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INFLUENCE OF LASER BEAM INTENSITY ON GEOMETRY PARAMETERS OF A SINGLE SURFACE TEXTURE ELEMENT

WPŁYW NATĘŻENIA WIĄZKI LASEROWEJ NA PARAMETRY GEOMETRII POJEDYNCZEGO ELEMENTU TEKSTURY POWIERZCHNI

Laser surface texturing is used more and more often in modern machines for the implementation of variety of purposes such as for example intensification of lubrication, intensification of heat exchange, stimulation of microfluidics, increasing the chemical activity of the surface. Owing to the development of technologies using a concentrated energy flux, including laser microprocessing, it has become feasible. The present paper concentrates on the selection of parameters of laser microprocessing with picosecond pulses so as to obtain the highest efficiency and accuracy of the execution of a single texture element.

Keywords: laser microprocessing, laser surface texturing (LST), laser ablation, ultrashort pulses

W nowoczesnych maszynach dla realizacji różnych celów m.in. takich jak przykładowo intensyfikacja smarowana, intensy-fikacja wymiany ciepła, stymulowanie mikroprzepływów, zwiększenie aktywności chemicznej powierzchni; coraz częściej stosuje się teksturowanie powierzchni. Stało się to możliwe dzięki rozwojowi technologii wykorzystujących skoncentrowany strumień energii, do których należy mikroobróbka laserowa. Tematyka opracowania koncentruje się na analizie parametrów mikroobróbki laserowej impulsami pikosekundowymi w celu osiągnięcia jak największej wydajności i dokładności wykonania pojedynczego elementu tekstury.

1. Introduction

The development of technology makes very great demands for reliability and durability of machine elements while constantly increasing the threshold limit values for parameters of their work. One way to meet these demands is to direct the efforts of designers and technologists towards activities involving the formation of micro-geometry of selected surfaces of machine elements. It is favoured by advances in technology which, in recent years, has made good progress, especially in the area of laser technology, enabling local intensified impact on the processed material.

To maximize the use of the material and the best of its performance, it is extremely important to modify surface properties. For example, one can influence the morphology of the surface and its absorption properties by changing the structure of the material [1], or chemical impurities contained in the surface.

The susceptibility of a material to wear and surface damage can be reduced by changing the chemical composition, morphology and the crystal structure of its surface [2]. Furthermore, forces of friction, adhesion and wetting occurring in the transitional layer (interphase) of a material can be considered to be largely determined by the size and shape of the elements present in the micro and nanoscale [3]. Currently, surface engineering focuses on the modification of the surface micro-geometry in order to improve its performance properties, while trying not to affect the structure and mechanical properties of the processed material.

A laser beam is a carrier that allows to obtain a very high concentration of energy in terms of area and time of the impact on the processed material. In laser microprocessing the area of the actual impact on the material is determined by the size of a laser spot in concentration or mask which transmits only the desired portion of a beam. Of particular importance is the

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impact of the time of a beam pulse, because depending on the intensity of radiation and exposure time, a variety of mechanisms of impact on the material can be used. This is due to the finite times of the response of electrons and atomic network of the material to photons. One of the main advantages of a laser as a tool for treatment of materials is the possibility of precise control over where and how fast energy is deposited. This control is performed by the appropriate selection of laser processing parameters in order to achieve the desired modification of the material [4,5].

Laser ablation is a removal of the material from the substrate by the direct absorption of laser energy. Laser ablation is generally discussed in connection with pulse lasers, but it can also be used for the intense radiation of permanent waves. Above the ablation threshold, the thickness or volume of the material removed, which is attributable to one pulse, usually exhibits a logarithmic increase together with fluence for short pulses or a linear growth for long pulses, according to the Beer-Lambert law. Microsecond and nanosecond pulses are long pulses whereas picosecond and femtosecond pulses are short or ultrashort pulses [5].

During the laser ablation different mechanisms of material removal can activate, depending on the specific material system and laser processing parameters such as wavelength, fluence and pulse length [6,7]. At low fluences, photothermal mechanisms of ablation include evaporation and sublimation of a material. In the case of multicomponent systems, more volatile components can be depleted more quickly, causing a change in the chemical composition of the remaining material. At higher fluences, the heterogeneous nucleation of bubbles with steam leads to the normal boiling.

The length of a laser pulse can have a significant impact on the dynamics of the ablation process. In general, since the duration of the pulse is shortened , the energy is rapidly accumulated in the material, which leads to its faster excretion. The amount of the material directly excited by a laser has less time to transfer energy to the surrounding material before excretion [7].

