Electric
solar
wind
sail

# ESAIL D24.1
# Auxiliary Tether Report

Work Package: **WP 24**

Version: **Version 1.0**

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(List of participants:)

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## Table of Contents

# 1 Introduction

The aim of this study was to find and test suitable materials, handling procedures and suppliers for electric sail auxiliary tethers for the first material tests and to perform the tests.

The study was split in following parts:

- Materials selection
- Material shaping and forming for the auxiliary tether requirements
- Handling methods of the material
- Selecting suppliers
- Procuring test samples
- Characterizing mechanical properties

# 2 Requirements

Material requirements:
- Vacuum compatibility
- Temperature range -100 C … +125 C
- High UV and other radiation tolerance
- Transparency or low absorbtivity & low reflectivity for visible light to avoid visible light solar sail effect

Application related requirements:
- 3D form after deployment versus “flat” 2D shape for micrometeoroid tolerance
- Rip stopping behaviour
- Damping of oscillatory strain (material loss modulus in suitable range)

Mechanical requirements
- Stretching behaviour under tension
    - Tension in range 10…60 gram
    - Elongation 0.3 … 3 % under said tension

Mass less than 300 g /km

# 3 Materials

## 3.1 Polyimide (Kapton)

Polyimide (PI) (various tradenames like “Kapton”) was considered from the beginning as a baseline. Polyimide films are widely available from several suppliers in several forms. Polyimide has a very large temperature range and is vacuum compatible as such. Polyimide is very resistant against UV and other radiation. Polyimide has very extensive space heritage. Polyimide is orange coloured in its basic form. At least one supplier has also colourless clear (visible light) form available as well as black form (antistatic opposed to very high resistivity basic Polyimide).

### 3.1.1 Polyimide Suppliers and Brands considered

**Nexsolve / Mantech**
( http://nexolve.mantech.com/nexolve/NeXolve.shtml )

PI films available in various thicknesses, colourless, white, black (anti static).
Nexsolve PI film main characteristics:

LaRC CP1 Polyimide

| | |
|---|---|
| Tensile Strength at 23 °C: | 87 MPa |
| Tensile Modulus at 23 °C: | 2.0 GPa |
| Tensile Elongation at 23 °C: | 16 % |

**Apical PI films, Kaneka Texas**
( http://www.kanekahightech.com/ )

PI films available in orange transparent form in various thicknesses.

Apical AV Polyimide

| | |
|---|---|
| Tensile Strength at 20 °C: | 245 MPa |
| Tensile Modulus at 20 °C: | 3.1 GPa |
| Tensile Elongation MD &TD °C: | 115 % |

**American Durafilm Co.**
( http://www.americandurafilm.com/ )

PI films available in orange transparent form in various thicknesses. (American Durafilm supplies Dupont Kapton.)

Kapton HN Polyimide

| | |
|---|---|
| Tensile Strength at 23 °C: | 231 MPa |
| Tensile Modulus at 23 °C: | 2.5 GPa |
| Ultimate Elongation at 23 °C: | 72 % |

## 3.2 Glass Fiber Strings

Strings made of glass fiber are suitable for auxillary tether application, if a suitable way to manufacture a three dimensional hoy/heytether / net like structure could be found.

Glass Fiber Strings are available from AGY, Aiken, SC, USA (www.agy.com).

AGY Type E Glass Fiber ECD1800 is made of 54 filaments of 5.5um fibers.

Single Filament Characteristics:
Tensile Strength, psi
@ -310°F 770,000
@ 72°F 500,000-550,000
@ 700°F 380,000
Tensile Modulus of Elasticity psi @ 72°F 10-10.5 x $10^6$
Elongation at Break, % 4.5-4.9
Elastic Recovery, % 100

## 3.3 Dyneema String

Dyneema is a tethered string like form of ultra high molecular weight polyethylene. Dyneema string has high tensile strength, 0.1 mm string has ultimate strength 6 kg. Dyneemas have been used in space environment, however UV radiation resistance needs some further qualification.

Like glass fiber strings, a sewing or manufacturing process for producing net or hey/hoytether kind micrometeoroid resistance structure should be found or developed.

