“The Laser Microengineering Experimental Station” at the Jefferson Laboratory Free Electron Laser Facility

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Proposed Effort

• Establish a working facility that will enable user-friendly application of the unique FEL properties for investigations in laser microengineering science and laser material processing technology development.

• Effort delineated into two segments.
  – Build
    • an engineering model and process development station at The Aerospace Corporation - called Aerospace-Engineering Model (A-EM)
    • a working model at the Jefferson FEL - called JLAB-working Model (JLAB-WM)
  – Operate
    • transition newly developed laser processes and techniques,
    • conducting fundamental investigations in laser material interaction phenomenon,
    • assisting/guiding new users.
The Laser Microengineering Laboratory at the Jefferson Laboratory FEL Facility

- FUTURE ROOM DOOR
- INTERLOCKED DOOR
- ~9' HIGH ODH HEAD
- ~2' HIGH ODH HEAD
- NEW ROOM WALL W/ ~10' CEILING
- ROOM DOOR
- LASER GUARD WINDOWS (2) 2'H x 3'W
- EQUIPMENT RACK
- UV/IR OTS
- Electrical Panel W/ Keep Out Area
- Curtain

Dimensions:
- 10.0' width
- 32.5' length
- 3' - 4' height
- 3' - 4' height
- 5.8' height
- 20.0' length
- 19.0' length

Date: 02-07-2005

Joe Gubeli
Examples of laser microengineering applications

- Multi-color direct-write microfabrication
- Volumetric exposure, multi-photon exposure processing
- Percussion machining, ablative machining
- Polishing
- Chemical vapor deposition (with special cell)
- Crystallization
- Micro-fusing
- Surface texturing
- Investigations Laser Material Interaction Phenomena
- Mass & optical spectroscopy of desorption and ablation
- Mass removal rate measurement
- Pump-probe physics
- Multiple pulse - rep-pulse physics
- Small Scale Pulsed Laser Deposition (PLD)
System Attributes

- A laser beam delivery system for processing in the UV and IR.
- Automated sequencing of tool changes (e.g. color, objective).
- User selects from three focusing objectives.
- A coordinated three-axis motion system, XY motion range of >100mm.
- An optical table with integrated vibration isolation capability.
- An automated means for laser power and repetition rate control.
- A vision system for process control.
- A means for the User to measure the laser spot size & intensity distribution.
- CAD software for solid modeling of patterns.
- CAM software for generating 3 axes tool-path.
- Software for visual verification of the tool-path geometry.
- Software for converting the tool-path geometry into motion language.
- A generic scheme for mounting user supplied sample holders.
- Additional laser beam delivery lines & stations for other experiments.
NASTRAN analysis used in designing optical support superstructure
Solve for lowest weight with first resonant mode > 90 Hz
Engineering-Model Status in Overview

- Engineering model has been operated (have machined parts) on one line (400 nm).
- Velocity Compensation and power control has been demonstrated in laser machining operation.
- Superstructure design has met relative displacement specifications during high speed (>400 mm/sec) patterning.
Measured Displacement of Superstructure and XYZ Stages with Motion: Velocity of 450 mm/sec
In Micromachining you generate Vibration Noise here

Exploring the use of “embedded” voicecoils & accelerometers to dynamically tune the table > 100Hz.

Initial data shows that surface vibrations can be damped in under 200 ms
JLAB Microengineering User Software
The MUSe
User Interface Computer  Machining Computer

Instr. 1  GPIB  GPIB to Ethernet

Instr. 2  GPIB  GPIB to Ethernet

Instr. 3  GPIB  GPIB to Ethernet

- Labview (MUSe)
- MasterCam (CAM)
- Solidworks (CAD)
- LBA-7 (Laser Beam Profiler)

- Labview (MUSe)
- MasterCam (CAM)
- Aerotech 3200 (Motion Control)
Software Phase 1.1
Query Session
March 2005

Generate User JOB profile (Phase 1.1.1)

Have Job Profile want to do CAD (Phase 1.1.2)

Have JOB Profile and CAD want to do CAM (Phase 1.1.3)

Have Job Profile, CAD and CAM, want to Post (Phase 1.1.4)

Have Job profile, CAD, CAM and POST, want to Launch Tool (Phase 1.1.5)

Just want to Use JOYSTICK and Set Laser Power (Phase 1.1.6)

Via Query Session

THE MUSE is DESIGNED TO GUIDE THE USER

User is Told of the accepted or Compatible CAM File Formats

User is Told of the accepted or Compatible CAD File Formats

Software Module Phase 1.4

Must Decide how to do this?

General User

WHO ARE YOU?

