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Optimizing the CO_2 laser cutting behavior of polycarbonate

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Abstract

Polycarbonate is a transparent and colorless plastic with excellent physical and chemical properties and is therefore used for a wide range of applications. CO_2 lasers are particularly suitable for cutting plastics due to their wavelength and the corresponding absorption curves. Despite the high absorption, the CO_2 laser cutting quality of polycarbonate is low and results in a brown discoloration of the cutting edge. This phenomenon has not yet been fully examined or understood.

The aim of this study is to improve the cutting quality and research the cause. To investigate the behavior of polycarbonate and improve the cutting quality, polycarbonate plates with different additives have been examined. The material has been cut with a CO_2 laser with different wavelength of 9.3 µm and 10.6 µm. Further parameters like the type of cutting gas, gas pressure and frequency have been varied. This parameter study gives an overview on how to choose the right polycarbonate and suitable cutting parameters to achieve the best possible edge quality for industrial applications.

Keywords: CO_2 *laser; Laser cutting; Plastic; Polycarbonate*

1. Introduction

Polycarbonate (PC) is a material that, due to its excellent physical and chemical properties, is in high global market demand. The advantage of this thermoplastic lies in its higher toughness, breaking strength and transparency as well as high heat resistance. These attributes make polycarbonate attractive in the automotive, medical and mechanical engineering industries. Additives can be used to further improve the properties of polycarbonate and allow its use in different environments.

In general, CO_2 lasers are particularly suitable for cutting plastics due to their long wavelength and the corresponding absorption curves of the plastics. Despite the high absorption of polycarbonate, when cutting it with a CO_2 laser the cutting quality is low. Although it is easy and fast to cut, the resulting cutting edge often shows yellow to brown discolorations as observed by Holl et al. (2015). Polycarbonate is often used as a substitute for glass or PMMA in optical applications and even a small tint can influence the transmission properties of the component as discussed by de Brouwer et al. (2015). Therefore, the aim of this parameter study is to find the best processing parameters, to achieve the best possible cutting quality.

Absorption describes the interaction between material and laser and is one important factor that influences the cutting quality. When a polymer absorbs infrared radiation, its chemical bonds will vibrate, which results in stretching and bending of that bonds. To achieve an efficient absorption the energy of the photons must match the distinct vibrational energy of the molecule bond. Polycarbonate shows an increased absorption at 1080 cm^{-1} which corresponds to a wavelength of 9.26 µm. This absorption peak represents the C–C–C bending vibrational modes in the backbone of the polycarbonate polymer chain as described by Kraus et al. (2008).

To compare the influence of the wavelength, experiments with 9.3 µm and the standard CO_2 wavelength of 10.6 µm were performed. Further parameters like type of cutting gas, gas pressure, cutting speed and laser frequency have been varied. The resulting test series shows a trend with a strong dependency on frequency and gas pressure. This paper gives an overview on how to choose the right polycarbonate and suitable cutting parameters to achieve the best possible edge quality for industrial application.

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2. Experimental Details

2.1. Setup

The Synrad Pulstar Series p150 and p250 lasers with the wavelengths of 9.3 µm and 10.6 µm were used for the material processing in combination with a fixed cutting head setup with a focusing lens. The output power of both lasers was measured and adjusted to an average power of 100 W.

The laser beam is directed to the beam delivery setup via three mirrors, where it is focused by a 3,75” lens on the material surface. The cutting head has an assist gas inlet and a pressure gauge to adjust the assist gas flow. The optics are fixed in position while the material moves through the stationary focus. The focused spot size on the surface of the material is approximately 160 µm.

2.2. Parameters

A lot of parameters must be taken into consideration when investigating this cutting process. These include laser parameters such as wavelength, laser power or frequency. The frequency influences the operation mode of the laser, at 1 kHz the laser sends out discrete pulses. At 50 kHz, due to a rise/fall time of 50 µs/100 µs, the laser works in a quasi-continuous wave mode. Further process parameters like the cutting speed, kind of assist gas and the assist gas pressure must be considered.

The main goal is to find the best parameters for the highest cutting quality. To achieve a complete cut-through in some cases it was necessary to reduce the cutting speed. Table 1 lists an overview of all parameters that have been varied during the experiments. Always one parameter was kept variable and the others were fixed. The assist gas pressure, the frequency and the cutting speed were tested within a certain range. All tests were performed with pressured air and nitrogen as assist gas and every cut was repeated for 9.3 µm and 10.6 µm. The laser power was chosen to be constant at an average power of 100 W for all tests and both wavelengths. All cuts shown in the results section were performed with a wavelength of 9.3 µm, if not mentioned differently.

