IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 8, 2022, accepted February 21, 2022, date of publication March 2, 2022, date of current version March 15, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3156280

Real-Time Monitoring and Control of Ultra-Fast Laser Engraving Process Utilizing Spectrometer

MIKA RUUTIAINEN[1], HAMID ROOZBAHANI[1], (Member, IEEE), MARJAN ALIZADEH[1], HEIKKI HANDROOS[1], (Member, IEEE), AND ANTTI SALMINEN[2]

[1]Department of Mechanical Engineering, Lappeenranta-Lahti University of Technology, 53851 Lappeenranta, Finland
[2]Department of Mechanical Engineering, University of Turku, 20014 Turku, Finland

Corresponding author: Hamid Roozbahani (hamid.roozbahani@lut.fi)

This work was supported by the Hub of Application Laboratories for Equipment Assessment in Laser Based Manufacturing (APPOLO) through the EU FP7-ICT under Grant 609355.

ABSTRACT The objective of this study was to develop a novel real-time monitoring and control method for ultra-fast laser scribing processes utilizing spectrometer. Adjustment of laser process parameters such as laser power with high precision in real-time is critical in the laser engraving process due to the premium quality and speed requirements of the process. An online monitoring system was established using the Ocean Optics spectrometer, IPG ytterbium pulsed laser, and PXIe-8880 industrial computer. An algorithm for real-time control of the laser scribing process was developed based on the monitoring outcomes using LabVIEW®software. Experimental methods were performed to evaluate the reliability of the developed monitoring system and control algorithm. The sensitivity of the spectrometer was assessed by changing laser power, pulse length, and focal point position. A workpiece consisting of two different metals, including stainless steel SS304L and steel S355, was used to evaluate the performance of the developed algorithm when scribing moved from one material to another. Instant accurate setting of the laser power based on the variations in intensities of metals from 750 AU to 1400 AU validated the reliability of the algorithm.

INDEX TERMS Laser scribing, real-time monitoring, real-time control, spectrometer, ultrafast laser.

I. INTRODUCTION

Ultrafast lasers have revolutionized laser processes in manufacturing industry and provided opportunities for various novel applications due to their high peak powers and extraordinary short pulse durations. Surface engraving can be performed by mechanical or laser methods. However, mechanical engraving has limitations for small details, materials range, tool wear, and workpiece clamping [1], [2]. Laser scribing technology has been actively developed in recent years and is replacing conventional mechanical methods. Laser engraving provides high precision for a wide range of materials in a contactless high-speed process with a high power of laser beam [3], [4]. Ultrafast lasers are favored to be engaged in laser engraving applications [5]. Laser engraving processes are much faster than other widely used applications such as laser welding or cutting processes, the speed of which can reach several meters per second [6]. Also, laser scribing processes demand high quality requirements, as even a minor defect in the scribing line can deteriorate the quality of the final product [6], [7]. A defect in this field refers to a disconnection in the scribing line. Due to the high speed and quality requirements an effective monitoring system is critical. Laser process monitoring is usually performed utilizing optical or acoustic methods, the most common of which are optical methods [8], [9]. Optical sensors have been significantly improved during the past years from simple sensors like photodiodes to advanced digital cameras [10]–[12]. So far, the most successful optical sensors are the ones that measure spatially integrated optical intensities such as spectrometers, which are capable to measure spectral ranges from gamma rays to microwaves [13], [14]. Spectral analysis is one of the most reliable methods in detecting spectrum from a plasma plume, which occurs due to high intensity power in laser processing [15]. Although several techniques have been developed for process monitoring and control of laser welding and cutting, high-quality monitoring and control systems have not been sufficiently studied and

The associate editor coordinating the review of this manuscript and approving it for publication was Norbert Herencsar.

implemented for the laser engraving processes [16], [17]. However, these types of processes are remarkably slower than the laser scribing process [18], [19]. The control of laser scribing process is typically performed by applying the parameters changes offline rather than in real-time. However, a closed-loop online monitoring and control system is essential for such a process since it requires high precision and fast speed.

The objective of this research was to develop a functional and accurate online monitoring method and real-time control algorithm for a laser scribing process using spectrometer. For this purpose, a test set-up for performing different experiments has been built to evaluate the feasibility and performance of the developed monitoring and control method. Process monitoring system was established using a pulsed ytterbium fiber laser, spectrometer, camera adapter, and industrial computer PXI system with Data Acquisition card and Real-Time Controller module. Using LabVIEW® software, two algorithms were developed for real-time control of the process based on the acquired data from the monitoring system. Spectrometer was utilized to sense different wavelengths and intensity of laser engraving process, while the attempt was to stabilize the engraving process apart of the material, which leads to uniform engraving quality even if the engraved component consists of different materials. This study addresses all required equipment setup for monitoring of laser engraving process and accurately describes a method for developing an algorithm to real-time control of a laser scribing process. The real-time monitoring and control method for laser scribing using spectrometer investigated in this study, contributes to implementing such a system in the industrial applications. Also, the developed technique of real-time monitoring and control utilizing a spectrometer can be applied for other laser applications such as laser-induced marking in different materials, where controlling the characteristics of parameterized marks for information recording are essential [20], [21].

