Processing of lightweight materials with high peak power ns-pulsed disk lasers

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Abstract

In the automotive and aviation industry more and more lightweight components are used to substitute traditional materials. This reduction of weight results in less fuel and energy consumption without affecting safety and stability characteristics. Materials like carbon reinforced plastics (CFRP), aluminum and titanium are hard to machine by mechanical processing tools. The solution is using ns-pulsed disk lasers with high a peak power (up to 220kW), excellent near diffraction limited beam quality and a tunable pulse width over a wide range of repetition rates. This paper shows various applications of lightweight materials with this high peak power ns-pulsed disk lasers. An outlook on the potentials of laser fine machining – drilling, cutting and 3D engraving – is given.

Keywords: nanosecond disk lasers; deep engraving; drilling, cutting; aluminum; CFRP; titanium

1. Introduction

Lightweight materials become more and more important, especially in the automotive and aircraft industry. In these industries new materials and material combinations are used like Titanium, Aluminum alloys (AlMg3) or thermoplastic and thermosetting carbon reinforced plastics (CFRP). They are much lighter than common materials like steel but have similar properties (e.g. tensile strength). There are many reasons for applying them, like less fuel and energy consumption due to less weight, less consumption of unwrought goods as well as designing characteristics for visible parts for optical or acoustic reasons.

But these lightweight materials require new processing technologies. It has been shown that common machining processes either technically (high wear of machining tools) or economically (long cycle times) come to their limits. Laser material processing has many advantages, there is no tool wear, no requirement for tool replacement during process and it is possible to create special geometrical layouts as well as adapted designs. Moreover, laser machining is independent of the mechanical properties of the material as for example hardness or ductility. The results of laser processing only depend on the laser parameters and the optical and thermal properties of the material. Due to the high peak power, ns-disk laser sources showed really good quality at low cycle times, especially in the micro processing laser machining.

In this paper the drilling, cutting and deep engraving results of CFRP, Titanium and Aluminum have been investigated.

2. Experimental Setup

Two different kinds of laser sources have been used for experimental investigation: the long pulse ns-disk laser JenLas\textsuperscript{®} disk IR70 and the short pulse ns-disk laser JenLas\textsuperscript{®} disk IR70E. Both lasers are independently

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tunable in repetition rate, pulse duration and output power. The maximum achievable peak power is ~220kW (IR70E) respectively ~25kW (IR70). In table 1 an overview of the parameter ranges for both lasers is shown.

The JenLas® disk IR70 is recommended for metal drilling and deep engraving applications, due to its moderate peak power (25kW) and its high pulse energy (up to 7mJ). The JenLas® disk IR70E is a better choice for heat sensitive materials like for example plastics, CFRP or dielectrics like ceramics or diamond. Short ns pulse duration (30ns) and high peak power (220kW) enable rapid processing with reduced heat affected zone [6].

For all experimental investigation a Galvo scanner with various F-Theta-optics (56mm, 100mm, 160mm and 254mm) has been used.

**Table 1. Laser Parameter Comparison**

<table>
<thead>
<tr>
<th></th>
<th>JenLas® disk IR70</th>
<th>JenLas® disk IR70E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1030nm</td>
<td>1030nm</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>NC*:650…1600ns</td>
<td>30…300ns</td>
</tr>
<tr>
<td></td>
<td>C*: 200…1100ns</td>
<td></td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>NC*:8…35kHz</td>
<td>10…300kHz</td>
</tr>
<tr>
<td></td>
<td>C*: 8…100kHz</td>
<td></td>
</tr>
<tr>
<td>Avg. Power</td>
<td>&gt;65W @ 30kHz</td>
<td>&gt;65W</td>
</tr>
<tr>
<td>Peak Power</td>
<td>25kW</td>
<td>220kW</td>
</tr>
</tbody>
</table>

**Experimental results**

2.1. CFRP

Main issues in processing CFRP are the thermal and optical properties of the thermosetting or thermoplastic resins and the carbon fiber mesh. The carbon fibers have a high thermal conductivity and a high absorption in the IR-wavelength, they do not melt but sublimate at high temperatures in the range of several thousand degree Celsius. The resins on the other hand have a low optical absorption, a low thermal conductivity and low melting point (thermoplastic) respectively a lower decomposition temperature than melting temperature (thermosetting) in the range of several hundred degrees Celsius. To overcome these issues it is necessary to induce short ns-pulses with high peak power into the material.

To demonstrate the influence of different resins and layer structures, thermosetting and thermoplastic CFRP with different amounts of fiber layers and therefore thicknesses have been investigated. An overview of chosen materials is given in table 2.

