9th INTERNATIONAL SCIENTIFIC CONFERENCE ON DEFENSIVE TECHNOLOGIES
OTEH 2020
Belgrade, Serbia, 15 – 16 October 2020

INFLUENCE OF IR CAMERA INTEGRATION TIME ON THE ACCURACY OF T_{MAX} DETERMINATION DURING LASER INTERACTION WITH CERAMICS

DRAGAN KNEŽEVIĆ
Military Technical Institute, Belgrade, city, e-mail: dragankn@gmail.com

SLAVICA RISTIĆ
Central Institute for Conservation in Belgrade, Belgrade, Serbia, e-mail: s1avce@yahoo.com

SUZANA POLIĆ
Central Institute for Conservation in Belgrade, Belgrade, Serbia, e-mail: suzanapolic64@gmail.com

BOJANA RADOJKOVIĆ
Institute of Chemistry, Technology and Metallurgy, Belgrade, Serbia, e-mail: bojana52@yahoo.com

LJUBIŠA TOMIĆ
Military Technical Institute, Belgrade, city, e-mail: ljubisa.tomic@gmail.com

Abstract: *This paper presents the results of an infrared thermography (IRT) application for monitoring temperature distribution on a ceramic surface during Nd: YAG laser irradiation. The laser operated in the Q-switch mode with λ= 1064 nm. The duration of a pulse was τ = 8 ns. The repetition rate was* f_l*= 1-20 Hz. FLIR, E40 and SC7200 IR cameras were used. Recording of the maximum temperature in the irradiated zones is very important information related to the damage threshold of materials. The tested sample is a piece of a ceramic tile. A large number of factors affect determination of the maximum temperature in the very fast processes as it is irradiation with laser pulse duration of 8 ns. One of them is the camera integration time. The experimental results have shown that IR cameras, even those with high performance such as SC7200, cannot record the maximum temperature value at the moment of laser operation, but only the average temperature of the bulk sample material after laser pulses. The microstructure and micromorphology of the ceramic surface after the laser treatment were analyzed by optical and scanning electron microscopy.*

Keywords: *Laser, IR thermography, ceramics, surface properties, OM, SEM*

1. INTRODUCTION

A ceramic is an inorganic material with excellent chemical and thermal stability, high hardness, and good electric and thermal insulation. Ceramics have many applications in different areas of industry: electronics, structural engineering, medicine, aerospace, military equipment, automotive industry and space program [1]. The difficulty on the processing of the ceramics is mainly due to the high hardness and brittleness. A lot of methods are used in ceramics processing; chemical, machining, water jet, plasma, laser and microwave [1-3].

Nd:YAG lasers with nano - second pulses are widely used in ceramics surface processing, cleaning, drilling and cutting. Laser interaction with materials is a very complex process [2-7] with many insufficiently known phenomena.

The laser beam can interact with a solid surface producing various effects, depending on the laser and material parameters [2,3]. The parameters that affect the interaction are: energy density of the laser beam, pulse length, wavelength and the energy distribution within the beam, t incident angle, material reflection and absorption coefficients, chemical and physical properties of the surface, its topology at the micro and nano-scales, homogeneity, surface temperature, thermal diffusion, melting and boiling coefficients.

Control of laser parameters during laser beam irradiation on the sample surface and detailed examination of the result of the laser-material interaction is crucial for successful laser implementation [3,7].

Laser material processing is applied for laser machining processes: cutting, drilling, marking and engraving, laser surface treating (hardening, glazing, alloying, cladding), laser shock processing or laser shock peening, other laser material processing applications.

Laser materials processing techniques are essentially thermal processes, where absorption of a large number of photons heats the material and performs surface modification, locally melting and re melting of the substrate. Therefore, it is especially important to accurately monitor the temperature rise during a very short laser pulse and the spread of heat in the material.

The time, during the laser pulse, is very short for significant heat conduction through the substrate. The rapid increase of thermal energy is only in the optical absorption depth, where the melting and vaporization of the material can occur.