Table 1. List of varied parameters and their range.

Parameters	Parameter Range
Wavelength	9.3 µm or 10.6 µm
Frequency	1 kHz to 50 kHz
Velocity	20 mm/s to 70 mm/s
Assist gas	Pressured air or nitrogen
Gas pressure	1 bar to 4 bar

A cooperation with Covestro Deutschland AG, a manufacturer of high-tech polymer materials, enabled us to test three different polycarbonate types. The materials are described as Makrolon® 2405 (standard grade), Makrolon® AL 2447 (UV-stabilized) and Makrolon® 6555 (flame-retardant). All polycarbonate plates have a dimension of 200 x 150 mm with a thickness of 2 mm.

3. Results

3.1. Influence of the gas pressure

The test was performed at 100 W average laser power with 50 kHz frequency and a cutting speed of 70 mm/s. Gas pressures of 1, 2, 3, and 4 bar were investigated.

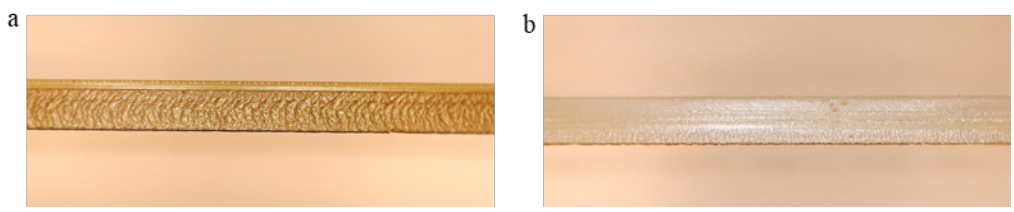

Fig. 1. (a) standard grade PC cut with 1 bar of pressured air; (b) standard grade PC cut with 4 bar of pressured air.

It was found that a high gas pressure results in a clean cutting edge with hardly any discoloration. This behavior seems to be linear as with increasing pressure the discoloration of the edge gets less pronounced. The assumption is, that the high pressure expels the melt and decomposition products more quickly, so it cannot interact with the surface of the cutting edge.

3.2. Influence of assist gas type

Pressured air and nitrogen as an assist gas were compared at 4 bar. The test was performed at 100 W average laser power with 50 kHz frequency and the cutting speed set close to the maximum full cut-through speed. Overall the results with both gasses are comparable and neither shows an improvement over the other.

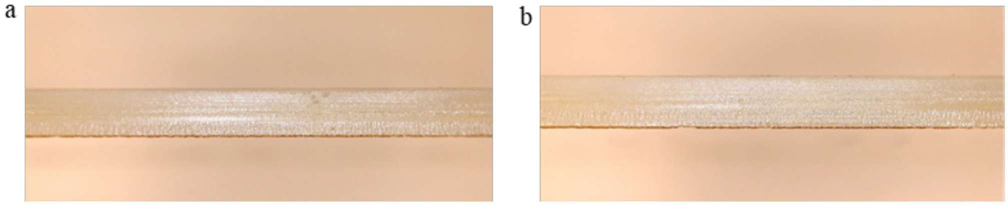

Fig. 2. (a) standard grade PC cut with 4 bar of pressured air; (b) standard grade PC cut with 4 bar of nitrogen.

The use of nitrogen could not prevent the discoloration or improve the cutting edge over the already excellent result using air. Due to the cooling effect of nitrogen the cutting speed must be reduced to achieve a complete penetration. As a result, the velocity in these tests was 70mm/s for air while it was 60mm/s for nitrogen.

3.3. Influence of the frequency

The frequency tests were performed with 100 W average laser power and 4 bar of assist gas pressure at a cutting speed of 70 mm/s. The following frequency steps were used: 1, 2, 5, 7, 10, 20, 30, 50 kHz. This row shows a noticeably linear behavior, as with increasing frequency the discoloration of the edge gets reduced.

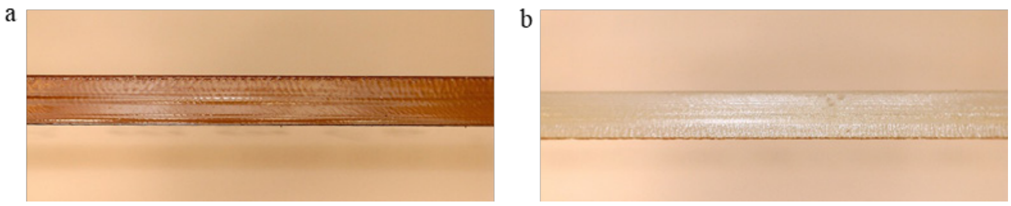

Fig. 3. (a) standard grade PC cut with a frequency of 1 kHz; (b) standard grade PC cut with a frequency of 50 kHz.

