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Detection of heat accumulation in laser surface texturing by fast infrared detectors

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Abstract

Laser surface texturing (LST) with high average power ultrashort pulsed lasers is starting to be used in industry. Using high repetition frequency of laser pulses leads to significant overlapping of laser spots and increasing of heat accumulation in the textured material. Heat accumulation has great influence on quality of the resulting surface texture. In majority of the research works the heat accumulation is analysed by mathematical modelling. In this work, a measurement system for time-resolved temperature measurement during the texturing process was developed. The system is based on high speed infrared (IR) detectors with sensitivity in near and mid IR wavelength (NIR and MIR). Measurement results during machining of straight lines and surface texturing of dimples on stainless steel are presented. The system can be used as a tool for technology developers for comparing different scanning strategies and material removal approaches and choosing the right one for the desired application.

Keywords: Laser surface texturing; heat accumulation; infrared detectors; process monitoring; temperature measurement

1. Motivation

Heat accumulation is an important factor influencing laser surface texturing done by ultrashort pulsed lasers. When the repetition rate of laser pulses becomes higher, the heat accumulation leads to decreasing of surface quality and processing efficiency. The reason of such negative influence of heat accumulation lies at undesired increasing of residual surface temperature upper than melting or boiling point (Weber et al., 2017). Uncontrolled heat accumulation at high repetition rate and low scanning speed leads to the onset of melting, oxidation, and pileup of material (Bauer et al., 2015; Neuenschwander et al., 2016; Wang et al.,

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2010; Weber et al., 2014). On the other hand, there are several research results, where the higher efficiency was determined as result of material processing at higher repetition rates. It was found that the efficiency has a maximum at specific repetition rate and it was explained by beneficial changing of thermo-physical properties of the preheated surface (Cabalín et al., 2011; Lopez et al., 2015). Reaching of the maximal ablation efficiency is highly material dependent and it can to be described as positive heat accumulation (Moskal et al., 2018).

Heat accumulation can be detected by surface temperature measurement. Measurement of surface temperature can be done by several means. There are methods based on an electrical conductance measurement (Grigoropoulos et al., 1996), on a reflectivity or transmissivity of the measuring laser (D.H. Lowndes, G.E. Jellison, R.F. Wood, 1984), on an IR radiation measurement of the sample surface (Doubenskaia and Smurov, 2006), a detection of the Raman scattering induced by the measuring laser (Hashimoto, 2015) or a XRD diffraction (Buschert et al., 1989). The most often is used the time-resolved reflectivity measurement and then the emission measurement using radiometric methods (Kučera et al., 2018).

In majority of the research works the heat accumulation is analysed by mathematical modelling. The modelling is always using assumptions and needs to be validated by experiments. In this work, a measurement system was developed and used for investigation of heat accumulation of laser micromachining of lines and laser surface texturing. Measurement of temperatures in microsecond and nanosecond time ranges and at the same time in micrometer scale is challenging. In this work, a measurement system based on infrared (IR) radiometry is proposed and used.

2. Measurement system

Heat accumulation was detected using measurement system with three photodiodes in IR spectrum (Fig. 1). The system was similar to the system used in (Kučera et al., 2018). The laser beam was focused on a metallic surface and caused material ablation and heat accumulation in subsurface layer. Detection of lower temperature heat accumulation was performed by MIR infrared sensor with wavelength sensitivity in range of 2–6 µm (first channel, CH 1). Ge filter was used for cutting out reflected laser radiation. Detection of high temperature radiation was performed by Si photodiode with long-pass filter and wavelength sensitivity in range of 0.8–1 µm (second channel, CH 2). Irradiation from laser reflection, ablation plasma plume, hot particles explosion and integral thermal irradiation from laser heated surface were detected by Si photodiode without filter (third channel, CH 3). Voltage from every diode was registered by oscilloscope using three channels. All the detectors were aligned on a fixed surface point with detection area near 1 mm^2.

