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Design and Development of a Multisensory Real-Time Monitoring Platform for Ultrafast Laser Engraving Process

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ABSTRACT Process online monitoring is a vital and integral part of high-speed laser scribing process in which speed and quality are paramount. In this study, a multi-sensory platform for real-time monitoring of the ultrafast pulsed laser engraving process has been developed. Four different sensors have been examined from various perspectives and the results have been analyzed and compared. The real-time monitoring system developed for this study consisted of IPG ytterbium pulsed fiber laser, scan head, illumination system, and four monitoring sensors, including a spectrometer, pyrometer, infrared (IR) camera, and high-speed camera. Various experiments were performed to evaluate the performance of the designed platform by applying each sensor to monitor a high-speed laser scribing process in real-time. The output of each sensor was analyzed by changing different laser and process parameters, such as laser power, focal position, beam speed, and pulse length. Strengths, weaknesses, and challenges of using each monitoring tool for the laser engraving process were discussed based on the obtained results.

INDEX TERMS Laser scribing, real-time monitoring, spectrometer, high-speed camera, infrared camera, pyrometer.

I. INTRODUCTION

High-speed pulsed lasers are widely used for material processing in various microscale and fusion relevant applications due to the valuable features that they provide, such as high pulse energy, rapid and strong induced absorption in materials, high rate of material removal, low ablation threshold, and reduced heat affected zone (HAZ) compared to longer pulse duration lasers [1]–[4]. Surface scribing is one of the vast adopted applications of high-speed pulsed lasers, where short-duration pulses with high peak power are demanded [5], [6]. Laser engraving can be applied to an almost an unbounded range of materials and plays a key role in modern manufacturing. However, maintaining the high quality of the laser scribed surface and simultaneously increasing the removal rate is challenging due to the complex thermal management of the process, which can be achieved by optimizing process parameters and pulse characteristics [5], [7]–[10]. Quality of the scribed surface is crucial in the laser scribing process, especially in the fields where precision level significantly affects the efficiency of the finished product [11], [12]. Monitoring the laser scribing process in real-time is an effective solution to improve the quality by realizing the occurring phenomena and detecting the defects online [13]–[15]. The purpose of real-time monitoring of the process is to manually correct the defective point if possible or provide the gathered process data to the control system in order to adjust the process parameters, such as increasing or decreasing the laser power, and consequently rectifying the defect online when the scribing process is carrying on. There are diverse methods for laser process monitoring, the most common of which are optical methods [13]–[16]. Optical approach has several advantages over other monitoring methods such as acoustic and electrical

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methods. Optical monitoring methods have a non-contact operation and provide a large amount of data based on the output of spatial or spectral techniques used [14], [16]. Different types of cameras, photodiodes, pyrometers, and spectrometers are examples of optical sensors that can be used for monitoring purpose [15], [17]–[19]. It should be noted that thermal methods can be included in the group of optical methods [16], [20]. In this paper, infrared cameras and pyrometers have been classified in the category of optical sensors. Monitoring of laser welding and cutting processes has been extensively studied and implemented; however, these processes are not as fast as the laser engraving process, thus, developing real-time monitoring and control system is less challenging for them [21]–[23]. Nevertheless, the development of an effective real-time monitoring and control system has not been sufficiently studied and implemented for the laser scribing process, mainly due to the high speed and quality requirements of this process. Typically, the control of laser scribing process is carried out offline and not in real-time.

The objective of this study was to design and develop a multi-sensory real-time monitoring platform for the ultrafast laser scribing process. For this purpose, four different sensors were used, including spectrometer, pyrometer, infrared (IR) camera, and high-speed camera, and the performance of the system was evaluated using each sensor. Optical sensors have been used to observe the emitted radiation of the process. A test set-up has been established using a pulsed ytterbium fiber laser, scan head, illumination system, and mentioned monitoring detectors. Various experiments have been conducted by applying each sensor to assess their efficiency and the challenges associated with monitoring the high-speed laser engraving process. Although some studies have been conducted to monitor the high-speed laser scribing process, the development of a multi-sensory real-time monitoring platform using four different sensors based on experimental methods has not yet been investigated to the extent discussed in this study. The results of the analysis performed in this study contribute to implementing an efficient real-time monitoring system in industrial laser scribing applications by perceiving the pros and cons of most available optical options based on experiments carried out under similar industrial conditions.

A. SENSORS INVESTIGATED IN THIS STUDY FOR MONITORNG LASER SCRIBING PROCESS

1) SPECTROMETER

Spectrometers are considered in the classification of spectrally resolved techniques and are one the most successful optical sensors used for monitoring various laser processes by analyzing the radiation intensity of material [19], [24], [25]. They can measure a wide spectral range from gamma rays to microwaves; however, the monitored range generally encloses ultraviolet and visible wavelengths for laser material processing [16], [26], [27]. Characteristics such as sensitivity, ability to resolve lines, and path configurations distinguish spectrometers from each other. Spectrometers can be used as a method to find the most reactive wavelengths. In this study, the suitability of spectrometer for online monitoring of the laser scribing process was evaluated. The sensitivity of the spectrometer was assessed by changing several process parameters, such as pulse length, focus position, and laser power, and evaluating the behavior of the spectrometer in response to variations in emission intensity. Also, the repeatability of the spectrometer measurement results was examined.

2) PYROMETER

Pyrometers can measure the thermal distribution in laser applications using the heat radiation data of the surface exposed to the laser beam and captured by the measuring optics. The pyrometer measurement is performed independent of the emissivity coefficient of the material and its variation as a function of temperature. Pyrometers can measure high temperatures above 400 °C [28], [29]. Some studies have investigated the use of pyrometer to monitor and control laser welding and laser sintering in additive manufacturing or processing of materials in terms of cutting and marking [29]–[32]. However, in this study, the pyrometer was examined to evaluate its suitability for online monitoring of the laser scribing process. Pyrometer sensitivity was tested by changing focal position, laser beam speed, laser power, and analyzing the influence on the temperature measured by the pyrometer. Repeatability of the pyrometer measurements was also examined.

3) INFRARED (IR) CAMERA

Infrared (IR) cameras can be used for laser process monitoring purposes since they can measure mid and long wave infrared radiations, which cannot be detected by other types of cameras. Using an infrared thermal camera, the characteristics of the molten pool can be determined, and the temperature of the deposited surface can be measured and observed. IR cameras provided acceptable results for thermal monitoring and control of laser welding and laser additive manufacturing [20], [33]–[35]. However, in this study, the eligibility of IR camera to monitor the laser scribing process in real-time was evaluated. The heating of the workpiece during processing as well as the cooling of the workpiece after laser processing were investigated using an IR camera.

4) HIGH-SPEED CAMERA

High-speed cameras with external illumination sources are widely used to monitor laser possesses by detecting the emission of the processed area during the melting process and enabling observation of the occurring phenomena. Advances in high-speed digital cameras have facilitated monitoring of laser interaction with the workpiece. Using these types of cameras, changes in the keyhole or shape of the melt pool can be measured [17], [36]. Various studies have been conducted on the use of high-speed cameras to monitor laser welding, laser cutting, and laser additive manufacturing [37]–[40].

In this study, a high-speed camera was assessed to monitor the laser scribing process. Resolution tests were performed using different frame rates of the high-speed camera. Also, different laser pulse lengths were examined to evaluate the impact on images captured by the high-speed camera.

II. EXPERIMENTAL SETUP

The experimental testbed built for this study is shown in Figure 1, which consists of IPG ytterbium pulsed fiber laser, scan head optics type Scanlab Hurryscan 14 II equipped with f100 telecentric lens, Cavitar illumination system, and various monitoring sensors, including a spectrometer, a pyrometer, an infrared camera, and a high-speed camera. The sensors are controlled through the main workstation using a laptop. The laser has the average power of 20 W, max pulse energy of 1 mJ, pulse length of 4 ns, laser beam speed of 1000 mm/s, pulse repetition rate of 1000 kHz, minimum laser spot size of 28 μm (actual 40 μm) and beam quality M^2 of 1.5. The working area was 54 $\times$ 54 mm. Scaps Samlight version 3.0.5 was used as the laser control software and Primes MicroSpotMonitor and Primes LaserDiagnoseSoftware were used to analyze the laser beam results.

Plates with size of 100 $\times$ 50$\times$6 mm made of stainless steel SS304L with composition of 2% of Mn, 0.75% of Si, 0.045% of P, 0.1% of N, 0.03% of C, 0.03% of S, 8-12% of Ni, and 18-20% of Cr were used for the experiments. A rectangular shape with the size of 4 $\times$ 4 mm and the hatching space of 0.02 mm in one dimension was the moving region of the laser beam. In most of the experiments carried out, one laser parameter was changed while the other laser parameters were remained constant.

