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Assessment of the dissertation thesis of Mgr. Denys Moskal

"Thermo-physical processes and ultrashort pulse laser scanning methods in surface texturing"

The submitted thesis of Denys Moskal is devoted to the characterization of thermo-physical processes in ultrashort pulse laser surface texturing (LST) and the development of laser scanning methods for high-speed processing with high precision and low heat accumulation.

Current significance of the dissertation topic

This work deals with an important laser radiation application issue – the efficient and precise laser surface texturing. The dissertation is by its nature a modern contribution to solve this challenge. It can be stated that the chosen topic of the work is up-to-date and requested by scientific community.

Scientific approach, procedures, and the results of the dissertation

The dissertation is divided into the 6 main chapters. Various methods of LST and their applications are reviewed in the first part. It was shown that the precision and effectivity of the scanning beam laser surface processing depends not only on parameters of the laser radiation pulses, but also on the correct choice of the scanning speed and the strategy of the laser beam positioning. The high-speed surface scanning leads to a decrease in precision, but low-speed scanning involves unusual heat accumulation in the laser-processed material.

The second chapter is devoted to a current state of the art in the LST of functional surfaces. The author explains the main principles of the laser surface processing with material ablation processes and its physical principles caused by ultrashort laser pulses. Also, he explains the scanning methods for laser surface texturing. The application of ultrashort laser pulses allows minimization of the heat affected zone in the laser surface processing. The literature overview presented in this chapter has shown a wide area for application of laser-textured surfaces in biology, materials engineering, medicine, optics, semiconductor electronics, etc.

The aim of the thesis is explained in chapter three. It presents the optimization of laser surface scanning strategies for overcoming heat accumulation and for high quality laser surface processing. Therefore, a proposal of new scanning strategies for a high-speed LST method based on inertial laser scanner is planned to be investigated together with an implementation of a picosecond laser and galvanometer scanner. Further the evaluation of heat accumulation and ablated plasma glow processes during LST and comparison with theoretical predictions is also planned.

The fourth chapter is devoted to methodology and materials. The author explains here which equipment was used for the measurement, in detail he describes the experimental arrangement and the methods used for the investigation. In the following part of this chapter the author describes the materials used for the experiments, evaluation methods of LST microobjects diameter deviation, depth profile analysis, infra-red (IR) surface radiation detection and analysis, evaluation methods and IR radiation data analysis during laser linear and two-dimensional surface scanning heat accumulation and plasma glow radiation analysis. Thermo-

physical model of heat accumulation in laser-scanned surfaces is also presented. At the end of this chapter the author summarizes the all experimental methods and analytical modelling.

The fifth chapter is the main part of the thesis - the results and discussion are shown here. At first the characterization of laser surface scanning regimes is described then the heat accumulation in one-dimensional laser surface scanning is presented. This makes it possible to identify the common principles of laser material processing with low heat accumulation. Also, the comparison of the evaluated heat accumulation data with literature sources are presented. The author shows greater influence of heat accumulation on the maximal achieved temperature at higher frequencies of the laser pulses. At the end of this section, author specifies four keynotes from the IR radiation signal analysis of the linear surface scanning and compares the experimental data with the theoretically predicted temperature changes. Further, scanning parameters of the two-dimensional LST method and thermo-physical processes are described. As a summary of this section, the main results and the advantages of new investigated method are pointed out.

In the sixth chapter the author summarizes the whole work and emphasizes the obtained results. He mentions that the developed shifted LST method can be used in the applications where the precision and higher scanning speed are principal factors of laser surface processing. He states that especially the shifted LST with equidistant laser pulse distribution and the possible low heat accumulation regime can be useful in the applications (in biomedicine or selective laser melting technology). This method can be useful for decreasing of lateral macroscale thermo-mechanical gradients and noticeably increases the speed for the filling grades formation in 3D laser printing. The application of the shifted LST method with the high-speed IR detectors and spatial light modulation opens new perspectives for high-speed laser microscale thermography. Further combination of the shifted LST method with multi-beam surface scanning will be able to increase the processing rates up to ten times.