The control of the real-time temperature distribution during laser processing can be carried out using an infrared camera. Infrared thermography (IRT) is a non-contact testing method, which has an increasing application in scientific laboratories, industry, construction, medicine. It can be most simply defined as a technique that registers IR radiation, characteristic of any object, whose temperature is above absolute zero [8-11]. With this technique, the thermal radiation of the object is visualized and displayed in the form of a thermogram. The parts of the ceramic surface under investigation are heated up by laser and the transient heat flux is observed by recording the temperature change at the surface as a function of time. The thermogram gives a clear thermal picture of the object. The generated image is in gray scale, but could be presented as pseudo color. Using the tools built into the thermogram processing software, the temperature at the selected points can be quantified from the image, or the temperature change over time can be monitored.

Thermograms, in these experiments were recorded as individual sequences (single shot mode) and continuous records, in order to monitor the change in temperature over time. Thermograms were extracted and analyzed from the continuous record with aim to obtain the threshold temperature, that is, the laser energy that leads to the expected changes.

When using thermography to measure the temperature of the laser irradiated zone, it is necessary to keep in mind that, there are a lot of variables, which make quantitative evaluations difficult and sometimes impossible, e.g. high speed of the tested processes, non-homogeneity of laser irradiation, changes of the target emissivity after ablation, extremely both high amplitude and short time of the ablation, changes of path transmission between target and camera and the radiation features during the ablation, variability of thermal losses (convection, radiation).

Initial tests, on first sight, yielded contradictory results [12,13]. OM and SEM showed that there are changes such as melting of the base material, and thermograms that the achieved temperature is lower in relation to the melting temperature of ceramics. Tests were conducted to show what the measured temperature depends on and how are the influences of the IR camera setting parameters during recording.

This paper presents the results of the influence of the IR camera integration time on the accuracy of the maximum temperature measurement.

2. EXPERIMENT

All experiments were performed in atmospheric conditions, using TEM_{00} mode Nd: YAG laser operated in the Q-switch mode with λ=1064 nm, pulse duration τ = 8 ns, repetition rate f_l = 20 Hz. The maximum energy of the laser beam with Gaussian distribution, for λ = 1064 nm, was E=510 mJ, the fluence ≈ 4 J/cm^2, on sample surface. The laser beam was focused by a lens with 150 mm focal length. The tested sample was positioned in front of the lens focus. The sample was exposed approximately 3s in every zone.

Two FLIR IR cameras [10], E40 and SC7200, were used for monitoring and recording the surface temperature during the laser treatments. The cameras were in the off-axial thermography setup (Fig.1a). The E40 IC camera has a 160 x 120 pixels, 30 Hz infrared detector with 0.07°C thermal sensitivity and a 20 to 650°C temperature range. The accuracy is ±2%, or 2°C, the spectral range is 7.5-13 µm. Camera can record 30frames/s. The integration time It is 16ms [13]. The SC7200 IR camera has a variable image size from 64x8 to 320x256 pixels, a spectral range of 1.5-5.1µm and the frame rate up to 11 KHz. The integration time can be changed between 1µs and 20ms. The temperature range is -20 to 3000 °C, the pixel pitch is 32 µm, and thermal sensitivity is 0.02 °C.

A piece of a ceramic tile with the some zones of interaction, after the laser irradiation, on unglazed side is presented in Figs. 1b.

a b

Figure 1. a- experimental set up and b-ceramics surface with tree laser treated zones

The ceramic surface structure and morphology of the laser treated zones were studied by an optical (OM) and a scanning electron microscope (SEM).

3. RESULTS AND DISCUTION

The advantages of the laser processing of ceramics are: precise spatial and temporal control, immediate change of laser parameters, and material selectivity [3,5,7,14]. However, very often, the thermal nature of the interaction causes unwanted side effects such as: chemical decomposition, thermal stresses, micro-cracking, melting and rapid re-solidification of the amorphous material. A special attention has been therefore paid to control the operation parameters that enable a safe application of laser procedures on ceramics. Many studies confirm that Nd: YAG lasers with wavelength λ = 1.06 nm and ns pulses duration are highly effective in ceramic processing [5-7,15-17].

