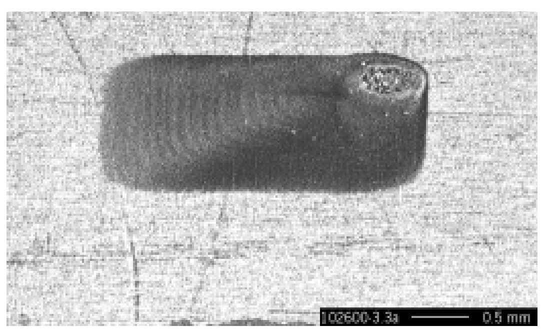
Due to external events and business decisions, LLNL was funded at a lower level to cover primarily space charges and manpower to support P&Ws commercialization efforts to various government and private agencies. In September 2003, the ALD system was shipped to P&W.

C. Technical Accomplishments

The following major project technical milestones were accomplished:
- Demonstrated feasibility of drilling holes using 1-2 W laser.
- Defined high average power requirements
- Demonstrated world's highest average power femtosecond laser at 50 W.
- First utilization of direct diode pumped Yb:YAG for femtosecond lasers.
- Invented and demonstrated novel high average power multi-layer dielectric gratings.
- Invented and demonstrated novel single grating stretcher and compressor architecture.
- Demonstrated ultra-thin phase plates for formatting the beam on target.
- Demonstrated ultra-high precision 35 W femtosecond laser.
- Demonstrated high speed drilling at 5 kHz PRF meeting P&Ws uniformity and metrology requirements.

Phase 1 - Process Research and Development
All of the goals outlined in section B were successfully met using an existing 1-2 W, 100 Hz Ti:Sapphire laser. Metrology and airflow experiments performed by P&W demonstrated that femtosecond lasers could drill precision holes with repeatability.

Shaped hole produced by a
1 W, 10-12 mJ, 100 Hz,
Ti:Sapphire laser



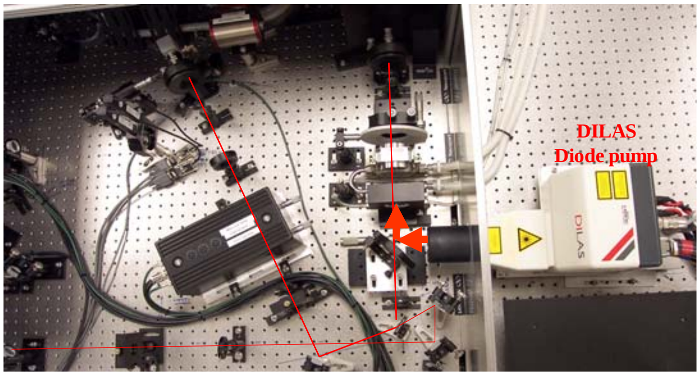
Another major goal of this phase was to define the requirements for the research laser. Based on this work the requirements of the ALD laser were 50 W average power, 10 mJ pulse energy, 5 kHz PRF and 2 ps pulse length. However, it was later shown that the 1 W laser was not capable of investigating or establishing the precision laser requirements that seriously affected the ability of drilling precision holes using the envisioned 50 W laser and it was later proven that these precision requirements were much more stringent for a 50 W system than a 1 W system. Specifically, an important requirement found to affect drill precision and collateral damage (melt) was beam pointing stability. The requirement affecting the quality and shape of drilled holes was the spatial beam profile at focus and temporal pre and post pulse.

Phase 2 - High Average Power Femtosecond Laser Technology Research and Development
Beginning in 1998 until mid 2000 research and development on a variety of laser technologies occurred. Several new technologies needed to be developed or invented:

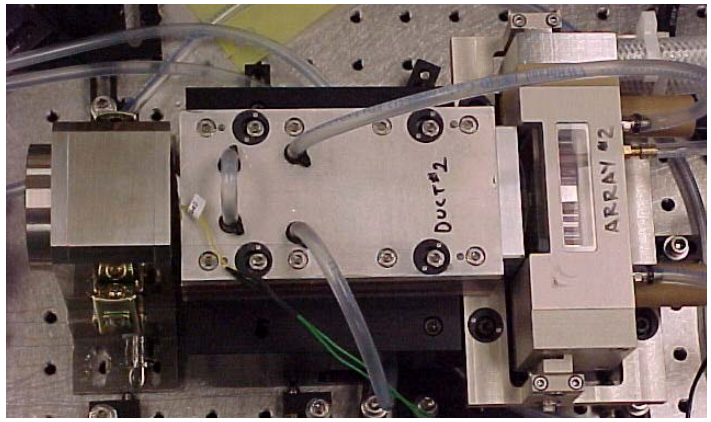
1. A single stage 50 W regenerative amplifier was the baseline design. This architecture required a high average Pockels cell q-switch. However, it was found that commercially available q-switches were limited to 5-10 W average power. The baseline design evolved to a low energy regenerative amplifier (0.5-1 mJ) output followed by a two-pass amplifier using two gain amplifiers.

