Lasers in Manufacturing Conference 2019

Influence of reinforcement materials in laser perforation of polymers

Martin Griebel[a*], Jean Pierre Bergmann[b]

[a]*JENOPTIK Automatisierungstechnik GmbH, Konrad-Zuse-Strasse 6, Jena 07745, Germany*
[b]*TU Ilmenau, Gustav-Kirchhoff-Platz 2, Ilmenau 98693, Germany*

Abstract

The laser treatment of polymeric parts becomes more and more popular for the plastic processing industry. In order to increase the mechanical properties the used basic polymers (e.g. polypropylen PP) are typically reinforced by materials such as glass fibers or talc powder in different volume levels.. These specific material features affect the cutting or perforation process in a significant manner. First empirical test series of cutting with laser beam show, that an influence is present and build an initial data base, in order to set up a scientific model of the process, which is not fully understood till now. A systematic relationship in order to develop a decision support for the users of laser machines is the main goal of this study. The test results show a strong difference between particles filled (talc) and fiber filled (glass) compounds. While for the first type a wide linear behavior between depth and laser power can be detected, for the second a quick saturation can be pointed out. Effects are described in the paper

Keywords: laser drilling plastics, additives

1. Introduction

The industrial use of advanced plastics is becoming increasingly important, especially in the automotive industry. The increasing demand on lightweight constructions can be met on the one hand by the substitution of metal elements with plastic and on the other hand by material mix. This follows that the proportion of plastics, especially in the interieur but even in the overall structure of automobiles continuously increases. This trend is further reinforced by the electrification of the automobile. As a consequence of this trend, machining processes that meet high standards of quality and productivity are needed.

Although the use of laser technology for the processing of fiber- or particle-reinforced plastics is steadily increasing, there are only a few scientific studies on the interactions that occur and in particular on the specific influences of various fillers. In 2005 F. Caiazzo (Univerity of Salerno) investigated the cutting of

* Corresponding author. Tel.: +49-3641-422-891;
E-mail address: martin.griebel@gmx.de.

different Polymers by CO_2-laser in general , F. Schneider,(Fraunhofer Institute Aachen) focused on HAZ reduction at the cutting of fiber reinforced polymers in 2013 and in 2011 A. Klotzbach (Fraunhofer Institute Dresden) published a paper regarding CFRP cutting with high brightness laser sources.

Fillers are used for the target optimization of thermal, mechanical and chemical properties. The type and concentration of fillers significantly affect the quality and efficiency of laser processing. Therefore, extensive investigations are required for each formulation of the plastic or of the compound, in order to set the correct processing parameters.

The typical process parameters when lase processing under industrial conditions are:

- laser power (amplitude, cw or pw)
- focusing (focal length) and spot size
- process gas type
- process gas pressure
- processing speed
- focus position towards surface of the part

The setting of the above mentioned parameters is in many cases empirical and determined through a high number of experiments, With the help of systematic investigations on relevant material types, basic interactions should be worked out, which is a valuable help for the user, as process parameters can be set faster without making long test series each time. These causal relations will help customers to achieve good results quickly.

The main goal of this study is to point out, how systemic influences of fillers affect the processing results of laser drilling and cutting. As the automotive industry uses a number of different plastics, the standard polymer polypropylene, which is installed in every car is tested.

The fillers are divided into fibrous fillers and particle fillers. Two typical fillers were selected, such as glass fiber as a fibrous filler and talc as particle filler.. The talc volume fraction of the different material samples is 5 - 30%, the glass fiber volume fraction 10 - 50%. The CO_2 laser is a universal tool used for plastic processing, as absorption and heat accumulation occurs on the surface, enabling melting and drilling.

Another purpose of this study is to determine the evaporated volume and the achievable perforation depth for multiple work cycles with constant parameters / energy input for the different filling materials and volume fractions. The basic polymer is always the same standard polypropylene grade. Due to huge variations between the polymer and the filling materials glass and talc (in terms of evaporation temperature and melting/evaporation energies) a strong influence of the filling material concentration can be expected. The geometrical shape fiber or particle should have minor influence.

The absorption of the 10.6µm wavelength of the CO2-laser is well suited for all material components.