The analysis of the laser irradiation effects on ceramics sample shows that, in most cases, irreversible microscopic and macroscopic changes have occurred when the applied fluence was close or above to the damage threshold for the ceramic (Figure 2). The dimensions of the heat affected zone vary depending on laser and material properties [7,14]. The duration of the entire ablation processes is within the nanosecond scale. The OM images show that the energy distribution into laser beam is non-uniform. The most pronounced traces of melting and hardening of the material are found in zone 1, which is the longest exposed. The OM images were recorded by 40 and 100x magnifications, the SEM ones by 150 and 500x.

Experimental data related with temperature monitoring are presented in **Table 1**.

IC camera E40 has fixed integration time I_t and repletion rate 30 frame/s. Camera SC7200 recorded with different I_t. The camera has the possibility of protection against excessive radiation intensity and in these situations it displays the level of saturated signal, i.e. the T_{max}, which can be obtained within the defined temperature window. The choice of frame frequencies depends on the size of the field of view, while the integration time depends on the selected frequency, temperature measuring range and temperature windows.

Table 1. Experimental data for temperature monitoring

		E40			SC7200			
Zone	t, s	**I_t, ms**	ΔT_{measur} °C	T_{max}, °C	**I_t, µs**	T_{range} °C camere	ΔT_{measur} °C	T_{max}, °C
1	3.0	**20**	19.75-117.6	117.6	**20**	117-239	140-250	250
2	2.9	**20**	20.25-102.0	102.0	**60**	66-161	145-181	181
3	2.8	**20**	20.40-84.8	85.0	**160**	27-110	25-125	125