   New laser amplifier materials were developed and tested to replace Ti:Sapphire. Ytterbium doped YAG (Yb:YAG) was chosen as the laser material. It was readily available, had sufficient bandwidth to support 2 picosecend length pulses, and could be pumped directly by laser diode arrays. Hollow lens ducts were used to focus the diode light into a Yb:YAG rod. A small amount of research explored the use of an OPCPA amplifier. Here a laser pumps a non-linear crystal, which in turn produces parametric gain and amplifies the chirped pulse. There are many advantages of this architecture, however, it was not sufficiently developed by 2000 and research was terminated in mid 2000.

Regen amplifier using commercial diode pump source.

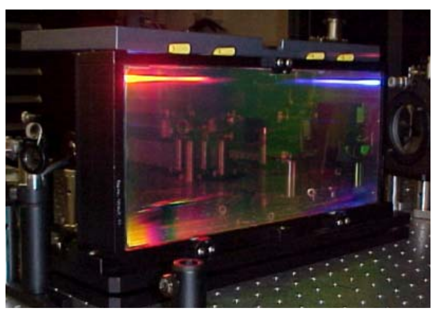


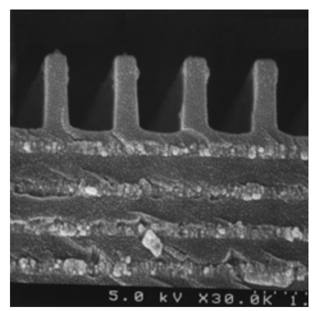
LNL developed hollow lens duct rod amplifier. Two amplifier heads are employed in the 2-pass amplifier.



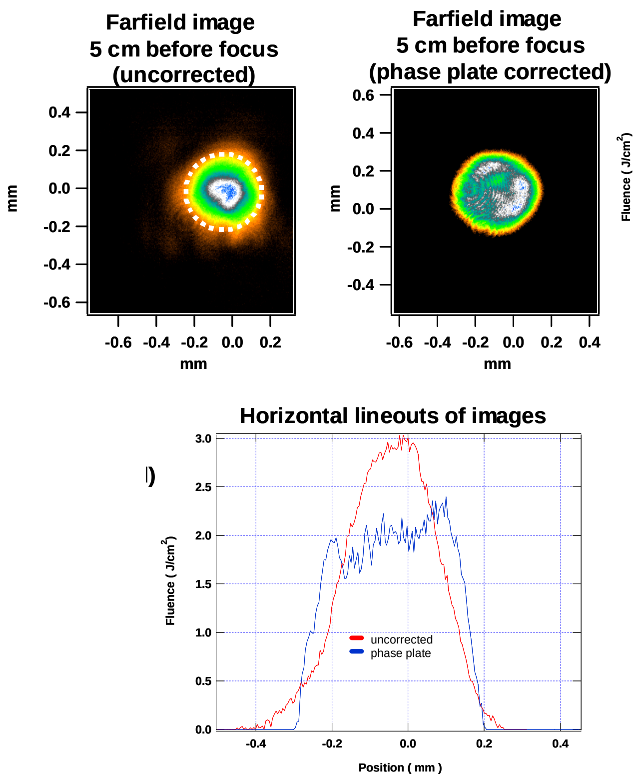
2. A mode locked oscillator operating at the Yb:YAG laser line of 1047 nm needed to be developed. LLNL turned to a commercial fiber laser manufacturer (IMRA) to develop a new fiber based mode locked oscillator. IMRA successfully deliver the oscillator in early 2000.
3. A high efficiency, average power, dielectric grating of sufficient size needed to be invented. Conventional gold gratings absorbed sufficient energy to make them impractical. LLNL invented, patented and successfully demonstrated high efficiency multi layer gratings.

20 cm multi-layer grating invented for the ALD laser and photo of grating structure





4. A novel design of a stretcher and compressor was invented and tested that uses a one common grating for both stretcher and compressor instead of a more conventional architecture that uses two or four separate gratings for the stretcher and compressor. The goal here was to save space and cost.
5. A process for etch phase patterns on ultra-thin (500 micron) glass was invented. A phase plate was developed to optimize the irradiance pattern at focus. Ultra-thin glass was required minimize B-integral self focusing. A new Margoni wet-etch machine was developed to remove glass material to produce the phase plates.



Uncorrected and phase plate modified beam profiles. Note energy in low irradiance wing of uncorrected beam causes melting.

