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Analysis of Laser Ablation of CFRP by Ultra-Short Laser Pulses with Short Wavelength

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Abstract

Material processing of carbon fiber-reinforced polymers (CFRP) by means of shape-cutting technologies is state-of-the-art today. These processes still perform in some applications with lack of part quality such as delamination and low processes productivity. Therefore, laser processing by ultra-short laser pulses has a great potential in material ablation of CFRP. Nevertheless laser process parameters have to be adjusted carefully to reduce extension of heat affected zone (HAZ) and its influence on part quality [1].

Keywords: laser ablation; CFRP; laser processing; pulse laser; pico-second laser; composite

1. Introduction

Laser material processing of CFRP by pulsed laser radiation has been analyzed since late 1980s and early 1990s [2, 3, 4, 5, 6]. Although great potential of laser processing concerning part quality has been demonstrated, available laser beam sources such as Excimer or pulsed Nd:YAG laser led to long machining time and therefore to low process productivity and low cost effectiveness. Hence, laser processing by pulsed laser radiation has not been launched industrially. Pulsed laser beam sources with high beam power and short pulses are available for industrial application only for some years. These laser beam sources are available for low investment cost with high repetition rate of pulses leading to high productivity. Thus, laser ablation of FRP and especially CFRP by pulsed laser radiation for industrial applications has to be analyzed carefully again [7].

2. Experimental Analysis

First step of laser ablation of CFRP by laser pulses is the analysis of the important laser ablation and process parameters. These parameters are shown in Figure 1. It was demonstrated by preliminary experimental analysis that laser beam power, pulse frequency and wavelength of laser beam have a considerable influence on quality

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characteristics such as HAZ or delamination. Therefore, the effect of these parameters on part quality was analyzed by experimental analysis.

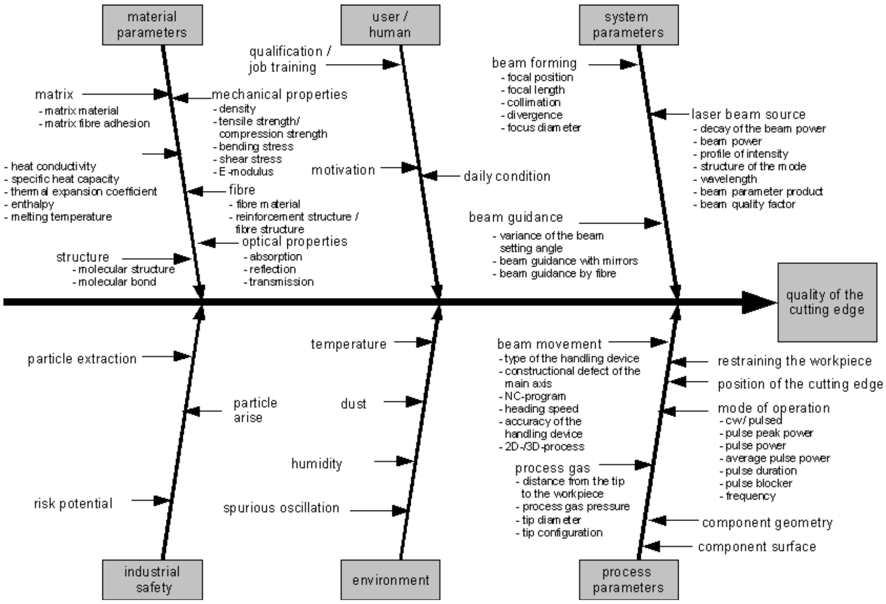

Figure 1 - Cause-Effect-Diagram of laser beam processing of FRP and CFRP

One challenge of laser processing of CFRP is the reduction of the extension of the HAZ at cutting edge, see Figure 2. Because of this HAZ, laser processing is not used in e. g. aerospace industry today. The HAZ is a result of the big difference between the decomposition temperatures of resin and fiber material. The decomposition temperature of carbon fiber is about 3000 K and of epoxy resin about 550 K.

