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Development of Fast Temperature Measurement System for Ultrashort Pulse Laser Material Processing

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Abstract

Laser material processing with high repetition frequencies of ultrashort laser pulses is able to initiate heat accumulation effects that can decrease processing quality. In order to gain deeper insights into these effects, a temperature measurement system with nanosecond time resolution was developed using infrared detector and a set of parabolic mirrors. This system was usable for scientific measurements on one small area (0.5 mm) of the sample. For measurement in more industrially relevant processes on larger areas (100 mm), alternative configurations were developed: 1) measurement through scanning head and 2) special multifocal ellipsoidal mirror placed beside a polygon scan head. This work focusses on comparison of advantages and limitations of the developed measurement configurations by sensitivity, signal to noise ratio, field of view and measurable temperature range. The measurement system was used for analysis of laser surface texturing of steel and ceramics substrates as a preparation for thermal spraying of coatings.

Keywords: heat accumulation measurement; laser micromachining; ultrashort pulsed lasers; infrared optics and detectors; process monitoring

1. Introduction

Laser material processing with ultrashort laser pulses is unique for high-efficient material ablation ensuring high accuracy and precision, which are essential in micromachining. But when using high power laser systems, residual heat stays in the material after application of many laser pulses. When using high laser pulse overlap, the temperature significantly increases and such effect is called in literature heat accumulation [1–3]. On the one hand, medium heat accumulation can enhance the efficiency of the laser ablation. On the other hand, high heat accumulation can induce surface damage, melting and oxidation in the laser processing area and the machining quality suffers. So far, measurement of heat accumulation during the process was not possible yet and only modelling provides ideas about the heat accumulative effect during ultrashort pulse laser machining [4–6]. In order to gain knowledge also in the experimental field, a measurement system was developed in our laboratory and used for the first heat accumulation measurement during picosecond laser micromachining [7]. The present article is about next steps in development of the temperature measurement system to be more focused on industrial applications.

2. Measurement system development

The temperature measurement system for ultrashort pulse laser micromachining was developed based on the previous experiences in thermal properties measurement of thin films by a pulsed laser [8] and temperature measurement in nanosecond laser marking [9]. The first measurement system is based on two parabolic mirrors (Fig. 1a) and a filter for cutting the laser wavelength. Such measurement system was used for analysis of picosecond laser micromachining using different scanning speeds, frequencies and pulse energies [7] and multibeam laser surface texturing with LIPSS formation using a high power picosecond laser [10]. In both cases, the measurements were carried out from one place with measurement area of about 0.5 by 0.5 mm^2 (Tab. 1). This measurement system was validated perfect for scientific purposes of analysing physical processes during laser-material interaction and for technical processes using static laser beam and moving a sample. But for applications using scanning head for moving the laser beam, the system has disadvantage of measurement only at one time during the process or at periodical times when laser runs through the measurement area.

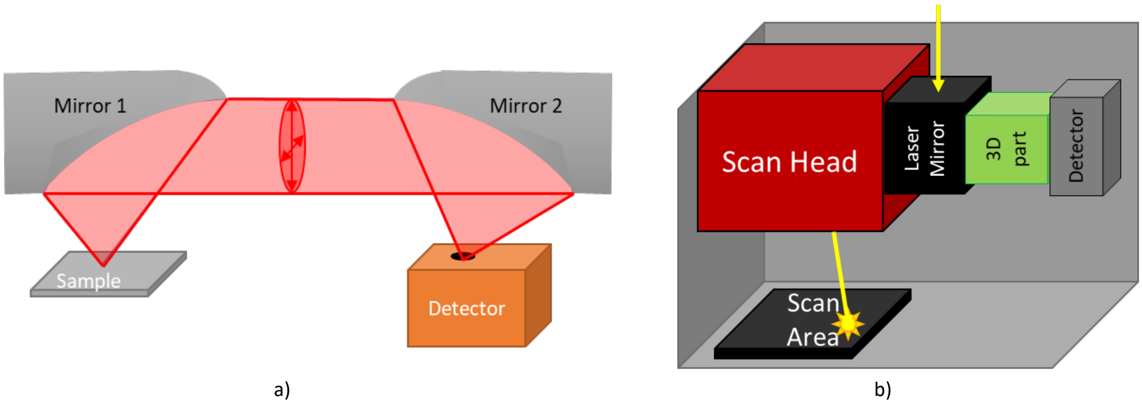


Fig. 1. Temperature measurement systems with (a) two parabolic mirrors and (b) measurement through the polygon scan head.

For achieving continuous measurement during laser processing with moving laser beam, considerably larger sensitive area or field of view was analysed. For this, a number of different optical configurations were tested using lenses and mirrors, but always a decrease of signal to noise ratio (SNR) resulted. So, a compromise goal was set in the ADVENTURE project [11] to create a measurement system with sensitive area with linear shape that would be compatible with a polygon mirror based scan head for ultrafast laser beam scanning. Accordingly, a new mirror was developed, called multifocal ellipsoid mirror (Fig. 2). It is based on rotation of an ellipse arc around its first focus and changing the length of the ellipse to maintain the second focus on a straight line. The detector is placed in the first focus and the laser machined line in the line of the second foci of the ellipses. The mirror was produced by 3D printing from plastics with subsequent metallic coating of the optical surface.