Table 1. Technical properties of matrix and fillers

Property	Poly-Propylen	Talc	Glass fiber
density (g/cm³)	0.946	2.58-2.83	2.55-2.58
melting temperature (°C)	160	1500	1000-1600
specific heat capacity (J/(g*K))	1.7	0.871	0.807

The needed energy to heat up the composite for evaporation depends on the volume fraction and type of filler. The following diagram shows the calculated energy increase to heat up one mm³ to smelting temperature, only for the two fillers at different volume fractions.

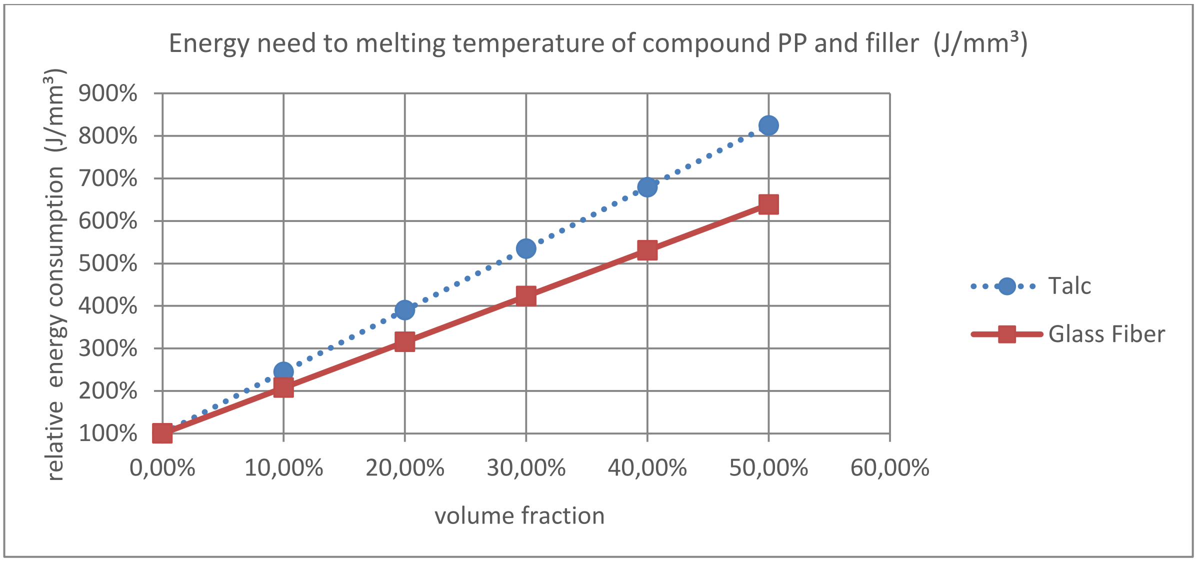

Fig.1. calculated energy increase to achieve melting temperature

Due to this estimation a similar reaction of the two filler types can be basically expected. To achieve equivalent perforation depths a proportional increase of the work cycles are necessary.

2. Experimental Setup

The laser processing run on a JENOPTIK VOTAN A Scan laser material processing machine. The beam source was a CO_2-laser with 400W average power. The model is operated in PWM (pulsed width modulation) mode and is characterized by a high pulse to pulse stability. The pulse peak values are 1500W, maximum Duty Cycle (DC) is 40% at 1000Hz repetition rate. The energy applied per work cycle at one hole is 0.525J with a TEM00 spot diameter of 0.45mm. The used 3-axis scanner has a focal length of 548mm which allows a scan field of 300x300mm.

