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AN EVALUATION OF THE USE OF LASER-VIBRATION MELTING TO INCREASE THE SURFACE ROUGHNESS OF METAL OBJECTS[1)]

ANALIZA MOŻLIWOŚCI WYKORZYSTANIA LASEROWO-WIBRACYJNEGO PRZETAPIANIA DO ZWIĘKSZANIA CHROPOWATOŚCI POWIERZCHNI ELEMENTÓW METALOWYCH

This paper presents preliminary, experimental results of a new, hybrid method of increasing the surface roughness of metal objects. In this new approach, metal objects are melted with a mobile laser beam while they are being rotated. A vibration generator provides circular vibrations with an amplitude of 3 mm, and the vibration plane is perpendicular to the moving laser beam. The melting tests were performed using flat carbon steel samples at a predetermined frequency of circular vibrations. The effects of laser power and laser beam scanning velocity on the melted shapes were studied. All laser melting procedures were performed at a vibration frequency of 105 Hz. The melted samples were subjected to microscopic evaluation and the R_a parameter, which characterises mean roughness, was measured using a profilometer. Melting metal samples with physically smooth surfaces (R_a = 0.21 μm) resulted in surface structures of varied roughness values, with R_a ranging from 5 μm to approximately 58 μm. The studies were undertaken to employ this technology for the purpose of passive heat exchange intensification of heating surfaces in practical applications.

Keywords: laser melting, surface roughness, laser treatment, vibration, nucleate boiling

W artykule zaprezentowano wstępne wyniki eksperymentalne nowej hybrydowej metody zwiększania chropowatości powierzchni elementów metalowych. W metodzie tej wykorzystuje się przetapianie ruchomą wiązką laserową elementów metalowych poddanych równocześnie wibracji kołowej. Generator drgań wytwarza wibrację kołową o amplitudzie 3 mm, a płaszczyzna wibracji jest prostopadła do osi przemieszczającej się wiązki laserowej. Próbom przetapiania przy ustalonej częstotliwości wibracji kołowej poddano płaskie próbki ze stali węglowej. Badano wpływ mocy laserowej oraz prędkości skanowania wiązki laserowej na kształt przetopień. Wszystkie przetopienia laserowe wykonywano przy częstotliwości wibracji f = 105 Hz. Otrzymane przetopy poddane zostały obserwacjom mikroskopowym oraz pomiarom profilometrycznym parametru R_a charakteryzującego średnią chropowatość. W wyniku przetapiania technicznie gładkich powierzchni próbek metalowych (R_a = 0,21 μm), uzyskano struktury o zróżnicowanych chropowatościach, dla których R_a mieścił się w przedziale od ok. 5 μm do ok. 58 μm. Badania prowadzono pod kątem potencjalnych możliwości stosowania tej technologii do pasywnej intensyfikacji wymiany ciepła powierzchni płyt grzewczych.

1. Introduction

Intensification of the heat exchange by the technically smooth heating surface with the application of the phenomenon of phase reversal by the medium emitting or absorbing heat has become an increasingly ineffective method of cooling contemporary technical devices. To overcome the resulting problems, a number of research projects have been carried out to devise new techniques for enhancing the heat exchange efficiency of heating surfaces.

The techniques enhancing heat transfer through the walls implemented so far can be divided into active and passive [1]. The most developed are passive techniques that involve the modification of characteristics and structure of surface exchanging heat thus enhancing the heat transfer coefficient. The purpose of the modification is to enhance the contact surface with the cooling agent or to enhance the number of active boiling nuclei. One of the methods for modification of the heat transfer coefficient, which has been intensively developed since the 1950s, is to enhance the surface roughness through the creation of appropriate geometrical structures on the surface. The impact of roughness on the intensification of heat exchange is a complex process and has not been thoroughly investigated. Based on theoretical and experimental research carried out to date, it has been possible to find out that roughness enhancement leads to a distinct decline of overheating temperature of surfaces that exchange heat [2], [10].