Phase 3 - Prototype ALD System Build and High Speed Drill Demo

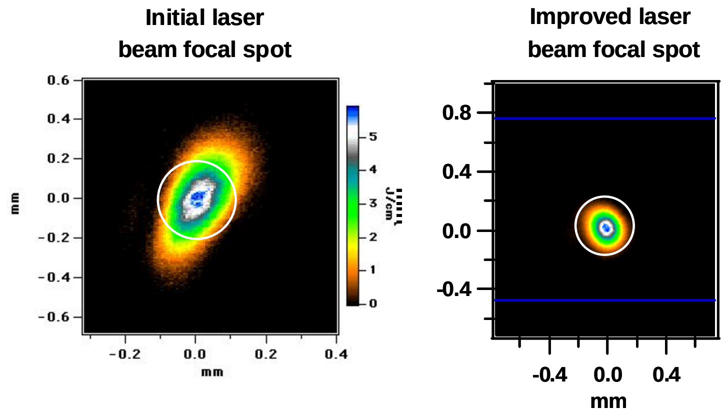
In January 2001, the laser produced 50 W average power, 10 mJ pulse energy, 5 kHz PRF, and 2 picosecond pulse length, meeting average power requirements defined in Phase 1. At this time the ALD laser was the highest average power short pulse laser in the world. In March 2001, drilling experiments at 50 W were initiated and produced very poor drill results. At this time it was determined additional ultra-high precision laser requirements were also need to be met, which were not originally well understood or defined at completion of Phase 1.

The primary issue was energy contained in the spatial and temporal portions of the beam and pulse having irradiances below the ablation threshold (10^{11}-10^{12} W/cm^2) were absorbed as heat. It was found that with a 50 W laser the energy absorbed as heat did not have sufficient time to diffuse away from the drill site, which leads to unacceptable material melting. Therefore the precision requirements (amount of energy in the pre- and post-pulse, energy in spatial wings of the beam and energy deposited to beam jitter) are much more stringent for a 50 W laser compared to the 1 W laser originally employed to define laser requirements.

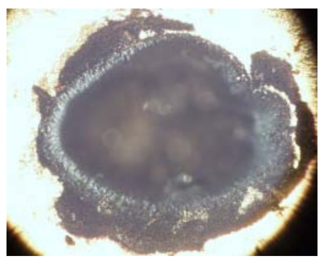
P&W and LLNL significantly modified the project plan and agreed on a one year effort to improve precision performance of the laser. Over the next year the laser was incrementally improved and the design was further modified significantly.

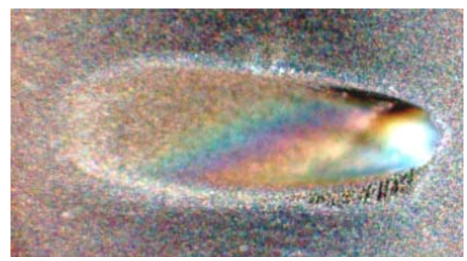
In March 2002, the reconfigured laser produced 35 W average power, 7 mJ energy, 5 kHz PRF, 2 picosecond pulse width, with excellent pointing stability, near diffraction limited ($M^2 < 1.5$) beam, and an optimized beam shape at drill site. This greatly surpassed the precision performance of the previous 50 W laser.

Beam spatial profile at focus before and after improvements.



Drill examples before (left) and after (right) laser improvements. Note in left photo melted material.