It is noteworthy that the attainable temperature of the electron mesh after a pulse is once again determined by means of electron cooling time and thus the achievable temperature and the temperature of the mesh grid at the end of the pulse are approximately equal. In terms of picosecond pulses a logarithmic relationship between the depth of ablation and the density of energy is observed. The evaporation of the material can be considered as a phenomenon of the direct transition of the solid phase into vapor, but the presence of the liquid phase is observed here. However, it is so small that it should be ignored. For ablation processes with nano-and pico-second pulses the heat conduction into the interior of the processed material can be omitted in the first approximation. The use of this type of ablation is preferred since it allows a precise laser processing technique called cold laser ablation [5].

Laser surface texturing has been used for years as a method of improving tribological properties of the surface. The formation of a controlled texture on one of the two sliding surfaces in relative motion can have many positive effects, such as reducing friction and wear and increasing the capacity of a sliding pair [4,5].

The aim of the investigations is the analysis of laser processing parameters influencing the morphology on the surface of the element made of 100Cr6 bearing steel and ensuring satisfactory performance and accuracy of the process.

2. Experimental

The investigations aimed at achieving the highest efficiency and accuracy of the execution of a single element of the texture were conducted at the Laser Processing Research Centre of the Kielce University of Technology and the Polish Academy of Sciences using the stand for microprocessing equipped with a TruMicro 5000 model 5325c picosecond laser with max 5 W average power, pulse energy up to 12.6 µJ and quality of the radius of $M^2 < 1.3$. The maximum pulse frequency is 400 kHz and can be modified by the introduction of a pulse divider taking the values of 200 kHz, 133,33 kHz, 100 kHz, 80 kHz, 66,66 kHz, etc. The radiation wavelength of a TruMicro 5325 c laser is 343 nm. The TruMicro Laser 5325c was equipped with a scanner head of the SCANLAB "galvo" type of the processing area in the form of a square of the side 90 mm and a scan speed (feed of the laser beam over the material) in the range of 100-5 000 mm / s and a lens with the focal length of 160 mm. The microprocessing of the 100Cr6 bearing steel was of interest here.

In order to select the optimum parameters of microprocessing, the first part of the experiment was carried out. It consisted in evaluating the impact of laser pulses on the processed material by changing the frequency of pulses, their duration and the power of the laser. The assessment consisted in observing the shape and form of the obtained trace of the impact of the laser beam on the material and in identifying processes such as melting of the material, loss with no signs of melting, the outbreak of the material. The energy value of a single pulse was 12.6 µJ at 100% of power whereas 6.3 µJ at the power settings of 50%. The exposure times used were within the range of 12.5 ms to 250 ms. As a result, changes in the number of individual pulses acting on the sample in the range of $N = 78$ to $N = 100000$ were obtained. During the processing of a sample beams were placed in the focus, and the processing zone was shielded with argon. Figure 1 shows exemplary scanning electron microscope images showing both the insufficient treatment capacity of the sample (*a*) and the ablation with remelting resulting from the too high fluence (*c*); n is the number of pulses in the processing cycle.

Further investigations were aimed at evaluating the influence of microprocessing parameters on the geometry of a single element of surface texture in the form of a cap. To make the experimental results applicable to any machine used for laser microprocessing, the dependence of the geometry of microcavities obtained on the fluence of laser radiation, which is a measure of the amount of energy supplied by radiation per area unit expressed in J/cm^2, should be used. In the case of laser
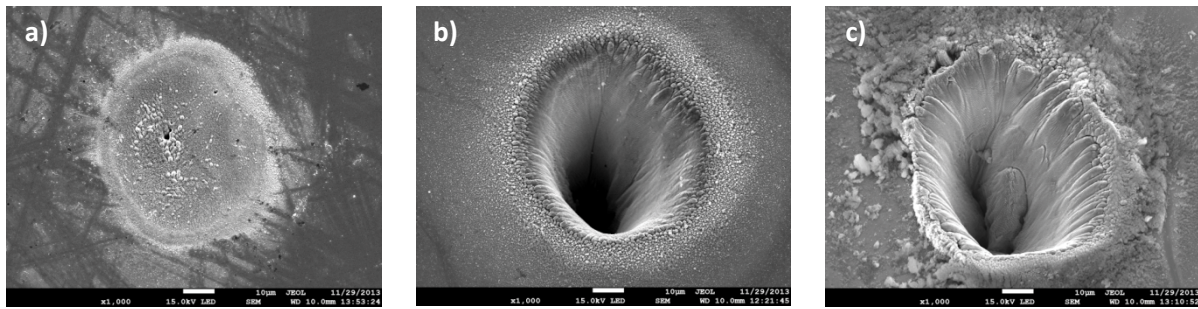
Fig. 1. Selected SEM views of the pictosecond laser beam traces of the impact on 100Cr6 steel: a) 5W, 57.14 kHz, 12.5 ms, n = 78, b) 5W, 400 kHz, 25ms, n = 10 000, c) 5W, 66.66 kHz, 250 ms, n = 3125

microprocessing using a galvo scanner head, the fluence of laser radiation depends on:

– single pulse energy and thus the average power of the laser,
– the impact area or field of the laser spot,
– frequency laser pulses,
– scan speed or speed of bundle feed over the material.