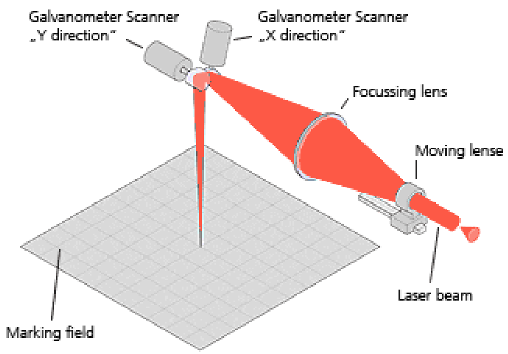

Fig.2. 3-axis scanning configuration

The scanning process requires several working cycles to finish the holes completely. The material sample remains fixed in its position, while the laser moves focused on the material sample surface along a predetermined contour. Each working cycle increases the depth of the holes by the exposition of a defined radiation energy volume to each hole

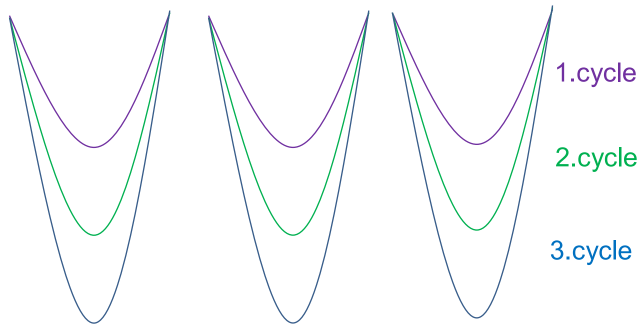

Fig.3. hole depth generation

The provided samples have a size of 80x80x4mm and are of Polypropylen, a basic polymer filled with different volumes of talc or glass fiber. To assure a proper analysis of all material samples a hole spacing of 1mm was chosen.

3. Results and discussion

3.1 Influence of the filler type on the penetration depth

The first series of tests should point out the influence of the material type referring to the reinforcement versus the increase of the penetration depth. Two types of material were tested:

Polypropylene reinforced with 30% talc

Polypropylene reinforced with 40% glass fiber

These two specific samples were chosen because of the same expected energy level needed to melt a defined volume as reported in Figure 1. The different properties of talc and glass causes the same energy increase for 30% talc and 40% glass fiber filling.

Test tracks with a steadily increasing number of work cycles were run on each material sample. In order to cover a larger range of thickness, three areas of material thickness were examined in single steps:

Table 2. ranges of working cycles

Range	PP GF 40 (work cycles)	PP talc 30 (work cycles)
1 (4mm material thickness)	1-9	1-9
2 (8mm material thickness)	23-28	26-31
3 (16mm material thickness)	52-55	55-62

After processing the sample, investigation was carried out along the perforation line through microscopy.