Stop

Hardware Module Phase 1.4
Software Phase 1.1.1
Generate Job Profile in Query Session
March 2005

Generate User JOB profile

THE MUSE IS DESIGNED TO GUIDE THE USER START

Via Query Session

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Super USER or Specialist Control

Software Phase 1.4 March 2005

Supper USER or Specialist

NO General User Option

THE MUSE IS DESIGNED TO GUIDE THE USER

Data Capture: Capture Positions of wavelength & Iris Setting axis into Table

Generate Calibration File: Surface Power vs Applied Power

Generate Calibration File: Surface Power as Function Laser IRIS Setting

Generate Calibration File: Surface Power As Function of EO Scaling Voltage

Run: TEST XYZ Motion Pattern

Run: Wavelength Test Motion Pattern

Manual: Just want to Use JOYSTICK and Set Laser Power

Via Query Session

Module 1.4.1
Module 1.4.2
Module 1.4.3
Module 1.4.4
Module 1.4.5
Module 1.4.6
Module 1.4.7
Software Module Sequences

Start

Finish

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Optical Beam Path
Upper Optical Table Vision System

Test Results: Horizontal FOV
Min = 50 µm
Max = 500 µm
Off axis camera for FOV >500 µm

In situ laser beam analyzer for on target laser spot size and intensity distribution measurements

Video camera with zoom

Laser Beam Entrance

Illuminator aperture imaged on to focusing optics

Laser Beam Exit
Pulse Picking
Velocity Compensation
Dynamic Control of Laser Power
Major Weaknesses in Conventional Laser Material Processing

- Limited power/photon control during processing
- No compensation for variations in part motion velocity (velocity compensation)
- No provisions for laser pulse modulation (intra-pulse, inter-pulse, extraction, temporal)
- Thermal energy transfer outside irradiated region
- Material removal from unexposed regions
- Thermal-induced effects
  - Defects, color centers, fractures, stress
- Difficult to investigate energy transfer from laser
  - → electronic system → bulk lattice
- Restricted to homogeneous materials
Need for Velocity Compensation During Processing

**Permanent Images**
- *Over-exposure* occurs at beginning and end of tool path segments

**Etched Structures**
- *Over-etching* occurs at regions of over-exposure
- *Over-exposure* occurs at regions where velocity < avg. velocity

**XY stage decels/accels in/out of corners**

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Laser Ablation of Dielectrics with Temporally Shaped Femtosecond Pulses

- **CaF$_2$ Ablation**
  - Multi-pulse sequences promote reduced exfoliation
  - Controlled heating surface preparation

- **a-SiO$_2$ Drilling**
  - Improvement in structure when employing pulse trains
  - Further increase in separation time worsens result due to enhanced thermal stress

Key to Laser Processing

Apply laser controls that are required for the specific material under irradiation at the OPTIMUM TIME

Conventional Approach

- Fix laser power
- Minimize laser power fluctuations
- Employ “cut-in” and “cut-out” techniques

Constant Velocity ON OFF

Processing Limitations

- No velocity compensation
- Adds appreciable overhead to machining code and processing time
- Limits types of motion sequences
- Cannot machine heterogeneous materials in a sequential motion process

Laser Wavelength/Power Repetition Rate Temporal/Spatial Intensity Coherence/Polarization

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Laser Pulse Modulation During Tool Path Motion

Advanced Laser Material Processing

Unique Features

- Control photon flux and energy that is delivered to each laser spot
- Pulse sequence (number and intensity) is determined by travel distance and is related to the spot diameter
- Feed rate of XYZ stages can be adjusted or “throttled” on a per tool path segment basis

Advantages

- Laser processing (exposure) is velocity-independent
- Each laser spot receives an equivalent photon dose
- Pulse profile can be tailored for a specific material
- Ideal for variegated or heterogeneous materials
Optical Power Control: Dynamic Attenuation

- Input laser pulse profile
- EO Driver
- Power Supply
- Output laser pulse profile
- Pulse extraction
- Intensity modulation
- Both
- P
- EOM
- A
Laser Pulse Modulation Scheme: Design Concept and Experimental Setup

Tool path File (CNC File) → PC → AWSG → Oscilloscope

Motion Control Drives → Position Synchronized Output Kernel

Pulse Generator for Synchronization

Laser

Power Supply → Driver

XYZ Position Encoder Data → Motion Control Stages

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Use of Digitally-Scripted Genotype Pulse Patterns

**GENOME** = Sequence of concatenated genotypes that define a “script”. “Script” contains attributes that are to be expressed according to the specific sequencing.