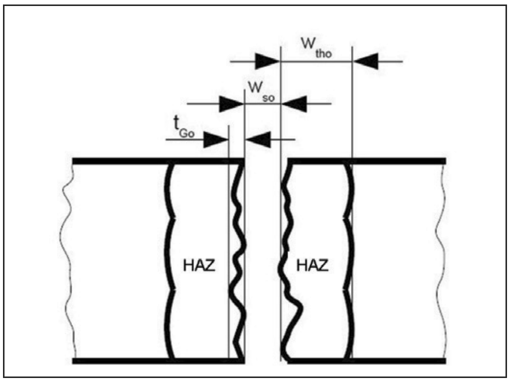

Figure 2 – Principle of measurement of the Heat affected zone at processed edge of cavity

As a result of last scientific investigations the HAZ measured at about 1.0 to 2.0 mm [1, 4, 5, 6, 7]. Therefore manufacturing engineers still do not reconsider laser processing of CFRP even though high quality of edge of processed cavity with a low HAZ is realizable today, see Figure 4 [q. v. 3, 4]. High part quality with a low HAZ was only realizable by infrared Excimer laser beam sources so far. But these laser beam sources are not attractive for industrial applications due to high investment cost and very low process productivity.

3. Results of experimental analysis

3.1. Determination of maximum process temperatures

In first investigations pyrolysis of the epoxy resin has been examined to determine maximum process temperatures at cutting edge. By a thermo gravimetric analysis (TGA) mass reduction with rising temperature of a polymer can be analyzed and thus the maximum process temperature can be determined. Up to a temperature of about 280°C the epoxy resin is stable and almost no mass reduction occurs. Mass reduction of about 0.5 to 1.0 percent is caused by evaporation of water which was bounded when a epoxy resin hardens. At temperatures above 280 °C the pyrolysis of the epoxy resin increases and at about 600 °C the epoxy resin is almost completely dissolved. Typically, a maximum process temperature between 80 to 120 °C is used for shape cutting or milling processes. As shown in Figure 3 temperatures higher than 120 °C have no effect in the pyrolysis of epoxy resin up to a temperature of 280 °C. This described approach is well documented in several publications and was used for other polymer-resins [4, 6]. Further studies will therefore focus on part quality at higher maximum process temperatures.

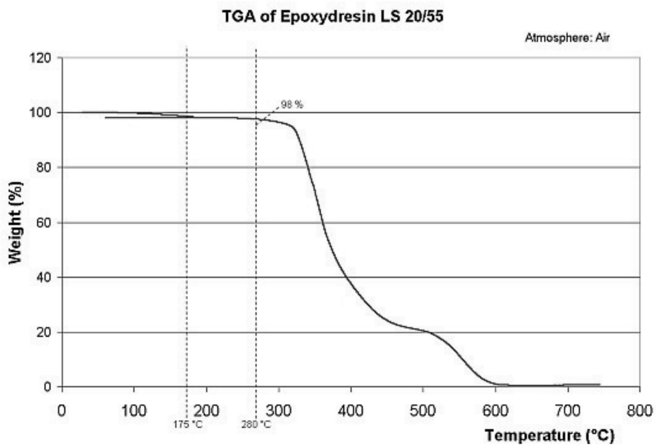

Figure 3 - Thermo gravimetric analysis of an epoxy resin (max. Temperature 700 °C, heating time 25 min, air atmosphere)

3.2. Identification of relevant process parameters

Since the 1980s the influence of laser process parameters on part quality was analyzed intensely [1, 4, 5, 6, 7]. The mayor parameters are shown in the cause-effect-diagram in Figure 1. This analysis turned out that laser process parameters such as laser power, feeding rate, wavelength or laser control mode have a dominant effect on part quality. Therefore, these parameters have been varied in order to analyze resulting part quality. A comparable experimental study has been conducted by Tagliaferi in 1987 for processing of glass fiber and aramid fiber reinforced polymers [6].

3.3. First results of experimental study using a 532 nm fiber laser and a 1.064 nm solid state laser

First experimental analysis concerning laser ablation of CFRP by means of 1 ns fiber laser beam sources with a wavelength of 532 nm and a 2 ps solid state laser with a wavelength of 1.064 nm were conducted. Therefore, quadratic cavities were machined into a CFRP laminate and the quality of the edge such as the extension of the HAZ was analyzed.