## 3.4 Materials purchased

### 3.4.1 Polyimide

7 um Polyimide / Kapton has been placed under ITAR regulations in USA. This made 7 um Kapton film unavailable for this study. Thinnest easily available thickness is 12.5 um Polyimide film. (Sometimes 7 um and 12.5 um thicknesses are referred as 7.6 um and 12.7 um.)

Two suppliers provided Polyimide film:
Kaneka, Texas: Apical AV Polyimide, two 30mm wide rolls, 30 meter length, 12.5 um.
American Durafilm: Kapton HN, 12 pieces 30 mm wide rolls, 20 meter length, 12.5 um.

Nexsolve / Mantech was tried, but they did not respond timely to our inquiries.

### 3.4.2 Glass Fiber String

Four ECD1800 rolls were received as a sample from AGY. Each roll had kilometers of the string.

ECD1800 was immediately found out to be unpractical for this application. The minimum bending radius of the string is too large for making knots. The string will brake. Thus net/hey/hoy-tether should be build by gluing etc. method. Even this is difficult if not impossible because of the large minimum bending radius of the string.

# 4 Polyimide patterning

Polyimide stripe needs to be patterned, that is a suitable repetitive hole pattern needs to be cut onto the material. Holes have three purposes: 1) rip stopping, 2) under tension they give flexibility and 3) under tension patterned polyimide stripe forms a micrometeoroid resistant 3D shape.

## 4.1 Patterning methods

### 4.1.1 Mechanical cutting

In this method a sharp cutting blade is used for mechanically cutting the material. Holes of almost any shape can be created. Cutting is made by a numerically controlled (NC) machine. The cutting method can be applied to a maximum 1 or 2 meter long film. The film is kept in place by an underpressure table (the underpressure below a porous table keeps the sample in place by pressure differential force). Mechanical cutting is not suitable for “roll-to-roll” cutting required for hundreds of meters long film processing. But for prototyping the patterns the method is suitable for short strips.

Several companies in Finland were contacted for die cutting. Tekniseri Oy volunteered for cutting tests (www.tekniseri.fi).

Apical AV Polyimide test sample was provided for Tekniseri. The cutting tests failed. Polyimide film was too thin and had a tendency to rip unpredictably or the film wrinkled because the underpressure table suction force was too low to keep the film in place and to resist the cutting blade force.

### 4.1.2 Die cutting

In die cutting method a punch is used to cut holes in regular pattern. The method can be applied for roll-to-roll cutting required for creating hundreds of meters long patterned stripes. The punch is usually custom made for each pattern.

Several companies were contacted for die cutting. Usually the same companies offer both mechanical blade cutting and die (punch) cutting.

Die cutting was evaluated as non-feasible by all companies contacted. The Polyimide film in question is too thin, removal of cut material from holes is unreliable and rip development tendency of the thin Polyimide film is difficult if not impossible to overcome.

### 4.1.3 Photoetching

Photoetching is a photochemical process for shaping and cutting various film and plate type materials. Polyimide etching is a standard process. The etching is made in specialized chamber and thus limited in size of the sample. Applying etching for roll-to-roll method is difficult and would probably require substantial investments in hardware.

For producing limited size test samples etching is feasible.

Polyimide photoetching is offered by Tech-Etch, Inc, MA, USA ([http://www.tech-etch.com/](http://www.tech-etch.com/)). Tech-Etch can process max 500 mm long stripes.

An order for Tech-Etch was placed for 5 test stripes, 500 mm total length, patterned section 400 mm in the middle and width 30 mm. Material was Kapton HN. Drawing of the test stripes is shown in Figure 1. Details of the pattern are shown in the Figure 2.