II. REAL-TIME CONTROL OF LASER PROCESS

An algorithm for the real time control of the laser engraving process based on the data acquired by spectrometer has been developed. LabVIEW software was used for designing the algorithm. Serial communication between the PXIe industrial computer and the laser was set so that the user could control the process through the laptop connected to PXIe through Ethernet, while all calculations would be carried out by the PXIe industrial computer. All the accepted parameters for pulse repetition rate and pulse duration were set in the drop-down menu. The laser power was aimed to be adjusted in real-time by connecting the intensity acquired by the spectrometer to the associated power outputs. A wide intensity range was considered for an efficient and accurate tunning of the laser power output range by dividing the acquired spectra into 2000 pixels with corresponding wavelength values. The highest peak of intensity among divided pixels was fed to the laser power control algorithm to tune the level of power. Graphical output of the spectrometer is illustrated in Fig. 1 with laser power of 20W, scanning speed of 1000 mm/s, pulse duration of 200ns, and pulse repetition rate of 200kHz. The goal of this experiment was to test the functionality of the spectrometer.

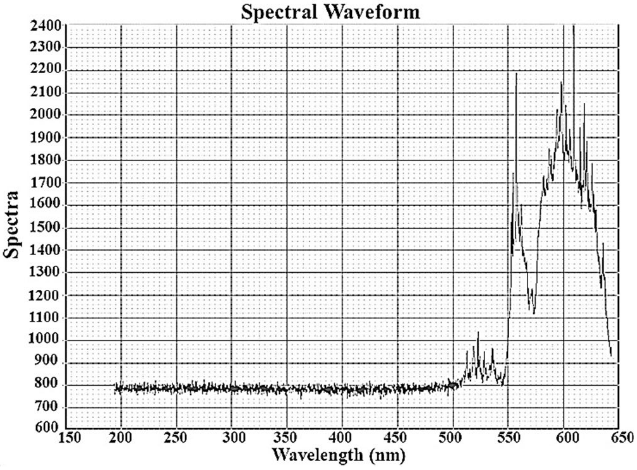


FIGURE 1. Sample of spectrometer data acquisition.

III. EXPERIMENTAL SETUP

Test bed shown in Fig. 2 was built for the experiments. It consists of IPG ytterbium pulsed laser, Scanlab Hurryscan 14 II scan head, Scanlab camera adapter, Scanlab RTC 4 interface card, Ocean Optics HR2000+ High-Resolution miniature fiber optic spectrometer plus adapter, and CaviLux illumination laser. The controlling of laser was performed using IPG YLP C-series software. Scanlab Hurryscan 14 II scan head controls the movement and speed of the mirrors with high speed and precision. Speed of the mirrors inside the scan head was at least 100mm/s. Controlling of the scanner head and the laser parameters was performed using SCAPS SAMLight version 3.0.5 build-0582. In order to acquire data using spectrometer, Scanlab camera adapter was installed between the laser flange and the scan head to observe the path of laser light through the mirrors. Scanlab RTC 4 PC control board was used to real-time control of scan and laser system with PCI interface. The Ocean Optics spectrometer used in this research operates with SpectraSuite software and provides resolution of 0.035 nm, wavelength range of 200–1100nm, and integration time of 1 ms to 65 s. Ocean Optics HR2000+ provides several methods of acquiring data. The voltage level on the spectrometer's trigger pin can be triggered by the laser pulse or an outside event to start spectral acquisition. As soon as the laser control software starts the laser and executes the scribing pattern, it simultaneously triggers the spectrometer, illumination laser, and the data acquisition computer to record the data. National Instruments industrial computer PXIe-8880, which is an embedded controller, along with NI PXI-8430 serial port module was engaged for data acquiring

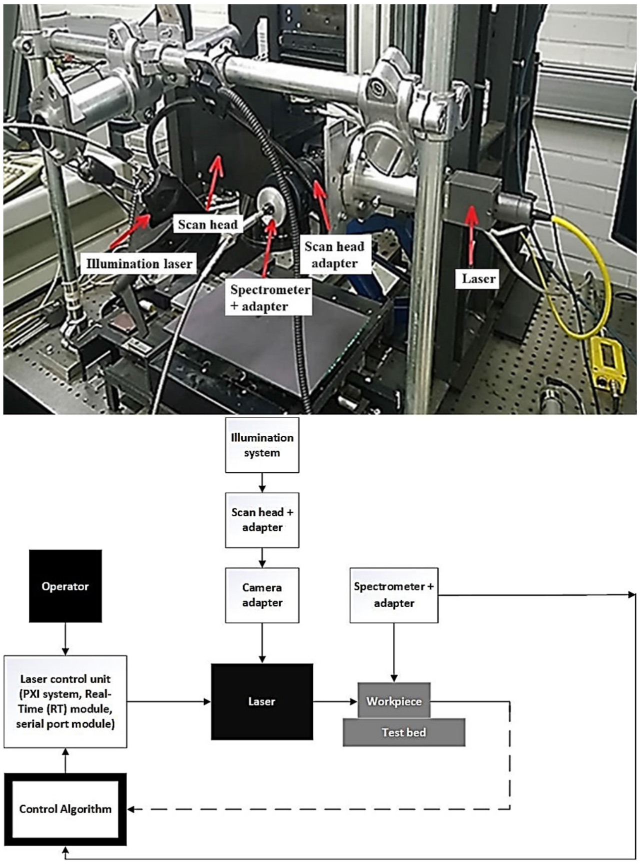


FIGURE 2. Experimental equipment and its schematic diagram [22].

and tunning the parameters in real-time. Reflection and relative irradiance tests were performed to ensure functionality of the setup.