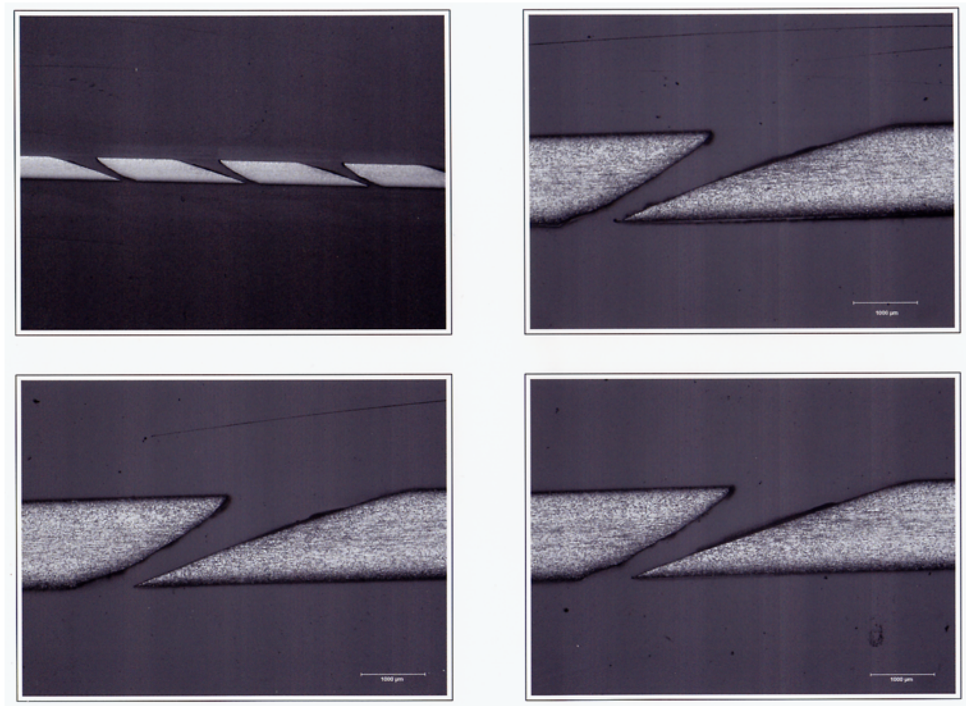


Drilling experiments with the improved system were initiated and it was determined through process experiments that 20-25 W was the maximum power at 5 kHz PRF to produce shaped holes with acceptable part heating. Drilling at higher average powers would require increasing the PRF. Since the laser was limited by the regenerative amplifier's Pockels cell switch rate of 5 kHz, higher average power would require additional laser reconfiguration.

In June 2002, the ALD laser successfully demonstrated short pulse laser drilling of shaped holes, however the drill times were not able to be reduced sufficiently to meet the business case requirements. The uniformity and metallurgy of the test holes met Pratt & Whitney's requirements. This was a major milestone demonstrating high average power short pulse material processing with this unique laser system. Between June and September 2002, high-speed drill experiments at 25 W focused on developing a prescription for drilling precision shaped holes meeting P&W specifications and significant progress was being made.

Cross section Of P&W shaped hole

Multiple shaped holes demonstrating repeatability



ALD system enclosure and coupon drill station.

During this phase P&W also designed, built and delivered to LLNL a large drill station for drilling turbine engine blades. Drilling experiments so far were limited to small test coupons and employed a small drill station. Due to additional investments needed to address the slow drill times and external business factors, in September 2002, P&W decided to terminate any future laser developments, integration of the P&W drill station with the laser, and further process development and concentrate on commercialization and attracting outside business partners.

Phase 4 - Commercialize the ALD System and Activate at P&W
During this phase P&W would be responsible for commercializing the ALD system and LLNL would assist P&W in activating the system at P&W. Between September 2002 and June 2003, P&W concentrated on commercialization of the system and attracting investment partners. Since the size, complexity and cost of the system had increased substantially over that originally envisioned due to technology hurdles and changing laser requirements needed to meet drill requirements, the ALD laser was no longer attractive to OEM laser manufacturers. In addition, the current system was limited to 25 W instead of the original 50 W, increasing the drill time to an unacceptable amount. The ALD system was dismantled in August 2003 and shipped back to P&W.

D. Expected Economic Impact

At the beginning of this project the estimated savings associated with the elimination of EDM produced holes is approximately $4M per year. Replacement of conventional laser processing with the femtosecond Laser could have provided additional savings of up to $1.5 M per year from increased part throughput, $300,000 per year from rework reductions, $500,000 per year from reductions in scrap and $200,000 per year in reduced inspection cost. Additional savings would have been realized at the overhaul and repair depots as airfoils will have a longer life through improved film cooling and greater reliability. This would have reduced the number of inspection cycles and replacement cost associated with these airfoils. However, the size, complexity, potential cost and lack of overall performance has greatly diminished the potential of the actual ALD system. Given the inability to drill at the needed speeds the potential for economic impact is significantly reduced, but has not been studied.

D.1 Specific Benefits

Benefits to DOE Program:

The following three technologies developed as part of this CRADA potentially benefit DOE Programs:

High Efficiency Multi Layer Dielectric Gratings
High efficiency multi layer dielectric gratings that operate at high damage fluence are required for high-energy short pulse lasers of relevance to stockpile stewardship's high energy density physics experiments. High-energy short pulse lasers are being proposed at several DOE supported facilities, including Rochester, NIF, and Los Alamos. A NIF beamline could produce ~ 5 kJ pulse energy in beams formatted to be compressed to short pulses. A compressor system employing conventional gold gratings would require gratings having several square meters of area. In addition, the beam size would need to be greatly enlarged, which would be difficult to achieve on NIF for multiple beams in a quad. Full utilization of NIFs energy potential for short pulses requires compressor gratings that are efficient and operate and fluences 5-6 times higher than conventional gold gratings. Dielectric gratings invented and demonstrated under this CRADA are a key enabling technology to permit high energy short pulse laser operation on NIF and at other facilities benefiting stockpile stewardship and other high energy density physics programs of interest to DOE.