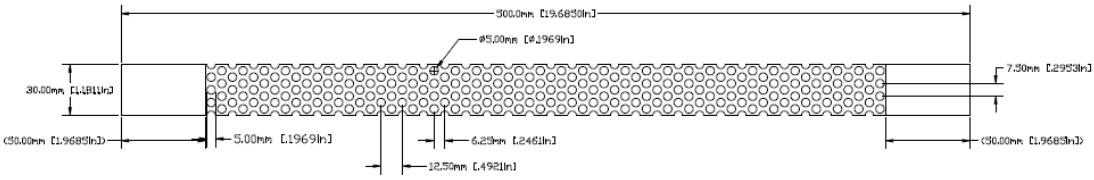



**Figure 1** Drawing of the hole pattern ordered from the Tech-Etch Inc.

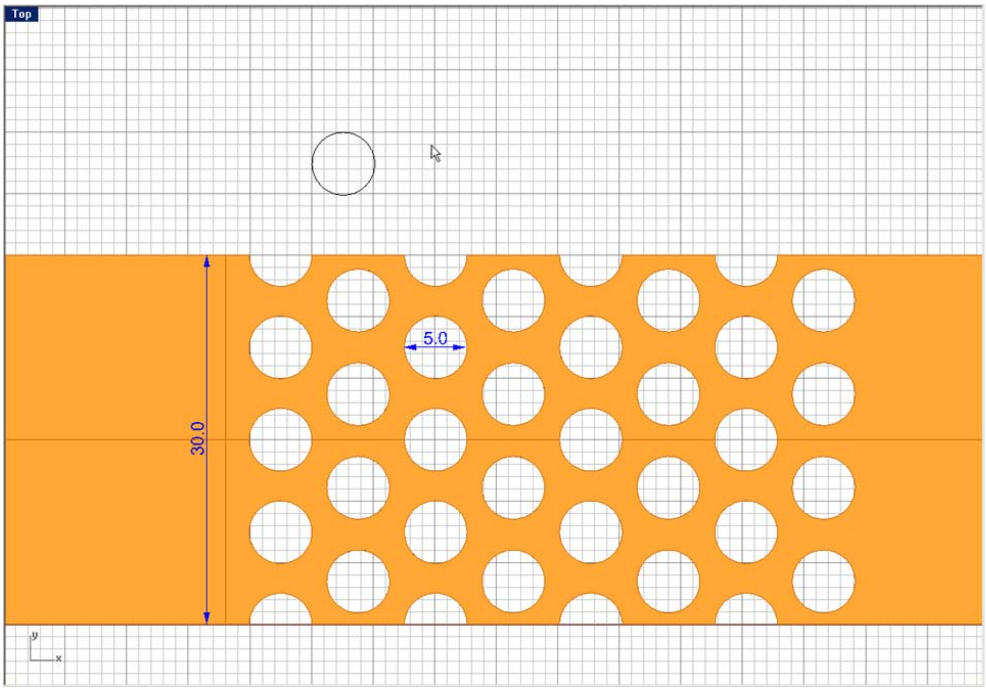



**Figure 2** Hole pattern details

### 4.1.4 Laser Cutting

Cutting by a laser beam is compatible in principle with roll-to-roll processing, thus enabling hundreds of meters long stripes. Laser cutting of Polyimide plates by a UV-laser is industry standard technology. Roll-to-roll processing however needs at least some hardware tuning at minimum. Therefore for this study 500 mm long sample stripes were processed.

LPKF Laser & Electronics AG, Germany (http://www.lpkf.com/), provides Polyimide laser cutting services. Two sample stripes were cut by them from the Kapton HN from American Durafilm.

The pattern was identical to the photoetched samples shown in Figure 1 and in Figure 2.

LPKF provided test & analysis document of the work performed with photographs of the details of the holed stripes. Analysis document is in the Appendix.

# 5 Testing

Test stripes processed by Tech-Etch were exposed to tension test for evaluating the spring constant and stripe re-shaping under tensions.

The principle of the test arrangement is shown in Figure 3. The stripe is hung in front of a mm-paper. Weights were added on the other end of the stripe (mass of 1.32 g was found to be suitable unit piece). The setup was photographed and the strain in mm was determined from the mm-paper.

Attachments onto the stripe were difficult to resolve. Best working solution was a tape on the ends (visible on the photograph on the right on the Figure 3). A drawback was that the tape made the stripe less flexible from the ends thus locally limiting the 3D shaping. However this test setup gave the most linear and repeatable results and it gives a rough estimate of the behaviour of the stripe under tension.