IV. RESULTS

Two experiments were performed using the developed algorithm to analyze the spectrometer output and evaluate the performance of the control algorithm for laser scribing on a metal plate from different materials.

A. SPECTROMETER OUTPUT ANALYSIS

Stainless steel SS304L plate with the size of 100 × 50 × 6 mm3 was used for this experiment. The moving zone of the laser beam was within a 4 × 4 mm^2 rectangular shape. The hatching distance was 0.22 mm in one dimension without including the contour of the shape. Laser parameters include laser power of 20W, pulse length of 4 ns, laser beam scanning speed of 1000 mm/s, and pulse repetition rate of 1000 kHz. The spectrometer focal length was 520mm and the direction of observation was perpendicular.

1) REPEATABILITY

The repeatability of the spectrometer was evaluated by repeating the same test six times. each time executing for two seconds. The sum of all intensities along the wavelength range was calculated for each test to measure the intensity deviation. The sum of intensity varied from 1,568,357 AU to 1,585,605 AU, which revealed the difference of 0.0109%. Therefore, it could be concluded that the spectrometer provided the reliable spectral data and measurement repeatability was validated. The repeatability test results are presented in Fig. 3.

2) IMPACT OF LASER POWER

The impact of laser power on radiation intensity was examined by altering the laser power from 2W to 20W in 2W increments and retaining the rest of parameters by default. By increasing the laser power, the radiation intensity raised as well (Fig. 4). The difference in radiation intensity for power of 2W and 4W was relatively small; however, from the power of 6W to 20W, the increment in radiation intensity was 150 units per watt of the laser power, which meant an almost linear relationship between the intensity enhancement and the increase in laser power. Although spectra were changed constantly due to a high sensitivity of the spectrometer, the increase or decrease in power could still be observed with good accuracy.

3) IMPACT OF PULSE LENGHT

The sensitivity to various pulse lengths was examined by varying the pulse length corresponding to the nominal pulse repetition rate in such a way that the highest pulse energy was obtained for each pulse and the average power was retained constant. Pulse length to pulse repetition rate were arranged as 4ns/500kHz, 8ns/200kHz, 14ns/125kHz, 20ns/105kHz, 30ns/85kHz, 50ns/60kHz, 100ns/40kHz, and 200ns/20kHz. The corresponding pulse energies were 0.04, 0.1, 0.16, 0.19, 0.235, 0.33, 0.5 and 1 mJ, respectively. A significant difference equal to 1400 AU was pointed between the intensities related to the longest pulse length and the shortest pulse length at the wavelength of 550nm. The efficiency of laser engraving process is highly dependent on the accurate ratio of pulse length and pulse repetition rate. The highest scribing efficiency was achieved at 200ns/20kHz, while the scribing quality was low. In contrast, the lowest scribing efficiency was achieved at 4ns/500kHz, while the scribing quality was proper. Fig. 5. demonstrates the test results.

4) IMPACT OF THE FOCAL POINT POSITION

The effect of changing the focal point position was evaluated by varying the level of focal plane ±2mm (by 0.5mm increments) from its base position at 126 mm. Adjusting the primary level at 124.0mm caused a very low laser intensity and inefficient scribing. However, by 0.5mm increments, the intensity of the process was significantly increasing. The scribing efficiency reached to its maximum level at 126.5mm. The intensity started declining afterward, and at 128.0mm the impact of changing the focal point position resembled the result of focal point at 124mm. From the results (Fig. 6), it could be concluded that the spectrometer was highly sensitive to the position of the laser focal point.