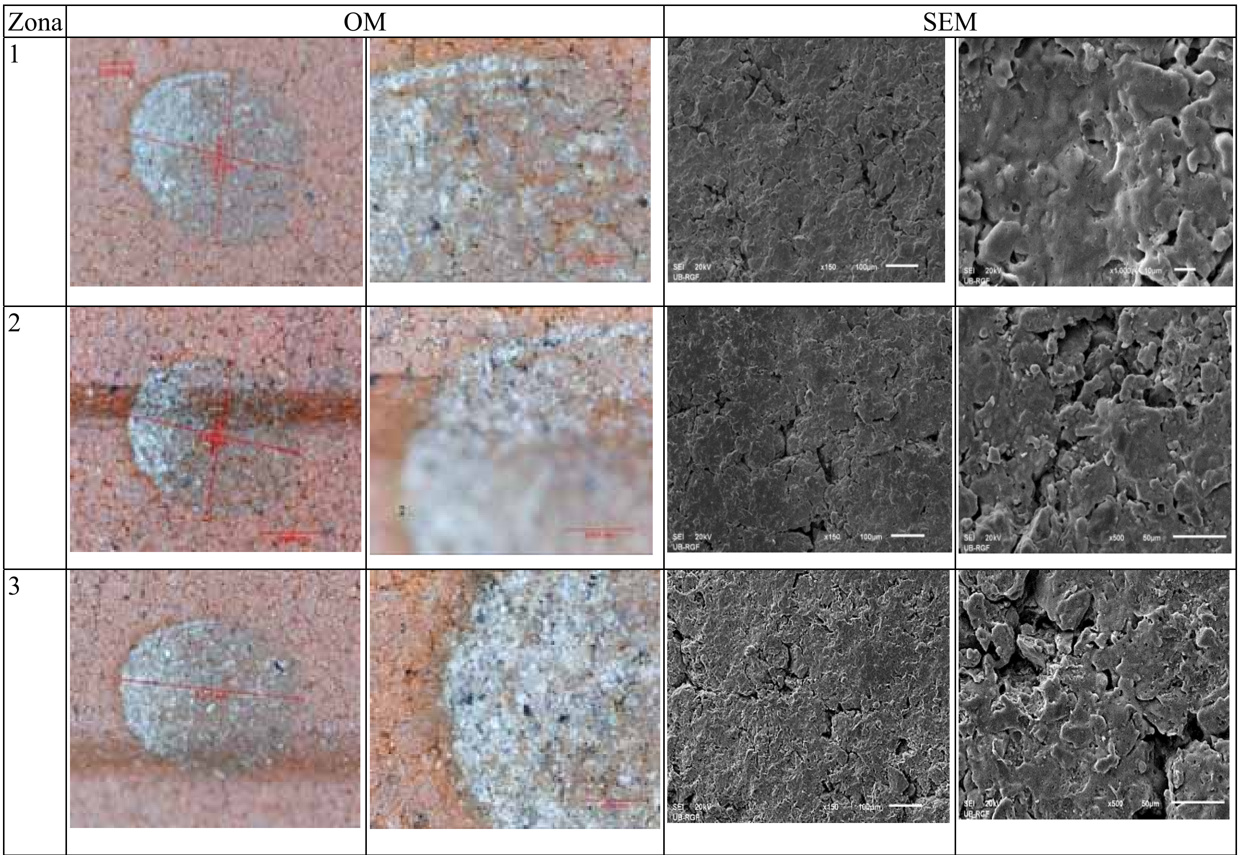


Figure 2 OM i SEM images of zones 1,2 and 3

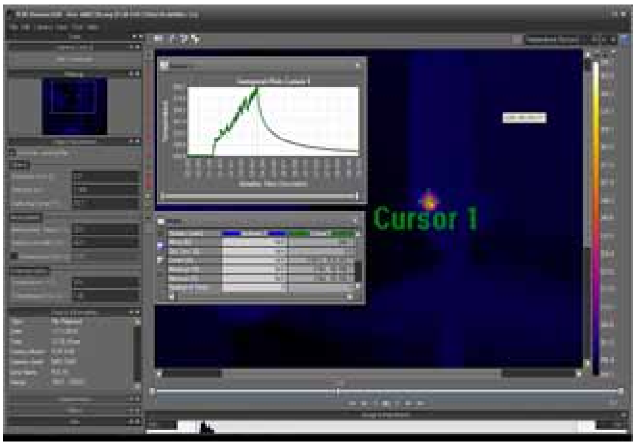
Figure 3 presents the results of temperature monitoring in zone 1. The main ResearchIR window with some main regions (IR camera E40), the sample thermogram, and the cursor as a measuring tool, the statistics and the temporal plot for a point with the maximum temperature value are shown in **Figure 3a**. The temperature bar is on the right side, while the camera setting parameters are on the left. The distribution of temperature in heat affected zone is shown in **Figure 3b**. Figures 3c, 3d and 3e show temperature changes recorded by SC7200 camera for the same zone.

The thermogram for frame number 1280 recorded by SC7200 camera is presented in **Figure 3c. Figure 3d** shows temperature changes recorded by SC7200 camera during 5s with 1 KHz sampling rate, while maximum temperature peak is presented on Figure 3e. The temperature range of SC7200 camera is automatically determined and amounts to 117-239 °C. Therefore, only a time diagram of the temperature change in that interval was recorded. In Fig. 3d, it can be seen that the cooling coefficient of the material is such that the surface of the sample does not cool at the initial temperature before the next laser pulse. So there is a successive rise in temperature on the irradiated surface, but frequency of laser pulses was low enough to protect surface against dangerous high or long-time overheating.

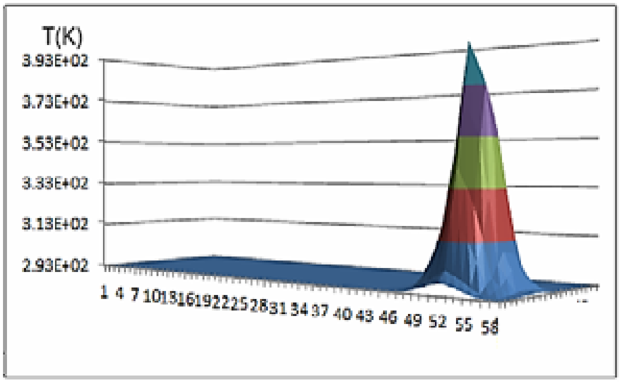
Figures 4 and **5** give thermographic results for zones 2 and 3. The duration of laser irradiation in zone 3 is less than 3 s and the obtained diagram shows the state of the temperature before the start of irradiation, during the laser treatment and the cooling period of the sample after laser action.