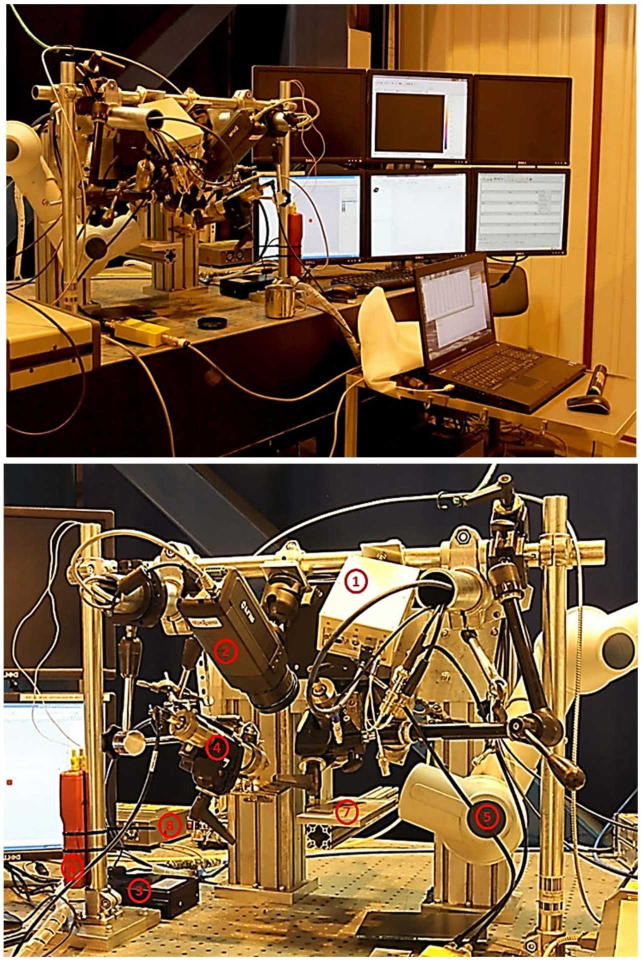

FIGURE 1. Experimental testbed and its sensors: 1- High Speed Camera, 2-IR Camera, 3- Spectrometer, 4-Pyrometer, 5- Gas vacuum, 6-Thermometer, 7- Workpiece stand, 8- Laser.

III. RESULTS

Different experiments were performed using a spectrometer, a pyrometer, an infrared camera, and a high-speed camera to evaluate and compare the performance of the monitoring system for laser engraving process using each of the mentioned sensors. The output of each sensor was analyzed from different aspects.

A. SPECTROMETER

The spectrometer used in this study was Ocean Optics HR2000+, which provides optical resolution of 0.035 nm (FWHM) and capability of transferring 1 ms spectra continuously. The HR2000+ is responsive from 200–1100 nm, but the specific range and resolution depends on grating and entrance slit selections. SpectraSuite software program was used to capture and analyze spectral data, which operates in real-time and can be externally triggered on and off.

The sensitivity of the spectrometer was investigated by changing several process parameters and evaluating the behavior of the spectrometer in response to the variation of emission intensity. Sensitivity of the spectrometer to the pulse length, focus position, and laser power was studied. In all experiments, the other parameters were the same as the default parameters. The repeatability of the measurement results of the spectrometer for monitoring the laser scribing process was also tested. Figure 2 shows the spectrometer sensor relative to the scan head and work piece, and also the measuring area of the spectrometer corresponding the laser processed area. The sensor head was positioned 180 mm from the work piece at a 25° angle of incidence. The integration time used with the spectrometer was 40 ms, as with the shorter integration time, the sensor did not seem sensitive enough to small changes in parameters.

1) REPEATABILITY

Repeatability of the readings obtained by the spectrometer was examined with six repetitions of the same experiment with the default parameters. Figure 3 shows the intensity wavelength of each test. Average intensity values were not only calculated at the highest intensity point, but during the entire time the laser was on (1.038 s), which ranged from 2421.503 to 2434.277. The deviation between the mean intensity values of each test was only 4.7 units, meaning the average intensity values differed only less than 0.2% of the mean values between the experiments. It should be noted

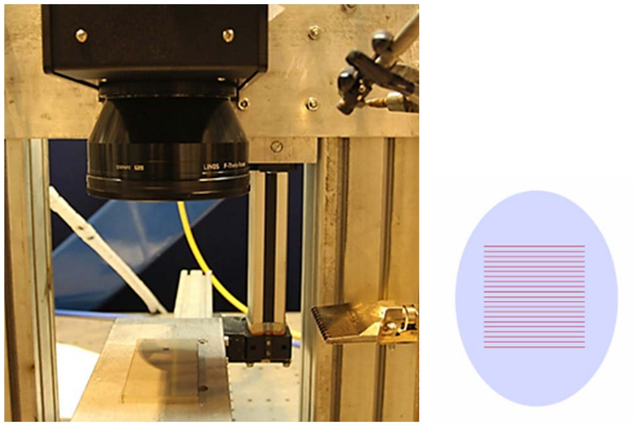

FIGURE 2. Left: spectrometer setup. Right: the laser hatching area (red) and the spectrometer measuring area (blue).

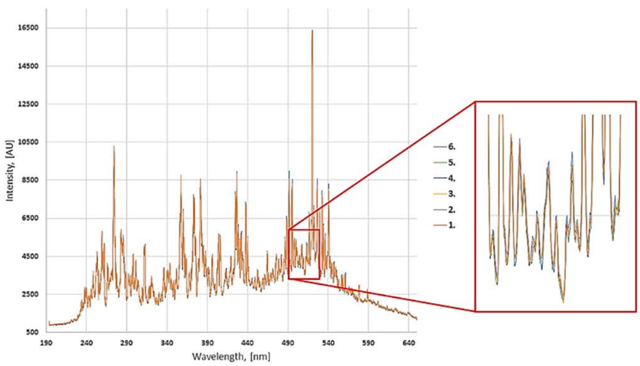

FIGURE 3. Six sets of repeatability experiments measured by the spectrometer.

that the maximum intensity in these experiments was more than 16800 units at 520 nm. Hence, it can be concluded that the spectrometer measurements are repeatable and highly reliable.

2) PULSE LENGTH EFFECT

Impact of pulse length was tested by changing the pulse length and using the corresponding nominal pulse repetition rate, to obtain the highest pulse energy for each pulse length to maintain the average power constant. Pulse lengths and their nominal pulse repetition rates examined for this experiment were: 4 ns with 500 kHz, 8 ns with 200 kHz, 14 ns with 125 kHz, 20 ns with 105 kHz, 30 ns with 85 kHz, 50 ns with 60 kHz, 100 ns with 40 kHz, and 200 ns with 20 kHz. The related pulse energies were: 0.04, 0.1, 0.16, 0.19, 0.235, 0.33, 0.5, and 1 mJ. Results demonstrated that as the pulse energy dropped and pulse length shortened, the radiation intensity between the measured wavelength range decreased. The difference between the longest and shortest pulse lengths (200 ns and 4 ns) was significant (~4000 AU), which revealed that the spectrometer is highly sensitive to the pulse length and pulse energy. Figure 4 displays the exponentially smoothed intensity diagrams for each experiment. Figure 5 illustrates

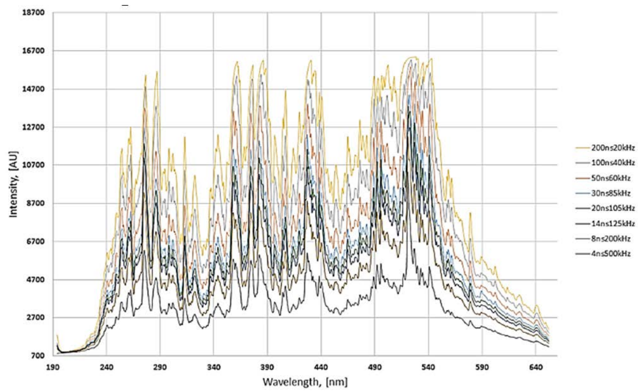

FIGURE 4. Radiation intensity spectra – pulse length effect.

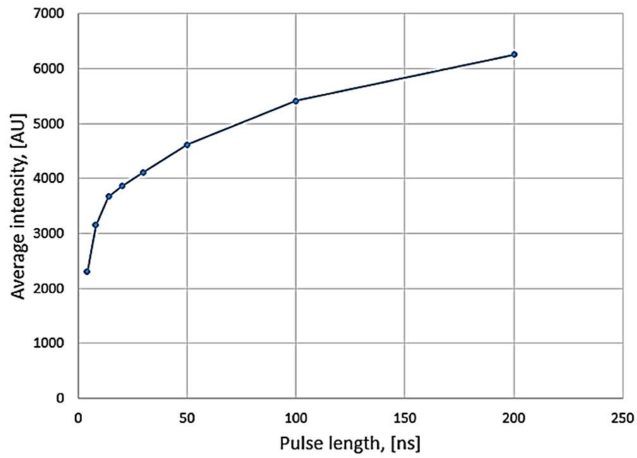

FIGURE 5. Impact of pulse length on average radiation intensity levels between 200-650 nm.

the average intensity values of the whole process for each experiment.

3) FOCAL POSITION EFFECT

Effect of focal position was investigated by changing the focal position from +2 mm above the workpiece to −2 mm below the workpiece with 0.5 mm increments. Results shown in Figures 6, 7 divulge that the spectrometer is sensitive to the change in focal position even with small variation of 0.5 mm in each direction; however, this is not surprising since the Rayleigh length with this optical setup is about 0.4 mm. The difference between 0 and ±0.5 mm is more noticeable when the focal position is below the surface but since the 0 focal position was initially localized manually, there might be some error in that the actual focal position was not where it is measured in these experiments. It was obvious that the spectrometer was very sensitive to the focus of the laser beam and could be used find the position where the radiation intensity is highest, i.e. the focal point. From the experiments it could be concluded that the actual focal point (or the maximum intensity) is about −0.1 mm below the zero plane. This fact could be used with a laser control loop to

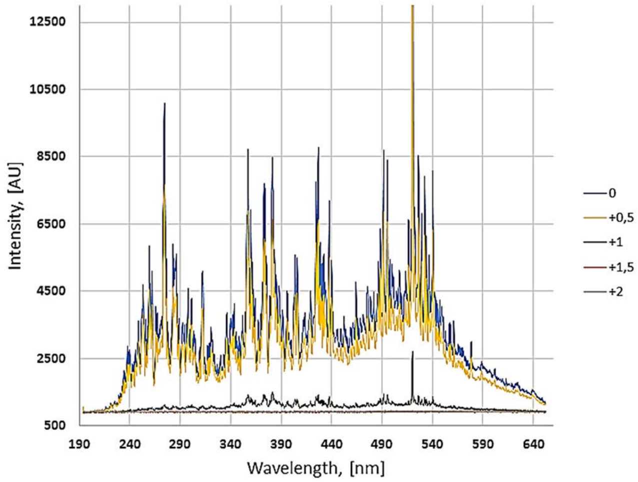

FIGURE 6. Radiation intensity spectra – plus side focal position effect.