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At present, the efficiency of roughness enhancement techniques is being examined. The techniques are used to modify the metal surface by means of, among others, the following types of reaction:

a) chemical – pits obtained through chemical reactions, [3], [8],
b) thermal - sintering of metal particles, [4],
c) mechanical – creating microribs on the surface, application of finely cut grooves, making valleys, holes, projections or sand blasting, shot-peening, treatment with abrasive paper or abrasive compounds [7], [8], [9],[11], [12],
d) laser beam – (making microholes by means of a laser beam, laser melting) and electrical discharge machining (EDM) [5], [6], [10].

The presented paper discusses the preliminary results of experimental research on the new technology of enhancing the roughness of metal elements. This is the technology of the melting of metal surfaces by laser-vibration. In this technique metal elements are melted by the use of a mobile laser beam and are subjected to vibration at the same time. The introduction of vibration into the laser treatment is intended to induce additional forces in the melted metal bath that would make the metal bath vibrate in such a manner as to obtain the uneven position of metal bath solidification front that is created behind laser beam. The impact of the tested treatment on the degree of surface roughness change was evaluated based on the measured values of mean roughness R_a of interfusions selected for analysis, followed by their comparison with R_a values obtained using other surface roughness enhancement techniques. The selection of that parameter was dictated by the fact that in the scientific literature on heat transfer intensification, the R_a parameter is frequently used for quantitative characterisation of the degree of roughness enhancement of heat transferring surfaces.

2. Construction of the experimental stand

The experimental stand for vibration-laser melting is presented in Figure 1. It consists of a work-stand equipped with laser technology, and additionally with a vibration generator mounted on a solid metal structure to ensure stable vibrations. For experimental purposes an oscillatory grinder generating circular vibrations was purchased in a DIY store and mounted on the aluminium vice. The working surface of the grinder was appropriately redesigned to allow for fixing samples to be subjected to vibration melting. Using the presented work-stand, the work surface of the grinder with the mounted vice makes the examined element vibrate circularly and perpendicularly to the laser beam axis.

To carry out experimental research, a work-stand with a laser machine tool Lasercell 1005 was used. It is installed at the Center For Laser Technologies of Metals at the Kielce University of Technology, Poland. The operational parameters of laser machine tool were as follows:

- wave length – 10.6 μm,
- maximum power – 6.5 kW,
- laser beam mode – TEM_{01*}
- active laser medium – CO_2,
- flying optics work-stand
- operational mode: CW

In order to focus the laser beam, a mirror parabolic laser head was used with a focal distance of 200 mm forming a beam with circular symmetry. The process gas used was argon fed using a blast coaxial with the laser beam, with a feed rate of 15 l/min.

The operational characteristics of the vibration generator were as follows:
– power supply 220 V
– diameter of oscillatory vibrations approx. 3 mm
– vibration frequency approx. 105 Hz.

Fig. 1. Vibration-laser stand for melting metal elements

3. Course of experimental tests

The vibration melting process was applied to flat carbon steel samples with a carbon content ~0.45% with dimensions of 120×100×3 mm. The cut out samples were positioned in the vibration generator's vice as shown in Figure 1. The melting process using a laser beam focused on the sample surface was performed using a specially pre-programmed trajectory of the laser beam movement in accordance with diagram shown in Figure 2.

The above diagram shows the outline of a sample vibrating with a circular motion and is melted by laser beam in accordance with the drawn out trajectory. The laser beam with a specific power and pre-programmed velocity starts material melting at the spot marked as 'start'. Then, on the material surface, it creates seven characteristic, repetitive interfusion paths consisting of rectilinear arms, with a length of 50 mm each, combined with a semicircle with a radius of r = 3 mm. While the laser beam was passing to melt consecutive paths with repetitive shape, at places marked on the diagram with a cross, the scanning velocity was automatically enhanced by

0.5 m/min. Such programming of laser parameters enabled the performance of seven interfusions on a single sample, with the difference being only laser beam scanning speeds. Once the interfusions were made using selected vibration and laser parameters, the steel sample was replaced with a new one, and on the basis of a short visual analysis of interfused laser paths, a new set of laser treatment parameters was determined.