**Table 2. Overview of used CFRP.**

<table>
<thead>
<tr>
<th></th>
<th>Material A</th>
<th>Material B</th>
<th>Material C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin type</td>
<td>Thermosetting</td>
<td>Thermosetting</td>
<td>Thermoplastic</td>
</tr>
<tr>
<td>Number of Layers</td>
<td>3</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.75mm</td>
<td>2.10mm</td>
<td>1.00mm</td>
</tr>
</tbody>
</table>

Processing of CFRP can be done with various laser types as for example CO2-lasers, cw-fiber lasers, ns-fiber lasers and ns-disk lasers. If CO2- and cw-fiber lasers are used for cutting they induce edge damage and delamination because of a suboptimal thermal management during the process. Cracks, delamination and residual fibers as well as high heat affected zones (HAZ) appear in the process area [4]. In comparison ns-pulsed lasers create a much better quality, there is no delamination of fibers, much smaller HAZ and the cutting or drilling edge is very smooth. [2]

2.1.1. Drilling of CFRP

In the automotive and aircraft industries micro holes are used to improve acoustic behavior whereas macro holes are used for clamping or fixing points.

Micro holes have been drilled into material A and C, macro holes have been drilled into material A and B. An F-Theta-optic with a focal length of 160mm has been used. Both hole sizes were drilled using the spiral-helix-method with the JenLas® disk IR70E to achieve best quality. A pulse duration of 30ns and a repetition rate of 10kHz at highest peak power lead to the following results:
Table 3. Application results of CFRP drilling.

<table>
<thead>
<tr>
<th>Material</th>
<th>Entrance diameter (µm)</th>
<th>Taper angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - micro</td>
<td>250</td>
<td>5</td>
</tr>
<tr>
<td>A - macro</td>
<td>680</td>
<td>6</td>
</tr>
<tr>
<td>B - macro</td>
<td>810</td>
<td>6</td>
</tr>
<tr>
<td>C - micro</td>
<td>300</td>
<td>5</td>
</tr>
</tbody>
</table>

For all CFRP drilling applications a taper angle of 5° to 6° could be reached with an accuracy of ±0.2°. This taper angle can be reproduced quite accurately for all different CFRP materials and thicknesses.

As an example for material C it was possible to drill micro holes with a repetition rate of 30kHz at a drilling time of 0.17s per hole [1][2]. Depending on the application requirements, edge quality can be improved by using a higher repetition rate or reduced pulse energy. Both lead to a higher number of scans/shots which increase the drilling time. Highest drilling rates can be achieved at maximum peak power.

![Image of CFRP drilling results](image_url)

**Fig. 2.** Macro holes drilled into CFRP; material A (left), material B (middle), Micro holes drilled into CFRP material C (right) [2].

2.1.2. Cutting of CFRP-material

Materials A and C have been also used for cutting trials. Two different cutting strategies (single-pass and multi-pass) were tested and it was found out that minimum damage of material occurs by multi pass ablation method with high peak power. In a single pass at low scanning speed, heat management is quite difficult because the local heat impact is very high and HAZ becomes very large. It is essential to keep thermal impact as small as possible; therefore the JenLas® disk IR70E was used with short pulse width. Higher scanning speed leads to lower thermal impact; therefore cutting was done with multi pass at high peak power.

For Material C it can be stated that with increasing pulse duration or higher repetition rates the number of passes increase for a full cut though the material. The removal rate depends on the peak power. The highest removal rate was found at highest peak power (220kW). Of course, the scanning speed of the Galvo scanner is also important for the removal rate. The higher the scanning speed the less heat impact into the material and therefore more passes are required. Higher heat impact leads to higher damages of cutting edges and a bigger HAZ. The HAZ is smaller with the ns-pulsed disk lasers than with a cw-fiber laser or a CO2-laser. [4]

For material A a similar cutting strategy was chosen than for material C. Due to the different resin a wider cutting kerf had to be chosen. The results for both materials are shown in table 4. [2]

Table 4. Application results of CFRP cutting.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ablation rate (mm³/min)</th>
<th>Size of HAZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20</td>
<td>not detectable</td>
</tr>
<tr>
<td>C</td>
<td>11</td>
<td>&lt; 100µm</td>
</tr>
</tbody>
</table>

![Image of CFRP cutting results](image_url)
2.1.3. Deep engraving of CFRP-material

Deep engraving of CFRP can be used for example for repairing the outside paneling of airplanes. These paneling surfaces are typically 3D shaped and not flat. In that case a defined negative 3D structure of a patch has to be machined into the surface to fit a positive part (patch) with exactly the same structures afterwards. By using the JenLas® disk IR70E with short pulse duration at 30ns and low repetition rates at 10kHz, the material can be removed very precisely. There is no visible damage of the surrounding material like delamination of the fibers or melting of the polymer. The surface is clean and smooth. Like in the other CFRP applications described, using higher peak power increases the productivity. The shorter pulse width minimizes the damage of the surrounding material.

With the JenLas® disk IR70 a removal rate of more than 100mm³/min can be achieved [2]. Compared to fiber-based ns-lasers with a peak power of tens of kWs the removal rate is nearly doubled with the JenLas® disk IR70, thanks to the peak power of more than 220 kW.