Achieved goal of the work

The goal of this dissertation was to characterize the thermo-physical processes in ultrashort pulse laser surface texturing and the development of laser scanning methods for high-speed processing with high precision and low heat accumulation. The planned goal of the dissertation was fulfilled. Mgr. Denys Moskal designed, experimentally investigated, and even tested in the application new process leading to increase the processing rates up to ten times.

Formal and linguistic side of the work

As for the formal side of the thesis, the dissertation is carefully prepared. The individual chapters are arranged in a logical sequence. The dissertation has 132 pages, the text is supplemented by 75 explanatory figures and by 9 tables summarizing the substantial data. Also, the summary of references and list of the author's publications, 2 appendices and descriptions of designators and abbreviations are presented.

From the linguistic point of view, the work is carefully processed, there are only isolated insignificant typos in the text as: page 17th: „Fig. 2.1.3 is shows... ". Some very minor mistakes can be found in Czech text as: page 6th: "...laserového texturovaní povrchu ..."; "...elektronice ad" it should be "...atd."; "...Další část obsahuje dosažené výsledky" better "...Další část obsahuje přehled dosažených výsledků.."; "...výsledky měření IR záření". It could be " ...výsledky měření IČ záření", and it should be specified what the "IČ"means.

Significance for scientific development and applications

The significance of the dissertation for laser-plasma scientific community as well as for applications is apparent. The optimized parameters for LST method will contribute to other applications in the manufacturing industry. An accepted patent is a proof that the results can be useful.

Questions

1. In text the description of the used laser system is stated following: „For the LST experiments, a PX25-2-G solid-state ultrashort laser with InnoSlab technology (EdgeWave GmbH) was used. Which active material is used in this laser?
2. Can you consider the effect of radiation wavelength on ongoing processes?
3. Most of the cited publications and conference contributions were created in collaboration with authors collaborators. Can the author determine his participation in these works?
4. Has your patent been used already in some application?

Conclusion

The presented dissertation is the result of a systematic and purposeful theoretical and experimental study of the PhD. student in the field of a laser surface processing by ultrashort laser pulses. The whole work is presented in a didactic spirit, while the author tries to create an overall picture of the scientific challenge. He demonstrates the ability of independent scientific work with his own scientific contribution and publishes the results of this work. The core of the dissertation was published at the international journal or presented in Czech or international conferences. He obtained also patent granted in two places.

The results of Mgr. Denys Moskal have proven his ability to work scientifically and constructively. It can be stated that he has all the prerequisites for further professional growth in the given field. Overall, I consider the submitted dissertation to be very successful. It contains a number of original results which have been largely presented at major international conferences and published in significant journals. The author has certainly demonstrated the ability of independent scientific work.

I can conclude that the submitted dissertation materially and formally meets the aspects of generally accepted requirements for the dissertation. From this point of view, the work is in accordance with § 47, point 4 of Act No. 111/98 Coll., and I therefore unequivocally recommend to award Mgr. Denys Moskal, after a successful defence, by the academic title Doctor in "Physics of plasma and thin films".

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Evaluation of PhD Dissertation:

Thermo-physical processes and ultrashort pulse laser scanning methods in surface texturing

Submitted by Mr. Denys Moskal

Evaluation of the significance of the doctoral thesis

It is well known, that bioinspired surface structures containing features in the nanometer/micrometer scales offer significant commercial potential for the creation of functionalized surfaces. In this frame, technologies capable to modify surfaces instead of creating composites or spreading coatings on surfaces can offer new industrial opportunities, such as laser based fabrication methods. However, typical limitations of laser-based technologies are related for instance to heat-accumulation and shielding effects, which can either negatively affect the functions of surfaces or reduce the efficient of the process. These limitations define the objectives of the work, which are very relevant today, in particular due to the development of new laser sources which can even operate with several hundreds of watts and short and ultra-short pulses. Thus, the research objectives proposed by Mr. Moskal are the development of new scanning technologies for ultrashort pulsed laser sources, the development of a method for characterizing heat accumulation, and finally the design of functionalized surfaces.
Several of the results presented in Mr. Moskal's work are outstanding and can be considered to be very relevant in the future for improving throughput keeping surface heating (heat accumulation) at the lowest possible level.