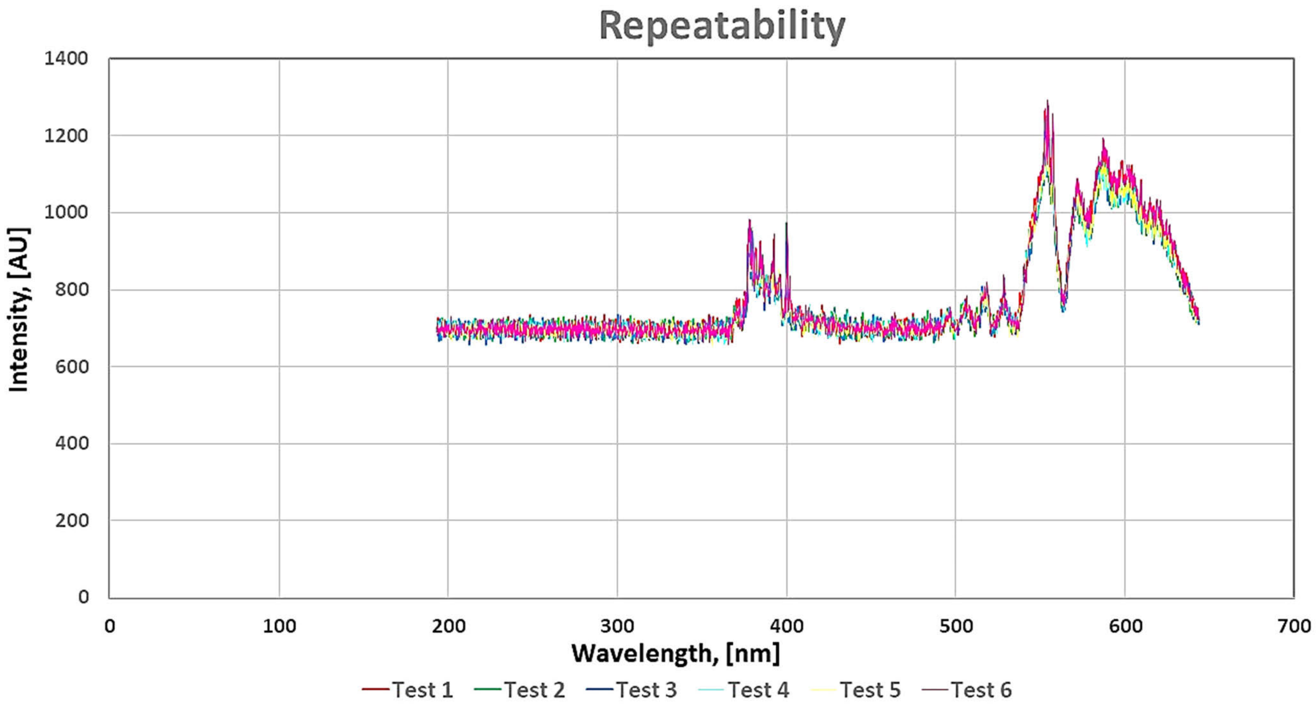


FIGURE 3. Repeatability test results.

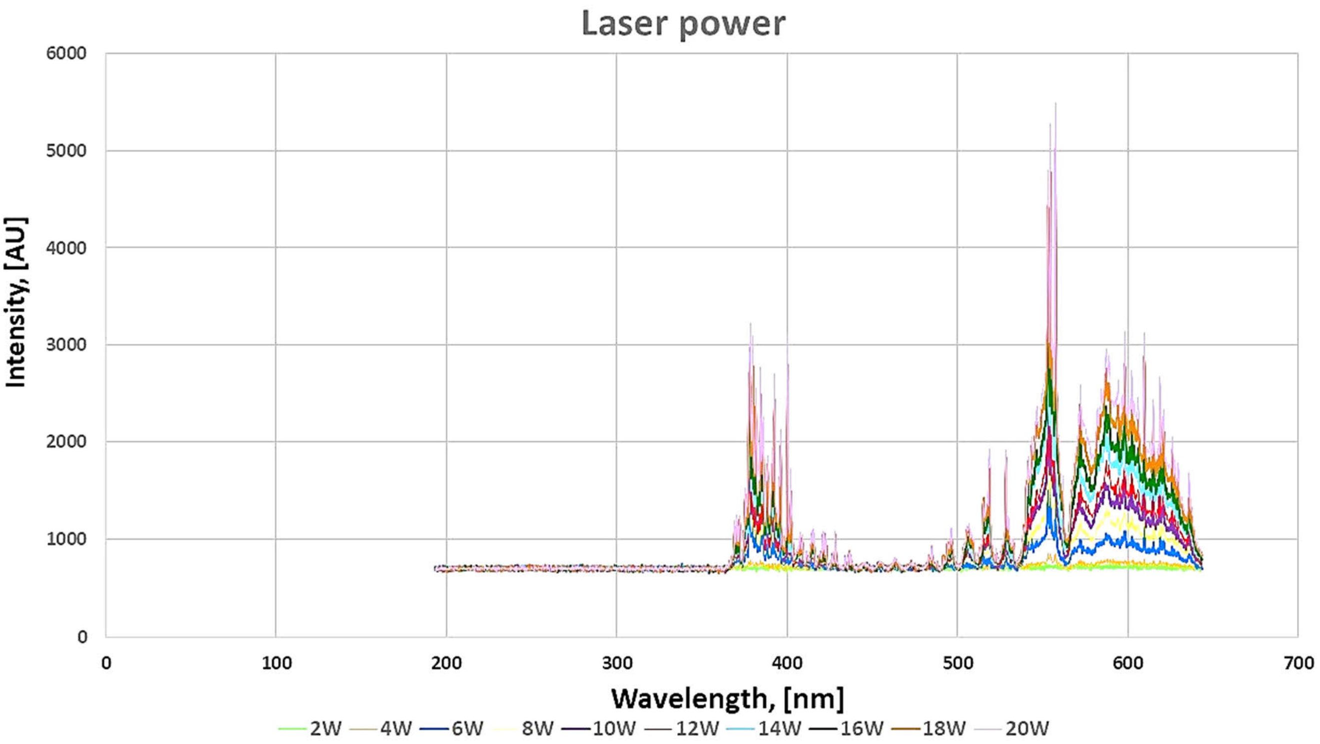


FIGURE 4. Effect of the laser power.