- Laser-processing programmer develops a pulse “script”
- “Script” is synchronously matched with the laser tool path
- “Script” can be altered on a per laser spot basis
- Feed rate can be “throttled” to control speed, exposure and resolution

Ultrafast and high repetition rate lasers are ideally suited for digitally-scripted laser processing

Technology Under Investigation NOT PART of Deliverable
Laser Material Processing Using Modulated Pulse Sequences

- **Process**
  - a] Ablation
  - b] Welding
  - c] Texturing
  - d] Dosing

**Technology Under Investigation NOT PART of Deliverable**

**Laser Pulse Structure**

**Ablate**

**Weld**

**Texture**

Material 1

Material 2

Material 3

**Dose**

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Experimental Setup for Synchronized Pulse Modulation

- PSO Card
- Encoders
- XYZ Stages
- Laser
- EO Cell
- Amplifier
- Pulse Script
- Arbitrary Waveform Generator and EO Power Supply
Information Process Flow

MasterCAM GUI

Tool Path Geometry

Laser Tool Parameter Page

Define spot size

G-Code

Spot size inserted into PSOCFG

Initialization of PSO Configuration Subroutine

Aerospace Post-Processor

MasterCAM GUI

Tool Path Geometry

Laser Tool Parameter Page

Define spot size

G-Code

Spot size inserted into PSOCFG

Initialization of PSO Configuration Subroutine

Aerospace Post-Processor
Laser Pulse *Intensity Modulation*

- Can precisely modulate *intensity* of each laser pulse
Laser Pulse Selection (Extraction)

- Can precisely control laser pulse frequency via individual pulse extraction

No EO Modulation
2 kHz pulse train

With EO Modulation
1 kHz pulse train

Voltage Profile-Pulse Script

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Synchronized Motion and Laser Pulse Delivery

Feedrate: 500 μm/s
PSO Distance: 3.0 μm
Repetition Rate: 5.0 kHz

30 laser pulses delivered to each spot diameter

Acceleration/deceleration through corners and “stepover”
PSO-AWSG Application Example

- PSO firing frequency of 400 kHz corresponds to a pattern velocity of 400 mm/s and a laser spot size of 1.0 µm
- PSO and AWSG signals are synchronized with tool path motion
Heterogeneous (Multi-Material) Laser Processing

- 4-bit signals (M-codes) sent from PSO card to AWSG
- M-codes embedded (M6000-M6015) in tool path motion code
- Each M-code is assigned to a specific, resident pulse pattern on the AWSG (2 channel, 32 patterns total)
- Laser pulse profile (genotype) can be altered for each laser spot

If 1000:
- Technology Under Investigation
- NOT PART of Deliverable

If 1111:
- Light out
Ablation of Glass Using Modulated fs Laser Pulses at 400 nm

- Spallation and debris formation
- Fractures and thermal-induced stress

- Localized material removal
- Patterns are clean and well defined

Velocity Comp. OFF

Debris

Velocity Comp. ON

10 µm offset

3 µm spot diameter
Single Pulse Ablation of Glass Using Modulated fs Laser Pulses at 400 nm

- Single 500 fs laser pulse delivered to each spot
- Overexposure or multiple-pulse behavior not observed
Exposure of Photosensitive Glass Using Modulated fs Laser Pulses at 400 nm

- **Velocity Comp. OFF**
  - 10x
  - Over-exposure
  - 50x
  - Multi-pulse regions

- **Velocity Comp. ON**
  - 10x
  - Uniform exposure
  - 50x
  - 30 pulses/spot
Summary

- Permits the precise control of photon flux during laser processing
  - Intensity modulation
  - Pulse selection
  - Temporal modulation
  - Velocity independent
  - Heterogeneous (multi-material) processing

- Takes into account all primary experimental parameters
  - Material type
  - Surface finish
  - Photon dose history
  - Type of material processing
The Co-Orbiting Satellite Assistant (COSA) Project
and
Manufacturing Performance Metrics for Fabrication
with KW UV FEL
COSA Prototype Propulsion Module (Circa 2004)

**Attributes of a Glass Ceramic Mass Producible Satellite**
- Designed for mass production
- Multi-functional glass ceramic material
- Reduced number of piece-parts
- Satellite can be pre-shaped/molded into complex shapes
- Microstructured elements in macroscopic material
- RF transparent; low radar cross section
- Integrated structure and optical bus
- Local control of material transparency and strength
- Wide operational temperature range
- Radiation shield for gammas, X-rays
- Low thermal conductance
- 30 m/s \( \Delta V \) capability (2 modules and 1kg satellite)

**Prototype Propulsion Module**
- Size: 100 mm x 21 mm, Weight: 330 g (wet)
- Integral attitude control capability with wireless telemetry
- Integral thrust nozzles (8) and fuel tank
- 15 m/s \( \Delta V \) capability
- Designed for 2-week duration observation mission
- Optional balloon de-orbit capability
A Propulsion System with GNC in PSGC Material

The Aerospace Corporation
Co-Orbiting Satellite Assistant (COSA)
All Digital Direct Manufacturing

Electronics, Comm Fluid distribution

Valves, battery, nozzles Plenum

Fuel tank
Fuel heater

10 cm
The Prototype Propulsion Module Circa 2005

MEMS GYRO  Pressure Sensor (x2)  Magnetometer  Wireless Telemetry
Swarms to alter Space Age

AEROSPACE: New use for old materials—glass and ceramics—can cut the costs of putting satellites into orbit.