Ultra Thin Glass Figuring
This CRADA was the first demonstration of formatting short pulse beams at focus utilizing ultra-thin glass phase plates. A novel wet etch technique developed by other LLNL projects was used to modify the optical path length of 500 micron sheets of glass to correct phase errors of the ALD laser and modify the phase of the beam to produce a more flat-top beam at focus. This was a key technology break through that permitted processing at average powers > 10 W. Ultra thin glass is required to format the compressed short pulse beam so as not to introduce B-integral self-focusing on the beam. This technology would be required (1) for future high average power material processing to eliminate heat and part melting and (2) to potentially format a high energy short pulse beam to produce a required focal spot size on target used on NIF or other DOE high energy short pulse facilities.

High Average Power Ultra Precision Material Processing
The 35 W ultra precision laser invented and demonstrated under this CRADA has significantly higher potential process throughput compared to other short pulse laser processing systems. For example, the Oak Ridge Y-12 Plant ordered and was delivered a 10 watt Femtosecond Laser Cutting System from LLNL. This system will was developed for disarmament and refurbishment of nuclear warheads (Stockpile Modernization). The same laser and control technology developed by this CRADA would increase the process speed by 3-4x and permit more precision processing. This technology will open up new opportunities for applying laser-matter interactions. Since this laser transmits no heat into the bulk material, thus eliminating the potential for ignition of energetic materials, it is ideally suited to arms disassembly / de-militarization applications. The order of magnitude increase in average power performance addresses previous roadblocks, which centered on throughput.

Benefits to Industry

The benefits to industry are currently unclear because the CRADA did not produce a final "production" laser.

E. Partner Contribution

Pratt and Whitney, the industrial partner, provide several key contributions to this CRADA. They provided the funding for the project totaling ~ $14.5 M. Their understanding of industrial processing provided the necessary basis to define the size, complexity, robustness and cost goals for the system. P&W provided key technical personnel to help develop and refine the process development. In addition, they performed metrology and flow tests of test coupons. P&W were responsible for the design and build of the large scale drilling station capable of processing turbine engine blades. They successfully built and delivered the system to LLNL. Finally, P&W was responsible for commercializing the ALD system. There were no subject inventions created solely by P&W during this CRADA.

F. Documents/Reference List

Reports
Technical reports that were sent to P&W included: technical progress, schedule status, and later in the project detailed accounting.

Copyright Activity

None

Subject Inventions

Joint Subject Inventions:

IL-11071A – Patent pending

IL-10747A – Patent pending

LLNL Sole Subject Inventions:

U.S. Patent No. 6,784,400 (LLNL Docket IL-10744A) – *Method of Short Pulse Hole Drilling without a Resultant Pilot Hole and Consequent Backwell Damage*; issued 08/31/04; Inventors: Paul S. Banks, Brent C. Stuart, Michael D. Perry

IL-10746A – Patent application to be filed

IL-10748A – Patent application to be filed

U.S. Patent No. 6,717,104 (LLNL Docket IL-10776A) – *A Programmable Phase Plate for Tool Modification in Laser Machining Applications*; issued: 4/6/04; Inventors: Charles A. Thompson Jr., Michael W. Kartz, James M. Brase, Deanna Pennington, Michael D. Perry

U.S. Patent No. 6,739,728 (LLNL Docket IL-10811A) – *Short Pulse Laser Stretcher-Compressor Using a Single Common Reflecting Grating;* issued 5/25/04; Inventors: Gaylen V. Erbert, Subrat Biswal, Brent C. Stuart, Joseph M. Bartolick, Steven Talford

U.S. Patent No. 6,760,356 (LLNL Docket IL-10812A) – *Application of Yb:YAG Short Pulse Laser System;* Issued: 07/06/04; Inventors: Gaylen V. Erbert, Subrat Biswal, Joseph M. Bartolick, Brent C. Stuart, Steve Telford, John Crane, Michael D. Perry

IL-10813A – Patent application to be filed

IL-10914A – Patent application to be filed

Background Intellectual Property

LLNL disclosed the following Background Intellectual Property at the commencement of the CRADA project:

U.S. Patent No. 5,907,436 (LLNL Docket IL-9566A) – *Multilayer Dielectric Diffraction Grating;* Issued: 05/25/99; Inventors: Michael D. Perry, Jerald A. Britten, Hoang T. Nguyen, Robert Boyd, Bruce W. Shore

IL-9566B – Patent application not pursued

U.S. Patent No. 5,720,894 (LLNL Docket IL-9775A) – *Ultrashort-pulse Laser for Materials Processing;* issued: 02/24/98; Inventors: Joseph Neev, Luiz B. Da Silva, Dennis L. Matthews, Michael E. Glinsky, Brent C. Stuart, Michael D. Perry, Michael D. Feit, Alexander M. Rubenchik