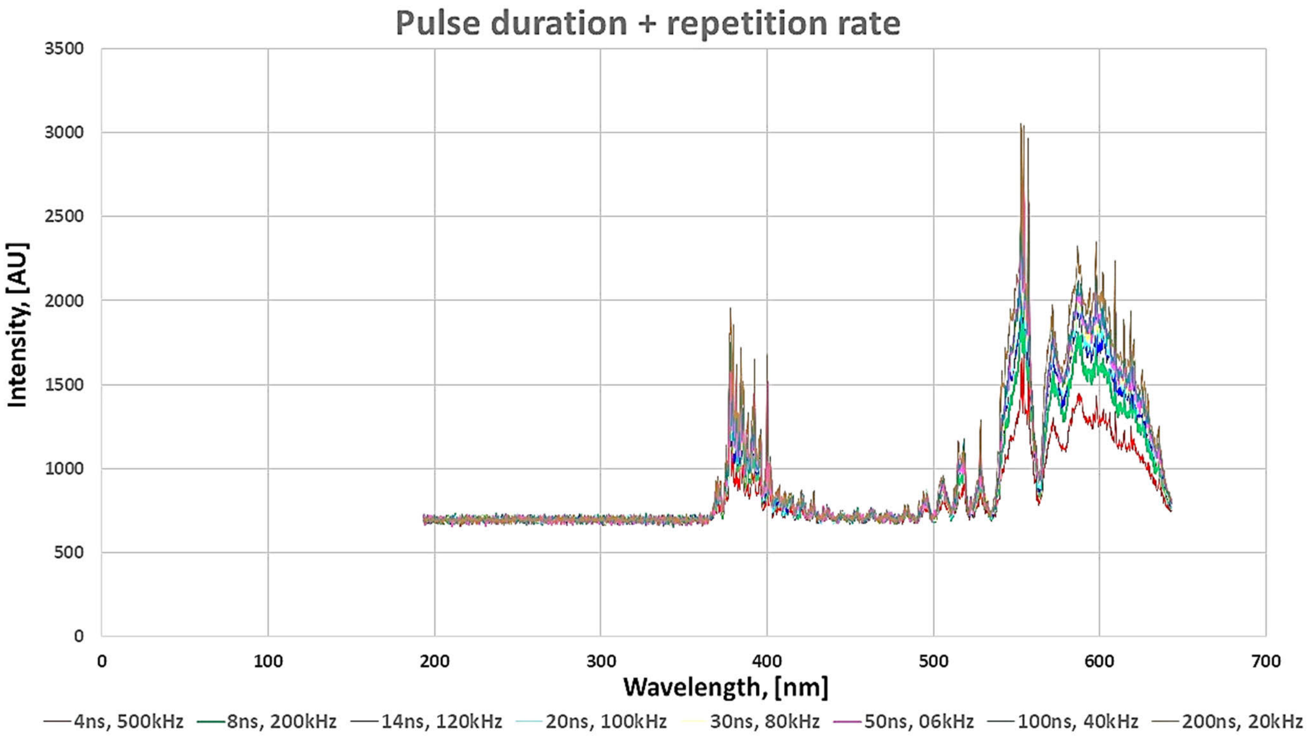


FIGURE 5. Effect of the pulse length.

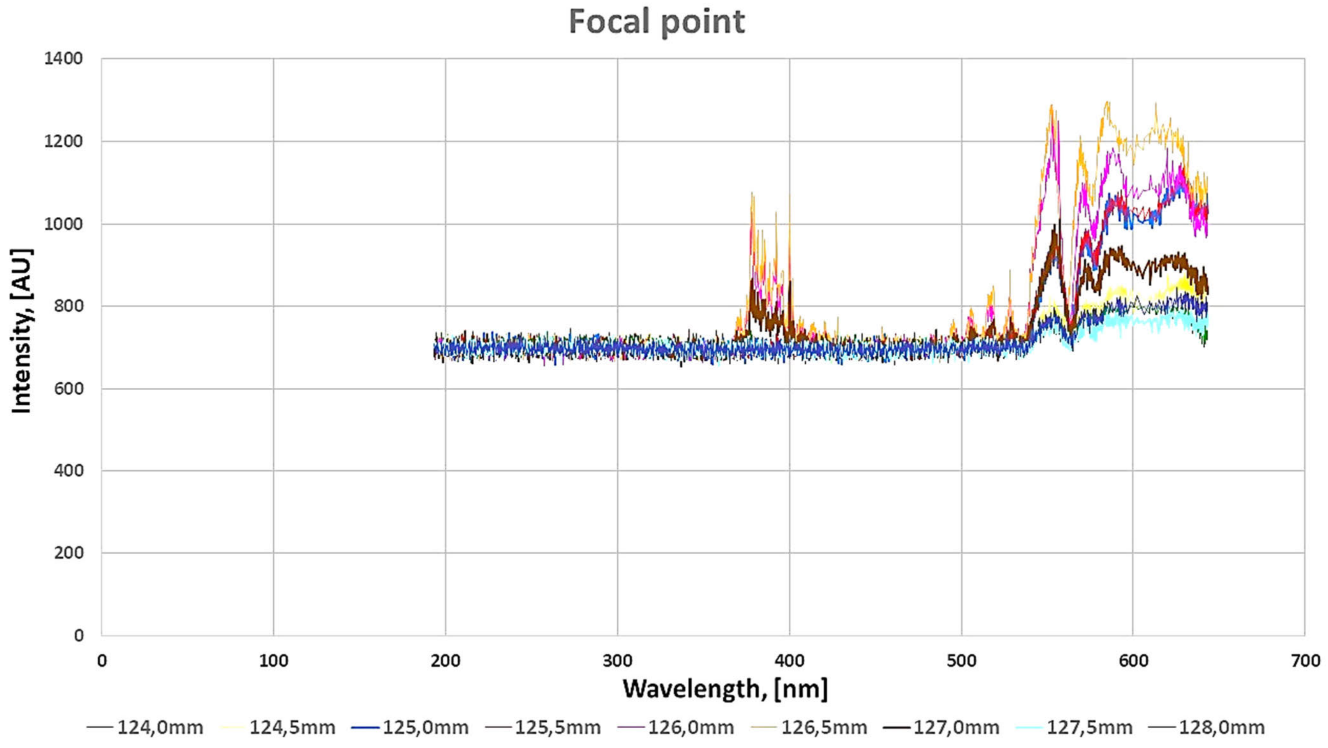


FIGURE 6. Effect of the focal point position.