The range of the average power of laser radiation from 5 W to 1.5 W and frequencies of laser pulses of 400 kHz, 200 kHz, 133.33 kHz, 100 kHz, 80 kHz, 66.66 kHz were tested. For average powers of less than 1.5W and for frequencies lower than 66.66 kHz, the fluence (F) was less than 1.33 J/cm^2; there was no significant effect of processing on the material or loss of ablative mass. It can then be concluded that 1.33 J/cm^2 is the threshold fluence for 100Cr6 steel. All the samples were made for the scan speed constant of 100 mm/s. The nominal diameter of a micro-cavity was 100 μm. The surfaces of the samples were prepared before the laser processing on the polisher for metallographic specimens (Ra = 0.392÷0.694, Rm = 1.336÷1.919).

To determine the geometry of microcavities formed, a Tyler Hobson Talysurf CCI optical profiler using the method of coherent correlation interferometry of the extent of 2.2 mm and the resolution of 0,01 nm equipped with a ×50 zoom lens that allows the measurement of the area of 330 μm ×330 μm and the slope angle up to 27.7°. For each sample, 3 measurements were made. They were concentrated at a depth h_p, deviations of the obtained diameter from the nominal diameter $\Delta\phi$, the volume of material removed in the ablation process V, and the height formed in the processing of the multidirectional flow h_w, as shown in Figure 2.

TABLE 1

List of selected laser microprocessing parameters of samples tested

N	P [W]	f [kHz]	F [J/cm^2]	N	P [W]	f [kHz]	F [J/cm^2]	N	P [W]	f [kHz]	F [J/cm^2]
1	5	400	4.76	47	3.25	80	2.92	75	2	133.3	1.85
2	5	200	4.69	48	3.25	66.66	2.88	76	2	100	1.82
3	5	133.3	4.62	49	3	400	2.85	77	2	80	1,8
4	5	100	4.56	50	3	200	2.81	78	2	66.66	1.77
5	5	80	4.49	51	3	133.33	2.77	79	1.75	400	1.66
6	5	66.66	4.43	52	3	100	2.73	80	1.75	200	1.64
7	4.8	400	4.52	53	3	80	2.69	81	1.75	133.3	1.62
8	4.8	200	4.46	54	3	66.66	2.66	82	1.75	100	1.6
9	4.8	133.3	4.39	55	2.75	400	2.62	83	1.75	80	1.57
10	4.8	100	4.33	56	2.75	200	2.58	84	1,75	66.66	1.55
11	4.8	80	4.27	57	2.75	133.33	2.54	85	1.5	400	1.43
12	4.8	66.66	4.2	58	2.75	100	2.51	86	1.5	200	1.41
13	4.5	400	4.28	59	2.75	80	2.47	87	1.5	133.3	1.39
14	4.5	200	4.22	60	2.75	66.66	2.43	88	1.5	100	1.37
15	4.5	133.3	4.16	61	2.5	400	2.38	89	1.5	80	1.35
16	4.5	100	4.1	62	2.5	200	2.35	90	1.5	66.66	1.33