This observation indicates that pulsed laser operation, especially at low frequencies, results in a more discolored cutting edge. It is assumed, that the high peak power of 550 W at 1 kHz leads to the decomposition of the polycarbonate. Additionally, the low heat affected zone in the surrounding area in combination with the long off-time between the pulses results in the quick solidification of the discolored melt and decomposition products, before they can be expelled by the cutting gas. In order to achieve a clean cutting edge, cutting in a quasi-continuous mode is required.

3.4. Influence of the cutting velocity

The maximum cutting speed for the standard grade polycarbonate at 100 W average power and 4 bar of pressured air was found to be 70 mm/s. The velocity was reduced to 50, 30 and 20 mm/s and compared.

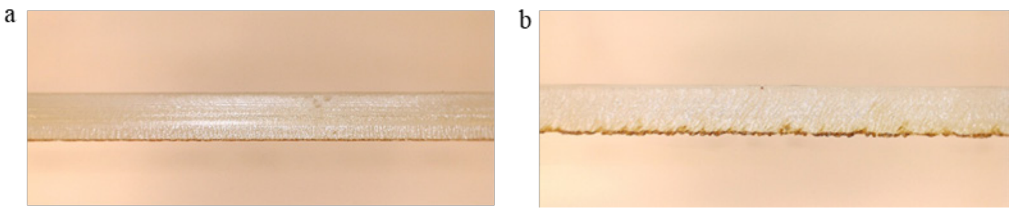

Fig. 4. (a) standard grade PC cut with a velocity of 70 mm/s; (b) standard grade PC cut with a velocity of 20 mm/s.

It is observed, that at lower speeds the discoloration tends to concentrate further down the cutting edge. At 20 mm/s a distinct line is visible at the edge on the laser exit side. This could be due to the cutting gas which has more time to interact with the melt and pushes it down, where it then accumulates and solidifies. Furthermore, the longer exposure time to the laser might result in more decomposition and melting. All this adds up to a roughened cutting edge with a more visible discoloration.

3.5. Influence of the laser wavelength

A Bruker Alpha Diamond ATR Spectrometer was used to measure the absorbance spectra curve of the standard grade polycarbonate. As shown in Fig. 5. the absorption of polycarbonate at 9.3 µm is approximately four times higher compared to the CO_2 standard wavelength 10.6 µm.

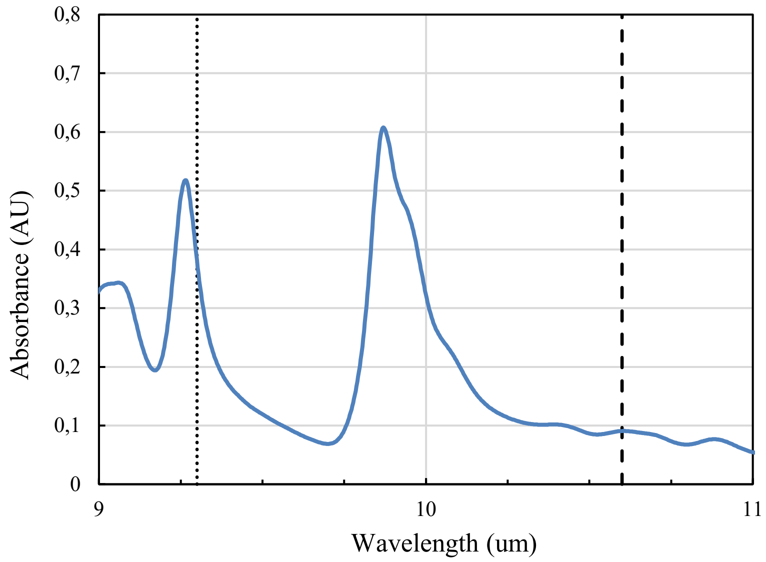

Fig. 5. A measured FT-IR absorbance curve of a standard grade PC. The 2 vertical lines indicate the 9.3 µm (dotted line) and 10.6 µm (dashed line) wavelengths.

