Laser Ablation of Metal Doped Polymers with CO₂ Laser

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Properties of Laser Ablation Products of Delrin with CO₂ Laser

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Laser Ablation of Metal Doped Polymers with CO2 Laser

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See also ADM001699, EOARD-SPC 03-3061. The original document contains color images.
OUTLINE

- Who is DLR – Institute of Technical Physics (TP)?
- Lightcraft Research at TP
- Experimental Setup and Sample Types
- Results: Flat samples in air
  - 3-D expansion
  - Vacuum
  - Comparison of different sample types
  - Tests with a light concentrating structure
- Scanning electron micrographs
- Conclusions and proposal
DLR - INSTITUTE OF TECHNICAL PHYSICS

German Aerospace Center

Astronautics
Traffic
Energy
Aeronautics

Institute of Technical Physics

HEL / COIL
SSL / NLO
Active opt. Systems

Studies & Concepts
Akquisition & Support
HOW IT ALL BEGAN ... (1998)

Bicycle Headlight Reflector
LIGHTCRAFT FLIGHT
ACKNOWLEDGEMENT

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Dr. Ingrid Wysong (EOARD - London)

(and all the others in the background)

for making our research and this visit possible.
**EXPERIMENTAL EQUIPMENT**

**Lightcraft**
- Parabola with
  - Diameter: 10 cm
  - Focal Distance: 1 cm

**Vacuum Tank**
- Diameter: 80 cm
- Height: 110 cm

**E-beam sustained CO₂ Laser**
- Pulse Energy: 420 J
- Repetition Rate: 100 Hz
- Wavelength: 10.6 µm
- Pulse Length: 3 ... 12 µs

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INVESTIGATIONS FOR EOARD (Phase I – 2002)

Comparison of measurement techniques and performance of US and German lightcraft.
INVESTIGATIONS FOR EOARD (Phase II – 2003)

Air breathing propulsion possible to altitudes of about 30 km!

With Delrin in vacuum $v_{ex} = 2400 \pm 200$ m/s

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LASER LAUNCH SYSTEM DEVELOPMENT ROADMAP

Phase 1: Basic Research
- 16 Mio Euro

Phase 2: Pre-Prototype
- 85 Mio Euro

Phase 3: Commercial
- 275 Mio Euro

Timeline:
- 2004: Laboratory flight tests
- 2006: Free flight testing
- 2008: Launch of sounding rockets
- 2010: Launch of satellites
- 2012: Commercial operation

Laser Power (kW):
- Laboratory flight tests: 10
- Free flight testing: 100
- Launch of sounding rockets: 10,000
- Launch of satellites: 100,000

Cost:
- 2004: 16 Mio Euro
- 2006: 85 Mio Euro
- 2008: 275 Mio Euro
EXPERIMENTAL SETUP

Laser Pulse Profile

Sample
SAMPLE HOLDER

Guiding Tube for 1-D Expansion

Sample

Guiding Tube

- Diameter: 20 mm
- Length: 41 mm
- Inner diameter of Sample: 15.5 mm
SAMPLE FORMULATIONS

POM = PolyOxyMethylene = Polyacetal = Delrin®

POM + Al 0, 20, 40, 60 % by wt.
Epoxy + Al 0, 3, 5, 10, 17, 30, 40, 50 % by wt.
Epoxy + Mg 0, 3, 5, 10, 17, 30, 40 % by wt.

Others: Polybutadiene + Al, POM + Fe, POM + Ti
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REPRODUCIBILITY

![Graph showing coupling coefficient vs pulse number (left) and impulse vs laser pulse energy (right).]

- **Left Graph:** Coupling Coefficient (N/MW) vs Pulse Number
  - Atmosphere Pressure: POM - 1D Expansion
  - Pulse Energy: 295 +/- 5 J
  - Data points for 0%, 20%, 40%, and 60% Al

- **Right Graph:** Impulse (mNs) vs Laser Pulse Energy (J)
  - Atmospheric Pressure: POM + Al
  - 1D Expansion
  - Data points for 0% and 40% Al

*Shot to shot result on one sample*  *Scatter for individual shots*
ABLATED MASS IN AIR