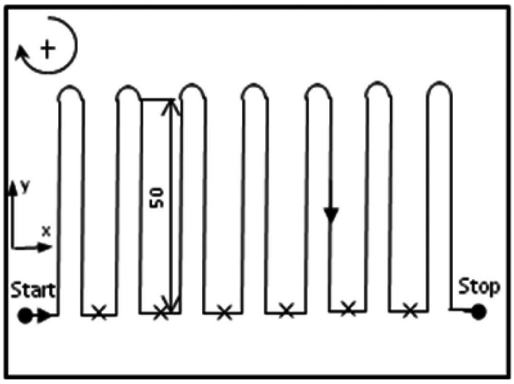

Fig. 2. Diagram showing vibration-laser melting of samples

Following the above test pattern three interfusion series were performed for the following sets of parameters of laser power (P) and initial scanning velocity v_0:

Sample No. 1 : P=1500W, v_0 =1.0 m/min

Sample No. 2 : P=2500W, v_0 =1.0 m/min

Sample No. 3: P=3500W v_0 =2.0 m/min

In addition, for comparison purposes, a typical laser interfusion was performed without any vibration involved. A full set of vibration-laser parameters for melting carbon steel elements is shown in Table 1, where in addition to sample numbering also numbering of individual interfusions was introduced.

The interfused laser beam paths were subjected to examination by microscope using a workshop microscope OLYMPUS SZX10 with maximum magnification of 126 times. Then, it was followed by the measurements of R_a parameter for selected surfaces alongside interfusions along their symmetry plane.

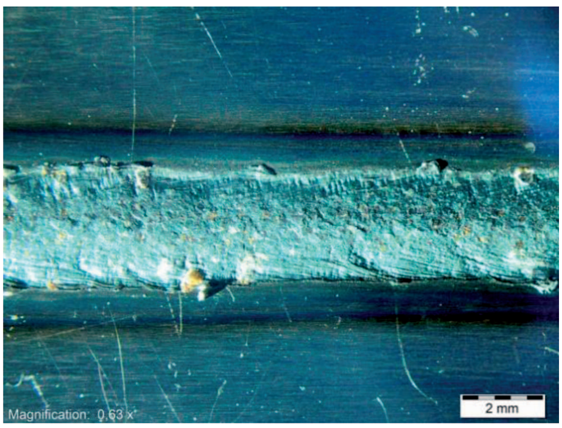

Fig. 3. Typical shape of laser interfusion

To ensure comparability of the measurements of individual interfusions, the roughness of the piece of rectilinear paths preceding laser beam passing into semicircle was always analysed (Figure 2). The roughness measurements were taken at the Department of Mechanical Technology and Metrology at the Kielce University of Technology using a Talysurf profilometer in compliance with the Polish standard numbered PN-ISO 3274: 1997. Additionally, R_a of the technically smooth treated samples was measured as well as R_a of the front of typical interfusion without vibrations as shown in Figure 3.

TABLE 1

Results of mean roughness R_a measurement

Sample No.	Interfusion No.	Laser power [W]	Scanning velocity [m/min]	R_a [µm]
1	A1	1.5	1	8.877
	A2	1.5	1.5	7.523
	A3	1.5	2	5.298
	A4	1.5	2.5	11.187
	A5	1.5	3	19.117
	A6	1.5	3.5	19.008
	A7	1.5	4	13.132
2	B1	2.5	1	X
	B2	.5	1.5	11.086
	B3	2.5	2	10.604
	B4	2.5	2.5	14.141
	B5	2.5	3	21.994
	B6	2.5	3.5	26.344
	B7	2.5	4	25.840
3	C1	3.5	2	X
	C2	3.5	2.5	X
	C3	3.5	3	X
	C4	3.5	3.5	X
	C5	3.5	4	X
	C6	3.5	4.5	31.842
	C7	3.5	5	57.951
Melting without vibrations				2.92
Technically smooth surface				0.21

4. Analysis of experimental testing results

4.1. Microscopic evaluation

Following experimental tests, the sample surfaces were subjected to microscopic observation and recording using the digital movie camera built into the microscope. Figures 4, 5, 6 show pieces of rectilinear interfused paths, prior to the transition of the laser beam into a semicircle.