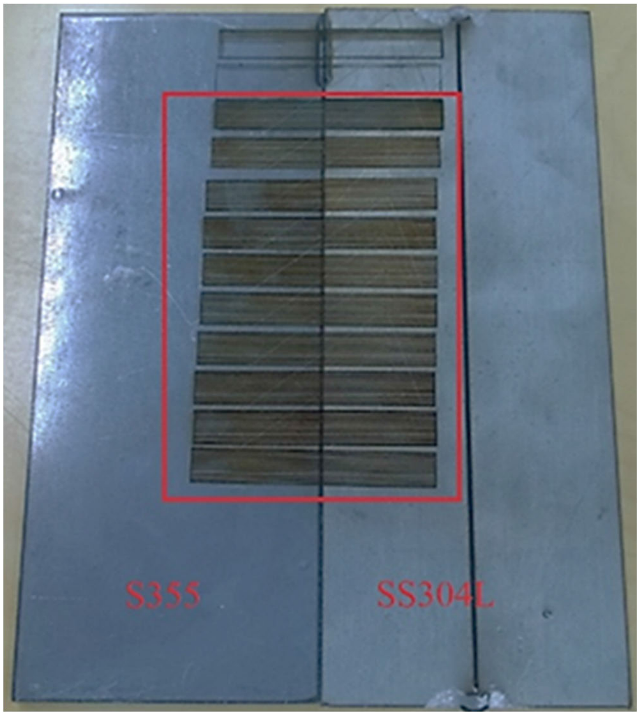


FIGURE 7. Scribing test on the plate made of SS304L and S355 [22].

B. EVALUATION OF CONTROL ALGORITHM IN CASE OF CHANGE OF WORKPIECE METAL PROPERTIES

The second experiment was performed to evaluate the performance of the developed control algorithm for laser scribing on two welded plates from stainless steel SS304L and steel S355 when scribing was passing from one material to another. The goal was to maintain the engraving process independent of the material to uniform engraving quality even if the engraved component consists of different materials. The algorithm was aimed to adjust the laser power based on the intensity levels. The moving area of the laser beam was rectangular with the dimensions of 40 × 10mm^2 and hatch distance of 0.8mm in such a way that each half of the rectangular was on one of the materials (Fig. 7) [22]. Pulse duration and pulse repetition rate were hold on 200ns and 20kHz, respectively.

Scribing on SS304L emitted more light than scribing on S355, which meant the intensity level was higher for SS304L. The spectrometer could recognize the difference between intensities when scribing moved from SS304L to S355 and vice versa. Noises can be observed for both S355 and SS304L due to the nature of the utilized pulsed laser and impurifications on the surface of both samples. The spectrometer detected a higher level of intensity in the case of SS304L. The difference in intensity of S355 and SS304L was remarkable due to the different chemical compositions of these metals. The higher amount of chromium and nickel available in the SS304L caused a wider range of spectra for this metal compared to S355. The intensity of SS304L was at the highest level about 1400AU and instantaneously around 800AU, while it was between 750 to 900AU for S355. Fig. 8 and 9 illustrate the acquired spectra for SS304L and S355. Based on the intensity data acquired from the spectrometer, the developed algorithm succeeded in adjusting the laser power in real-time. In other words, the power rose at lower intensities and decreased at higher intensities. However, as the intensity was momentarily around 800AU for SS304L, real-time laser power control was challenging for SS304L in the range around 800 AU, which caused power fluctuation. In general, the control algorithm was able to instantly adjust the power based on the set intensity values, which authenticated that the algorithm acted as intended.

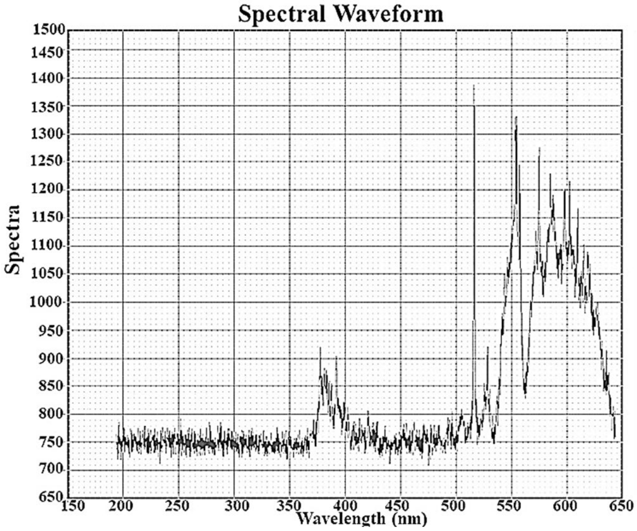


FIGURE 8. Spectra of scribing process for SS304L.

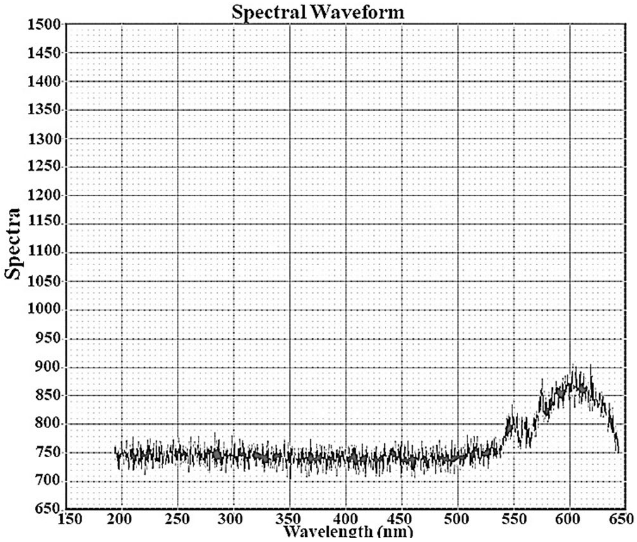


FIGURE 9. Spectra of scribing process for S355.

