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Multiple-pulse Laser-induced breakdown spectroscopy for monitoring the femtosecond laser micromachining process of glass

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HIGHLIGHTS

- Laser-induced breakdown spectroscopy applied for laser micromachining monitoring.
- Proposed schema allows burst micromachining and process monitoring simultaneously.
- Multi-pulse excitation improves the analytical performance of laser spectroscopy.

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ABSTRACT

Laser-induced breakdown spectroscopy (LIBS) can be applied for laser micromachining not only as a tool for determining the chemical composition of the sample but also for monitoring the process itself. Multiple pulses in comparison to a single pulse improve the analytical performance of LIBS, enable special applications and increase the ablation rate in laser material processing. In this report, we present results on the application of multiple-pulse LIBS in monitoring the micromachining of soda-lime glass with femtosecond high repetition rate pulses.

1. Introduction

Ultrafast laser micromachining is an advanced technology for high-precision and quality material microprocessing. This procedure provides many advantages over other conventional processes [1]. The threshold fluency of damage and ablation is orders of magnitude less than for traditional nanosecond laser machining. Compared with long-pulse lasers, femtosecond laser pulses allow for extremely high peak power densities to be achieved with low pulse energies. The short pulse duration enables strong multiphoton and electron avalanche mechanisms that provide benefits such as a small heat-affected zone [2], settled threshold for precision microprocessing [3,4], and minimized mechanical and thermal damage [5]. At high power densities, nonlinear absorption resulting from multiphoton ionization enables excitation of electrons in high bandgap materials such as ceramics and glasses, which are hard to process with conventional industrial lasers [6,7]. Thus, ultrafast lasers are widely applied in micromachining dielectrics [8], glasses [9,10], forming optical circuits in glasses [11], and filament scribing of glass panels [12].

While the reduced heat-affected zone is a major advantage of the ultrafast laser-material interaction, the rapid energy dissipation can cause a strong shock and a quick heating and cooling cycle. It can produce such harmful effects as microexplosions [13] and microcracks [14]. One promising method to reduce these effects is to use a burst of laser pulses at high repetition rate where residual thermal energy does not diffuse out of the laser interaction zone before the next laser pulse arrives. In this case, a thermal modification zone can be built to temporally modify the material property in this focal zone and redirect the overall laser interaction to provide a more beneficial outcome from the burst laser pulses [15].

Recently, high average power femtosecond laser systems have become more applicable due to an increase in processing throughput, however, maintaining the efficiency of the process comparable to lower power systems without introducing additional thermal damage is a great challenge [16–17]. A new technique – burst mode processing was demonstrated for micromachining materials with better efficiency than the conventional systems [18–20]. By using this technique the single pulse is separated into multiple pulses (burst) by a certain time delay (varying from ~100 ps to ~10 ns). In this case, the relatively large pulse energy can be divided into a sequence of pulses with pulse energy values that are closer to the optimal ablation rate setting while the integrated energy of the burst remains high.

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In this paper, we present femtosecond laser micro-machining of soda-lime glass with bursts of multiple pulses. In our experiment we formed a sequence of multiple femtosecond laser pulses by specially constructed optical schema. At the same time for online monitoring of the process, multiple pulse laser-induced breakdown spectroscopy (MP-LIBS) was used. LIBS technology makes possible the extended capability for monitoring laser processes and getting actual information back to the laser manufacturing process. This allows online process parameter supervision for laser processing [21–28].

During laser-induced material breakdown, the intense laser pulses initiate an expanding plasma plume, which emits light from the atomic, ionized and molecular constituents of the sample [29]. The spectra of plasma light emissions can provide analytical information about the elemental composition of the material being ablated [29–31]. LIBS has several attractive features for sample analysis: an easy, fast, real-time and in-situ measurement due to minimal sample preparation, and multiple element detection capability regardless of the physical form and aggregation state of the material. This technique is suitable for a wide range of applications such as: depth profiling, surgical selective tissue removal, authentication of artworks, monitoring and control of laser material processing etc. [21–28,32–34].

Using dual-pulse LIBS, atomic emission intensities, signal-to-noise ratio, precision, and detection limits can be improved [35]. Dual-pulse LIBS configuration consists of a sequence of two laser pulses temporally spaced in the order of hundreds of picoseconds or microseconds (depending on the laser pulse duration). These two pulses can ablate the same area and create two temporally spaced plasmas, or the second pulse can reheat the plasma induced by the first pulse. The dominating mechanisms of double pulse intensity enhancement in femtosecond laser-induced breakdown spectroscopy (fs-LIBS) according Ref. [36] are the increased number of atoms in plasma due to the larger volume of double pulse ablation craters and the higher plasma temperature. The atomization of nanoparticles by laser plasma-particle interaction contributes much less. The intensity enhancement is highest at lowest energy of the first pulse. Fs double pulse LIBS may thus enable elemental imaging with improved lateral resolution, higher sensitivity and increased elemental contrast.