The dimensions of laser paths obtained in Figures are close to the actual dimensions. Additionally, to facilitate the analysis of the obtained structures, the images of the surface of selected interfusions are presented in Figures 7-15.

First of all it should be noted that, regardless of the laser treatment parameters used, the presence of vibrations with preset parameters did not block the melting process of metal samples, but had a material impact on the change of metal bath solidification conditions.

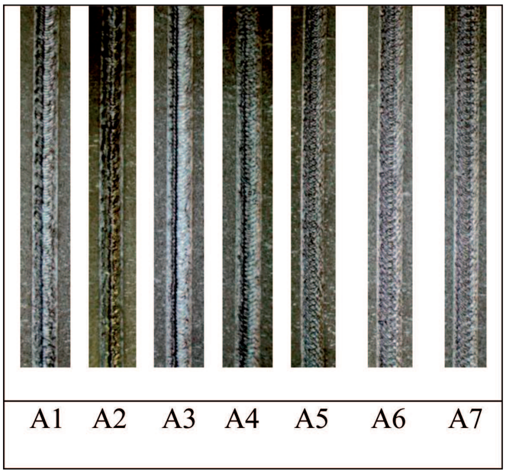

Fig. 4. Vibration-laser interfusions made using Sample No. 1

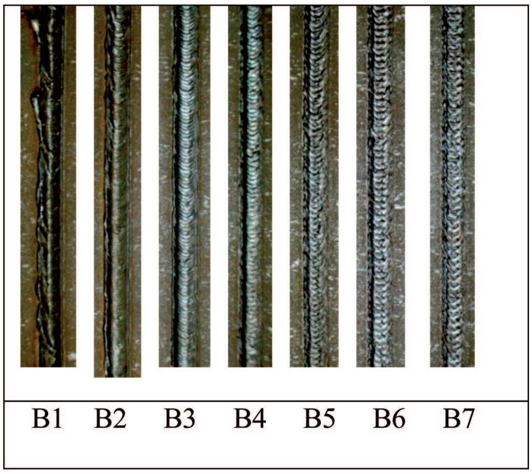

Fig. 5. Vibration-laser interfusions made using Sample No. 2

Instead of obtaining a smooth front typical of a laser interfusion without vibrations, shown for comparison purposes in Figure 3, the obtained paths were 2.5 mm-3 mm wide with varied and characteristic shapes (Figures 4, 5, 6). The obtained shapes are in the form of specific arches overlapping one another alongside the whole length of the paths.

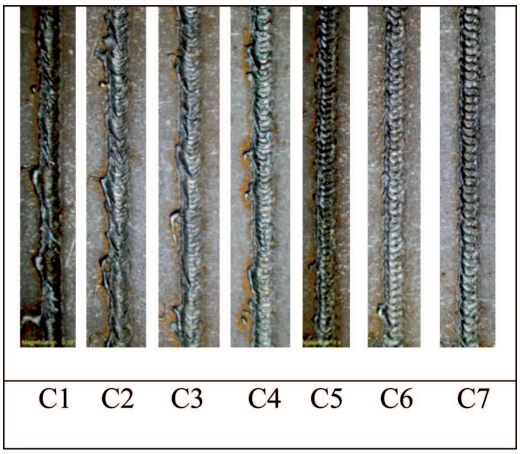

Fig. 6. Vibration-laser interfusions made using Sample No. 3

The occurring arch-shaped interfusions are a consequence of the spiral movement of metal bath solidifying on the surface, with the movement trajectory being a combination of rectilinear movement of laser beam with circular movement of treated material. The regularity and clarity of arches grows with the increase in laser beam scanning velocity.