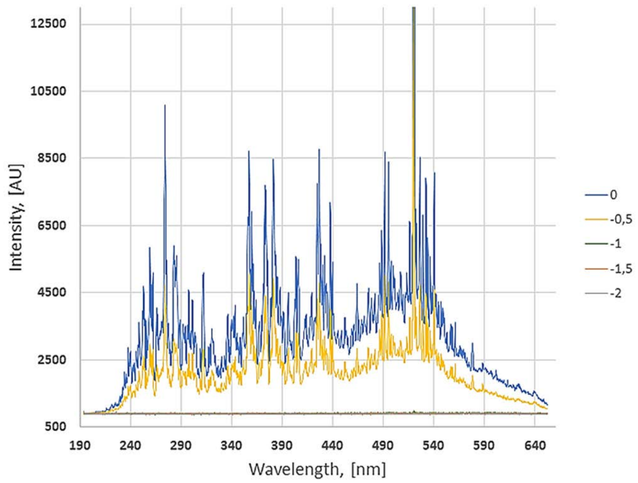

FIGURE 7. Radiation intensity spectra – minus side focal position effect.

automatically hold the laser beam in focus during the laser scribing process.

4) LASER POWER EFFECT

The laser power effect on the emission intensity was tested by changing the laser power from 2 W to 20 W in 3 W increments, while other parameters were kept as the default parameters. As shown in Figure 8, the highest intensity level is a function of measured wavelength range. The average intensity corresponding to different power levels is illustrated in Figure 9. An almost linear correlation is observed between the increase in radiation intensity and the laser power in the figures. The average difference in radiation intensity was approximately 120 units per each watt of laser power. So, it can be concluded that the spectrometer is relatively sensitive to changes in laser power. Since the spectrometer measurements in repetitive executions are so accurate, even 10 units of difference between measurements can indicate that the laser power is not constant.

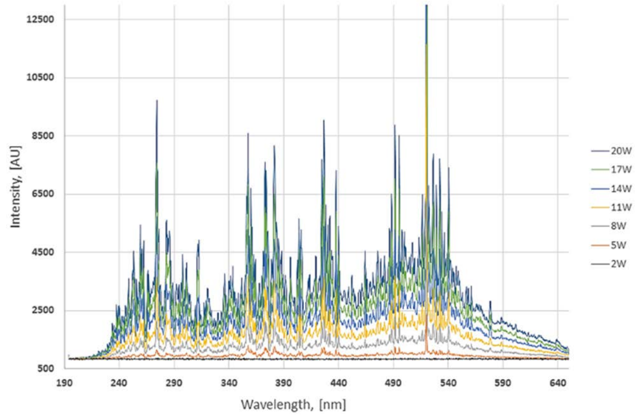

FIGURE 8. Radiation intensity spectra – laser power effect.

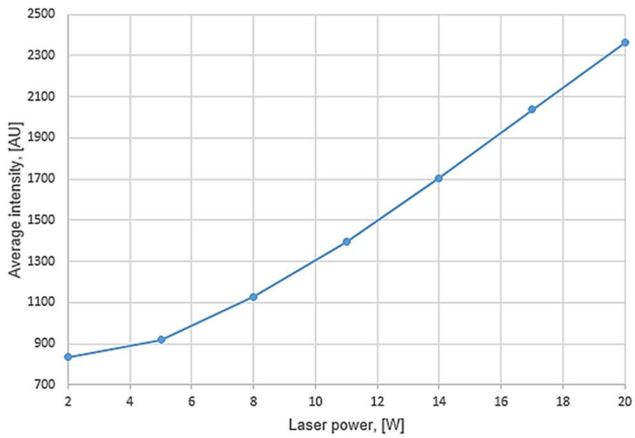

FIGURE 9. Impact of laser power on average radiation intensity levels between 200-650 nm.

5) EVALUATION OF SPECTROMETER FOR MONITORING OF LASER SCRIBING PROCESS

The sensitivity of spectrometer to changes in process radiation is its main advantage to be employed for monitoring of laser scribing process. It provides a good resolution of 0.035 nm in terms of wavelength sensitivity. Unlike other laser processes such as high-power laser welding, laser scribing produces very similar radiations in each similar experiment; therefore, the spectrometer data can be used as an indication of whether the process is operating optimally or not, and if not, what kind of a problem exists. However, since the spectrometer is sensitive to changes in process and laser parameters, the environmental disturbances may affect the measurements. It should be noted that the spectrometer has to be used coaxially with the laser beam in order to obtain the best results. Due to its small size, the spectrometer can be easily integrated into large systems. It can measure a wide band wavelength range from 200-600 nm or 600-1100 nm with high reliability; however, it requires a different grating and entrance slit to measure the infrared radiation. Intensity peaks at certain wavelengths can be seen in relation to other peaks. It was found that in scribing at very high speeds, slow

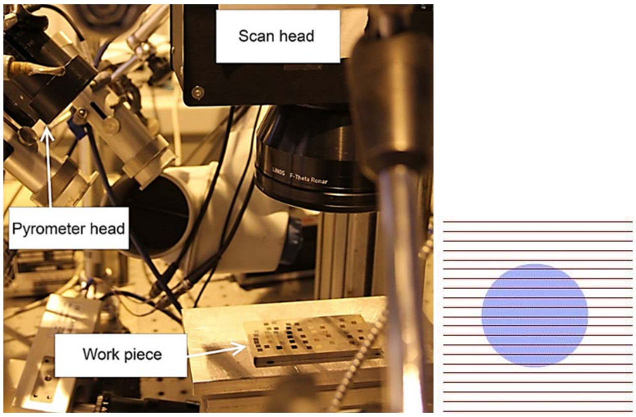

FIGURE 10. Left: pyrometer setup. Right: the laser processed area (red) and the pyrometer measuring area (blue).

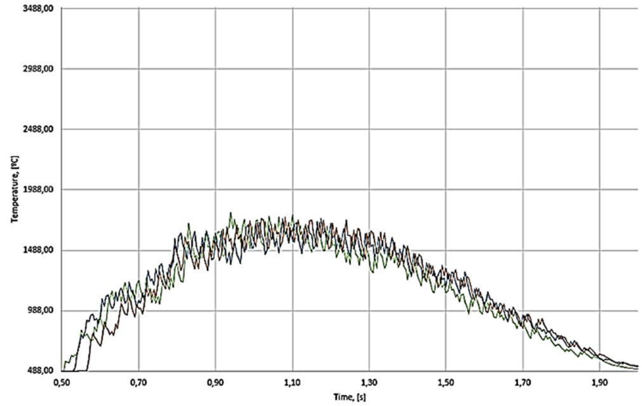

FIGURE 11. Three sets of identical pyrometer temperature measurement experiments for laser scribing.

integration time (40 ms) in relation to the processing speed may cause a problem. However, if the sensor head can be held close enough to register the process radiation or if the radiation is strong enough, an integration time of 1 ms can be used. As a result, based on all the experiments performed, the spectrometer was assessed as appropriate for monitoring the laser scribing process.

B. PYROMETER

Pyrometer, Temperature-Control-System (TCS), with temperature measuring range of 400 to 1600 °C was used for the experiments. Pyrometer sensitivity for laser scribing was tested by changing some critical laser parameters and analyzing how it affected the measured temperature by the pyrometer. Sensitivity to focal position, laser beam speed, and laser power was studied. Repeatability of the pyrometer measurements was also examined. The pyrometer measured temperature at 200 Hz within an area of 1-2 mm depending on how close the measuring optics were. Thus, the pyrometer measured temperature within the laser processed area of 4 × 4 mm but not the whole of it. Since the measuring area of the pyrometer was so small, laser beam speed of 500 mm/s was used as it provided more reliable results than the default 1000 mm/s. Figure 10 illustrates the setup and the measuring area of the pyrometer.

1) REPEATABILITY

Repeatability of the pyrometer readings was tested by repeating the same experiment three times with the default parameters, except for the laser beam speed which was set to 500 mm/s. Results of these experiments are displayed in Figure 11, which were exponentially smoothed for ease of comparison. Some variations between the measurements can be noticed but are not statistically significant based on the F-test run on Excel (F ratio $0.07 < F$ crit 3.00). It can be concluded that the pyrometer provides similar results in similar circumstances even though it is not as exact as the spectrometer.

2) PULSE LENGTH EFFECT

Sensitivity of pyrometer measurements to different pulse lengths was tested by varying the pulse length and using the corresponding nominal pulse repetition rate, to obtain the highest pulse energy for each pulse length. The laser beam speed was set to 500 mm/s, while other parameters were maintained as default parameters. Tested pulse lengths and their nominal pulse repetition rates were: 4 ns with 500 kHz, 8 ns with 200 kHz, 14 ns with 125 kHz, 20 ns with 105 kHz, 30 ns with 85 kHz, 50 ns with 60 kHz, 100 ns with 40 kHz, and 200 ns with 20 kHz. corresponding pulse energies were: 0.04, 0.1, 0.16, 0.19, 0.235, 0.33, 0.5, and 1 mJ. Figure 12 shows the results of all eight experiments performed. for pulse lengths from 4 to 50 ns no significant difference in the temperature of the process or workpiece could be noticed, and the difference between 100 and 200 ns was also negligible. in addition, even though there appeared to be a difference in the maximum temperature values between the 4-50 and 100-200 ns groups, there is no significant difference in the average temperatures, as can be observed in Figure 13.