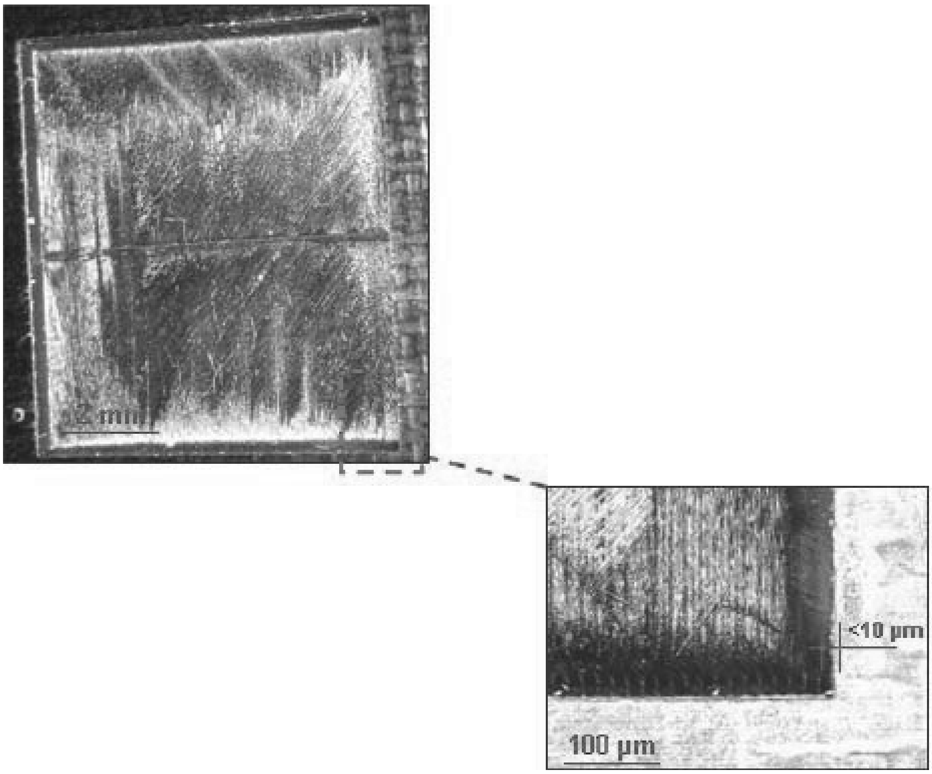

Figure 4 - Small extension of Heat Affected Zone at the edge of processed cavity by a green fiber laser (laser power 5 W, feeding rate 400 mm/s, pulse frequency 300 kHz, pulse length 1 ns)

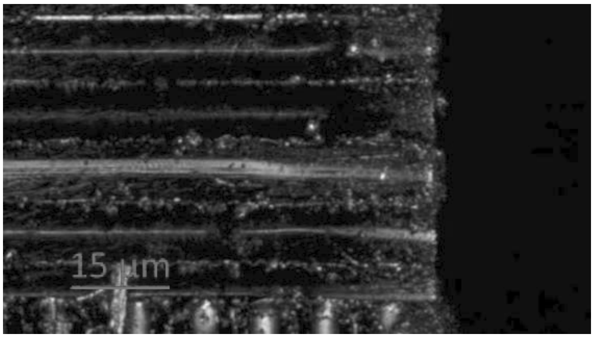

Figure 5 - Extension of the HAZ at the processed edge by a Pico-second laser

Extension of the HAZ is typically between 10 µm and 20 µm as shown in Figure 4 and Figure 5. At edge of processing no cracks or delamination could be determined. Therefore, no thermal damaging influence occurs on material and material properties by laser ablation. Thus, the so called “cold material processing” with almost no thermal influence on material can be realized by laser ablation.

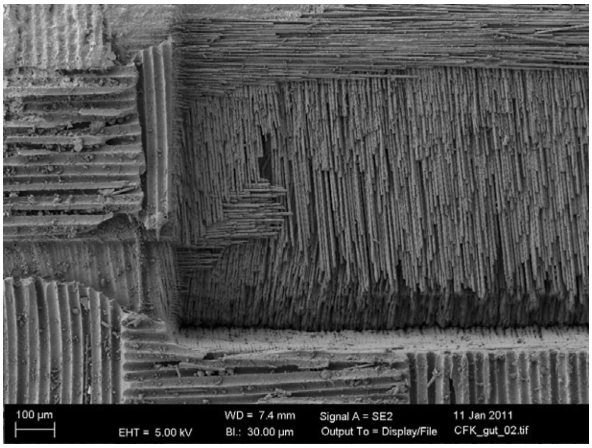

Figure 6 - SEM micrograph of the edge of processed cavity

By SEM analysis it turned out that very high qualities with low thermal influence on material is realizable, see Figure 6. In Figure 6 little delamination with free-standing fibers could be determined. But this effect is overall very low and comparable to conventional processing by shape-cutting technologies.