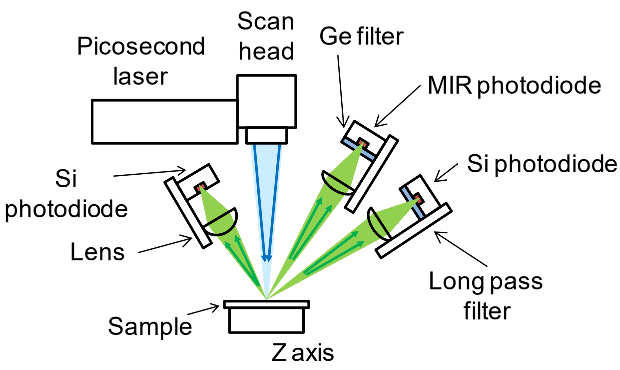


Fig. 1. Schematic representation of the experimental setup with three IR photodiodes and picosecond laser with scan head.

3. Laser surface texturing

Laser surface processing was done using a picoseconds laser with wavelength 515 nm, pulse duration 10 ps, scan head objective focal length 255 mm and laser spot diameter 25 µm. The sample material was stainless steel AISI304.

The measurement system was first used for investigation of heat accumulation in machining of straight lines. Three different pulse energies Q_p (10, 30 and 100 µJ) with corresponding fixed pulse repetition frequencies (1000, 454 and 140 kHz) and wide range of scanning speeds (0.007, 0.03, 0.07, 0.15, 0.3, 0.7, 1, 2, 3, 4, 5, 6, 7 and 8 m/s) were used. The scanned line was 5 mm long and the center of the scanned line was matched with the center of the detected area. For each measurement, new part on the sample surface was used. Each measurement was done 5 times.

The system was also used to compare heat accumulation in different laser texturing methods. They were: 1) classic path, 2) shifted path, 3) classic hatch and 4) shifted burst methods. The classic path strategy is done by consecutive writing of concentric circles on sample surface (Fig. 2. a). The shifted path strategy (Martan et al., 2019) has the same final positions of laser pulses, but in different order - the laser beam moves fast across straight lines with consequential shifting of the linear rasters (Fig. 2. b). The classic hatch strategy fills the circles by short straight segments with following one by one laser pulses. The laser beam start and stop for every short segments for synchronization of the mirror position with the laser switching sequence (Fig. 2. c). In the shifted burst strategy (Moskal et al., 2018), the circles are filled by the same straight segments, but the laser beam moves across long direct lines without synchronization of the scanning mirrors with laser switching sequence (Fig. 2. d). Classic methods of texturing have scanning speed lower than 1 m/s, shifted method have 8 m/s in both variants (Martan et al., 2019).

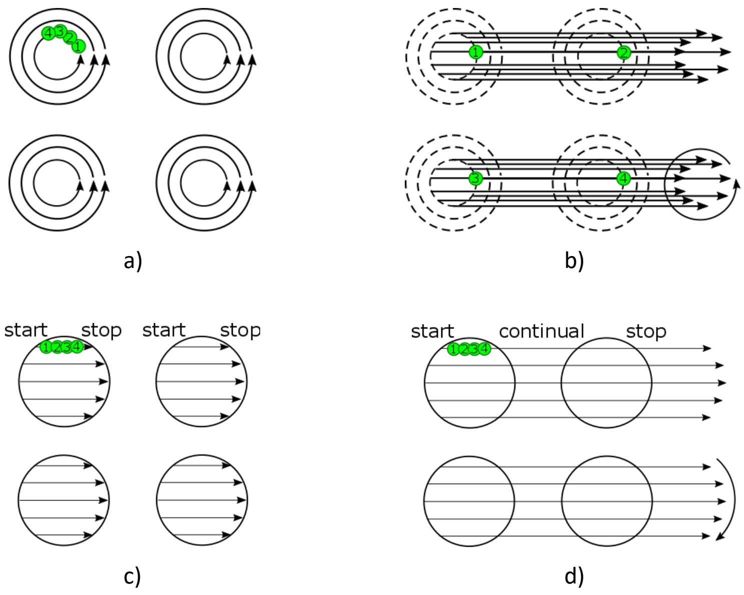


Fig. 2. Four scanning strategies for laser writing of microobjects: a) classic path, b) shifted path, c) classic hatch, d) shifted burst.