U.S. Patent No. 5,960,016 (LLNL Docket IL-9983A) – *Aberration-Free, All Reflective Laser Pulse Stretcher*; issued: 09/28/99; Inventors: Michael D. Perry, Paul S. Banks, Brent C. Stuart

U.S. Patent No. 6,621,040 (LLNL Docket IL-10126A) – *Ultrashort-Pulse Laser Machining of Metals and Alloys*; issued: 09/16/03; Inventors: Michael D. Perry, Brent C. Stuart

IL-10129 – Patent pending

U.S. Patent No. 6,150,630 (LLNL Docket IL-10179A) – *Laser Machining Of High Explosives*; issued: 11/21/00; Inventors: Michael D. Perry, Brent C. Stuart, Paul S. Banks, Booth R. Myers, Joseph A. Sefcik

U.S. Patent No. 6,268,586 (LLNL Docket IL-10244A) – *Method and Apparatus for Improving the Quality and Efficiency of Ultrashort-Pulse Laser Machining*; issued: 07/31/01; Inventors: Brent C. Stuart, Hoang T. Nguyen, Michael D. Perry

The above Background Intellectual Property, with the exception of IL-10129, was licensed to United Technologies Corporation, acting through its Pratt & Whitney division, under LLNL License Agreement No. TL-1586-99, executed on July 29, 1999.

The following Background Intellectual Property was disclosed by LLNL during the course of the CRADA and may be added to the License Agreement No. TL-1586-99 by written amendment at the request of UTC/P&W.

U.S. Patent Application No. 09/651,658 (LLNL Docket IL-10571A) – *Tapered Laser Rods as a Means of Minimizing the Path Length of Trapped Barrel Mode Rays;* issued: 08/20/05; Inventors: Raymond J. Beach, Eric C. Honea, Stephan A. Payne, Ian Mercer, Michael D. Perry

U.S. Patent No. 6,160,934 (LLNL Docket IL-10273A) – *Hollow Lensing Duct*; issued: 12/12/00; Inventors: Raymond J. Beach, Eric C. Honea, Camille Bibeau, Scott Mitchell, John Lang, Dennis Maderas, Joel Speth, Stephen A. Payne

UTC/P&W disclosed significant background intellectual property for this project, which included turbine engine material characterization data, turbine engine component hole drilling design criteria and requirements, turbine engine cooling configuration and requirements, etc.*****
Please see Section E (Partner Contribution) for more information.

*****The BIP disclosed by UTC/P&W is Proprietary Information.

G. Acknowledgement

Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.
2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures generated by his/her respective company and attributable to the project have been disclosed and included in Section E or are included on a list attached to this report.
4) The Participant certifies that if tangible personal property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

Christopher J. Lehane — Date
United Technologies Corporation

Scott Davis, Contracts — Date
United Technologies Corporation

[signature] 6-13-2007
John Crane, LLNL Principal Investigator — Date
Lawrence Livermore National Laboratory

[signature] 6/13/07
Karena D. McKinley, IPAC Director — Date
Lawrence Livermore National Laboratory

Attachment I – Final Abstract

Industrial Partnerships and Commercialization

Mail Station L-795

Ext. 2-6416

Fax 3-8988

June 13, 2007
45207.06ljs

MEMORANDUM

To: Memo to File

From: Lori Straley

Subject: United Technologies Corp. / Pratt & Whitney Division
CRADA Final Report – TC-1526-98

In accordance with DOE procedures, the CRADA Final Report for TC-1526-98, United Technologies, Inc. (UTC), has been submitted for review and signature without the partner's signature.

Beginning April 2005, IPAC/LLNL made numerous and extensive attempts to obtain concurrence and signatures of UTC's PI and Contracts contacts. After a number of exchanges and revisions to the final report, we received an email in April 2007 from the partner indicating the final report was acceptable. They have not, however, returned a signed copy. After attempting to obtain a signature for two months after this acknowledgement, the partner was informed we are planning to proceed with the report submission without their signature.

Laser Materials Processing

Final Abstract (Attachment I)
CRADA No. TC-1526-98
Date Technical Work Ended: December 31, 2003

Date: February 21, 2007 Revision: 3

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and United Technologies Corporation (UTC).