3.4. Influence of pulse length and wavelength on extension of HAZ according to first results of experimental analysis

Major challenges for material processing of multiple component material such as CFRP or GFRP are highly different thermal and optical material properties. Different properties of fiber and resin material are the challenge for laser material processing of CFRP. In the model for description of absorption of laser radiation with short wavelength the fiber is described as a so-called “full absorber” whereas resin is “transparent”. Absorption of CFRP laminate is therefore described as a combination of both fiber and resin material and is strictly dependent of the wavelength of laser radiation. Maximum of absorption is reached at 10.6 μm wavelength of a CO_2 laser beam source while minimum is reached at about 1.0 μm wavelength of solid state laser beam sources. For decreasing wavelength such as 532 nm the absorption rises again to a certain extend but is still lower than for 10.6 μm wavelength. Therefore, laser material processing of CFRP by CO_2 laser beam sources is state-of-the-art today. Laser material processing with shorter wavelength has to be analyzed carefully.

It was demonstrated that very high process quality with a small extension of HAZ is realizable by means of laser ablation technologies see Figure 4. Extension of HAZ is less than 20 micron and therefore up to ten times lower than in past analysis. The minimum radius at the corner of cavity is lower than 50 micron. Thus, it was demonstrated in first analysis that laser processing of CFRP by an industrially available ultra-short pulse laser is realizable with highest part quality. Wavelength of laser beam has still an influence on process quality and maximum feeding rate and therefore process productivity. But state-of-the-art fiber lasers have been able to show their industrial applicability. Increasing absorption of laser radiation with a short wavelength such as 532 nm leads to both highest quality with low extension of HAZ and high process productivity with an ablation rate of material of some cm^3/min. Based on promising results, processing by 532 nm fiber laser is going to be analyzed intensely during further experimental study.

It turned out during experimental analysis that pulse length has a significant influence on quality of material processing especially for use of ultra-short pulse laser beam sources. Excitation of molecule chain of polymer resin and fiber material is reduced with decreasing length of laser pulses. Therefore, more energy of laser radiation is available for exceeding bond energy between molecules and thereby decomposition of CFRP laminate. Thus, extension of HAZ could be reduced by use of nano- and pico-second pulse laser beam sources. It is therefore acceptable to conclude that the influence of wavelength on quality of material processing decreases with decreasing pulse length. Laser material processing of CFRP by ultra-short lasers pulses such as pico-second pulses has to be analyzed carefully during further experimental study. State-of-the-art ultra-fast pulsed laser beam sources provide high productivity and due to low investment cost a competitive cost effectiveness compared to conventional shape-cutting technologies. Because of decreasing investment cost of laser system technologies in the next years these advantages will increase to a certain extend.

4. Conclusions

Shape-cutting technologies such as milling or drilling are state-of-the-art for processing of CFRP today. Due to significant development of laser beam sources during the last years, laser manufacturing processes are applicable today for cost effective processing of CFRP with high productivity. Highest quality of the ablation at edge processing such as the extension of HAZ of less than 20 micron leads to a great potential for industrial application of laser technologies. Therefore, laser processing is a competitive manufacturing technology compared to shape-cutting technologies and is going to establish as a competitor technology for drilling or milling processes.

References

[1] Emmelmann, C.; Goeke, A.: "Influence of laser cutting parameters on CFRP part quality" in Elsevier Physics Procedia 5, Pages 253-258 (2010)

[2] Trasser, F.: "Laserstrahlschneiden von Verbundkunststoffen : werkstoff-orientierte Prozessauslegung des Laserstrahlschneidens von aramid- und glasfaserverstärkten Duroplasten", PHD Thesis, RWTH Aachen (1992)

[3] Tagliaferri, V.; Dillo, A.: "Machining of fiber reinforced material with laser beam: cut quality evaluation" in Proceedings of the Sixt International Conference on Composite Material (1987)

[4] Pan, C.; Hocheng, H.: "The anisotropic heat affected zone in the laser grooving of fiber-reinforced composite material", Journal of Material Processing Technology Volume 62, Pages 54-60 (1996)

[5] Pan, C.; Hocheng, H.: "Prediction of laser-induced damage of fiber mat and fiber mad-ud reinforced polymers", Journals of Materials Engineering and Performance Volume 7, Pages 751-756 (1998)

[6] Tagliaferri, V.; Caprino, G.: "Maximum cutting speed in laser cutting of fiber reinforced plastics", Journal of Machine Tools and Manufacturing Volume 28, Pages 389-398 (1987)

[7] Richter, L.: "Schädigungsarme Präzisionsbearbeitung von CFK-Bauteilen", Talk at LAFA2009 – Laserbearbeitung von Faserverbundkunststoffen" (2009) 25, 1037-1067 (1953).