Statement on the approach to solve the problem, methods used and fulfilment of the given objective

The approach used to solve the problem in this thesis includes a significant amount of experiments following a classical systematic approach. In the experimental section (chapter 4), first the different used laser systems are introduced. Also in this chapter, the standard scanning technologies are described, as well as the developed "two-dimensional shifted LST" method (e.g. using burst of pulses). The characterization methods used are also appropriate. The developed simulation tool is of great importance for understating the results presented in this work. Some comparisons with the state of the art would require considering also

the laser power used, since clearly there is a correlation between laser power and throughput.
Regarding the fulfillment of the objectives, the most significant achievements include reaching structure size fluctuations up to 5% (precision) for the fabrication of circular dimple arrays. Moreover, the maximal precision and processing rate was reached for the shifted burst LST. Also, the heat accumulation was investigated for the different LST strategies, reaching temperatures below the critical values. The maximum IR signal was detected for the classical scanning strategies due to the lower achievable scanning speeds. Finally, different surface patterns were introduced, which might have potential on different applications fields.

Opinion on the results of the thesis and specification of the student's original contribution to the given area of knowledge

Several of the results presented in this doctoral thesis are very innovative. The approaches used to detect the IR signal in the standard as well as on the developed scanning strategies show very well the capabilities developed in this work for understating very precisely heat accumulation effects in LST. This includes the utilization of IR temperature signal as well as plasma glow duration.
The developed scanning strategies clear permit to improve both throughput as well as precision. This is for instance very clear when comparing the different scanning strategies (e.g. classical scale, shifted scale, classic hatch and shifted burst). Mr. Moskal also discusses and interprets the obtained results using appropriate literature sources as well as well-defined hypothesis (e.g. incubation effects). Regarding throughput, the processing rate could be also significantly increased. Also in this case, the interpretation of the results (e.g. for classical and shifted LST methods) is given.

Statement of the systematic approach, clarity, appropriateness of form and language

The grammar and form of the used language in the doctoral thesis is very appropriate. There are minor errors that could be improved, but are not relevant for understanding the thesis (some words could be replaced by more adequate synonyms like, "it was found" instead of "it was discovered"; there are also some non-common nomenclature in laser processing like "nanoobjects", "microobjects"; the world "laser fluencies" must be replaced by "laser fluences" etc.).
The instruction section (chapter 1) is quite general and it is not very clear for me why it was not combined with chapter 3, where the objectives of the work are introduced.
The "state of the art" section (chapter 2) gives an outstanding overview of the different topics that are relevant for understanding the topics addressed in the PhD. For example, different surface functions that have been addressed using laser surface texturing are introduced (such as wettability control, optical

properties, friction and wear, biological properties, etc.). In particular, this is supported by an impressive amount of references. In the same chapter, the physical principles of laser surface processing with ultra-short pulses are introduced, including the thermal energy transfer problem as well as a proper description of the effect of different parameters such as laser fluence. Other topics addressed in chapter 2 deal with the efficiency of LST as well as the description of incubation effects and heat accumulation, and finally with an overview of classical methods of laser beam scanning.
Some of the contents presented in chapter 4 (methodology and materials) could be better described in the results and discussion section or in a new chapter/sub-chapter related for instance with the "development of two-dimensional shifted LST method", the "development of monitoring strategy for LST" as well as "thermo-physical model of heat accumulation in laser scanned surfaces", since they have been introduced in this work. This would just show in a better way the impressive work conducted by Mr. Denys Moskal. In general, the chapter "methodology and materials" of a PhD thesis is related with standard methods and materials used in the work, but do not include the developments that resulted from a thesis.

Statement on the student's publications
Mr. Denys Moskal was able to produce 5 publications in peer review journals (4 as first author), as well as other 6 publications in proceedings books (non peer-reviewed, 4 as first author), which represents an exceptional performance in a PhD. In addition, he is listed as inventor in 2 patent applications regarding the contents of this thesis. In consequence, he has truly demonstrated to be capable to perform an outstanding high-level research work.

Based on these comments, I recommend the doctoral thesis for defense.

Dresden, 30 June 2020

Prof. Dr.-Ing. Andrés Fabián Lasagni