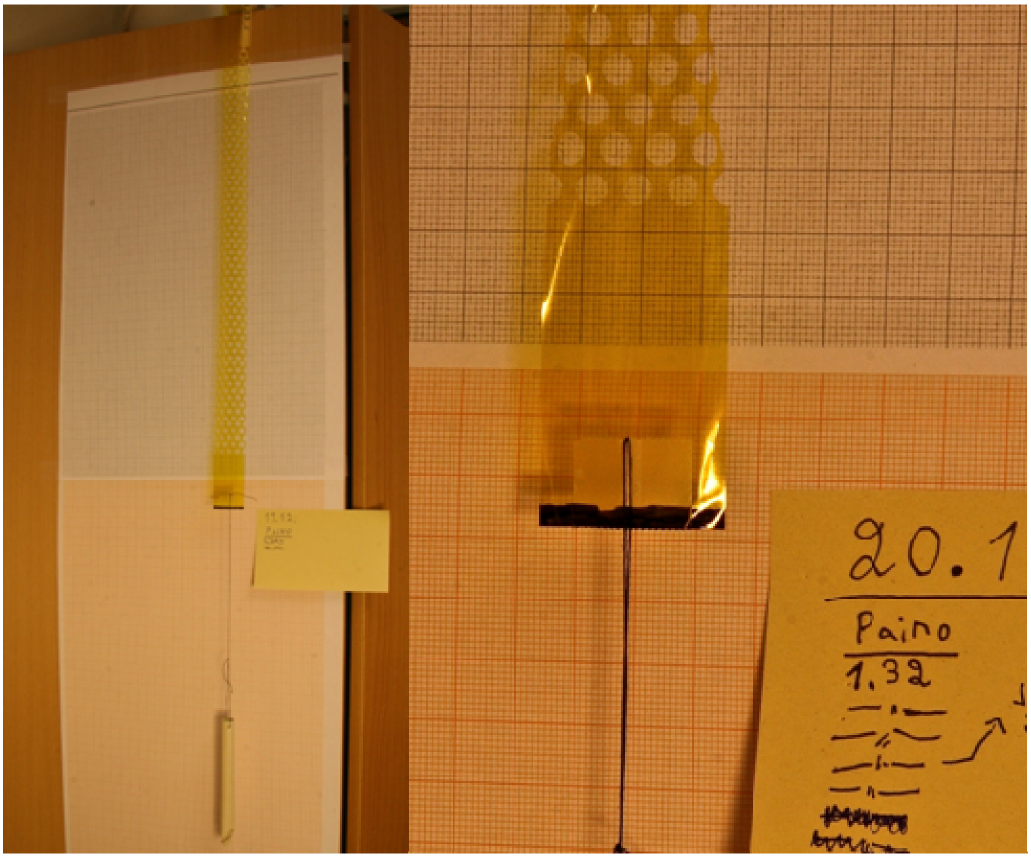



**Figure 3** Tension test arrangements

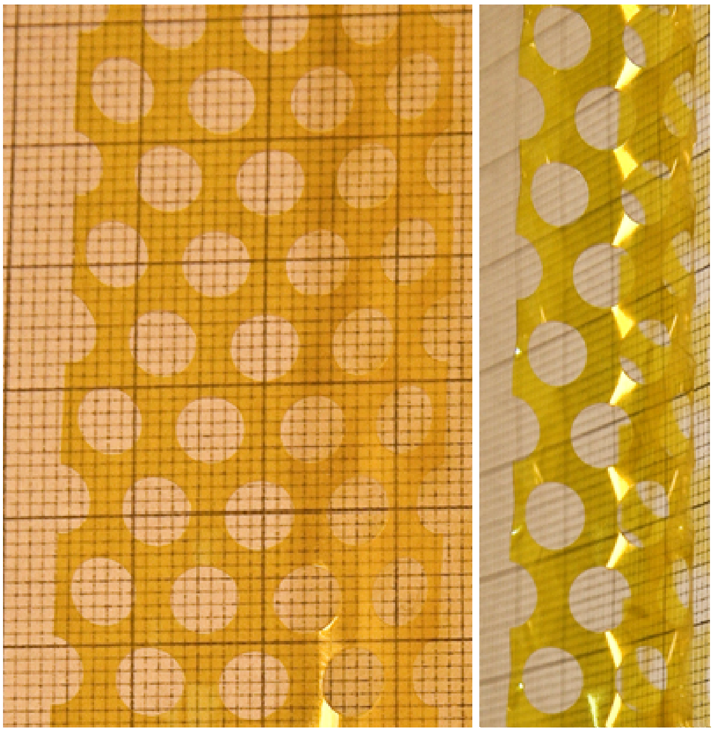


**Figure 4** Stripe without (left) and with (right) tension. Under tension the punched stripe forms a U- or O-shape.

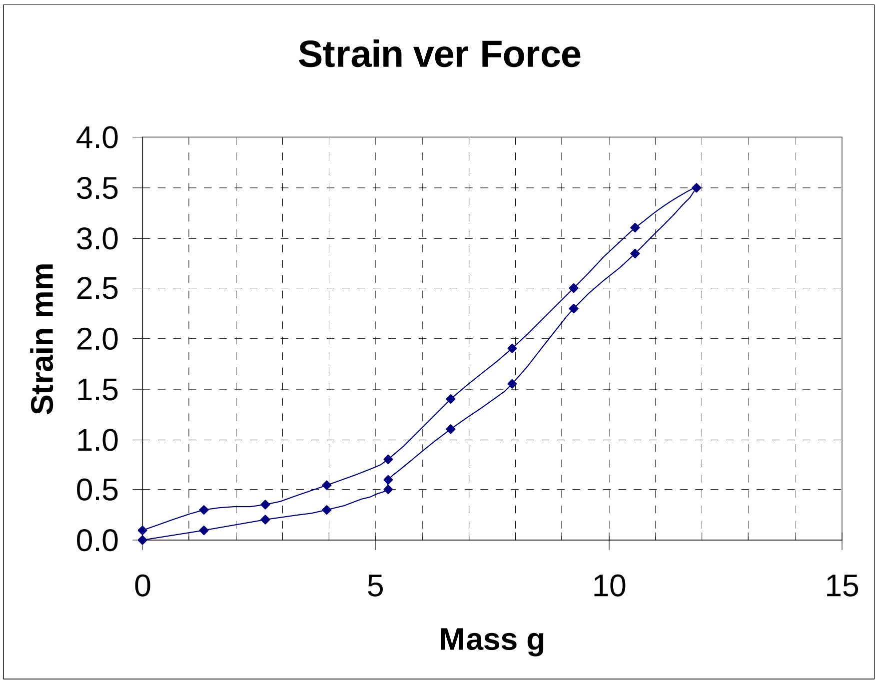



**Figure 5** Tension test, strain versus force

Figure 5 shows the strain versus force curve of a test stripe. It seems that in the beginning, until 5.3g mass, the tapes on the ends of the stripe limit the re-shaping of the test stripe as the tapes resists U-curving of the stripe. After 5.3 g mass the stripe starts to re-shape more efficiently also near the ends of the stripe, thus flexing more. Until 12 g mass the dependence is linear. 12 g mass was the highest mass used, because at that tension, the stripe was already on a quite tight roll around itself (forming a "tube"). The spring law F = kx, where force is given by constant k and strain x, can be applied.

The determined spring constant of the 400 mm (patterned section) sample here is thus
k= 2.3 g/mm.

A 12 g mass gives a 3.5 mm strain on a 400 mm stripe (patterned section), thus the elongation is about 1 % here.

# 6 Conclusions

## 6.1 Materials

Polyimide material in 12.5 um thickness is widely available and is suitable for auxiliary tether use. Applicability of 7 um thickness is more difficult as it is under ITAR licensing and thus more difficult to procure. ITAR could regulate and limit launch opportunities.

Glass fiber string ECD1800 was usuitable for this application. Minimum bending radius of the string was too large for manufacturing working net or hoy/heytether kind of structure. No efficient method for tether manufacturing could be found.

Applicability of Dyneema strings needs some further investigation.

## 6.2 Polyimide processing methods

Polyimide patterning and cutting is possible by photoetching and laser cutting methods. Photoetching limits the size and is thus suitable only for testing short, about 500 mm long stripes. Laser cutting is suitable for roll-to-roll processing. This however may need some additional H/W customizing at the factory.