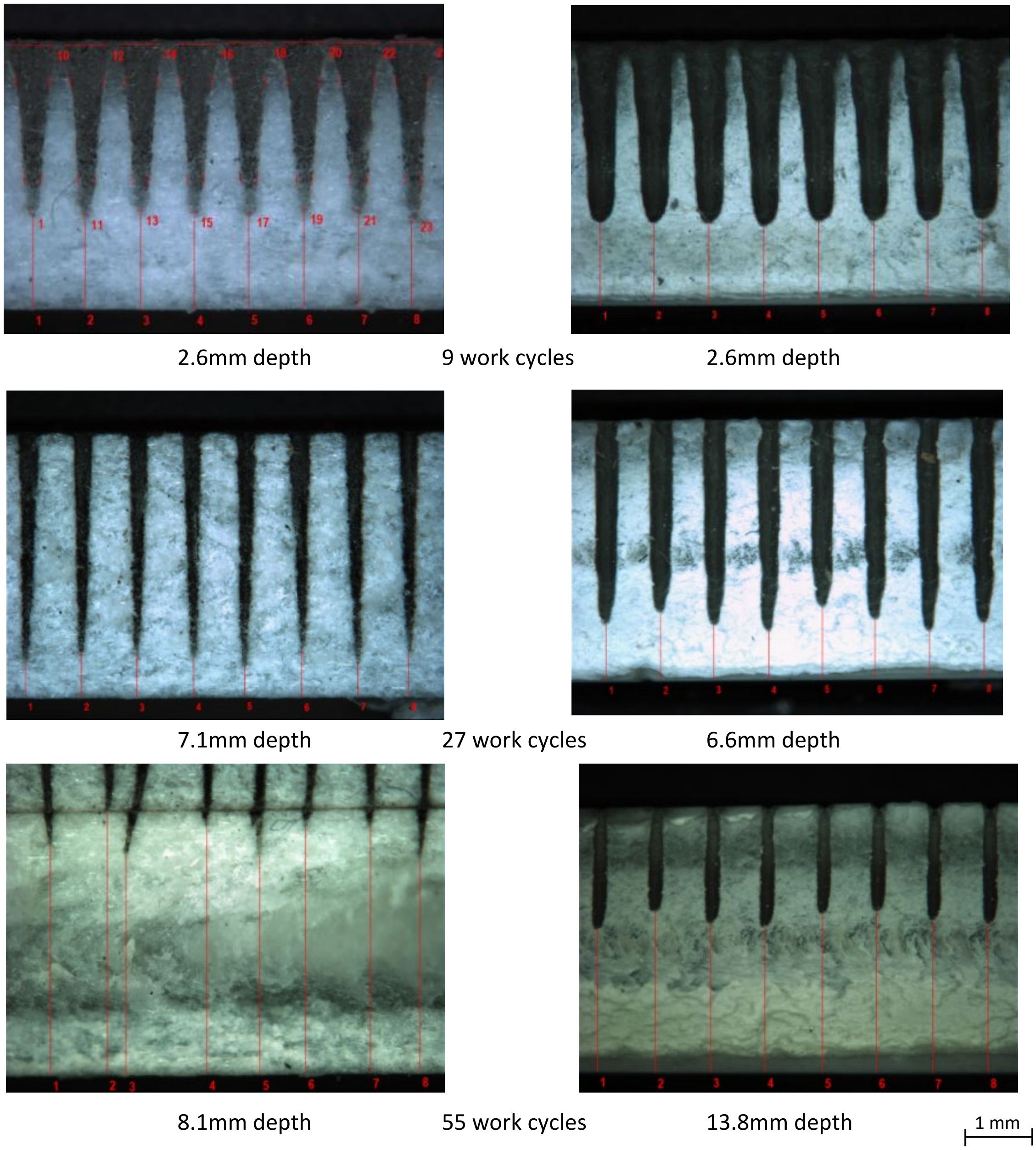

Fig.4. microscopic view after 9, 27and 55 working cycles (a) PP GF 40, (b) PP talc 30

Figure 4 illustrates the hole shape and depth at the 3 ranges of work cycle number at 9, 27 and 55 work cyles. The microscopic views show the bottom of the holes at different depth. In the first range up to 4 mm the depth increases simultaneous for both materials. The leading effect is the heating by heat conduction.

With increasing depth secondary effects become more important. First, the shape of the holes changes to very narrow in the glass fiber filled material at 8mm depth and then the drilling process stops for the glass fiber filled material. For the talc filled material the hole becomes slimmer by increasing depth but process does not stop.

The shape of the holes are significantly different by using glass fiber and talc as reinforcement material for the plastic component. While the holes in the GFRP (glass fiber reinforced plastic) show an arrow head shape the holes in talc filled plastic are more-less cylindrical up to high depth. The Gaussian energy distribution in the focal plane will shape the bottom of the holes only in talc filled samples.

The expectation is, that fibrous reinforcement materials show a much different reaction than particle consistent ones. Typically the evaporation temperatures and energy needs are much higher for the fillers than for the polymer matrix.

The following diagram illustrates how the penetration depth is increasing by the number of work cycles applied to the sample material.