Figure 6 was taken with a shorter integration time of 6μs. Short integration time is associated with high energies, for the range up to 300°C. Signals below 170°C were not recorded; they did not have enough energy, because only photons with the highest energies are captured. There are not enough photons for statistics.

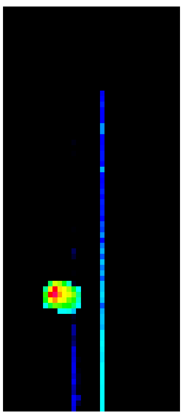
In addition to micro-morphological changes, on the surface of the ceramic, in the laser irradiated zones, there are changes in color, roughness and micro-hardness [15]. The XRF analysis was used to determine the qualitative and quantitative elemental differences between the irradiated and non-irradiated zones. The analysis of the results shows minor differences in chemical composition before and after laser irradiation [12,15].



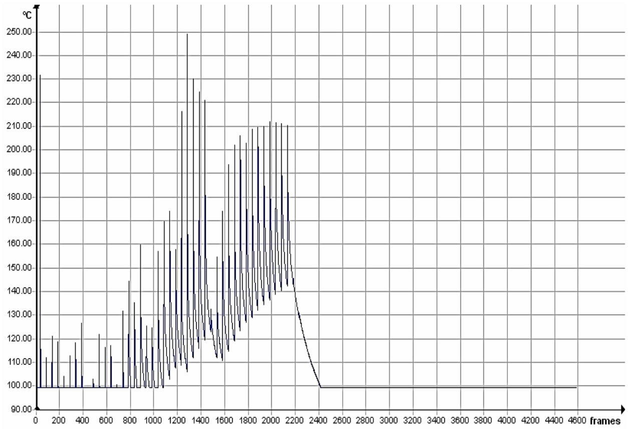
a



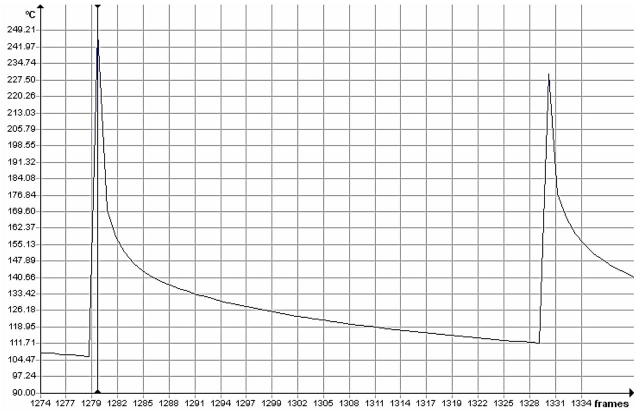
b



c



d

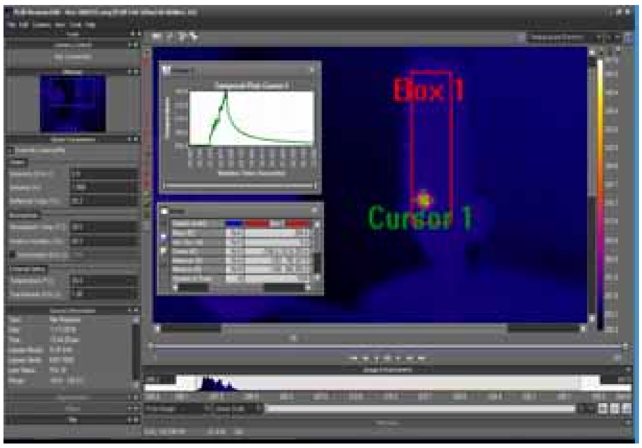


e

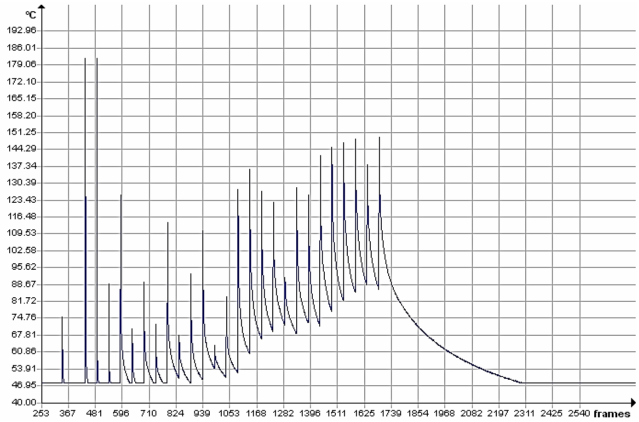
Figure 3. Thermographic measurement in zone 1.

Analysis of diagrams of temperature changes in the selected zone recorded with cameras E 40 and SC7200 show that they have a very similar shape. The difference is in the measured absolute values of temperature T_{max}. The character of the temperature diagrams indicates an exponential drop in temperature during cooling.