Both wavelengths were tested at the same average laser power, with 50 kHz and 4 bar of pressured air. Due to the difference in absorption, the maximum cutting speed at 10.6 µm is 50 mm/s instead of 70 mm/s at 9.3 µm. The cut with 10.6 µm produces a completely colorless edge but a very rough surface. The surface produced with 9.3 µm is much smoother but show some residual tint on the edge.

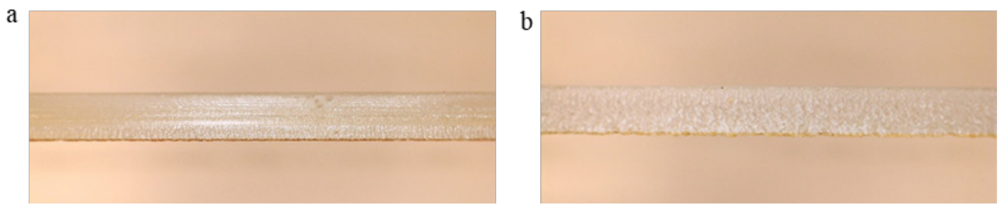

Fig. 6. (a) standard grade PC cut with a wavelength 9.3 µm; (b) standard grade PC cut with a wavelength 10.6 µm.

3.6. Influence of the material composition

As mentioned above three polycarbonates with different additives were provided. An absorption measurement with the spectrometer did not show a difference in the absorption behavior, but a difference in cutting quality is visible. Due to the manufacturing process the flame-retardant polycarbonate is insignificantly thicker, than the other two polymers.

Fig. 7. (a) standard grade PC (b) UV-stabilized PC (c) flame-retardant PC.

For all tests the standard grade and the UV-stabilized polycarbonate show similar results. These two materials can be cut close to perfection with the right choice of parameters. The polycarbonate with the flame-retardant additive behaves differently and no suitable parameter set could be found so far. The cutting edge shows distinct black ridges which probably occurs from carbonization.

4. Discussion

The aim of this parameter study is to find the best cutting parameters to achieve a clean cutting edge on different polycarbonate samples.

It was observed, that the additives have a significant influence on the cutting result, therefore knowledge about the composition of the material is crucial for industrial applications. Choosing a high frequency results in a quasi-continuous wave mode and leads to much better cutting results in comparison to pulsed operation. Due to the bigger pulse distance at low frequencies the assist gas can cool the melt more efficient, that then solidifies and sticks to the cutting edge.

The assist gas pressure is an important factor for improving the polycarbonate cutting quality, this is in accordance to the findings of Choudhury et al. (2010), who, as well, observed a significant effect of the air pressure on the cutting quality. The reason is, that at high assist gas pressure the melt can be cast out quickly and more efficiently. An advantage of nitrogen over air was not observed.

A comparison between the two wavelengths 9.3 and 10.6 µm reveals a difference in cutting quality and speed. Due to the lower absorption at 10.6 µm the energy is not used as efficiently, as the laser beam gets reflected and transmitted more. The excess energy dissipates further into the material and leads to a bigger melting zone. This results in less discoloration but a higher surface roughness. The reduced discoloration can origin from the lower absorption which results in less energy for chemical decomposition. Further the higher surface roughness observed with 10.6 µm indicates more melting, which could lead the conclusion, that the decomposition products might be expelled more efficiently due to the bigger melting zone. Overall the weaker absorption leads to a reduced cutting speed by approximately 30%.

Our findings lead to the conclusion that there is a temperature regime, where the material melts without decomposition. Above that decomposition and thus discoloration takes place.

The best result, in terms of avoiding discoloration, was achieved in quasi-continuous mode with a wavelength of 10.6 µm with an average power of 100 W, 50 mm/s and a gas pressure of 4 bar with compressed air. The economically most viable choice is a 9.3 µm laser in quasi-continuous mode. The resulting cutting edge suffers only from a very small discoloration but allows a higher cutting speed and surface smoothness at the same average output power. Furthermore, as nitrogen and pressured air result in a similar edge quality, pressured air should be chosen to reduce cost.

5. Conclusion

The present work shows the influence of some selected parameters on the CO_2 cutting quality of 2 mm thick polycarbonates. A good, high quality cutting edge was found. The discoloration reaction could not be fully prevented but by expelling the material from the interaction zone fast enough the cut surface remains clean.

Other parameters like focus size, laser power or material thickness have not been investigated but might be of interested in the future, as they have an influence on the laser cutting behavior. To study the effect of each parameter on the quality, as well as the interaction between the factors a factorial experiment might be of advantage. As this analysis considers all possible combinations of parameters and their values, it would provide more information and a better understanding of the overall cutting process.

As Fig. 5

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