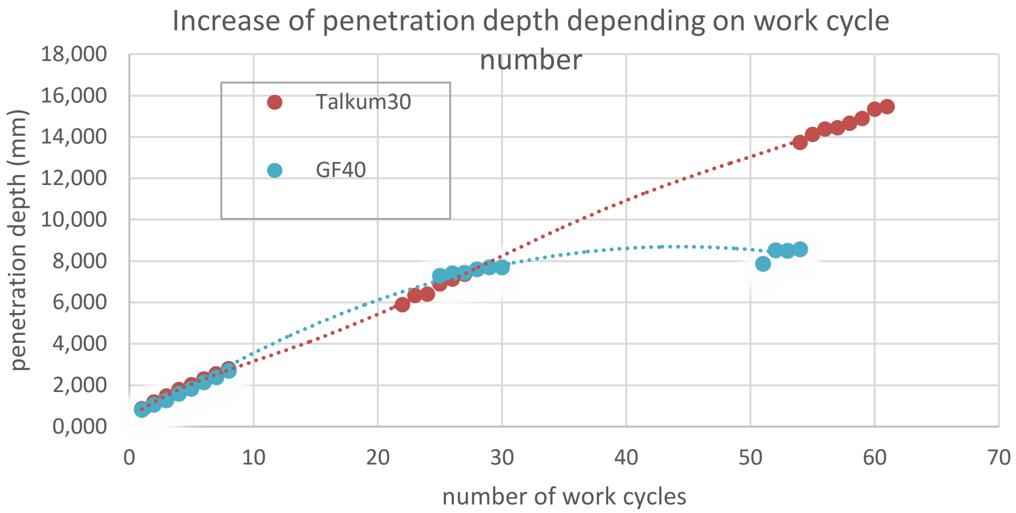

Diagram 1. increase of penetration depth depending on work cycle number

The test results approve that glass fiber filling will limit the penetration depth for a defined set of parameters. The same parameters allow a much higher depth for the talc filled compound.

It is assumed, that small particles will be directly exhaust with the evaporated matrix material. The plastic properties are important for the drilling process and the particles of the applied material should not evaporate. This saves energy and gives the cylindrical shape due to the low evaporation temperature of the polymer.

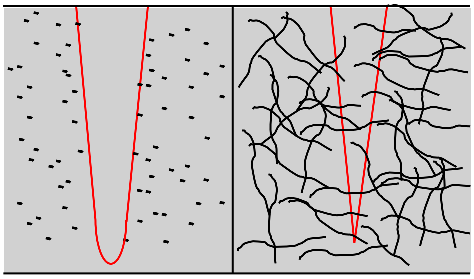

Fig. 5. schematic view a) talc filled b) glass fiber filled

For the glass fiber filled compound most of the fibers will stick into the solid polymer while the center of the hole is heated up and evaporated. The fiber material needs to be evaporated as well as the matrix. Due to the high intensity only the center of the Gaussian beam can evaporate the glass fibers directly. Remaining ends of fibers protrude into the hole and consequently block the radiation. Only the unidirectional distribution of the fiber orientation assures a certain percentage of fibers that reflect some radiation to the hole center. This may explain the high possible aspect ratio achieved at the narrow hole ground.

3.2 Influence of the concentration of the filling material to the process efficiency

Another test series investigates the influence of the degree of filling to the achievable depth at constant energy and work cycle level. Due to a strong difference between the properties of the filler and the matrix, a significant influence of the degree of filling to the hole volume can be expected.

To increase the accuracy of the measurement the hole shape was split into 5 sections approximated as truncated cones.