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B. Purpose and Description

This CRADA project was a joint effort between Lawrence Livermore National Laboratory (LLNL) and United Technologies Corporation (UTC)/Pratt & Whitney (P&W) to demonstrate process capability for drilling holes in turbine airfoils using LLNL-developed femtosecond laser machining technology. The basis for this development was the ability of femtosecond lasers to drill precision holes in variety of materials with little or no collateral damage. The ultimate objective was to develop a laser machine tool consisting of an extremely advanced femtosecond laser subsystem to be developed by LLNL on a best-effort basis and a drilling station for turbine blades and vanes to be developed by P&W. In addition, P&W was responsible for commercializing the system. The goal of the so called Advanced Laser Drilling (ALD) system was to drill specified complex hole-shapes in turbine blades and vanes with a high degree precision and repeatability and simultaneously capable of very high speed processing.

Accomplishing these goals required two major inventions: (1) a high average power (50 W), high precision, femtosecond laser system with performance significantly beyond the current state-of-art, and (2) the prescription for quickly and reliably drilling highly shaped precision

0.014” diameter holes with minimal heating of the part. In addition, the cost, complexity, reliability and maintainability of the laser machine needed to be commensurate with future industrial applications. At the start of the CRADA, femtosecond lasers were limited to 5-10 W, and were extremely large and complex. Developing a 5-10x higher power, more compact and simple system required significant technology innovation and invention. Also, at that time, all femtosecond material processing was limited to low speeds using 5-10 W lasers. Developing and demonstrating a high-speed process for precision shaped holes required a robust 50 W laser, which did not exist at that time. The success of this project required two major technology advances to occur simultaneously.

This CRADA originally started out as a nine-month project in 1997. There were two amendments to the original statement of work that expanded the scope of the project and extended the expiration date for an additional three years. Five no-cost time extensions were also executed, extending the final expiration date of this project to March 31, 2004. During the course of the CRADA, the project evolved based on LLNL performance and changes in the LLNL technical personnel. In particular, in June 2000 the original PI left LLNL with most of the key project personnel. Given the commitment by LLNL management, a decision by P&W was made to continue the CRADA.

The project consisted of following major phases: (1) material process research and development, (2) high average power femtosecond laser technology research and development, (3) prototype ALD system build and high speed drill demo, and (4) commercialize the ALD system.

Phase 1 - Process Research and Development
The primary goals of this phase were: (1) demonstrate drilling of shaped precision 0.014” diameter holes with a femtosecond laser, with no collateral damage (melting) to the material, and with a high degree of repeatability, (2) demonstrate scalability to shorter drilling times (< sec) with future higher average power laser systems, (3) develop requirements and specifications of the advanced laser subsystem, and (4) develop the requirements and specifications of a drilling station subsystem.

Two existing Ti:Sapphire lasers capable of producing 1-2 Watt average power, 10-20 mJ pulse energy, 100 Hz pulse repetition frequency (PRF), and 0.1-5 picosecond pulse, and a 5-6 Watt average power, 1 mJ pulse energy, 1000 Hz, and 0.1-5 picosecond pulse were utilized. P&W and LLNL worked together to successfully demonstrate that femtosecond lasers could drill shaped 0.014” diameter holes with the required precision and repeatability. Based on this work the high level requirements for the advanced laser to be developed by LLNL were: 50 Watts average power 10 mJ pulse energy, 5 kHz, and a 2 picosecond pulse length. P&W was responsible for designing and building a drilling station capable of securing and moving turbine blades in a vacuum chamber.

Phase 2 - High Average Power Femtosecond Laser Technology Research and Development
The goal of this phase was to develop and invent advanced laser technologies required for a 50 W femtosecond laser. Instead of scaling existing (<10 W) laser technologies to 50 W, P&W found it desirable to develop new patentable technologies. It was also thought that the size, complexity and cost of ownership of existing systems scaled to 50 W might not meet ultimate

industrial requirements. The baseline design was a compact but risky system employing a high average power regenerative amplifier, instead of a more conservative larger multi-stage amplifier.

Beginning in 1998 until late 2000 research and development on a variety of laser technologies occurred, which included: (1) new femtosecond laser amplifiers, (2) new mode locked femtosecond oscillator, (3) new high efficiency dielectric gratings, and (4) ultra thin glass phase plates to spatially format the beam at focus. In early 2000, many of the various options had been tested and a baseline design for the ALD system had been completed.

Due to many technical problems associated with the original baseline concept, the design significantly evolved and resulted in a much larger and more complex optical system. However, many of the new or advanced technologies that were required for the laser system were successfully developed. These included high efficiency dielectric gratings, transmission phase plates, and hollow lens duct diode pumped amplifiers. Several of these technologies are currently benefiting the National Ignition Facility Project.

Phase 3 - Prototype ALD System Build and High Speed Drill Demo
The goals of this phase of the project were: (1) build a 50 W femtosecond laser meeting requirements defined in Phase 1, using components invented and developed in Phase 2, (2) use the 50 W laser with LLNL's small drill station to demonstrate drill speed, quality and precision, using test coupons, (3) integrate the 50 W laser with P&W supplied drilling station, and (4) demonstrate high speed, precision drilling with turbine engine blades.