3) FOCAL POSITION EFFECT

The effect of focal position on the measured temperature by the pyrometer was studied by varying the focal position from −2 mm to +2 mm with 0.5 mm increments, where the minus sign (−) indicates that the focus is below the surface of the workpiece and the plus sign (+) indicates that the focus is above the surface. The parameters were kept as default except for the laser beam speed, which was changed to 500 mm/s. Results are shown in Figure 14 and 15. Due to the large amount of data and the ease of comparison between different experiments, the images have been shrunk to a small size. It is obvious that within half a millimeter from the focal position to each way coaxially with the beam, something changed in the process that caused the pyrometer to suddenly detect a high amount of heat. This phenomenon could be explained by considering the change or initiation of the ablation process when the power density became high enough with the smaller

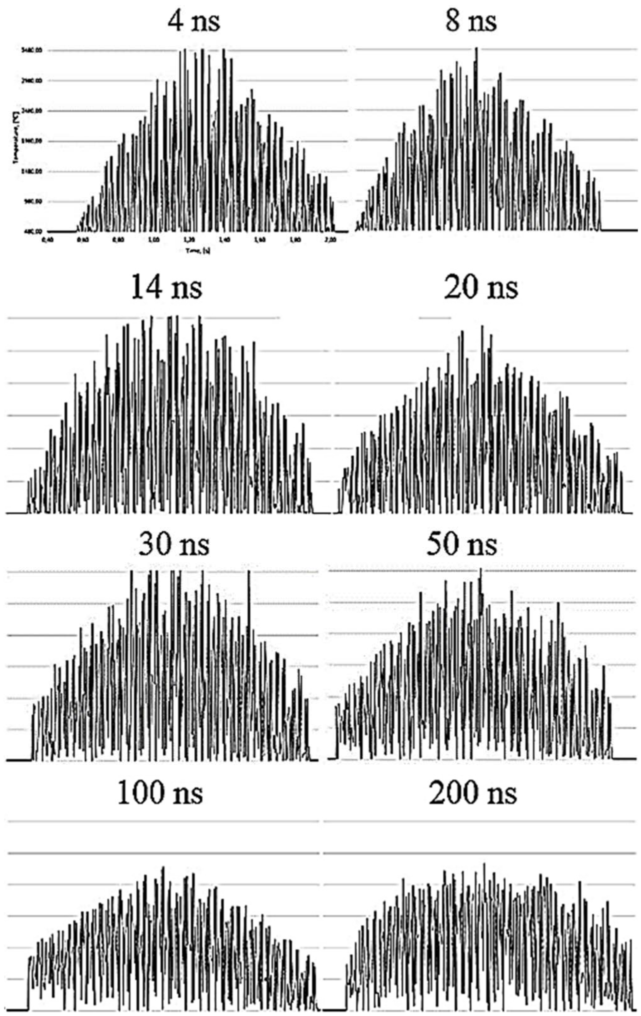

FIGURE 12. Effect of changing the pulse length on the temperature measured by the pyrometer. In each image, Y-axis is the temperature ranging from 480 to 3800 °C, and X-axis is the time ranging from 0.4 to 2.1 s.

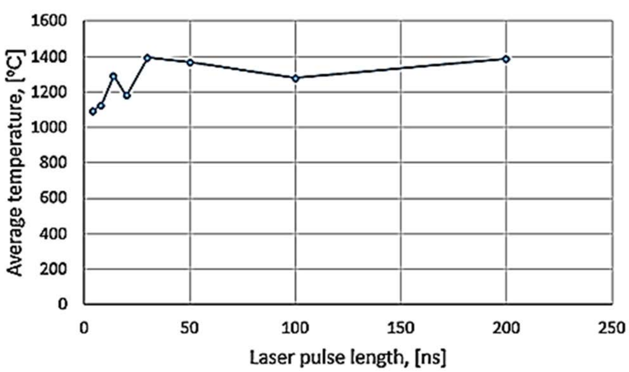

FIGURE 13. Average temperatures in laser scribing for different pulse lengths measured by the pyrometer.

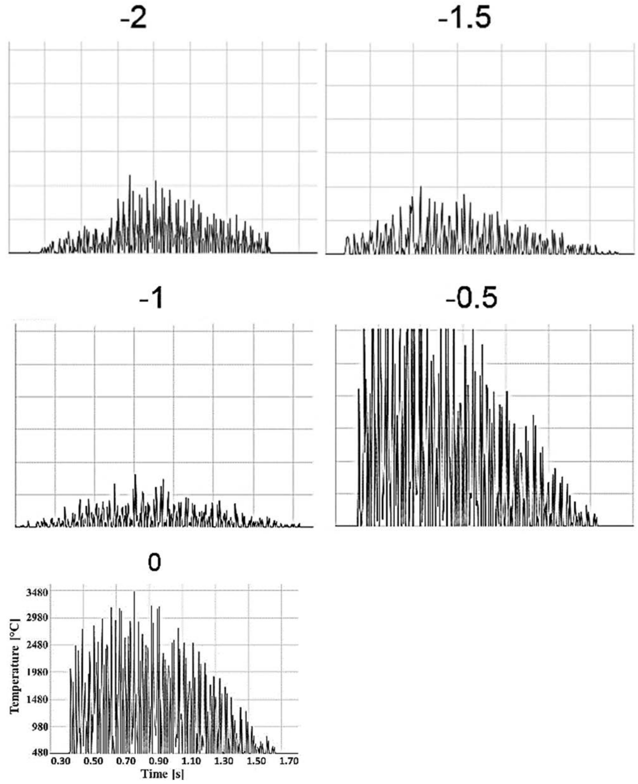

FIGURE 14. Effect of changing the focal position from −2 mm to 0 on the temperature measured by the pyrometer. In each image, Y-axis is the temperature ranging from 480 to 3800 °C, and X-axis is the time ranging from 0.5 to 2.1 s.

spot size. The maximum temperature difference between the focal positions of −1 and −0.5 was 2200 °C, whereas this difference between −0.5 and 0 was negligible. In fact, according to pyrometer readings, the process temperature when the laser beam was in focus was less than when it was defocused by 0.5 mm, suggesting that scribing is more efficient with a slightly defocused beam. However, this fact was not noticed in experiments performed with the spectrometer.

4) LASER POWER EFFECT

The effect of laser power on the temperature measured by the pyrometer was studied by changing the laser power from 2 W to 20 W with 3 W increments while keeping all the other parameters constant as default parameters (except the laser beam speed, which was set to 500 mm/s). The results are shown in Figure 16, where all the experiments have been compiled. The change in average temperature between different power levels is illustrated in Figure 17. Unlike the radiation intensity of spectrometer, the temperature measured by pyrometer did not increase linearly with rising laser power. Based on the obtained results, low power laser scribing did not induce much noticeable heat.

5) BEAM SPEED EFFECT

The effect of laser beam speed on temperature measured by pyrometer was studied by changing the speed from 100 mm/s to 1000 mm/s with increments in 7 stages: 100, 200, 300, 400, 600, 800, and 1000. For other parameters, default values

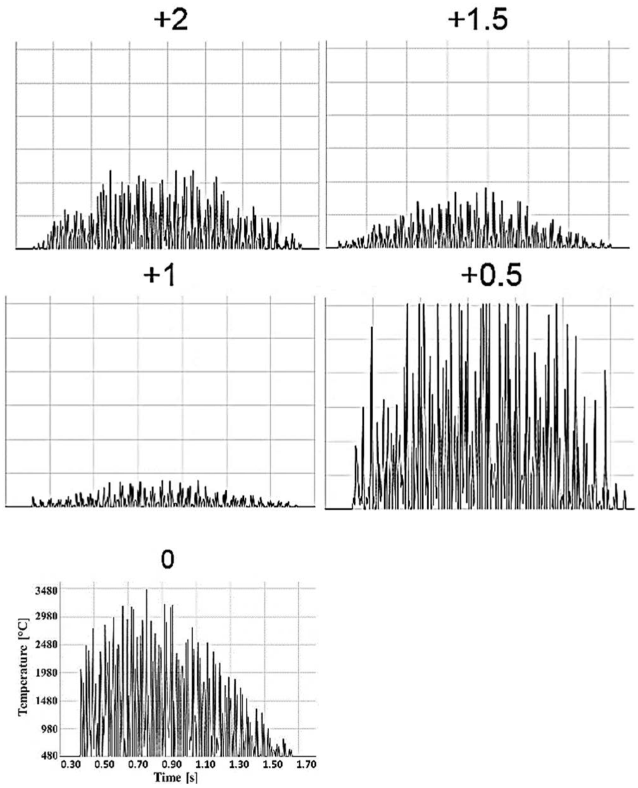

FIGURE 15. Effect of changing the focal position from 0 to +2 mm on the temperature measured by the pyrometer. In each image, Y-axis is the temperature ranging from 480 to 3800 °C, and X-axis is the time ranging from 0.5 to 2.1 s.