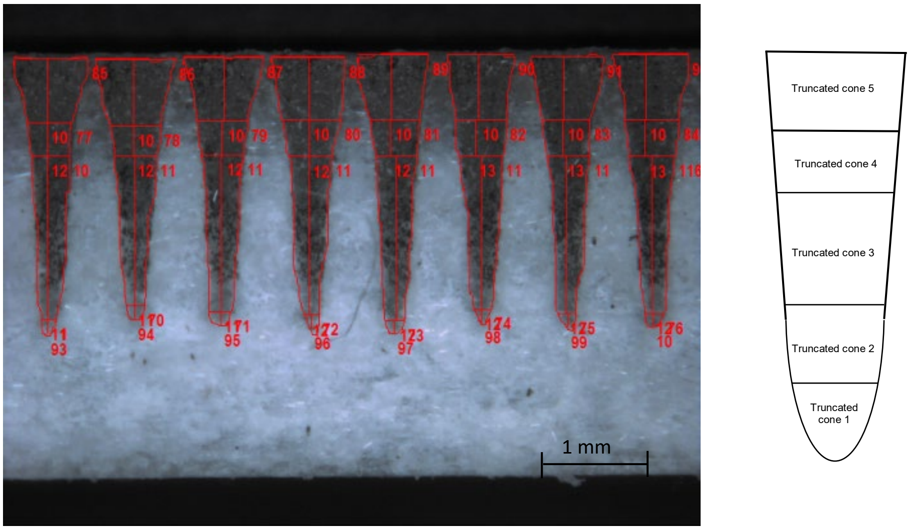

Fig. 6. Measurement scheme for volume calculation

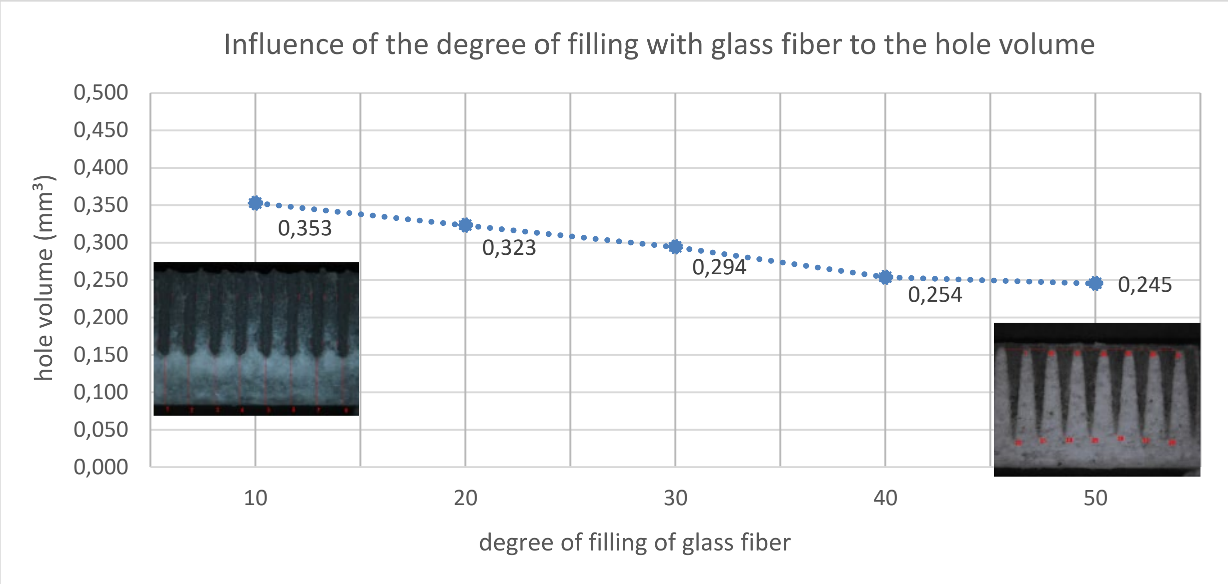

Diagram 2. influence of the degree of filling with glass fiber to the hole volume, standard deviation of the measurements is << 10%

The experimental results do not verify the theoretical expectation of a very strong increase of the proportional needed energy to the volume fraction of the glass fiber filling. Obviously the hole volume drops down with increasing the degree of filling but the effect is moderate compared with the material property change by increasing the filling rate from 10 to 50%. The reason must be found in significant side effects influencing the energy propagation inside the material. The fibers have a length of 3 to 6 mm and a diameter of 9 to 15 µm. The length of the fibers assure, that for typical hole diameters lower than 0.5mm, the fibers cannot be expelled by the generated gases. A diameter close to the wavelength will cause lower direct absorption inside the glass fiber and higher energy deflection into the matrix material.

4. Conclusion

Based on an analysis of the perforation result of plastic composites the influence of the filler concentration and filler properties as size and geometrical form to the process was investigated.

Two general statements can be derived:

1. The influence of the concentration is lower than expected. Even a volume fraction increase from 10 to 50% glass fiber results in a low hole volume drop of 30%.
2. The size and geometrical form shows the major effect to the perforation efficiency. As long the filler particles are much smaller than the exposed focal area they will be directly exhaust with the matrix material. Bigger particles such as glass fibers need to get evaporated as well what increase the energy need significantly.

As a result of the investigations it can be shown that the geometrical form of a filler material for plastic compounds is significant for the overall evaporation rate as well as the mechanical and thermal properties. The two compared materials talc and glass fibers are very close by melting temperature, density and specific heat capacity but show strong differences in the perforation result.

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