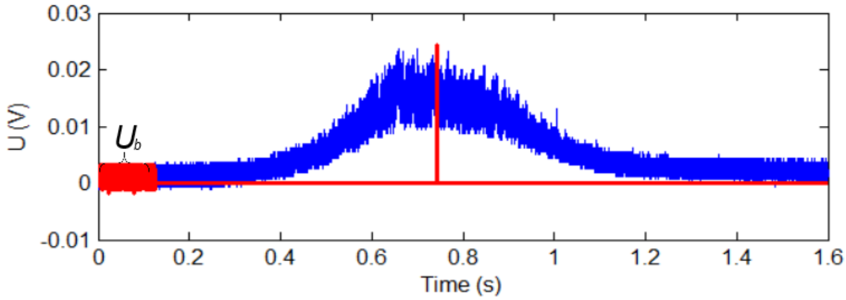
The goal diameter of the textured circular dimples was selected equal to 80 µm with distance between their centres equal to 200 µm. The geometry of the offered texture can be used for example in sliding bearing texturing (Houdková et al., 2017). The distance between centres of laser spots was 7 µm in all strategies. The distance between lines was 10 µm.

4. Algorithm of heat accumulation detection

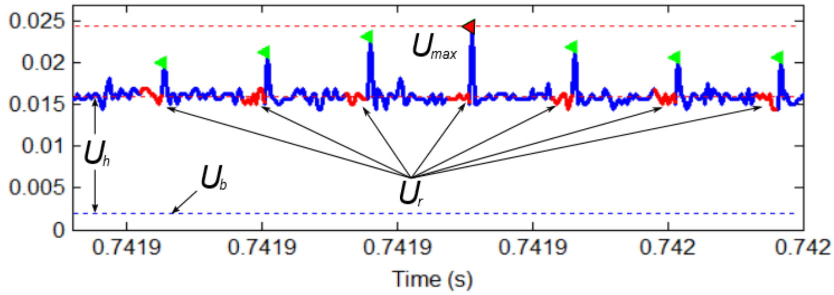
Before every measurement of the thermal radiation signal, the background noise level was recorded and the mean value of background signal was established (Fig. 3. a, left side):

$$U_b = \frac{1}{N_b}\sum_{i=1}^{N} U_{b,i} \tag{1}$$

where U_b – is the mean value of the background signal, N_b – number of the recorded values in the sequence without laser influence and $U_{b,i}$ – the value of the background signal voltage recorded in the time moment t_i and i – index of the signal value. At the next step, the signal from whole three diodes was recorded at the moment when the laser beam was scanning the surface. The signals from all channels were recorded in the 200 ms wide region with triggered signal in the centre (Fig. 3. a, centre). Detection of the heat accumulation was performed in the 40 µs short time window close to the maximal achieved signal. This is part of the signal, where the ablation is done on the place measured by the detectors.



a)



b)

Fig. 3. Determination of the heat accumulation in the first channel at scanning speed 0.007 m/s and laser pulse energy 30 µJ: a – determination of the background signal level U_b; b – determination of the residual heat signal U_r and maximal peak signal value U_{max}. Heat accumulation U_h is detected as differential value.

The residual heat signal (heat accumulation) is detected as mean value from the equidistant signal segments in the closest region to the next coming laser pulse regions (Fig. 3. b):

$$U_r = \frac{1}{R \cdot N_r} \sum_{p=1}^{R} \sum_{i=1}^{N_r} U_{p,i} \tag{2}$$

where U_r – is the mean value of the residual heat signal, N_r – the number of the signals which were analyzed in the closest region to the next laser pulse segment, R – the full number of the analyzed segments, $U_{p,i}$ – value of the signal recorded in the time moment t_i, p and i – the indexes of the analyzed segment and data index in the signal segment. The resulting heat accumulation U_h was defined as difference between residual signal and background signal mean values:

$$U_h = U_r - U_b \tag{3}$$

In the similar way, the maximal value of the signal for whole channel U_{mb} was detected – as a difference between absolute maximum in the signal U_{max} and background level:

$$U_{mb} = U_{max} - U_b \tag{4}$$

The difference between absolute maximum and residual heat will be indicated as relative maximum signal U_{mr}:

$$U_{mr} = U_{max} - U_r \tag{5}$$

5. Results

Results of heat accumulation in machining of straight lines are shown in Fig. 4. Significant heat accumulation was observed for very low scanning speeds 0.007 m/s and 0.03 m/s for all three pulse energies Q_p (10, 30 and 100 µJ). For higher scanning speeds, the heat accumulation was not high due to low average power of the used laser.