## 6.3 Test results

Patterned Polyimide stripes were exposed to tension/strain testing. According to test results it is feasible to tune strain properties of a Polymide stripe by patterning. Also it is feasible to re-shape the flat stripe into three dimensional shape by patterns. Thus micrometeoride survivability can be achieved.

Tension & strain characteristics of punched Polymide stripe are in the range of the requirements for auxillary tether concept. Properties could be fit more accurately by iteratively tuning.

# 7 Appendix

Laser cut Polyimide stripe test report by LPKF Laser & Electronics AG.

# Customers Application Report
# LPKF MicroLine 6120 P/ 6320 P

for

FMI

Robin Zimmermann -  LPKF Laser & Electronics AG

## Application Date

27th October 2011

## Laser System

- LPKF MicroLine 6320P and 6120P (2D-UV-Laser)

## Material

- Kapton, PI foil (thickness approx. 20 µm)

## Process

- Cutting (drilling holes)

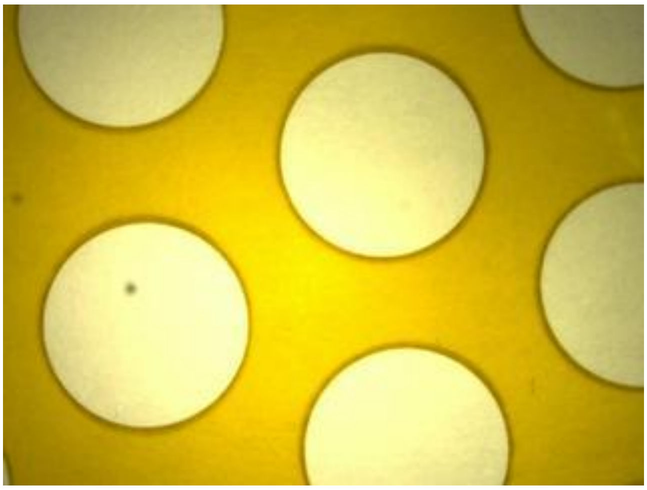
## Customer's Requirements

1. Process quality
2. Observations

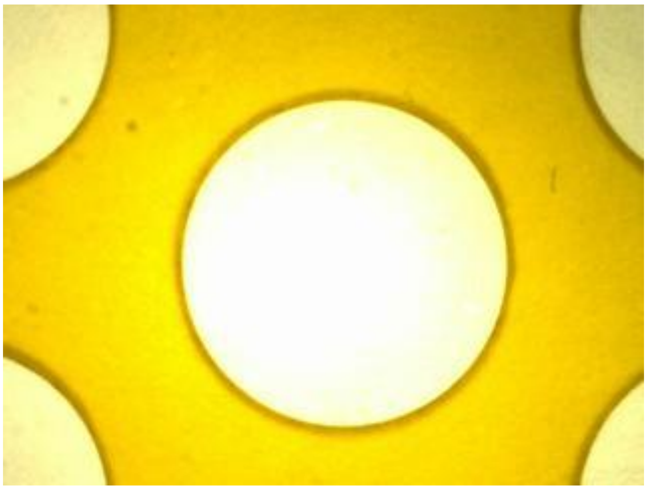
## Data

- Provided by customer (Kapton_Stripe_holes_only_101011.dxf)