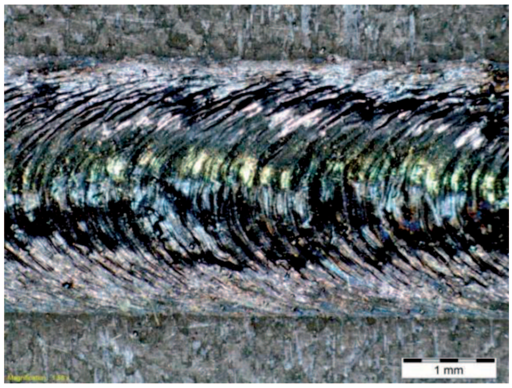

Fig. 7. Front of interfusion No. A1

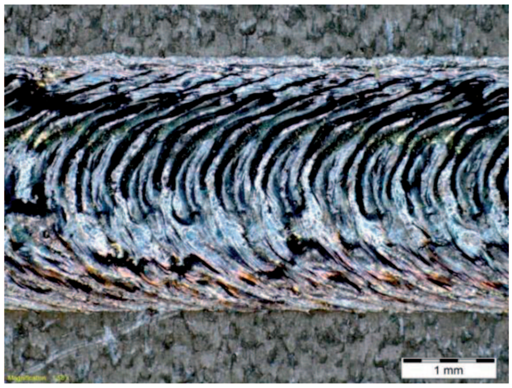

Fig. 8. Front of interfusion No. A4

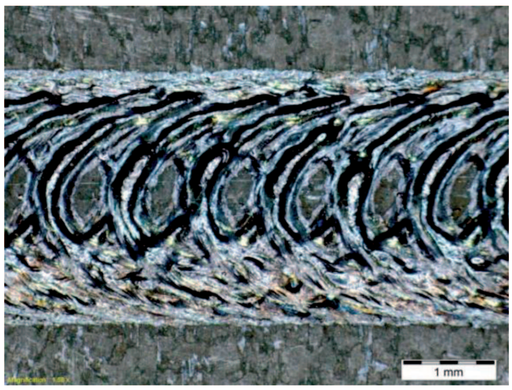

Fig. 9. Front of interfusion No. A7

The regularity and clarity of arch structures are visible for all interfusions made using laser power P=1.5 kW (Figures 7, 8, 9). For interfusions made using laser power P=2.5 kW and P=3.5 kW, the arch structures were obtained only at higher scanning velocities (v): for power P=2.5 kW, v>=2.5 m/min (Figures 11, 12), whereas for laser power P=3.5 kW, v=5m/min (Figure 15). At lower velocities of the laser beam movement, one can see clearly the presence of irregularly solidified pieces of molten metal (Figures 10, 13, 14).

Another feature that became apparent during microscopic observation is the clear dependence of the distance between vertices of individual arches on the laser beam movement velocity. The dependence is clearly visible in the Figures 7, 8, 9 presenting vibration-laser interfusions made with a laser power of P=1.5 kW.