It is evident that IR cameras setting parameters as I_t and ΔT have important influence on measured T_{max}. It is possible to adjust the camera's integration time or temperature range to the desired value, but if the integration time is chosen, the temperature range will be automatically adjusted.



a



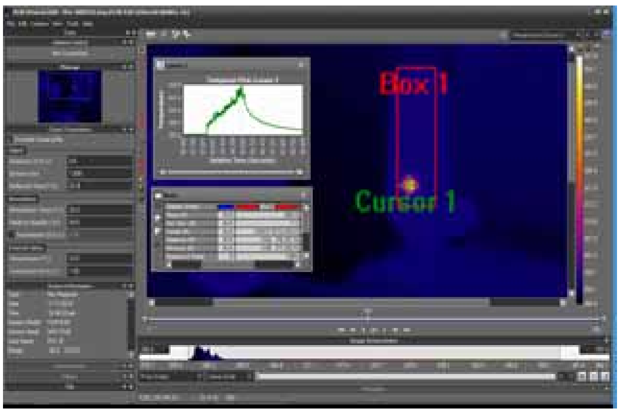
b

Figure 4. Thermographic measurement in zone 2.

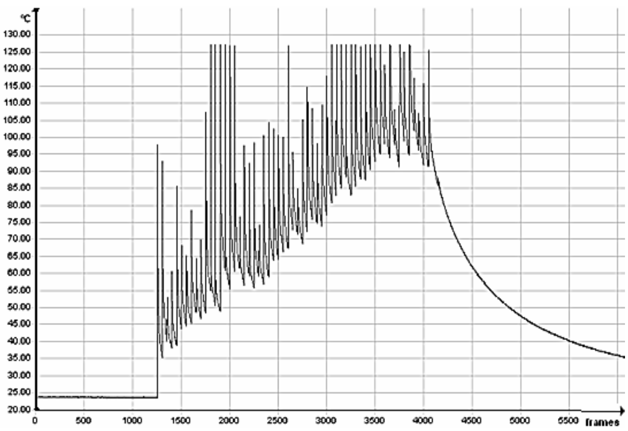
Thermographic measurements with SC7200 camera performed with different I_t show that the measured T_{max} decreases with increasing I_t, but that it is not a linear function.

Frequency of pulses was low enough to protect surface against dangerous high or long-time overheating (fig.5b). Diagrams on figure 5a and 5b show body initial temperature rising.

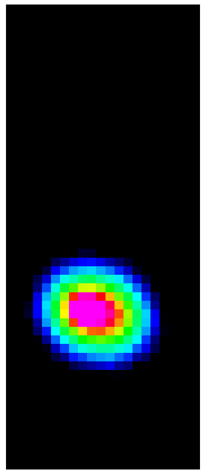
The introduction of thermography, as a non-contact testing method for temperature distribution measurement make possible to determine heath affected zones (HAZ).



a



b



c

Figure 5. Thermographic measurement in zone 3.