2.2. Aluminum

AlMg3 has a low density and is therefore much lighter than steel. Furthermore, it has a high structural rigidity and stability. This is one reason why aluminum is used in the automotive industry as a lightweight construction material to substitute steel in car body parts.

Milling, cutting and ablating with common machining methods came to their limits concerning good quality at high cycling times. For state-of-the-art laser processing with lamp pumped solid state lasers or pulsed-fiber lasers there is a limitation in ablation rate (max. 35mm³/min) due to low peak power of such systems [3][5].

For the experimental investigation AlMg3-sheets with a thickness of 1.0mm have been used.

2.2.1. Drilling of Aluminum

Aluminum drilling of micro holes can be used for example for filter applications. Depending on the hole diameter two different methods of laser drilling can be used, the percussion drilling and the trepanning drilling method. In a first experiment a hole diameter of ~100µm was drilled with percussion drilling. Both lasers have been tested to see the influence of pulse width and peak power. Maximum drilling rate with the JenLas® disk IR70E was ~340 holes per second comparing to ~620 holes per second with the JenLas® disk IR70.

For drilling applications in aluminum higher peak power (220kW) and shorter pulse length (30ns) did not lead to higher drilling rates but better quality. Whereas high pulse energy at lower peak power (10kW) and longer pulse duration (700ns) lead to higher drilling rates and comparable worse quality, see Figure 5. Under the estimation of constant focal diameter, absorption and laser power, thermal diffusion length characterizes the temperature distribution within the material. Thermal diffusion length scales with square root of the pulse length, therefore longer pulse duration leads to deeper and wider thermal diffusion than shorter pulse duration. In
general, longer pulse duration leads to higher temperatures in a certain distance within the material. Therefore melting or vaporizing temperature is achieved easier. [1]

![Fig. 5. Micro Holes in Aluminum a) done with JenLas® disk IR70 (left) b) done with JenLas® disk IR70E (right).](image)

### 2.2.2. Deep engraving of aluminum

When it comes to the ablation of special geometries or drilling of special holes geometries as for example turbine cooling holes the JenLas® disk IR70 and IR70E are good choices due to their high pulse peak power. In order to determine the maximum ablation rate for aluminum the repetition rate, pulse length, peak power, pulse distance and focal diameter were varied. The processed area was 5x5mm. After processing, the weight reduction was measured by a high precision scale to determine the material removal rate accurately even for very small ablation volumes.

It was found out that the removal rate depends on the repetition rate, pulse width and pulse energy (therefore on peak power) as well as on design parameters as for example line distance or overlap. The short pulse length (30ns) was not beneficial for high ablation rates due to its short thermal distribution length. The results of the experiments are shown in table 5:

<table>
<thead>
<tr>
<th></th>
<th>JenLas® disk IR70</th>
<th>JenLas® disk IR70E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal rate</td>
<td>130mm³/min</td>
<td>15mm³/min</td>
</tr>
<tr>
<td>Pulse width</td>
<td>1000ns</td>
<td>30ns</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>5mJ</td>
<td>6.5mJ</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>8kHz</td>
<td>10kHz</td>
</tr>
</tbody>
</table>

In comparison a 50W pulsed fiber laser with similar pulse length (~ 200ns) achieves a maximum removal rate of 35mm³/min at a peak power of 12kW with a pulse energy of 1mJ which is up to four times slower than using a JenLas® disk IR70 laser. For this application it affirms that higher pulse energy and longer pulse width lead to higher removal rates [3].

### 2.3. Drilling of titanium

Titanium is a high resistant material with excellent corrosion characteristics and a high melting point at 1660°C. It is used frequently in the aviation and medical industry and more and more in the automotive industry, for example for exhaust systems.

Frequent requests concerning titanium processing are drilling holes or blind holes with a diameter of 50 to 200µm into titanium sheets (1 to 4mm thick). The holes were drilled using the percussion drilling method with the JenLas® disk IR70. [1]

For titanium a high pulse energy and therefore a high peak power at an optimal pulse width of 700ns is beneficial for a high productivity. The diameter could be reproduced very accurate and in a very good quality, see figure 6.

Drilling rates of ~550holes/s were shown for holes in 1mm thick titanium. The resulting taper angle was in the range of 0.2°. For blind holes the drilling rate depends on the depth of the required holes.
3. Summary and outlook

It has been shown that both lasers, the long pulse ns disk laser JenLas® disk IR70 and the short pulse ns disk laser JenLas® disk IR70E, are suitable tools for micro machining in the lightweight material industry. For all investigated materials CFRP, aluminum and titanium a high throughput in combination with very good quality characteristics were achieved. For each of these materials different process parameters were needed because of different material properties. It can be stated that for metal processing (aluminum and titanium) high pulse energy and longer pulses are advantageous, for CFRP short pulses with high peak powers are the best choice. Compared to other laser sources like fiber-based ns-lasers the productivity with the JenLas® disk IR70 and IR70E is up to four times higher. Additionally, the surface and quality of the edges are better and the HAZ is much smaller.

Acknowledgements

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References