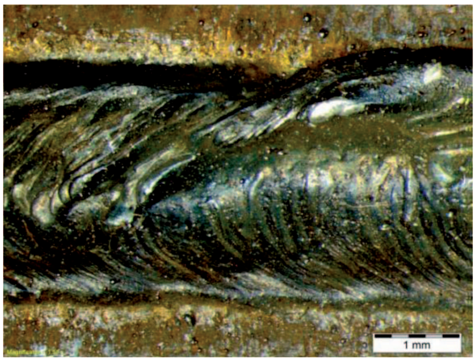

Fig. 10. Front of interfusion No. B1

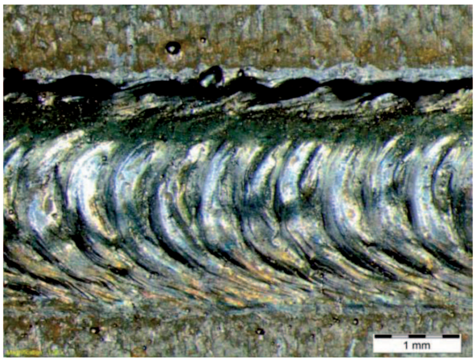

Fig. 11. Front of interfusion No. B4

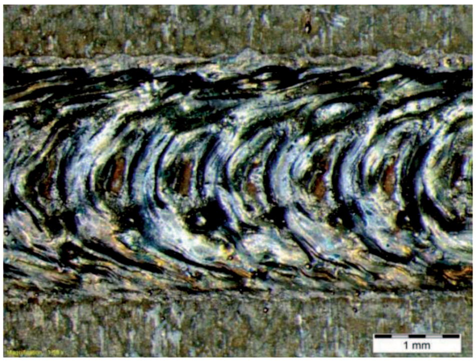

Fig. 12. Front of interfusion No. B7

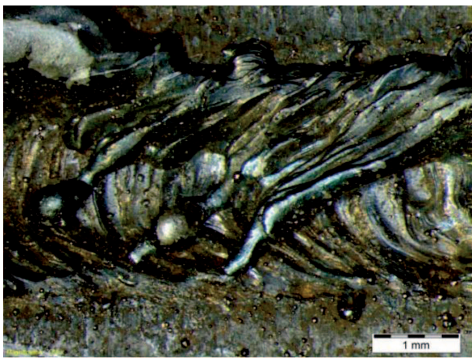

Fig. 13. Front of interfusion No. C1

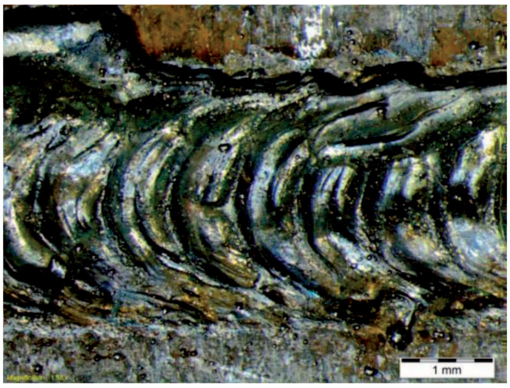

Fig. 14. Front of interfusion No. C4

For the lowest scanning velocity of v=1 m/min, the arch vertices visible in Figure 7 are very close to one another giving the impression of a quite smooth interfusion surface. With a laser beam movement velocity of v= 2.5 m/min (Figure 8), distinctly isolated single arch outlines can be observed. Meanwhile at the maximum laser beam scanning velocity of v=4m/min, an area of non-molten material appears among individual arch outlines (Figure 9).

Fig. 15. Front of Interfusion No. C7

During the melting of samples with higher laser powers this effect is less visible owing to the occurrence of processes causing chaotic solidification of metal. At the current stage of research, it is not yet possible to pinpoint unambiguously the reason for the occurrence of chaotically solidified metal structures. Only a supposition can be made that for certain parameters of vibration-laser treatment, conditions are created that are conducive to the breaking up of metal bath under the influence of existing centrifugal forces, and then it solidifies at various, random places on the material surface.

4.2. Profilometric evaluation

The results of measurements of the average roughness (R_a) are presented in Table 1. For some series of interfusions performed, measurements were not made owing to the risk of damage to the profilometer probe. The obtained values of R_a parameter for surface after vibration-laser treatment fall into the range from approx. 5 μm to approx. 58 μm. These are values that exceed significantly the values of R_a obtained for technically smooth surface (R_a =0.21 μm), or even the face of interfusion without vibration (R_a =2.92 μm). This proves the significant impact of vibrations on the change of structure of the material surface melted with a laser. The overall graph showing R_a dependence on the scanning velocity (v) and laser power (P) is shown in Figure 16. To facilitate graph analysis, the results of R_a measurements have been connected using sections. The findings show a strong dependence of the value of R_a parameter on the laser parameters applied. The highly beneficial impact of laser power is visible here. Regardless of the scanning velocity applied, an increase in laser beam power improves the conditions for surface roughness enhancement. Meanwhile, the impact of laser beam scanning velocity is more complex. For the lowest applied power of P=1.5 kW and for power of P=2.5 kW, it is possible to observe distinct minimum values and maximum values of roughness. The minimum values of R_a occur for both laser powers at velocity of v=2 m/min, whereas maximum values R_a = approx. 20 μm for v=3 m/min (P=1.5 kW) and R_a = approx. 26 μm for v=3.5 m/min (P=2.5 kW).