Beginning in October 2000, the build of the ALD laser began and in January 2001, the laser produced 50 W average power, 10 mJ pulse energy, 5 kHz PRF, and 2 picosecond pulse length, meeting laser requirements of average power defined in Phase 1. This performance represented a world record in high average power for a short pulse system. In January and March 2001, drilling experiments at 50 W were initiated and produced unacceptable drill results. The primary root cause was determined to be the very poor beam quality at this high power. The laser was reconfigured to improve performance and in March 2002, the reconfigured laser produced 35 W average power, 7 mJ energy 5 kHz PRF, 2 picosecond pulse width, with excellent pointing stability, near diffraction limited ($M^2 < 1.5$) beam, and an improved beam shape at drill site. This greatly surpassed the precision performance of the previous 50 W laser.

Drilling experiments with the improved system were initiated and it was determined through process experiments that 20-25 W was the maximum power at 5 kHz to produce shaped holes that had reasonable quality. In June 2002, the ALD laser successfully demonstrated short pulse laser drilling of shaped holes. The uniformity and metallurgy of the test holes met Pratt & Whitney's quality requirements, but drill times were too long. However, this was a major milestone demonstrating high average power short pulse material processing with this unique laser system.

Phase 4 - Commercialize the ALD System and Activate at P&W
During this phase P&W was responsible for commercializing the ALD system with LLNL assistance, and LLNL would assist P&W in activating the system at P&W. Between September

2002 and June 2003, P&W concentrated on commercialization of the system and attracting investment partners both within the government and private sectors.

Due to external events and business decisions, LLNL was funded at a lower level to cover primarily space charges and manpower to support P&W's commercialization efforts to various government and private agencies. In September 2003, the ALD system was shipped to P&W.

C. Benefit to Industry

The benefits to industry are currently unclear because the CRADA did not produce a final "production" laser.

D. Benefit To DOE/LLNL

The following three technologies developed as part of this CRADA potentially benefit DOE Programs:

High Efficiency Multi Layer Dielectric Gratings
High efficiency multi layer dielectric gratings that operate at high damage fluence are required for high-energy short pulse lasers of relevance to stockpile stewardship's high energy density physics experiments. High-energy short pulse lasers are being proposed at several DOE supported facilities, including Rochester, NIF, and Los Alamos. A NIF beamline could produce ~ 5 kJ pulse energy in beams formatted to be compressed to short pulses. A compressor system employing conventional gold gratings would require gratings having several square meters of area. In addition, the beam size would need to be greatly enlarged, which would be difficult to achieve on NIF for multiple beams in a quad. Full utilization of NIF's energy potential for short pulses require compressor gratings that are efficient and operate and fluences 5-6 times higher than conventional gold gratings. Dielectric gratings invented and demonstrated under this CRADA are a key enabling technology to permit high energy short pulse laser operation on NIF and at other facilities benefiting stockpile stewardship and other high energy density physics programs of interest to DOE.

Ultra Thin Glass Figuring
This CRADA was the first demonstration of formatting short pulse beams at focus utilizing ultra-thin glass phase plates. A novel wet etch technique developed by other LLNL projects was used to modify the optical path length of 500 micron sheets of glass to correct phase errors of the ALD laser and modify the phase of the beam to produce a more flat-top beam at focus. This was a key technology break through that permitted processing at average powers > 10 W. Ultra thin glass is required to format the compressed short pulse beam so as not to introduce B-integral self-focusing on the beam. This technology would be required (1) for future high average power material processing to eliminate heat and part melting and (2) to potentially format a high energy short pulse beam to produce a required focal spot size on target used on NIF or other DOE high energy short pulse facilities.

High Average Power Ultra Precision Material Processing
The 35 W ultra precision laser invented and demonstrated under this CRADA has significantly higher potential process throughput compared to other short pulse laser processing systems. For example, the Oak Ridge Y-12 Plant ordered and was delivered a 10 watt Femtosecond Laser Cutting System from LLNL. This system will was developed for disarmament and refurbishment of nuclear warheads (Stockpile Modernization). The same laser and control technology developed by this CRADA would increase the process speed by 3-4x and permit more precision processing. This technology will open up new opportunities for applying laser-matter interactions. Since this laser transmits no heat into the bulk material, thus eliminating the potential for ignition of energetic materials, it is ideally suited to arms disassembly / de-militarization applications. The order of magnitude increase in average power performance addresses previous roadblocks, which centered on throughput.

E. Project Dates

January 26, 1998 through December 31, 2003