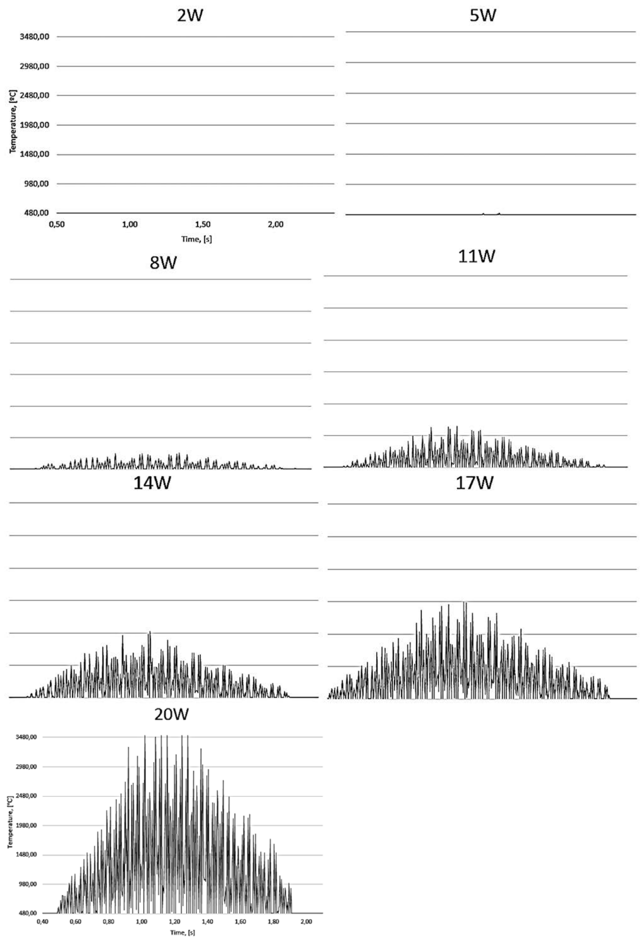

FIGURE 16. Effect of changing the lase power on the temperature measured by the pyrometer. In each image, Y-axis is the temperature ranging from 480 to 3800 °C, and X-axis is the time ranging from 0.5 to 2.1 s.

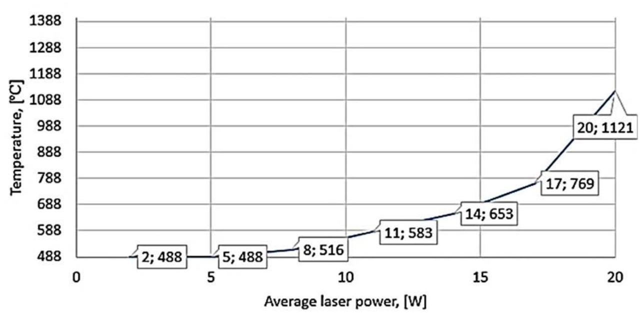

FIGURE 17. Average temperatures in laser scribing with different power levels measured by the pyrometer.

were used. Results of the conducted experiments are shown in figure 18, compiled in one image for ease of comparison. Contrary to what might be expected, the pyrometer demonstrated a significant enhancement in the measured temperature as the speed was increased. the lowest and highest temperatures were measured at the lowest and highest speeds, respectively. This illogical result might be related to the fact that pyrometer measures the average temperature over the entire measuring area. However, the laser beam necessarily introduces more heat to the workpiece using lower speeds, when all other parameters are constant; therefore, this result cannot be justified, and pyrometer measurements do not seem as reliable as other methods. This is exacerbated by the inconclusive results of pulse length experiments.

6) EVALUATION OF PYROMETER FOR MONITORING OF LASER SCRIBING PROCESS

Pyrometer measures high temperatures up to 1500 °C with a short integration time (∼ 2.5 ms) and fast analysis of the collected data. like the spectrometer, the pyrometer should be used coaxially with the laser beam to achieve the best results. Fairly large size and a small measuring area are counted as disadvantages of this equipment. External disturbances such as changing lighting do not affect the pyrometer measurements. Nevertheless, there are some challenges with using pyrometer in the laser scribing process, the most notable of which is that the pyrometer only reliably measures temperatures up to 1500 °C, however, in the laser scribing experiments, the pyrometer measured temperatures of 3500 °C and above. Since the measurements are significantly outside the operating range of the sensor, so their reliability is questionable. furthermore, the results gathered from the

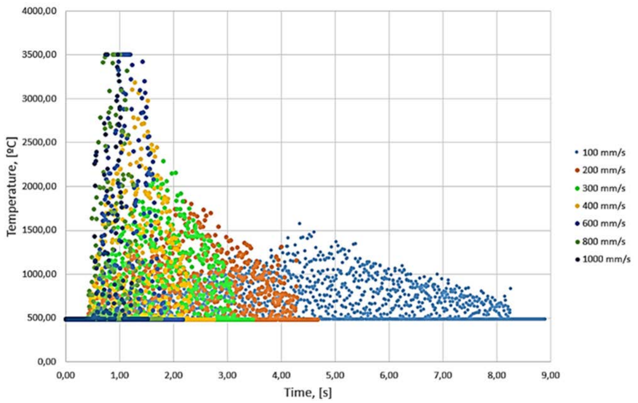

FIGURE 18. **Pyrometer temperature measurements using different laser beam speeds.**

laser beam speed experiments cannot be accurate (refer to section III.B.5).

C. INFRARED CAMERA

Suitability of Infrared (IR) camera for monitoring of laser scribing was studied by recording video of a 98.3-second-long scribing process with the infrared (IR) camera and analyzing the temperature data gathered by the camera. Flir A615 IR camera was used for this study. The camera takes 640 × 480 px images at 50 Hz. ThermalCAM Researcher Pro 2.10 software by FLIR Systems AB was used for capturing and analyzing the data. The captured video can be played back in the software and the temperature data can be analyzed frame by frame. Only the effect of heat outside the laser processed area was investigated to determine how significantly the workpiece was heated up during the process. Laser processed area was not included because readings would not be reliable due to the possible presence of plasma during the processing. Another reason that the laser area was not included was that after the processing, the surface emissivity of the processed area would be different from the rest of the material surface, which would also lead to poor results. This effect can be observed in all still images presented here, where the laser processed area looks much hotter than the rest, even though it is at or very close to room temperature. Further tests have been planned, where this effect is eliminated.

The test setup is demonstrated in Figure 19. The distance between the IR camera and the workpiece was 280 mm and the camera was at a 50-degree angle of incidence. With a macro lens, the camera could be moved closer and bigger magnification could be achieved. Basic lenses with a 1.7× and 3.6× magnification compared to the basic lens used in these experiments are available. Also dedicated macro lenses with 2.9× and 5.8× magnification specifically for small targets are available.

Two sets of analysis were done based on one 98.3-second-long scribing experiment. Default laser parameters were used. In one test set, the heating of the workpiece during the processing was investigated, while in another set, the cooling

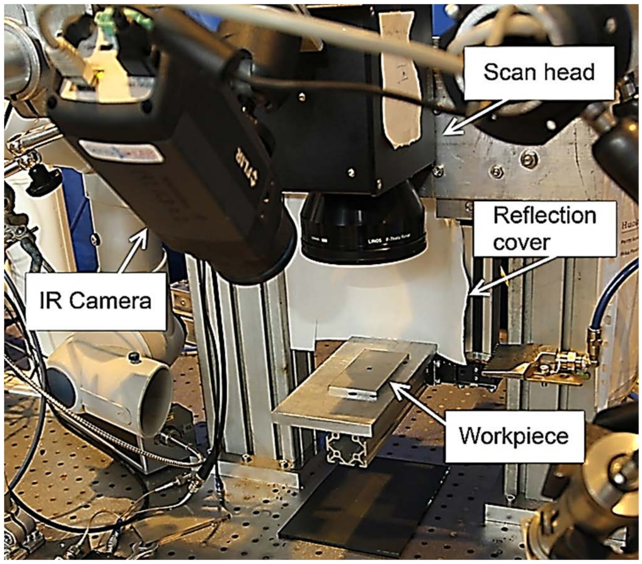

FIGURE 19. **Experimental setup with the IR camera for monitoring of laser scribing.**

of the workpiece after laser processing was investigated. Figure 20 shows an illustrative still image 10 seconds into the laser processing and the measuring lines along which the temperature was measured by the software. The temperature points along these lines were then compiled into a graph, shown in Figure 21. The software can do spot measurements and also measure the temperature inside an area, along curved or dotted lines. The four lines used here were manually placed and chosen to measure heat dissipation in all directions along the surface of the workpiece. The main disadvantage of using lines or areas in temperature measurement is that they determine the temperature at a certain point in time; however, if it is needed to plot temperature variations over a period of time, using spot measurements is a more uncomplicated tool. For this reason, spot measurements were also performed for the

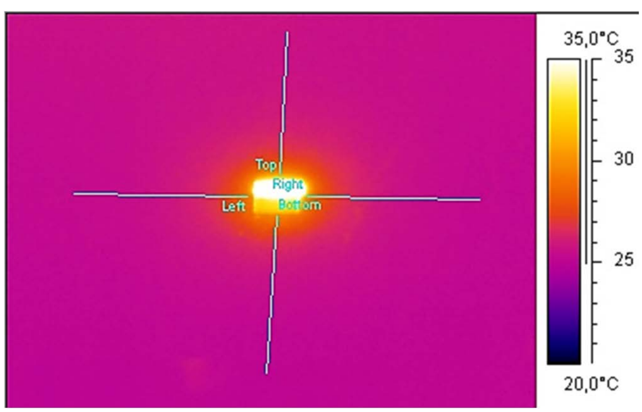

FIGURE 20. **Thermal camera image of the laser scribing process. The bright square (4 × 4 mm) in the middle is the laser processed area, and the brighter line inside is the laser spot moving sideways. Temperature was measured along the four lines, which were added to the video after the processing.**

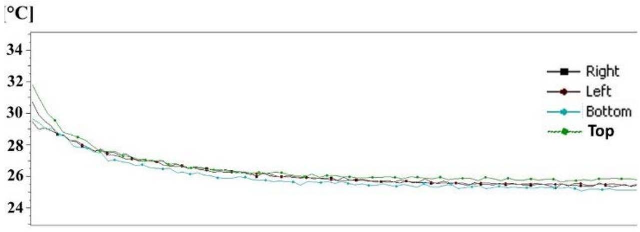

FIGURE 21. Four temperature graphs that correspond to the lines in Figure 21. Left side of the graph is closer to the laser processed area.

same experiments and the results were covered in more detail. However, one advantage of using lines and areas was noted. During the first few seconds of laser processing the process induced noticeable sparking, as displayed in Figure 22. This sparking is also visible in the line graphs in Figure 23 as a sudden increase in temperature whenever sparks cross the measuring lines.