By Mohammed Alachen

Sometimes at work, between the large structure and keeping up with scientific theory, Henry Helvajian floats a disk filled with a layer of a maskless air locking table.

One day, a similar disk may float over Earth's atmosphere. The tank is a satellite propulsion system that Helvajian, a senior scientist at The Aerospace Corp., has been experimenting with.

“The glass and ceramics are made of glass-ceramic materials. The process used to make the disk could be one day used in the deployment of thousands of tiny glass-ceramic satellites.”

—Henry Helvajian, Senior Scientist, The Aerospace Corporation

Swarms: New use for old materials can cut into launch costs

Glass-ceramic nanosatellites

Glass-ceramic: the veil of lightness: easy to launch-cost. But the system of launch is not a single satellite. Instead, the system is made of hundreds or even thousands of tiny satellites, each weighing less than a gram or being 22 pounds. Being above large masses or being a conventional model, these tiny satellites—known as nanosatellites—could be held in one hand.

In 1999, Jansen created the swarm nanosatellites, referring to satellites that are not only small but also light. These nanosatellites, however, can be used as “satellite assistants,” a role Jansen is working on. Many tiny satellites could be housed inside a large satellite. The small satellites could act as a second layer and circle the Earth, using cameras to send Earth images of damage to other problems in the Earth's atmosphere.

Once a glass-ceramic satellite has served its function, the device can be used to take up a balloon that carries against Earth's outer atmosphere to slow down. The small satellite can then descend into lower orbits, and by using light, it can be used to move the balloon without any power.

“Glass satellites are disposable satellites,” Jansen said. “This is not space garbage.” It’s possible to build small satellites out of conventional metals. But historically, if you take one big satellite and split it up into hundreds of different satellites, it will cost more using conventional manufacturing,” Jansen said. “That’s why we’re developing this new manufacturing technique.”

The technique, known as large direct manufacturing, creates a material Helvajian describes as a “ceramic of ceramic.”

The three-step process starts with instructions given to a computer, which directs a robot to expose ultrasonic waves to a certain type of glass, sketching a design that determines the material’s shape. The glass is then baked in an oven.

The last step involves dipping the glass in a fluid. The process can turn the glass into various shapes depending on the function, such as the shape of an antenna.

Depending on how long the material is treated in different stages of the process determines whether it ends up as flexible, transparent glass or opaque, stiff ceramic.

Glass and ceramic each can have different uses on a satellite. For example, ceramic might be appropriate for areas where thrusters are located. Glass might be used where light messages must travel through a transparent surface.
Fabrication Performance Metrics: Based on Data from Existing PSGC Material Formulation

Minimum Laser Power for Maximum Chemical Etching Contrast as a Function of Patterning Velocity
(Laser Spot Size Dia 2 microns. Laser Wavelength 355nm)

- High Precision Motor Drive Motion
- Galvanometer Motion
- Resonant Flexure Driven Motion

Fabrication Performance Metrics: Based on Data from Existing PSGC Material Formulation

High Throughput Manufacturing at Patterning Resolution Sufficient for COSA and Nanosatellites.

- With 600 W of UV pulsed laser light, a processing speed of 10 meters/sec with a spot size (resolution) of 11 microns, a 100 mm square surface is completely processed or “painted” in under 2 minutes.

DOE – Jefferson Laboratory Free Electron Laser Processing Facility
1KW UV pulsed laser light in 2006.
High Throughput Glass Ceramic Nanosatellite/COSA Manufacturing

- All digital direct manufacturing
- Design alterations are done on the digital model of the vehicle and reflected in the processed part.
- A complete set of COSA vehicle wafers can be patterned in less than 15 minutes.
- Multiple COSA vehicles can be assembled in batch mode in less than 15 hours.
- No processing limitation in area size and shape.
- Do not see physical limitation to satellite size and weight.
Conclusion

• JLAB equipment procurement on schedule.
• Software control program on schedule.
• Aerospace on schedule to deliver & install the JLAB module in July, 2005.
• Aerospace will begin Commissioning phase in August 2005.
• Aerospace expects full operation system by July 2006
5 Days 135 presentations

- Photochemistry
- Laser Processing Techniques
- Glass & Ceramic Material Processing
- Laser Joining
- Laser Surface Modification
- High Power Laser Processing
- Laser Microengineering
- Laser Nanofabrication
- Femtosecond Laser Processing & Technology
- Laser Nanomachining
- Laser Surface Texturing
Frank Livingston, Bill Hansen,
Lee Steffeney, Katherine Venturini

Thank YOU

Sponsors
AFRL, AFOSR, JLAB, DARPA,
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