As a second option, measurement through the scan head was analysed. In this case the detector need to be sensitive in the short wavelengths close to the laser wavelength, in order to detect the thermal radiation from the sample. The system was developed with InGaAs detector, a lens and several filters cutting the laser radiation (Fig. 1b).

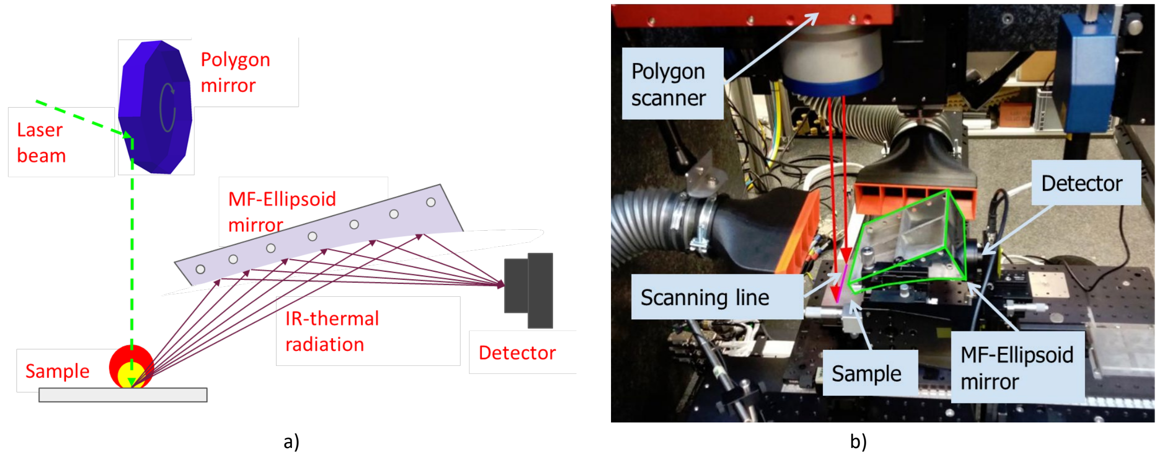


Fig. 2. Temperature measurement system with the newly developed multifocal ellipsoid mirror (a) in a schematic representation and (b) a photo of real implementation in a laser system.

For evaluation of the measurement systems, the signal to noise ratio (SNR) was calculated from the measured data by equation [12]:

$$SNR = \frac{\left|\overline{S} - \overline{N}\right|}{\sigma_N}, \tag{1}$$

where $\overline{S}$ and $\overline{N}$ represent mean value of the signal and noise respectively, and σ_N is a standard deviation of the noise.

Evaluation of the measurement systems was done by using femtosecond laser systems with average power 40 and 80 W, wavelength 1030 nm, pulse energies 40 µJ and pulse repetition frequencies of 1 and 2 MHz. The used laser beam scanning speeds were 5 to 25 m/s by using a galvanometric scan head and further increasing from 25 to 500 m/s with the polygon scan head. Samples were from steel.

3. Results

Results of evaluation of measurement systems for heat accumulation measurement is shown in Tab. 1. The highest signal to noise ratio was obtained with the parabolic mirror system. The system using multifocal ellipsoidal mirror is 10 times less sensitive and the measurement through the scan head is 26 times less sensitive. On the one hand, although the SNR for the measurement through scan head is the lowest, the ratio is higher than 10 and so the signal can be well distinguished in the noise. On the other hand, the low signal performance of the optical system increases the lower limit of the measurable temperature range of the detector. In this case, from 200°C for the InGaAs detector with the parabolic mirrors to about 330°C. Good signal starts at about 450°C (SNR > 3).