V. CONCLUSION

In this research, an online monitoring and real-time control of laser engraving process using spectrometer has been developed. For this purpose, an algorithm has been designed using LabVIEW® software. The spectrometer output was analyzed by changing laser and process parameters. Results showed that the spectrometer could sense even very faint laser power and was totally appropriate to tune the laser parameters. Another experiment was performed to evaluate the developed control algorithm when scribing was performed on two pieces of metal from different materials of S355 and SS304L.The aim was to stabilize the engraving process independent of the material when utilizing a spectrometer to sense different wavelengths and intensity of laser engraving process. The spectrometer detected the difference between the intensities of the materials as soon as the scribing was moved from the first material to the second one and adjusted the laser power based on the acquired intensity. The results of the experiment validated that the developed algorithm performs as intended and could cope with the high intensity fluctuations and provide a successful real-time control of laser power.

REFERENCES

[1] D. Klaviš, L. Lazov, A. Pacejs, R. Rēvalds, and E. Zaicevs, "Research of laser marking and engraving on brass alloy 260," in *Proc. Environ. Technol. Resour. Int. Sci. Practical Conf.*, vol. 3, Jun. 2019, pp. 119–123, doi: 10.17770/etr2019vol3.4167.

[2] S. Nikolov, R. Dimitrova, and I. Topov, "New approach at mechanical engraving of details with large sizes," in *Proc. 2nd Int. Conf. High Technol. Sustain. Develop. (HiTech)*, Oct. 2019, pp. 10–11, doi: 10.1109/HiTech48507.2019.9128261.

[3] L. Xie, X. Chen, H. Yan, H. Xie, and Z. Lin, "Experimental research on the technical parameters of laser engraving," *J. Phys., Conf. Ser.*, vol. 1646, no. 1, Sep. 2020, Art. no. 012091, doi: 10.1088/1742-6596/1646/1/012091.

[4] M. N. B. Haron and F. R. M. Romlay, "Parametric study of laser engraving process of AISI 304 stainless steel by utilizing fiber laser system," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 469, no. 1, Jan. 2019, Art. no. 012124, doi: 10.1088/1757-899X/469/1/012124.

[5] K. A. Hubeatir, M. M. Al-Kafaji, and J. O. Hadeel, "A review: Effect of different laser types on material engraving process," *J. Mater. Sci.*, vol. 6, no. 4, pp. 210–217, Nov. 2018.

[6] H. Roozbahani, P. Marttinen, and A. Salminen, "Real-time monitoring of laser scribing process of CIGS solar panels utilizing high-speed camera," *IEEE Photon. Technol. Lett.*, vol. 30, no. 20, pp. 1741–1744, Oct. 15, 2018, doi: 10.1109/LPT.2018.2867274.

[7] C.-H. Li and M.-J. Tsai, "Multi-objective optimization of laser scribing for the isolation process of solar cell wafers using grey relational analysis," in *Proc. IEEE Int. Symp. Ind. Electron.*, Jul. 2009, pp. 1154–1159, doi: 10.1109/ISIE.2009.5218137.

[8] P. Lott, H. Schleifenbaum, W. Meiners, K. Wissenbach, C. Hinke, and J. Bültmann, "Design of an optical system for the *in situ* process monitoring of selective laser melting (SLM)," *Phys. Proc.*, vol. 12, pp. 683–690, Dec. 2011, doi: 10.1016/j.phpro.2011.03.085.

[9] F. Sikström, M. Nilsen, and I. A. G. Eriksson, "Optical methods for in-process monitoring of laser beam welding," in *Proc. 6th Swedish Prod. Symp.*, Göteborg, Sweden, Sep. 2014, pp. 1–9.

[10] T. Purtonen, A. Kalliosaari, and A. Salminen, "Monitoring and adaptive control of laser processes," *Phys. Proc.*, vol. 56, pp. 1218–1231, Sep. 2014, doi: 10.1016/j.phpro.2014.08.038.

[11] H. Roozbahani, A. Salminen, and M. Manninen, "Real-time online monitoring of nanosecond pulsed laser scribing process utilizing spectrometer," *J. Laser Appl.*, vol. 29, no. 2, May 2017, Art. no. 022208, doi: 10.2351/1.4983520.

[12] P. De Bono, C. Allen, G. D'Angelo, and A. Cisi, "Investigation of optical sensor approaches for real-time monitoring during fibre laser welding," *J. Laser Appl.*, vol. 29, no. 2, May 2017, Art. no. 022417, doi: 10.2351/1.4983253.

[13] C. Z. Tan, "Rotatory dispersion in optical activity and a rotary Fourier transform spectrometer," *Optik Int. J. Light Electron Opt.*, vol. 124, no. 17, pp. 2798–2802, Sep. 2013, doi: 10.1016/j.ijleo.2012.08.050.