Ablated Mass vs. Pulse Energy

Apparent Deposited Energy

→ Upper limit
EXAMPLE: LIMITS TO THE VELOCITY

Upper Limit: 8500 m/s
No air exhausted

Lower Limit: 1200 m/s
All air in tube exhausted
3-DIMENSIONAL EFFECTS

Mass Loss: 3-D vs. 1-D

Impulse: 3-D vs. 1-D
REDUCED PRESSURE

Ablated Mass vs. Pressure

Apparent Deposited Energy
Correct only in vacuum
REDUCED PRESSURE

**Coupling Coefficient vs. Pressure**

- Pulse Energy 280 J
- 1-D Expansion
- POM + Al

**Apparent Jet Velocity**

- Exhaust Velocity (m/s)
- Correct values

*Jet Efficiency in vacuum < 0.03*

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Deposited Energy vs. Pulse Energy
Coupling Coefficient vs. Pulse Energy
Sample Comparisons - Ablated Mass

In Vacuum: Deposited Energy = \[
\begin{cases} 
50 - 70 \text{ MJ/kg} & \text{POM + Al} \\
20 - 60 \text{ MJ/kg} & \text{Epoxy + Al} \\
30 - 90 \text{ MJ/kg} & \text{Epoxy + Mg}
\end{cases}
\]
SAMPLE COMPARISONS - Coupling Coefficient

Pulse Energy 200 J
SAMPLE COMPARISONS - Jet Velocity

Pulse Energy 200 J

\[ \eta < 0.03 \]
COMPARISON WITH LIGHT CONCENTRATING STRUCTURE ("BELL NOZZLE") IN AIR – 200 J

**Mass Loss per Pulse (mg)**

- POM 0: 5 mg
- POM 40Al: 10 mg
- E1 17Al: 15 mg
- E1 17Mg: 20 mg

**Impulse (mNs)**

- POM 0: 200 N/MW
- POM 40Al: 100 N/MW
- E1 17Al: 200 N/MW
- E1 17Mg: 100 N/MW

**Apparent Deposited Energy**

- 20 ... 50 MJ/kg
- 100 MJ/kg

**Coupling Coefficient**

- 200 N/MW
- 100 N/MW
POWER PROFILES

POM + 40 % Al in air

40 J

Energy 40 J
Atmosphere: POM + 40% Al
Average over 4 pulses

Transmission

Signal

Reflection

0.000 0.002 0.004 0.006 0.008 0.010

0 2 4 6 8 10 12 14

40 J

Pulse Energy 120 J
Atmosphere: POM + 40% Al
Average over 4 Pulses

Transmission

Signal

Reflection

0.000 0.002 0.004 0.006 0.008 0.010 0.012

0 2 4 6 8 10 12 14

120 J

Pulse Energy 200 J
Atmosphere: POM + 40% Al
Average over 4 Pulses

Transmission

Signal

Reflection

0.000 0.005 0.010 0.015 0.020 0.025 0.030

0 2 4 6 8 10 12 14

200 J

Pulse Energy 280 J
Atmosphere: POM + 40% Al
Average over 4 Pulses

Transmission

Signal

Reflection

0.000 0.005 0.010 0.015 0.020 0.025 0.030 0.035

0 2 4 6 8 10 12 14

280 J
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ELECTRON MICROSCOPE PICTURES

Before Laser Irradiation

POM + 20 % Al  400x

RE-Mode

POM + 40 % Al  400x

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ELECTRON MICROSCOPE PICTURES

Before Laser Irradiation

Epoxy + 17% Al 1000x

RE-Mode

Epoxy + 17% Mg 100x
ELECTRON MICROSCOPE PICTURES

After Laser Irradiation

SE-Mode

POM – edge 100x

POM - center 100x
ELECTRON MICROSCOPE PICTURES

After Laser Irradiation

POM + 20 % Al - center 100x

SE-Mode 200 J vacuum

POM + 40 % Al 1500x
CONCLUSIONS

- Goals for $I_s = 800$ s not met
- In air $\rightarrow$ accelerated air fraction unknown
  $\rightarrow$ all related values are wrong
- In vacuum $\rightarrow$ deposited energy goes up with increasing metal fraction, but coupling coefficient decreases
- Strong evidence for large energy loss in a decoupled laser absorption wave
- Nature and characteristics of absorption wave need investigation
- Can shorter pulse lengths help prevent decoupling?
PROPOSAL FOR NEW EXPERIMENTS

PD 1 2 3 4

Energy

Wave Velocity

Variation of pulse length 2 ... 12 µs

CO₂ Probe Laser

Sample

KCl Wedge

CO₂ Laser Pulse

PDt

PDi

PDr

Absorption TOF-measurement
THANK YOU

POM after laser irradiation  3000x