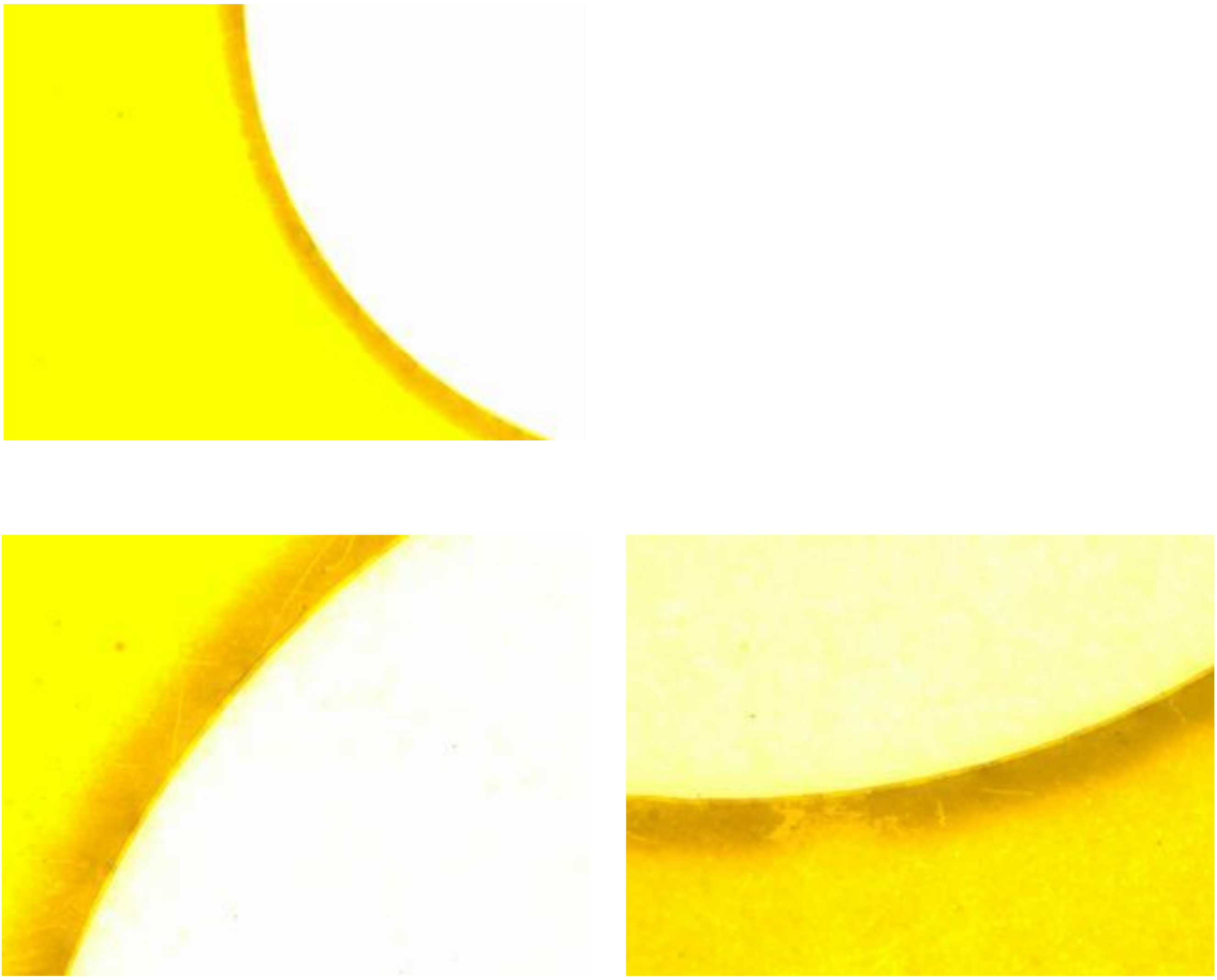
# PROCESS QUALITY



Picture 1: Drilled holes by UV-Laser



Picture 2: Zoomed drilled hole



Picture 3, 4 and 5: Zoomed cutting edges with some carbonisation

## SUMMARY

**Process parameter:**

- Estimated cycle time per complete required stripe of 1 m * : ca. 23,33 min.
- Effective cutting speed: 8 mm/s  (Mark speed / Repetitions)

*Please note: Cycle Time includes also Height Measurement phases.

**Observations**

Due to the thin material (approx. 20µm) the laser power has to be decreased and the repetitions have to be increased to avoid accretion and stress in the extant material.

Due to the max. working area of approx. 21 x 24 inches of the ML6000 Series it was not possible to structure a stripe of 1 m length! Therefore I used smaller stripes.

Some of the outer holes (the half ones) are not completely cutted. This is depending on the not exactly positioning of the stripe on the working area because we have no fiducials!

I recommend a fixture for more exactly positioning every time in this case. Furthermore I would suggest if the half outer holes are bigger in the dfx-file than the required size. That means they should be overlap the stripe edges. Than you have the guarantee to cut every half outer hole completely.

**The material was not cleaned!**