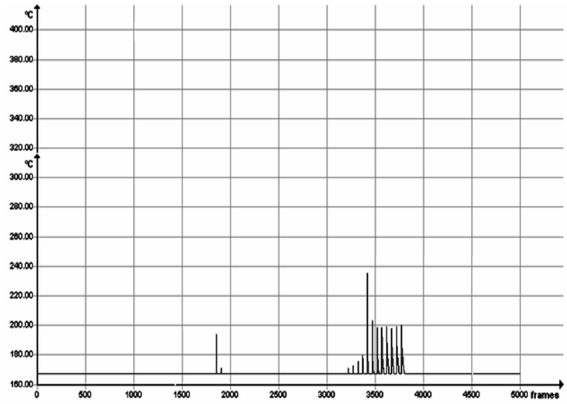


Figure 6. Thermographic measurement with I_t=6 μs.

It seems that thermography does not have the ability to be used to monitor the T_{max} in areas irradiated with short laser impulses, but the obtained thermographic results can be used as input data in the numerical simulations of temperature distribution on ceramics surface in the heat affected zones [15]. A numerical simulation of temperature changes on the surface was performed using COMSOL Multiphysics software. The results were compared and used to verify the applied methods. The numerical average temperature value for a integration period of 60μs is approximately 485 K. The IR camera 7200 has measured average temperature 200 °C (473 K). The difference between the numerical values for the mean temperature and the values obtained by the SC7200 camera is less than 10%, and the values measured by the E40 camera are about 40% [15].

Verified numerical method can be used to predict the maximum temperature for different laser fluences.

On the other hand, by applying Romberg's integration and Richardson's extrapolation, more accurate results can be obtained for T_{max} [18,19].

An approximate estimation of the T_{max} can be made based on the radiance reading from the thermographic sequence recorded at the time when peak on the diagram is reached. The radiance recorded with I_t=160 μs corresponds to radiance emitted during the laser pulse (8ns). By solving the transcendent equation (assuming the laser beam has an approximately rectangular shape in the central region) the sample surface temperature during the laser pulse can be estimated. The radiance read from the thermogram (fig.5c) is 14.71 W/sr·m2. It is transformed into 294200 W/sr· m2 (20000 times the pulse duration is shorter). By solving the transcendent equation, a value of 294332 W/sr·m2 was obtained for the radiance. This radiance value corresponds to a temperature of (2285 ± 1%) K.

SEM images (fig 2) confirmed that the induced heath rise the temperature above melting point. A laser remelting process is the fundamental process in which the ceramics surface is melted locally by the laser beam and then it solidifies.

4. CONCLUSION

The aim of this paper is to present the results concerning the usage of IR thermography for temperature monitoring during and after laser-ceramics interaction. The real time control of interaction parameters is very important for successful laser implementation in different material processing. FLIR, E40 and SC7200 IR cameras were used with the aim of recording the maximum temperature in the irradiated zones. The results have shown that IR cameras, even those with high performance such as SC7200, cannot record the maximum temperature value at the moment of laser operation, but only the average temperature of the bulk sample material after laser pulses.

Ir camera setting parameters have important influence on measurement results. I_t is the most important parameters. Results show that the measured T_{max} decreases with increasing I_t, but that it is not a linear function.

IR thermography of thermal effects during and after laser-material interaction can be performed with some special cares and limitations and to study of post-ablation residual heating, only.

Application of modern data representations techniques allowed extracting single temporal-spatial thermogram from long sequences of thermal images and estimate Tmax according recorded radiance. The obtain results or IRT monitoring of laser-material interaction can be used as input data in the numerical simulations of temperature distribution on ceramics surface in the heat affected zones and verified numerical method, which can be later used to predict the maximum temperature for different laser fluences.

The usability of IR thermography, as an additional tool during laser processing, increases. Obtained results encouraged for widening research in this field.