Another approach is multi-pulse LIBS (MP-LIBS) [37–38]. With this method, more than two pulses are used in a collinear mode. MP-LIBS approaches demonstrated by several research groups [39–41] showed that it is analytically advantageous to use more than two laser pulses in LIBS, as they provide increased material ablation and enhanced signal emission [42–44].

LIBS has been used in monitoring and control of laser material processing mainly by using nanosecond pulses [21–28]. It's worth mentioning the T. Sibillano's sensor, based on LIPS technology designed for monitoring and controlling the laser welding process [25]. T. Tong adapted the LIPS technology to control laser micro-processing of the multilayer elements by recording and comparing spectra [23]. D.D. Vallejo applied LIPS technology to observe and evaluate the focal plane position of the specimen and identify different layers of material [26–28]. However, these authors used nanosecond or two-pulse systems, and we decided to explore the possibilities of using multiple femtosecond pulse systems. LIBS systems of the ultrashort pulses are distinguished by their stability and precision, due to the specific short-pulse interactions with the material. With the help of multiple pulse LIBS systems, the LIBS signal is amplified, and the processes efficiency and quality are enhanced as well.

The aim of our present work was to apply femtosecond MP-LIBS in monitoring the micromachining of soda-lime glass by a burst of femtosecond high repetition-rate pulses and to investigate the main influences of different processing parameters.

2. Experimental setup

A schematic representation of the experimental setup is shown in Fig. 1. The experiments were performed using the Carbide® Yb:KGW femtosecond laser system (Light Conversion Ltd) operating at 1030 nm (pulse width 280 fs, average power up to 5 W, 60 kHz). The maximum laser energy of a single femtosecond pulse was approximately 80 μJ.

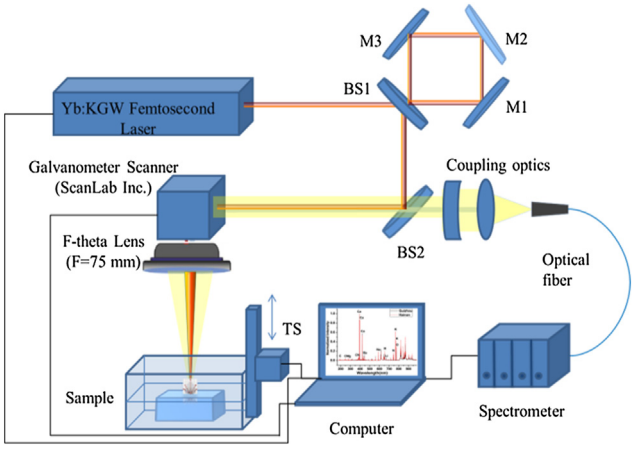

Fig. 1. Experimental setup of the multi-pulse LIBS-monitored femtosecond laser processing system. Optical components include beamsplitter (BS), mirror (M), coupling optics. TS-translation stage.

The burst of multiple pulses was formed by dividing the beam with the beam splitter BS1, which transmitted 70% and reflected 30% of the incident light. The transmitted part of the laser radiation, undergoing multiple reflections by high reflective (99.95%) dielectric multi-layer mirrors M1-M3, formed a sequence of endless multiple pulses with decreasing energy (Fig. 2). Thus, if the energy of the primary single pulse was 80 μJ, the energies of the multiple pulses in the sequence were ~24 μJ; 39.2 μJ; 11.8 μJ; 3.5 μJ etc., respectively. Optical delay line consisted of M1-M3 mirrors was used to form the delayed pulses. By choosing the length of the delay line equal to 15 cm, the 500 ps delay time was formed and kept constant during the whole experiment. This value for the delay between the pulses was chosen because the range of the delay time 200–800 ps has been determined to be optimal for obtaining high-intensity LIBS signals using double-pulse femtosecond excitation [45]. The two axis galvanometric scanners (ScanLab Inc.), controlled by SCA fabrication software (Altechna Ltd), were used for

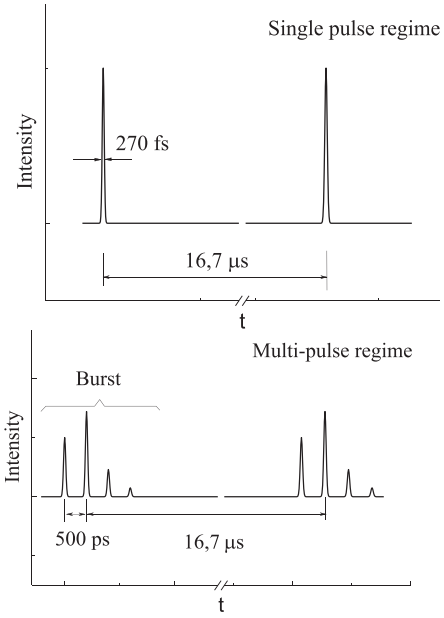

Fig. 2. Single-pulse (up) and multiple-pulse (burst- down) regimes used in the experiment.