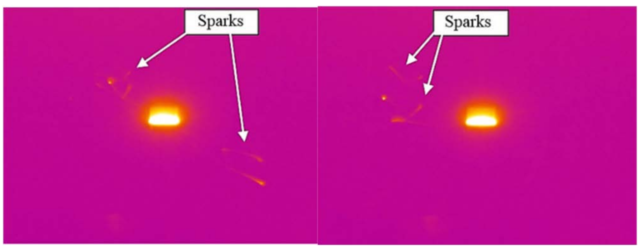

FIGURE 22. Sparks in thermal images during laser scribing.

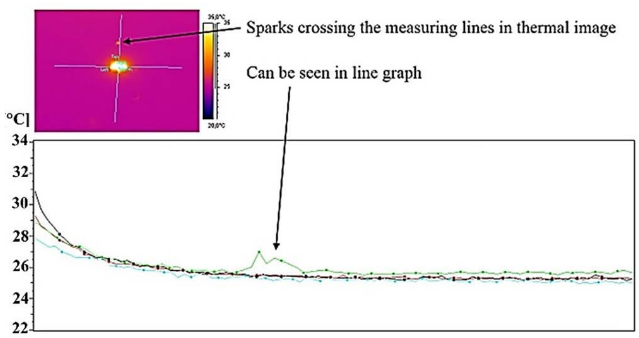

FIGURE 23. Illustration of how sparking in laser scribing can be noticed in thermal imaging in ThermalCAM researcher pro software.

1) THERMAL IMAGING OF THE WORKPIECE DURING LASER SCRIBING

Figure 24 demonstrates the spot placements for the temperature measurements during the experiment. Temperature was measured in 12 spots in three ring-like shapes around the 4 × 4 mm laser processed square. 4 spots were right adjacent to the square, 4 spots were at a distance of 5 mm, and the last 4 spots were at a distance of more than 10 mm from the laser processed square. Figure 25 presents the measured

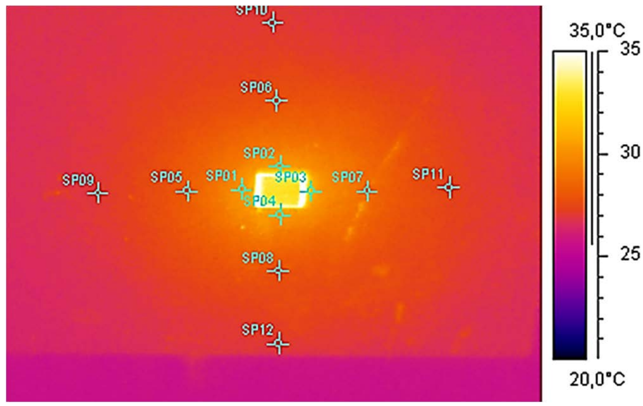

FIGURE 24. Thermal image of the laser scribing process showing the 12 spots at which the temperature was measured during the experiment.

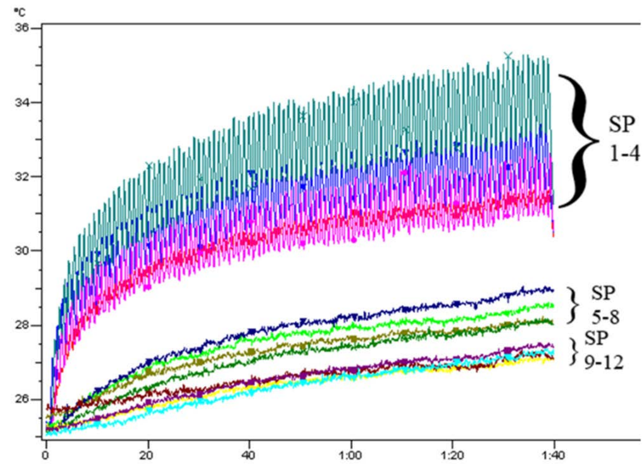

FIGURE 25. Temperature measurements in 12 different spots by the IR camera during laser scribing.

temperatures over the whole laser processing time of 98.3 seconds.

Spike-like variations in spots 1-4 are due to the movement of the laser beam to the measuring spot and the instantaneous heating of the material. As the laser beam moves away, the material cools rapidly. Since the room temperature was around 25.5 ° C, the workpiece was heated to a maximum of 7 ° C close to the processed area. The temperature seems to increase more rapidly for up to 20 seconds, after which the temperature continues to increase slowly and linearly but at a slower rate. From the results of spots 1-4, it can be noticed that the temperature with these parameters may plateau at around 33-34 degrees near the laser processed area.

2) THERMAL IMAGING OF THE WORKPIECE AFTER LASER SCRIBING

The heat effect of laser processing and workpiece cooling was analyzed by taking thermal imaging video of the workpiece surface after the laser processing. Similar spot measurements were used as experiments during the laser processing, however, this time each side of the processed area was measured

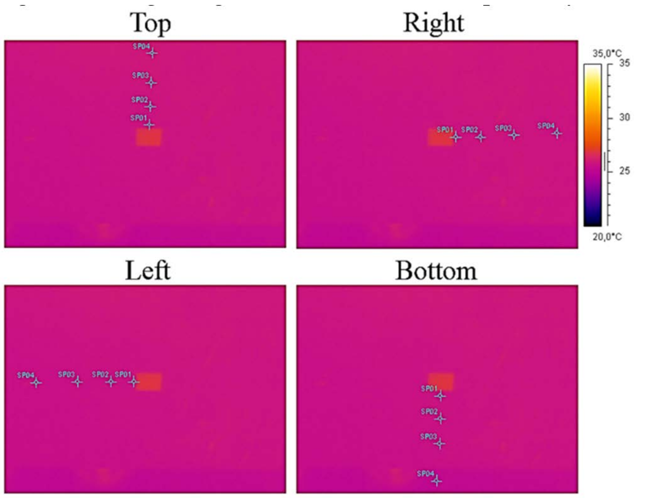

FIGURE 26. Thermal image of the laser scribed area showing the measuring spots used in the study of heat dissipation after laser scribing.

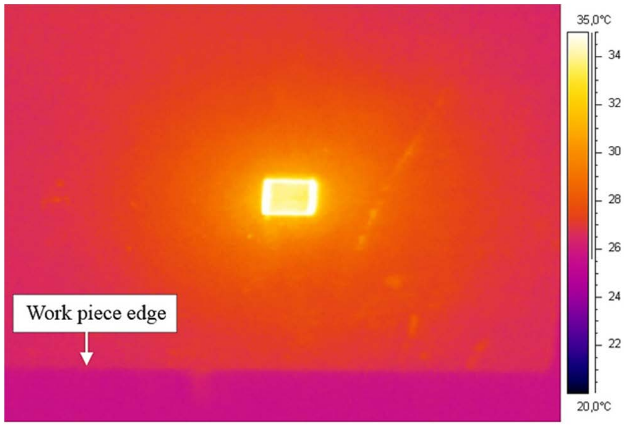

FIGURE 27. Thermal image of laser scribing right after laser processing for 98.3 seconds.

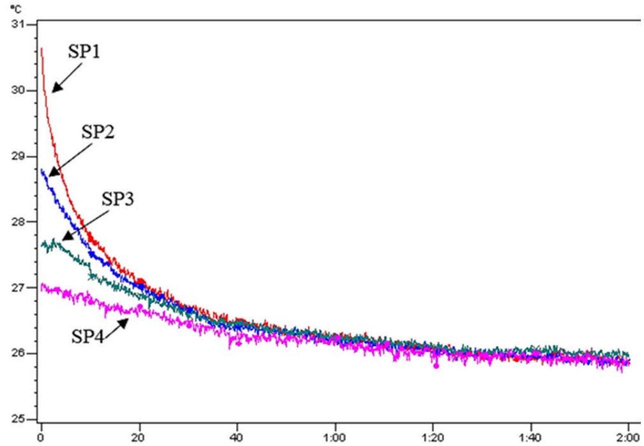

FIGURE 28. Temperature measurements for the top side of the laser processed area.

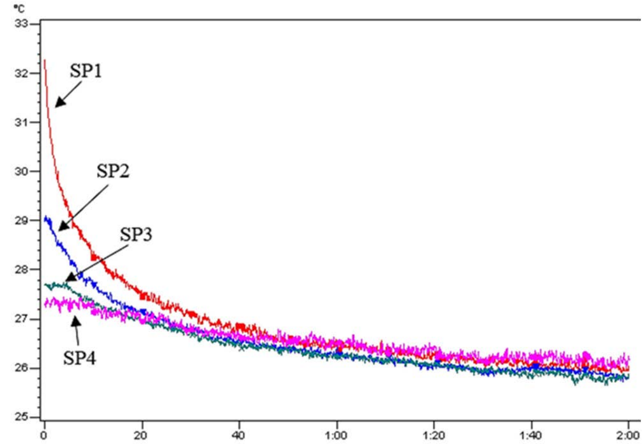

FIGURE 29. Temperature measurements for the right side of the laser processed area.

separately. Figures 26 and 27 show the measuring spots used in this experiment and the situation right at the beginning of the measurement, respectively.