To evaluate the results of the laser impact on ceramics, An analysis of the microstructure and micromorphology of the ceramic surface before and after the laser treatment was carried out by optical and scanning electron microscopy.

ACKNOWLEDGEMENT

The authors are grateful to the Ministry of Culture and Information, Military Technical Institute and Ministry of Education, Science and Technological development of the Republic of Serbia for financial support through TR-34028 project.

REFERENCES

[1] Ceramic Materials: Processes, Properties and Applications, Editor(s): Philippe Boch Jean-Claude Niepce, First published: 2007, Print ISBN: 9781905209231 Online ISBN: 9780470612415, DOI: 10.1002/9780470612415.

[2] Webb, C., Jones, J., *Handbook of Laser Technology and Applications,* Taylor & Francis, 2003.

[3] *Advances in laser materials processing Technology, research and applications*, Edited by J. Lawrence, J. Pou, D. K. Y. Low and E. Toyserkani, Published by Woodhead Publishing Limited, Cambridge UK, ww.woodheadpublishing.com, 2010, ISBN 978-1-84569-981-9 (e-book).

[4] *Advanced Lasers*, Editors: Shulika O., Sukhoivanov I., Springer, ISBN 978-94-017-9481-7 (eBook), 2015.

[5] Li, L., *The Challenges Ahead for Laser Macro, Micro and Nano Manufacturing, Advances-in-Laser-Materi. Processing*, chapter 2, (2018) 23-42.

[6] Samant A. N., Dahotre N. B., "Absorptivity Transition in the 1.06 lm Wavelength Laser Machining of Structural Ceramics", *International Journal of Applied Ceramic Technology*, 8(1) (2011) 127-139.

[7] Radojković B., Physico-mechanical and micro-chemical changes on the ceramic and metal artefacts surfaces treated with laser, University of Belgrade, Faculty of technology and metallurgy, doctoral dissertation, 2017. (in Serbian)

[8] Litos, P., Honner, M., Kunes, J. 'Thermography Applications in Technology Research‘, University of West Bohemia, InfraMation 2004, Proceedings ITC , 104 A, 2004-07-27

[9] Bagavathiappan, S., et. al.," Infrared thermography for condition monitoring – A review", Infrared Phys. Techn, 60 (2013) 35–55.

[10] ***Flir Systems, FLIR T-Series, www.flir.com (visited 15.10.2016).

[11] D. Knežević, et.al., "Minimum resolvable temperature difference model, simulation, measurement and analysis", *Opt Quant Electron* 48 (2016), 332. https://doi.org/10.1007/s11082-016-0598-7

[12] B. Radojković, S. Ristić, S. Polić. "Lasers in ceramic processing", *Ecologica*, br.85, 2017, 176-181

[13] Ristić S. S., S. R. et.al, Termografija u kontroli efikasnosti i bezbednosti laserskog čišćenja" *Tehnika* 5 (2019) 623-629.

[14] Ristic, S. et.al. "Analysis of ceramics surface modification induced by pulsed laser treatment", *Processing and Application of Ceramics*, 8 (1) (2014) 15–23.

[15] Knežević M. D. et.al. "Monitoring of a Ceramic Surface Temperature Field Induced By Pulsed

Nd:Yag Laser", *Thermal Science* 2019, https://doi.org/10.2298/TSCI190811425K.

[16] Sola D., Peña J. I., "Study of the Wavelength Dependence in Laser Ablation of Advanced Ceramics and Glass-Ceramic Materials in the Nanosecond Range", *Materials* (Basel), (6) 11 (2013) 5302–5313.

[17] Shukla, P., Lawrence, J., *Characterization and modification of technical ceramics through laser surface engineering, Laser Surface Engineering Processes and Applications*, Woodhead Publishing Series in Electronic and Optical Materials, 2015.

[18] J. Dutka, *Richardson Extrapolation and Romberg Integration,* Historia Mathematics 11 (1984) 3-21

[1] The birth of numerical analysis, edts: A. Bultheel, R. Cools, World Scientific Co.Ltd, London, 2010.