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Spectral analysis of laser processing of carbon fiber reinforced plastics

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Abstract

Spectra of the optical process emissions of carbon fiber reinforced plastics (CFRP) processing with a continuous wave (cw) thin disk laser are recorded for a basic characterization of the ablation process. The observed line spectra show a characteristic spectral line at a wavelength of 588.95 nm that is found to be atomic sodium (Na I). No spectral lines of atomic or ionized carbon appear in the recorded spectra leading to the conclusion that only a small fraction of C-atoms is ionized.

Keywords: CFRP; laser cutting; optical spectroscopy; thin disk laser

1. Introduction

Analysis of optical process emissions in continuous wave (cw) laser processing of carbon fiber reinforced plastics (CFRP) is one important step towards basic understanding of the process. Spectroscopic investigations of optical process emissions provide information about the temperature and particle density in the interaction region as well as the excitation state of the atoms and molecules during the ablation process. Therefore identification of the spectral lines and their respective elements and selection of appropriate lines is the first step. Furthermore, detection of characteristic signals in the process emissions is the key to develop process monitoring and process control.

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There are numerous studies dealing with laser processing of carbon materials to be found in literature. Most of them are focused on the investigation of optical process emissions during pulsed laser ablation of carbon materials using lasers of different wavelengths including UV, Abdelli-Messaci et al., 2005, solid state lasers in the near IR, Harilal et al., 1997 and Parigger et al., 2003, up to CO$_2$ lasers, Camacho et al., 2008. The observed spectra in these studies are mostly dominated by line emissions of molecules, atoms and ions of carbon or the surrounding ambient gas. But the high energy densities that are obtained by pulsed laser ablation are not reached in cw laser processing. However, there are only few studies dealing with cw laser processing of CFRP. Niino et al., 2012 investigated the optical process emissions in the ablation plume during cw laser cutting of CFRP with a fiber laser. They observed blackbody emission of 2500 K superposed with line emissions of C$_2$ and CN molecules.

The investigations in this paper are focused on the optical process emissions from the process area during cw laser processing of CFRP.

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<th>Nomenclature</th>
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<td>$A_{nm}$</td>
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<td>$c_0$</td>
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<td>$\varepsilon_{nm}$</td>
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<td>$\lambda$</td>
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2. Theory

In laser processing of CFRP the laser radiation is absorbed by the carbon fibers and epoxy resin and the material is removed by evaporation. So there is a certain amount of evaporated material and hot gas surrounding the process area. In a hot gas emission of spectral lines can appear due to electron transitions between different energy levels in the atoms or ions in the gas. If the gas is in local thermodynamic equilibrium (LTE) the emission coefficient of a spectral line can be expresses as: Bernhard, 2004
\[ \varepsilon_{nm}(\lambda, T) = \frac{h \cdot c_0 \cdot g_n \cdot A_{nm}}{4\pi} \cdot \frac{n(T)}{\lambda_{nm}} \cdot Z(T) \cdot \exp\left(\frac{-E_n}{kT}\right). \]  

(1)

In Eq 1 \( \varepsilon_{nm} \) yields the total radiance emitted spontaneously by a spectral line. This radiance, however, is not emitted by an ideally thin line of one single wavelength, but is distributed within a line profile of a certain width. The center wavelength \( \lambda_{nm} \) of the spectral line is determined by the energy difference between the upper and lower energy level of the respective electron transition, whereas the shape of the spectral line profile depends on the broadening mechanism. There are different mechanisms of line broadening resulting in different line shapes. The natural line width is determined by the lifetime of the excited energy levels, Bergmann-Schaefer, 1981. It is independent of the wavelength and yields a Lorentz-profile with a line width of \( \Delta \lambda_{H} = 1.18 \times 10^{-5} \text{ nm} \), where \( \Delta \lambda_{H} \) is the full width at half maximum (FWHM), Traving, 1968. Other broadening mechanisms are the Doppler broadening which yields a Gaussian profile with line widths typically in the order of several hundredths of nm (FWHM) and the pressure broadening which yields again a Lorentz-profile. In the case of pressure broadening the line width can be up to several nm and it can also result in a shift of the center wavelength of the spectral line, Bergmann-Schaefer, 1981. The distribution of the emitted radiance within the profile can be taken into consideration by inserting the normalized line profile \( S(\lambda) \) of the spectral line into Eq 1 and so the emission coefficient can be written as:

\[ \varepsilon_{nm}(\lambda, T) = \frac{h \cdot c_0 \cdot g_n \cdot A_{nm}}{4\pi} \cdot \frac{n(T)}{\lambda_{nm}} \cdot Z(T) \cdot \exp\left(\frac{-E_n}{kT}\right) \cdot S(\lambda). \]  

(2)

If the shape of the spectral line is a Lorentz-profile the line profile can be described by:

\[ S(\lambda) = \frac{1}{\pi} \cdot \frac{\frac{1}{2} \Delta \lambda_{H}}{\left(\frac{1}{2} \Delta \lambda_{H}\right)^2 + (\lambda - \lambda_0)^2}. \]  

(3)

In addition to the previous described broadening mechanisms, which are all caused by the emitting gas itself, there is also a broadening which results from the optical system used to record the spectra. In most cases, however, the broadening of a spectral line isn’t caused by a single mechanism, but by a combination of different mechanisms. If all contributing mechanisms yield the same type of line profile, the resulting line profile is also of this type. If the broadening mechanisms are of different profile types, then the resulting line profile is a convolution of the different profile types, Traving, 1968.

Furthermore, if there are molecules in the hot gas, there can appear emissions of molecular bands which are caused by transitions between different rotational or vibrational states of the molecules in the gas, Lochte-Holtgreven, 1968.