[14] M. Nilsen, F. Sikström, A.-K. Christiansson, and A. Ancona, "Monitoring of varying joint gap width during laser beam welding by a dual vision and spectroscopic sensing system," *Phys. Proc.*, vol. 89, pp. 100–107, Sep. 2017, doi: 10.1016/J.PHPRO.2017.08.014.

[15] S. S. Kumar, R. Reshmi, N. V. Joshy, A. C. Saritha, and M. K. Jayaraj, "Optical emission spectroscopic analysis of plasma plume during pulsed laser deposition of PZT," *J. At. Mol. Phys.*, vol. 2014, pp. 1–9, Feb. 2014, doi: 10.1155/2014/125843.

[16] T. Sibillano, A. Ancona, V. Berardi, and P. M. Lugarà, "A real-time spectroscopic sensor for monitoring laser welding processes," *Sensors*, vol. 9, no. 5, pp. 3376–3385, May 2009, doi: 10.3390/s90503376.

[17] W. Huang and R. Kovacevic, "Development of a real-time laser-based machine vision system to monitor and control welding processes," *Int. J. Adv. Manuf. Technol.*, vol. 63, pp. 235–248, Nov. 2012, doi: 10.1007/s00170-012-3902-0.

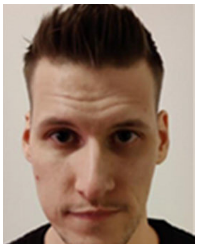
[18] D. Y. You, X. D. Gao, and S. Katayama, "Review of laser welding monitoring," *Sci. Technol. Weld. Joining*, vol. 19, no. 3, pp. 181–201, 2014, doi: 10.1179/1362171813Y.0000000180.

[19] N. Levichev, G. C. Rodrigues, and J. R. Duflou, "Real-time monitoring of fiber laser cutting of thick plates by means of photodiodes," *Proc. CIRP*, vol. 94, pp. 499–504, Sep. 2020, doi: 10.1016/j.procir.2020.09.171.

[20] V. A. Gnatyuk, "Capabilities of laser-induced marks as information carriers created in different materials," *J. Laser Micro/Nanoeng.*, vol. 11, no. 2, pp. 164–169, Jul. 2016, doi: 10.2961/jlmn.2016.02.0005.

[21] K. S. Zelenska, S. E. Zelensky, L. V. Poperenko, K. Kanev, V. Mizeikis, and V. A. Gnatyuk, "Thermal mechanisms of laser marking in transparent polymers with light-absorbing microparticles," *Opt. Laser Technol.*, vol. 76, pp. 96–100, Jan. 2016, doi: 10.1016/j.optlastec.2015.07.011.

[22] M. Ruutiainen, "Real-time adaptive control of ultra-fast laser scribing process with spectrometer online monitoring," M.S. thesis, Dept. Mech. Eng., LUT Univ., Lappeenranta, Finland, 2016.



MIKA RUUTIAINEN received the B.Sc. degree in mechanical engineering-Design, manufacturing, production technologies, from a dual degree program between the Saimaa University of Applied Sciences, Finland, and Hochschule Schmalkalden, Germany, in 2013, and the M.Sc. degree in mechanical engineering-design and manufacturing from the Lappeenranta-Lahti University of Technology, Finland, in 2016.

HAMID ROOZBAHANI (Member, IEEE) received the D.Sc.Tech. and Master of Science degrees in the field of mechatronics from the Lappeenranta-Lahti University of Technology (LUT). For several years, he has been working as a Project Manager in several projects, since 1999. He is currently working as a Research Scientist, a Project Manager, and a Lecturer with the LUT. He is also the Project Manager of EU funded project APPOLO and TIERA-LUT Mobile Robot Project.

MARJAN ALIZADEH received the B.Sc. degree in electrical engineering–control from the Ferdowsi University of Mashhad, Iran, in 2003, and the M.Sc. degree in electrical engineering–industrial electronics from the Lappeenranta-Lahti University of Technology, Finland, in 2017. From 2003 to 2015, she was working in the field of electrical engineering in industry. She is currently working as a Project Researcher at the Lappeenranta-Lahti University of Technology.

HEIKKI HANDROOS (Member, IEEE) received the D.Sc. (Tech.) degree from the Tampere University of Technology. He has been a Professor of machine automation with the Lappeenranta-Lahti University of Technology, since 1992. He has been a Visiting Professor with the University of Minnesota, Peter the Great St Petersburg Polytechnic University, and the National Defense Academy, Japan. He has published about 250 international scientific articles and supervised around 20 D.Sc. theses. He has held several positions of trust in the American Society of Mechanical Engineers. He has led several important domestic and international research projects. His research interests include modeling, design, and control of mechatronic transmissions to robotics and virtual engineering.

ANTTI SALMINEN is currently pursuing the Docent degree in manufacturing technology with the LUT University. He is also a Professor of mechanical engineering at the University of Turku. He has more than 30 years of experience of laser-based manufacturing processes and welding in both academia and industry. He has been a principal investigator in several research projects funded by national, Nordic, and European funding agents. His specialization is in the process and laser system development, product design utilizing laser processing and additive manufacturing, and monitoring of thermal processes especially for welding and additive manufacturing. He has published more 100 peer-reviewed scientific and more than 150 scientific conference publications. He has supervised ten Ph.D.'s, 70 master's, and 16 bachelor's theses and is also supervising eight Ph.D. theses. He is a member of the Board of Finnish Association for additive manufacturing and the Deputy Member of the Board of Finnish Welding Society and a National Delegate in IIW commissions I, IV, and X.

• • •