Results of these experiments are presented in Figures 28, 29, 30, and 31. It is worth mentioning that since the laser processed area was symmetrical and the workpiece was homogenous and symmetrical in the vicinity of the processed area, heat was dissipated similarly in all directions along the workpiece surface. After the laser processing was completed, the temperature dropped very quickly. In about 20 seconds, the temperature difference has already largely evened out between the different measurement spots. The SP4 in the graph corresponding to the bottom side of the laser processed area shows a lower temperature than the rest of graphs because the SP4 was located outside the edge of the workpiece, as seen in the previous image (Figure 27). The surface emissivity of that area is slightly different from the surface of the workpiece where all the other spots are located.

3) EVALUATION OF INFRARED CAMERA FOR MONITORING OF LASER SCRIBING PROCESS

IR camera can be used for real-time monitoring of laser scribing process or offline monitoring by saving the data for later analysis using the advanced software included with the system. IR camera takes video with a higher frame rate than a normal camera (50 Hz). Although the IR camera does not detect missing laser pulses due to poor image resolution, it is still useful in monitoring laser scribing, at least in cases where a large amount of material needs to be removed and the process lasts longer. Temperature scale can be adjusted manually from −40 to 600 °C. Heat accumulation into the work piece can be seen via the IR camera. With nanosecond pulses, a significant amount of heat enters the work piece, while with picosecond or femtosecond lasers, less heat is applied, but the process is never completely cold. In these cases, thermal imaging shows how much heat was present in the base material. Due to the flexibility of thermal imaging software, the data can be analyzed in a way that makes more sense for any given application. Sparking can also be detected

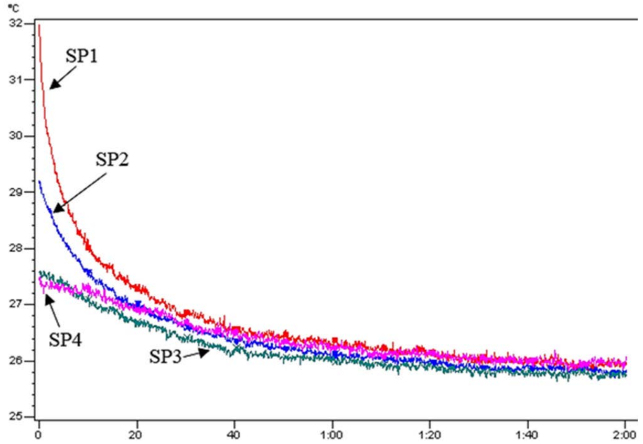

FIGURE 30. Temperature measurements for the left side of the laser processed area.

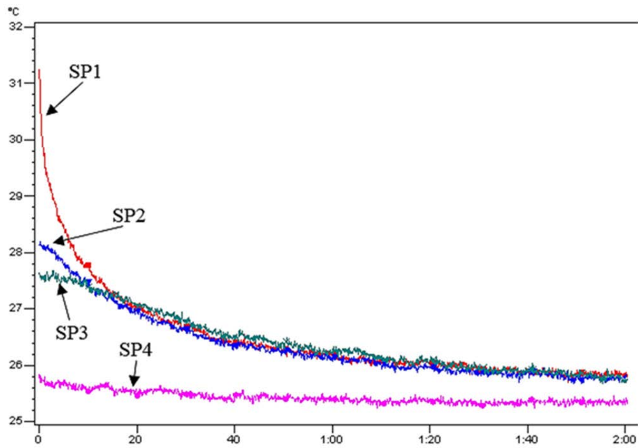

FIGURE 31. Temperature measurements for the bottom side of the laser processed area.

during the process using the infrared camera. In addition, since the infrared camera is sensitive to surface emissivity, thermal imaging can be used for post processing of laser scribing to evaluate if the area is homogeneously processed. Even small disturbances in the process can be later detected by examining the thermal image to check whether the change in emissivity has been uniform. This is especially true in cases where the laser beam passes the processing area only once. In addition to the basic lens, which is usually used for larger area monitoring, macro lenses are also available for smaller scale process; however, they are quite expensive. Based the experiments performed in this study, it can be concluded that IR camera is a promising tool for use in monitoring of laser scribing process. While the pyrometer can be better used to estimate the temperature of the ablation plasma cloud, the IR camera is a more effective tool for studying the heat impact to the workpiece. The major disadvantage of integrating an IR camera into production for monitoring purposes is its cost. Also, its integration time is quite long for high-speed systems (20 ms).

D. HIGH-SPEED CAMERA

High-speed camera with and without an active illumination system was studied to assess its eligibility to monitor the laser scribing process. The high-speed camera chosen for this study was Optronis camera model CR3000 × 2. The purpose of the active illumination system was to record videos of laser processes with an intense laser radiation that impaired vision. The system included a high-speed camera, an illumination system, a control unit, and control software. Illumination source was provided using a pulsed diode laser. The diode laser wavelength of 810 nm was passed through the filter located in front of the camera. High-speed mode pulsing was used. The control unit and its software synchronize the pulses with the high-speed camera frame rate. The location of high-speed camera was 180 mm from the work piece at a 40° angle of incidence. Experimental setup is illustrated in Figure 32.

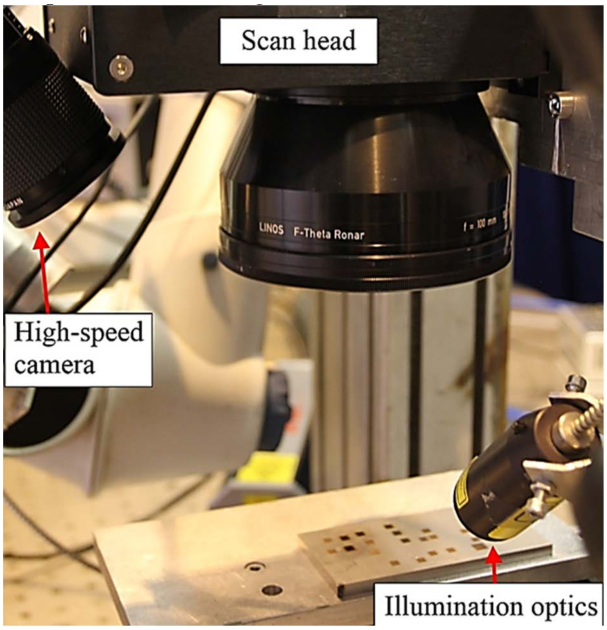

FIGURE 32. Experimental setup with the high-speed camera to monitor the laser scribing process.

The first experiment was performed without using the illumination system. The result showed that since the laser process generates high intense radiation, using a camera without an illumination system was meaningless. Therefore, the rest of the experiments were performed only with the help of the illumination system. Two images of a high-speed camera with the same process parameters with and without the use of the illumination system are compared in Figure 33.

1) RESOLUTION TESTS

The high-speed camera is capable of capturing images with frame rates of 500 to 50000 Hz. Frame rate is inversely related to the number of pixels in an image. The slowest frame rate results in the largest image with 1696 × 1710 pixels, and conversely, the highest frame rate leads to the smallest image

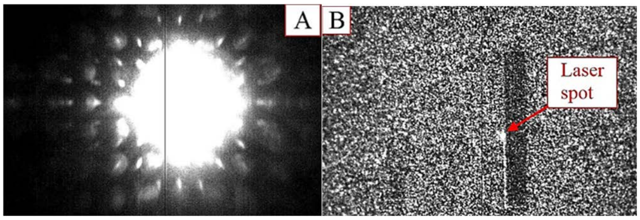

FIGURE 33. Laser scribing images from the high-speed camera: A) without the illumination system B) with the illumination system.

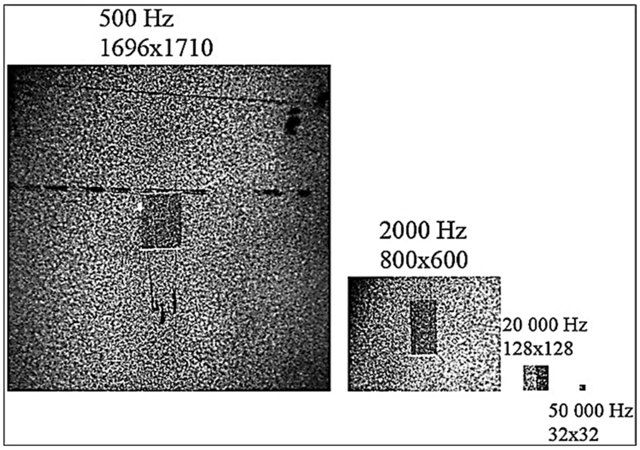

FIGURE 34. Difference between laser scribing images using different frame rates of the high-speed camera.

with 32 × 32 pixels. In the experiments performed, the pixel density was 70 px/mm meant an area of 0.46 × 0.46 mm and 24.2 × 24.4 mm using the highest and lowest frame rates of the camera, respectively. Figure 34 illustrates the difference between the images captured by the high-speed camera using different frame rates.