Table 1: Comparison of performance of the developed measurement systems

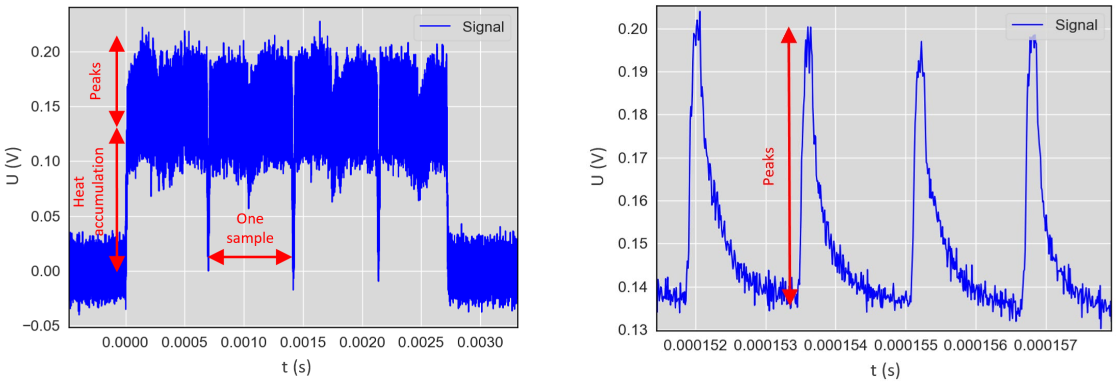
Optical system	**Possible detectors**	**Signal to noise ratio (-)**	**Field of view (mm x mm)**	**Measurable Temperature Range (°C)**
Two parabolic mirrors	HgCdTe, InSb, InGaAs	390	0.5 x 0.5	> -20
Through scanning head	InGaAs	15	150 x 150	> 330
Multifocal ellipsoidal mirror	HgCdTe, InSb, InGaAs	40	150 x 3	> 100

The field of view of the measurement system is biggest for the measurement through the scan head. It is in general unlimited and is equal to the field of view of the scanning head. For the measurement with the multifocal ellipsoidal mirror, the longer axis of the field of view is given by the size of the mirror. In the first prototype it is 150 mm. The second axis is given mainly by the size of the detector (2 mm).

The multifocal ellipsoidal mirror seems to be a good compromise for the applications using polygon scan head for one axis of laser beam movement and sample movement for the second axis. The SNR is significantly higher than for looking through the scan head and the choice of detector is not limited by the transmission of the lenses. The lowest measureable temperature is about 100°C in this case. It should be applicable even for temperature sensitive materials, e.g. plastics. While the measurement through the scan head can be well used for example for stainless steel processing, where the degradation temperature is about 607°C [1].

The developed configurations of the measurement system were used in the ADVENTURE project for analysis of laser surface texturing of substrates during preparation for thermal spray coating. Examples of results of measurement can be seen of the Fig. 3 showing the thermal radiation voltage signal U (V) as reference value for the sample surface temperature as a function of laser irradiation time t (s). To obtain real value of temperature, the systems need to be further calibrated for each material and laser spot size or by observation of a solidification phase change.

In the first example, steel samples were textured by a femtosecond laser with 800 fs pulse duration, 80 W average power, 2 MHz repetition rate and polygon scanner with 35 m/s scanning speed (Fig. 3a). The measurement was done through the scan head with InGaAs detector with 5 MHz frequency bandwidth. On the one hand, a significant noise of the detector can be seen. On the other hand, a very flat response from the whole laser texturing area (10 cm) is present. The heat accumulation value was almost constant, except holes between samples and sample centres, where higher surface roughness or height was present due to its preparation by turning.



a) b)

Fig. 3. Examples of measured thermal radiation signals: a) measurement through the scan head, texturing of steel by femtosecond laser, four samples of 25 mm diameter each; b) measurement with multifocal ellipsoidal mirror, texturing of YZS ceramics by nanosecond laser, detail on thermal effects of each laser pulse.

As another example, Al_2O_3 ceramics with grey colour was textured by a nanosecond laser with 150 ns pulse duration, 200 W average power, 625 kHz repetition rate and polygon scanner with 50 m/s scanning speed (Fig. 3b). The measurement was done with multifocal ellipsoidal mirror and extended InGaAs detector with 25 MHz frequency bandwidth. In the measurement curve, the SNR is significantly better, even when using detector with higher bandwidth and lower size and amplification. The thermal effect of each laser pulse can be seen. The temperature increases fast during the laser pulse and then it decreases slowly until next laser pulse comes. The measurement was also combined with FPGA (Field Programmable Gate Array) for fast hardware signal analysis and using such a device, heat accumulation from the whole machining process was analysed and recorded. In this way, the big data record is reduced, so that from each laser pulse, only one data point is recorded, the heat accumulation, and the amount of data is possible to be handled. Even a real time for process control would be possible.

4. Conclusion

Development of temperature measurement system for detection of heat accumulation in nanosecond and ultrashort laser micro-processing was described. The newly developed solutions of multifocal ellipsoidal mirror and looking through the scan head were presented and analysed. Both of them are perspective for certain industrial applications.

Performances of the optical systems were compared. The two paraboloid mirrors system is the best for detailed scientific analyses with the best signal to noise ratio (SNR) and unlimited temperature range, but it is limited in the field of view. It can be used also for industrial laser systems using fixed laser optic and movement of the machined piece. Looking through the scan head system is good for all direction laser scanning and is able to observe signal from all parts of scanning field, but has lower SNR and limited lowest observable temperature. The multifocal ellipsoidal mirror system is good for combination with linear scanning, e.g. using polygon scanner, and machined piece movement in the second axis. It is applicable also for temperature sensitive materials. Its SNR is between the other two systems.

Examples of thermal radiation measurements during laser surface texturing of steel and ceramics substrates, as a preparation for thermal spray coatings deposition, were presented.

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