In case of laser treatment with power of P=3.5 kW, both values of measured average roughness are quite high: from more than 30 μm for v=4.5 m/min, to approx. 58 μm for v=5 m/min.

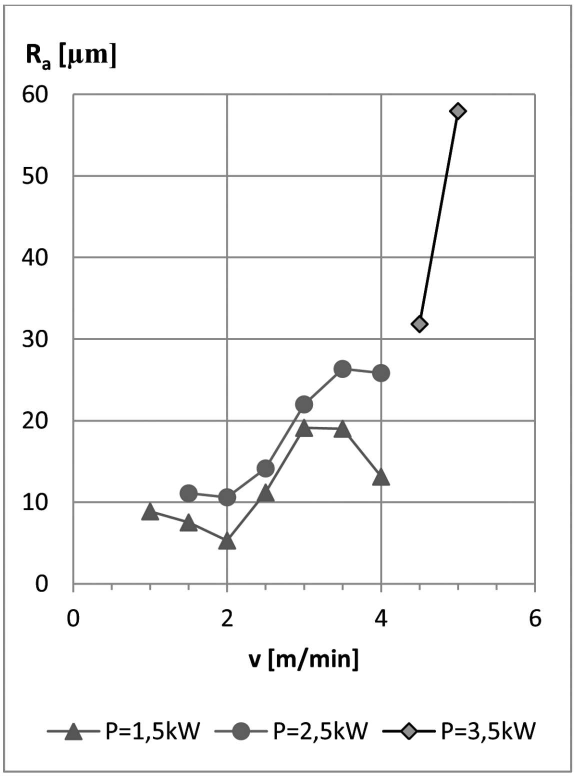

Fig. 16. Dependence of measured average roughness as a function of laser power (P) and scanning velocity (v)

Based on a review of selected literature presented in the bibliography concerned with the issues of heat transfer intensification involving the working medium phase, the highest values (R_a) of sample surfaces used for tests were recorded as follows: 10 μm in [10], 10.5 μm in [12], 13.04 μm in [9] or 13.33 μm in [11]. As a consequence of applying vibration-laser treatment, the R_a values are significantly higher and should have a significant impact on the improvement of heat dissipation properties. Also, it should be noted that the mean roughness is one of the parameters describing roughness quality, which necessitates further additional research.

5. Conclusions

The paper presents the assumptions for new vibration-laser technology for metal surface roughness enhancement. The degree of intensity of surface roughness enhancement was adjusted by means of the main treatment parameters: laser power (P) and laser beam scanning velocity (v). The experimental investigations conducted for the study made it possible to draw the following preliminary conclusions:

1. The presence of circular vibration, having pre-determined parameters, does not block the process of laser melting of metal surfaces, it does however, significantly affect the conditions of the metal bath solidification.

2. Instead of laser interfusion characteristic shapes with relatively smooth surfaces, interfusions of varied shapes are obtained. Interfusion shapes received while applying vibration depend, to a large extent, on the laser beam scanning velocity and power.

3. Surface roughness level, measured with the R_a parameter, also depends on the laser melting parameters. An increase in the laser power, and within a certain range, in the laser beam scanning velocity, produce an increase in the melted surface roughness.

4. As a result of the conducted experimental tests, interfusions were obtained on carbon steel samples with roughness measured with R_a parameter (5 μm $<R_a<$ 58 μm), many times higher than the roughness of interfusions without vibration or higher than technically smooth surfaces or roughness values obtained using other mentioned techniques.

Full identification of the potential for the application of the proposed technology as a passive technique for the intensification of heat transfer of heating plates requires further experimental testing.

Acknowledgements

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