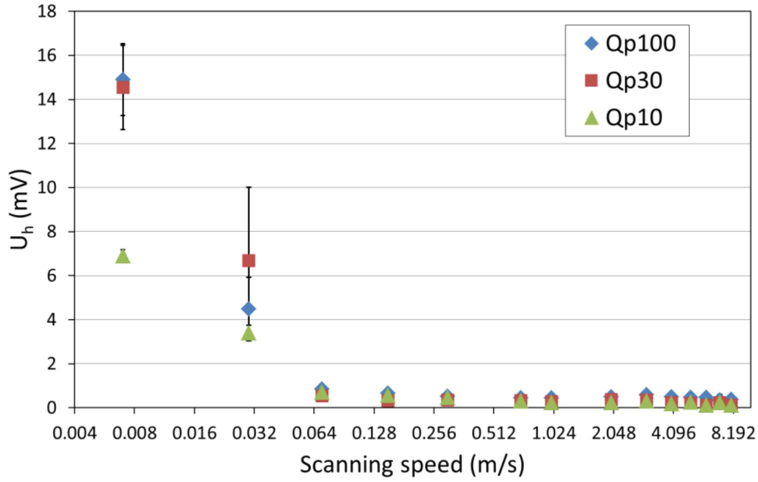


Fig. 4. Heat accumulation signal from CH 1 obtained for different laser beam scanning speeds in machining of straight lines and different pulse energy.

Results of heat accumulation during laser surface texturing are shown in Fig. 5. Heat accumulation was observed in classic hatch strategy for highest pulse energy (100 µJ) and with lower intensity for shifted burst strategy for middle pulse energy (30 µJ). For other measurements, the heat accumulation was low. The scanning speeds, repetition frequencies and process speeds are very different for the four strategies. The classic path method with lowest scanning speed had the same heat accumulation for all pulse energies. The classic hatch and shifted path strategies both showed increasing heat accumulation with pulse energy, although they are very different processes. For the shifted burst strategy the maximum heat accumulation was observed in the middle pulse energy, which seems strange. These results need more detail study to be well understood.

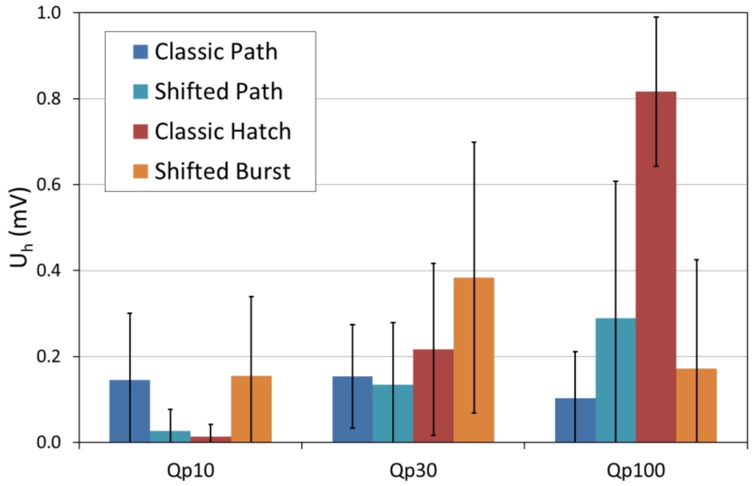


Fig.5. Heat accumulation signal from CH 1 obtained for different laser beam scanning methods of laser surface texturing and different pulse energy.

6. Conclusion

Measurement system for observation of heat accumulation in laser surface texturing was developed and presented. It is based on high speed IR photodiodes. Algorithm for heat accumulation evaluation from the measured signal was shown. Significant heat accumulation in machining of straight lines was observed for very low scanning speeds (<0.05 m/s). The presented IR measurement system showed that it is capable of recording thermal radiation changes in nanosecond and microsecond time scales from locally heated microscale areas during laser micromachining. One of the further steps will be calibration of the system to be able to measure temperature values.

For higher scanning speeds of machining of straight lines and for laser texturing of surface, low heat accumulation was detected due to low average power of the used laser. In future laser systems with kW range average power ultrashort pulsed lasers, significant heat accumulation can arise and cause significant problems. The present measurement system can be then used for comparing different scanning strategies and material removal approaches and choosing the right one for the desired application.

Acknowledgements

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