At a frame rate of 50000 Hz, the captured image is small; however, since the laser spot could not move between the frames due to lack of time, it indicates the laser beam and the process more properly compared to images captured at other frame rates. With a laser speed of 1000 mm/s at the mentioned frame rate (50000 Hz), the laser beam is able to move only 0.02 mm between each frame, while at the frame rate of 2000 Hz, this displacement reaches 0.5 mm. Also, in some instances where the frame rate of the high-speed camera is higher than the repetition rate of the laser pulse, high frame rate is beneficial since single laser pulses can be viewed with the high-speed camera. Figure 35 displays a 700% magnified image from the high-speed video at a frame rate of 50000 Hz. Considering the pixel density, the size of the molten pool is calculated as 48 μm.

2) PULSE LENGTH EFFECT

Experiments using different laser pulse lengths were performed to evaluate the impact of pulse length change on images captured by the high-speed camera. Laser pulse lengths of 14, 50, 100, and 200 ns were used for the

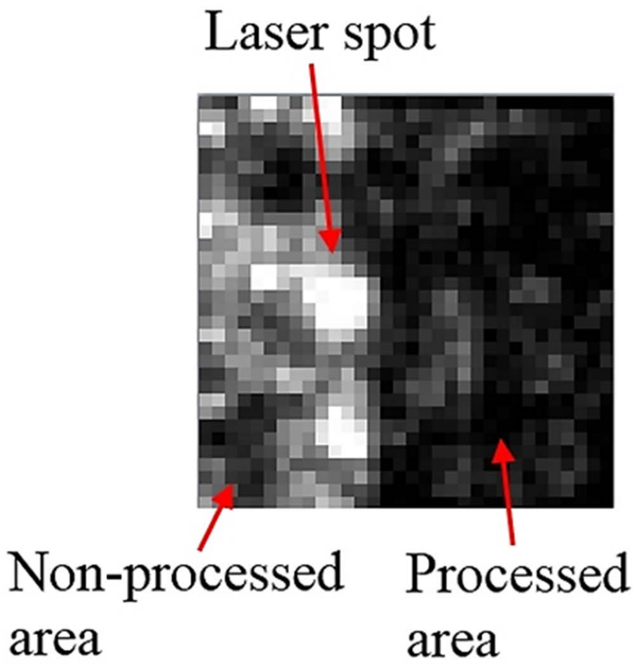

FIGURE 35. Laser scribing image with 700% magnification of a high-speed video with a frame rate of 50000 Hz.

experiments and the other laser parameters were kept the same as the default parameters. Capture frame rate of 5000 fps with an image size of 600 × 400 px was used for the high-speed camera. Results are presented in Figure 36. The bright point in the images is the laser spot while the darker region of the images is the laser processed area. The notable difference between the obtained images is the relatively brighter laser processed area for laser pulse length of 14 ns, otherwise, the images seem identical with visual inspection. In order to determine the behavior of the laser point with different pulse lengths, the images have been taken far enough.

3) EVALUATION OF HIGH-SPEED CAMERA FOR MONITORING OF LASER SCRIBING PROCESS

Using high-speed camera with an illumination system, the changes in the material during the movement of the laser beam can be recognized. The quality of images are high and even transient phenomena in the laser scribing process can be captured using high-speed videos. The transient occurrences are determinative since they provide insight into the actual state of the interaction between the laser beam and the material. The laser spot can be observed behind the ablation plasma cloud using the high-speed camera with an active illumination system. However, since the laser spot is too small, viewing the circumstance of the laser spot effect area is difficult. In addition, each laser pulse can be observed using this system if the high-speed camera frame rate is maintained higher than the laser pulse repetition rate. In this case, the system can be used to detect and alarm about the missing laser

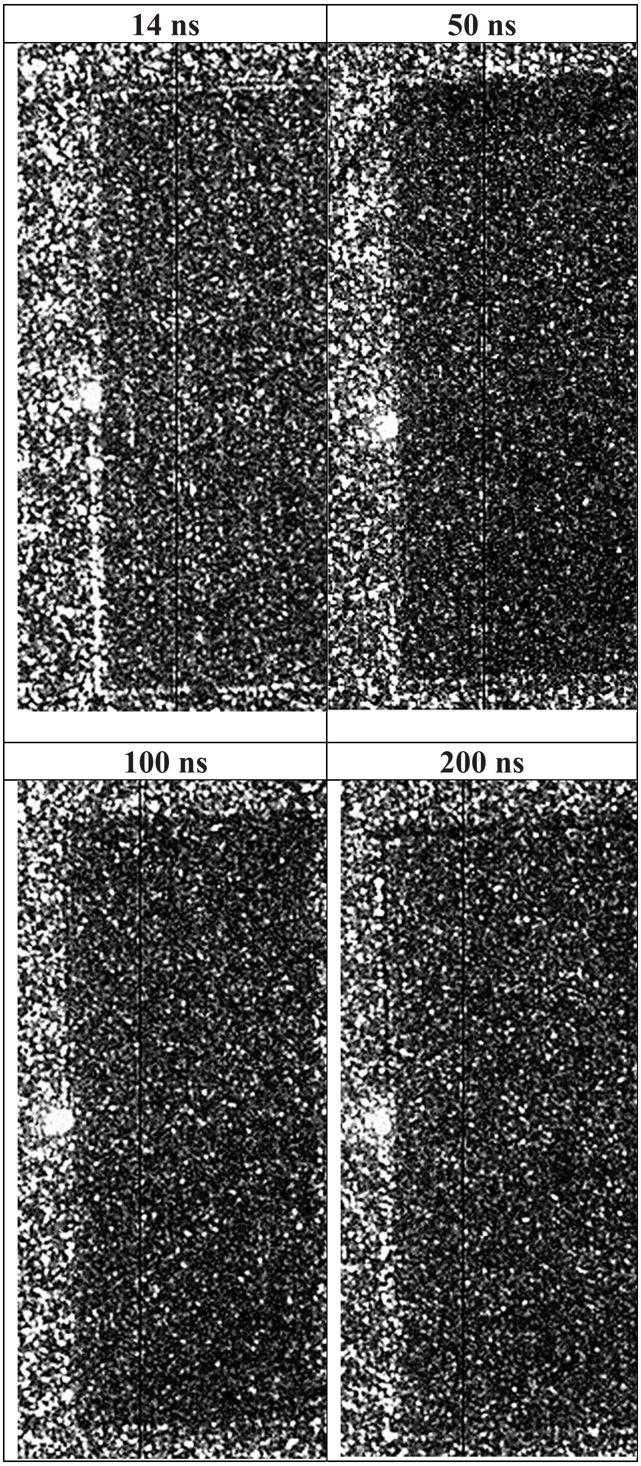

FIGURE 36. Impact of pulse length change on the high-speed images of laser scribing.

pulses. Due to the megahertz pulse repetition rates of ultrafast lasers, usage of a monitoring system capable of recording data with a very high speed such as high-speed camera is viable. However, the type of camera and the method of recording the data are crucial for the successful monitoring of such an ultrafast process. For example, in the case of using a high-speed camera equipped with data recording memory on the camera, analyzing the large amount of data produced using a high-speed camera system is difficult due to the limited memory of the camera. The memory capacity of the camera limits the length of videos that can be captured, for example, 1 second of video at 5000 Hz equals 690 MB. Therefore, the best solution is to use a high-speed camera that only captures the image and sends it to an ultrafast computing platform to process and analyze the image in real-time. Using this method, the monitoring process becomes real-time and can be continued without stopping, because the data is analyzed in real-time and if there is no defect in the process, the memory is cleared to enter new data for processing. It should be noted that although the entire system, including the high-speed camera and illumination system, is quite compact in size, it is relatively costly.

IV. CONCLUSION

In this study, a multi-sensory platform for real-time monitoring of the ultrafast pulsed laser engraving process has been developed and examined by applying various sensors, including spectrometer, pyrometer, infrared (IR) camera, and high-speed camera.

1) Results showed that the spectrometer provided a good resolution and was highly sensitive to changes in process radiation; thus, it was considered eligible to be employed for monitoring of laser scribing process. Also, it can be easily integrated into large systems due to its small size. However, external disturbances could affect the spectrometer measurements. According to the sensitivity results, spectrometer data could determine the type of a problem raised, if the scribing process was not proceeding optimally.
2) The results obtained from pyrometer measurements were based on temperatures up to 1500 °C, which could not be reliable for the laser scribing experiments with temperatures of 3500 °C and above. Also, the pyrometer has a relatively large size and a small measuring area, making it inappropriate for industrial applications. Unlike spectrometers, however, environmental disturbances did not influence pyrometer measurements.
3) The IR camera was considered a promising tool for use in monitoring the laser scribing process, despite that it did not detect missing laser pulses due to poor image resolution. Using the infrared camera, sparking could also be detected during the laser scribing process. In addition, it was found that due to the sensitivity of the IR camera to surface emissivity, thermal imaging could be used for post processing of laser scribing to ensure that the area was processed homogeneously. Compared to the pyrometer, which could be better used to estimate the temperature of the ablation plasma cloud, the IR camera was assessed a more effective tool for studying the effect of heat on the workpiece. However, the

integration time of IR cameras for high-speed systems is quite long and applying it in industrial applications is quite costly.

4) According to the experiments performed, using a high-speed camera with an active illumination system, transient events in the process could be captured and visual phenomena that might be hidden behind the ablation plasma cloud could be noticed. Moreover, it turned out that if the frame rate of the high-speed camera was higher than the repetition rate of the laser pulse, each laser pulse could be observed, and the missing laser pulses could be detected. It was concluded that using the high-speed camera was feasible for ultrafast laser scribing process. Nevertheless, the type of the high-speed camera and the data recording method are determinative in real-time monitoring of the ultrafast laser scribing process. Best results can be achieved using a high-speed camera, which only captures the image and sends it to an ultrafast computing platform to process and analyze the image in real-time. However, the whole system, including the high-speed camera and illumination system, is relatively expensive.

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