3. Experimental setup

The experiments are made with a Trumpf TruDisk5001 thin-disk laser operating at a wavelength of 1030 nm. The laser beam is delivered to the focusing optics through an optical fiber with a core diameter of 100 μm. The focusing optics consists of a collimation and a focusing lens with focal lengths of 200 mm each, resulting in a focal diameter of 100 μm. A sketch of the experimental setup is shown in Fig 1.
The spectroscopic measurements are carried out during cw cutting of CFRP samples with unidirectional fibers with cutting direction perpendicular to the direction of the carbon fibers. The thickness of the samples is 2 mm and the focus position is on the sample surface. The laser power is varied between 1 kW and 5 kW and the feed rate between 5 m/min and 20 m/min. Optical process emissions are collected coaxially to the incident laser beam into a diagnostics fiber with a diameter of 100 μm using a beam splitter and an imaging lens of 300 mm focal length. The imaging setup leads to an observation area with a diameter of 66.7 μm. Process emissions are recorded with a spectrometer coupled to the 100 μm diagnostics fiber. During a single cut multiple spectra are recorded with a constant temporal gap. Recording of spectra is triggered manually. Integration time for all spectra is 3.8 ms and the observed wavelength range is between 500 nm and 700 nm with a spectral resolution of 0.8 nm (FWHM).

4. Results and discussion

Most of the observed spectra are line spectra with a continuous background. These spectra show emission or absorption of spectral lines, depending on the process parameters. A typical emission spectrum is shown in Fig 2(a). Between 500 nm and 560 nm there are features that may be attributed to molecular band emissions of the C₂ Swan system. These emission bands are also mentioned in investigations of pulsed laser processing of carbon materials by Abdelli-Messaci et al., 2005, Camacho et al., 2008, Harilal et al., 1997 and Parigger et al., 2003 and of cw cutting of CFRP by Niino et al., 2012. Several spectral lines appear in the observed wavelength range with one very strong line at 588.95 nm which appears in all recorded spectra. A blackbody radiation background underlying the line spectra features, as mentioned by Niino et al., 2012, can’t be observed in the recorded spectra.

First step of the examination of the data is to identify the elements and respective electron transitions belonging to the spectral lines. Therefore the NIST Atomic Spectra Database, NIST, 2012, is searched for spectral lines of possible elements at the respective wavelengths. The theoretical spectra of atomic (C I) and singly ionized carbon (C II) are calculated using Eq 1 and are shown in Fig 2(b) together with the observed spectrum. The atomic physical properties necessary for the calculation of the theoretical spectrum are also taken from the NIST Database, NIST, 2012. Comparison of the observed spectrum with the line positions of atomic carbon shows that none of the recorded lines clearly matches a C I line.
A spectral line of singly ionized carbon, consisting of three unresolved lines, fits well to the characteristic line at 588.95 nm. This C II line is also mentioned in investigations of pulsed laser processing of carbon materials by Camacho et al., 2008 and Tasaka et al., 1995, but not for cw laser cutting of CFRP, Niino et al., 2012. To check the plausibility of this matching spectral line a consideration of the atomic physical properties as well as the theoretical spectrum is necessary. The theoretical spectrum shows another C II line at 658 nm with much higher line intensity, shown as large, scaled orange line in Fig 2(b). However, this strong C II line doesn’t appear in any of the recorded spectra. Moreover, the energy levels of this electron transition are at relatively high energies, NIST, 2012. Together with the absence of spectral lines of atomic or singly ionized carbon in the observed spectra this leads to the conclusion that only a small fraction of C-atoms is ionized. Otherwise there should be spectral lines of carbon visible in the measured spectra as the emitted radiance of a spectral line also depends on the amount of atoms or ions in the respective excitation state (see Eq 1). So the energy inside the gas is not high enough to produce a sufficient amount of excited atoms and ions. Assuming that the excitation of the gas is mainly caused by thermal excitation this also leads to the conclusion that the temperature in the gas is relatively low.

Further investigation of possible transitions at this wavelength reveals a spectral line of atomic sodium (Na I) consisting of two unresolved lines. A more detailed calculation of the theoretical spectrum of atomic sodium takes into account the line profile of the spectral line which is assumed to be a Lorentz-profile. So the theoretical spectrum is calculated using Eq 2 and Eq 3 with consideration of the background radiation. The calculated Na I spectrum and the observed spectrum are shown in Fig 3. The theoretical spectrum of atomic sodium contains no further lines with significant line intensity in the observed wavelength range. The resulting calculated spectral line shows good agreement with the observed spectral line at 588.95 nm, although there is a slight wavelength shift that might be caused by pressure broadening of the spectral line. Moreover, the energy levels of this electron transitions are much lower, NIST, 2012. The origin of the sodium is not yet clarified. One possibility is that the sodium is included in the carbon fibers to a certain amount during their production. Another possibility is that the emission of the Na I line is caused by the glass wires in the material which are used to hold together the carbon fiber bundles before the infiltration process.
Fig. 3. Observed emission spectrum at $P = 5$ kW and $v = 10$ m/min with calculated Na I spectrum

5. Conclusion

The detailed spectral measurement shows that no spectral lines of atomic or singly ionized carbon appear in the observed spectra. This leads to the conclusion that only a small fraction of the C-atoms in the interaction region is ionized during cw laser cutting of CFRP with thin disk lasers. With the assumption of thermal excitation being the main excitation mechanism in the gas this also leads to the conclusion that the temperature in the carbon vapor must be relatively low. The characteristic spectral line at 588.95 nm is identified to be atomic sodium. The sodium might be included in the carbon fibers itself during their production or might be contained in the glass wires which were used to hold together the carbon fiber bundles before the infiltration process. There also appear molecular band emissions of the C$_2$ Swan band between 500 nm and 560 nm.

References