where: N – number of a sample; P – laser power set [W]; f – frequency of laser pulses [kHz]; F – fluence of laser radiation [J/cm^2]
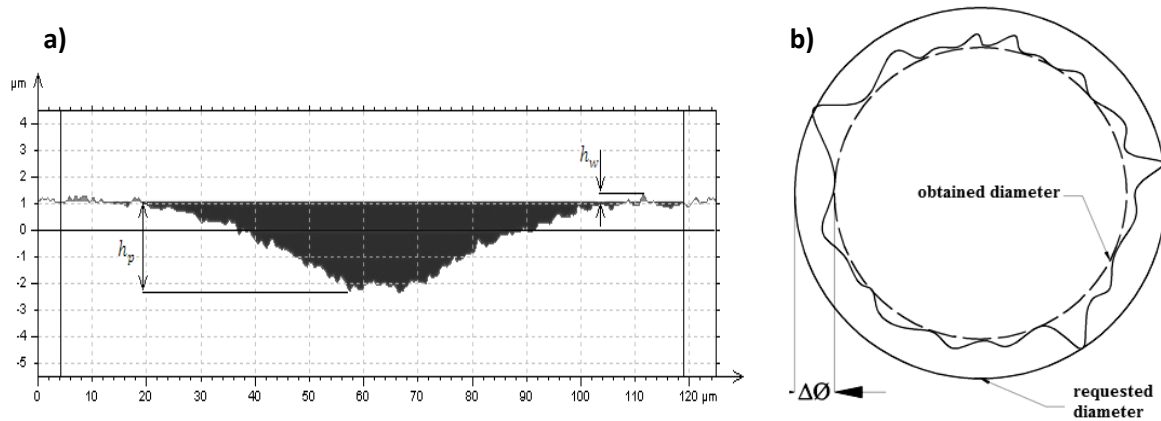
a)

b)

Fig. 2. a) exemplary measurement report of values h_p, h_w and V, b) the method of measurement $\Delta\phi$

Selected results of measurements of the geometry of samples tested

N	h_p [μm]	V [μm³]	h_w [μm]	$\Delta\phi$ [μm]	N	h_p [μm]	V [μm³]	h_w [μm]	$\Delta\phi$ [μm]
1	3.37	7039.1	1.03	1.08	47	1.03	3085	0.27	0.1
2	1.31	4691.5	0.74	0.99	50	1.82	5277	0.53	0.11
4	1.11	3842.2	0.68	0.81	61	2.19	4994	0.39	0.22
7	2.86	8878.6	2.64	1.04	72	0.51	1390	0.11	0.33
20	1.56	5085.9	0.63	0.8	73	1.28	2939	0.22	0.42
28	1.51	4912.2	0.41	0.52	77	0.88	1276	0.13	0.31
29	1.53	3369.4	0.32	0.5	82	0.67	1815	0.15	0.69
39	1.12	3611.2	0.21	0.09	83	0.74	1452	0.13	0.66
40	0.85	1348	0.16	0.08	89	1.01	801.6	0.07	0.58
41	0.85	1347.2	0.15	0.08	90	0.42	553.7	0.05	0.55

To determine the effect of fluence on the geometry of a single microcavity, an analysis of dependences of quantitative variables was used. The analysis was done in the SAS system (Statistical Analysis System), version 9.4, determining the mathematical dependence of factors considered. The regression dependences under consideration showed high significance in the statistical sense. Determined regression dependences with confidence intervals and the regression equations (dependences 1 to 4) for the correlation of the studied traits are presented below.

3. Concluding remarks

During the point impact of the picosecond laser on 100Cr6 steel a clearly shaped cavity appears only at the impact of 3125 pulses. It should be noted that only at the execution of cavities using the frequency of 400 kHz a regular cavity for the full range of pulses, i.e. from 5 000 to 100 000, was obtained. For lower frequencies from 200 to 80 kHz about 5 000 pulses were necessary for the execution of regular cavities. For frequencies of 66.66 and 57.14 kHz cavities appeared at 3125 pulses but were irregular in nature. With a small number of pulses, the energy of laser interaction is sufficient only for the coarse defragmentation of the material and much larger particles are formed as a result the phase explosion. Furthermore, the force

of the explosion is not able to discharge defragmented particles to the periphery of the trace. They remain in the center of the track. With a small number of pulses the trace of the processing resembles an eruption of a volcano with cracks at its top. This phenomenon does not occur at 50% of the laser power. Observing changes in the image of the trace of processing at a frequency of 400 kHz, it can be noticed that with an increase in the number of pulses, the participation of mechanisms of thermal character increases . Remeltings are clearer on the walls of the funnel and the multidirectional flow stands out more clearly. These adverse effects are not observed for the processing with the number of pulses of 5 000 to 10 000. Therefore, the use of processing with the frequency of 400 kHz and the number of pulses from 5 000 to 100 000 is the most favourable for 100Cr6 steel.

An analysis of the dependence of the geometry of a single texture element on the fluence of laser radiation showed a strong influence of laser processing parameters on the shape and accuracy of the execution of a microcavity. The statistical analysis showed that with an increase in the value F by one unit, the value h_p increases by an average of 0.327 of the unit, V by an average of 1188.7 units, and h_w by an average of 0,173 of the unit. The highest accuracy in the execution of a micro cavity was obtained for the range of 2.62 to 3.57. For the value F of less than 2.62 J/cm² an insufficient quality of a single texture element is observed to be caused by an insufficient amount of energy supplied
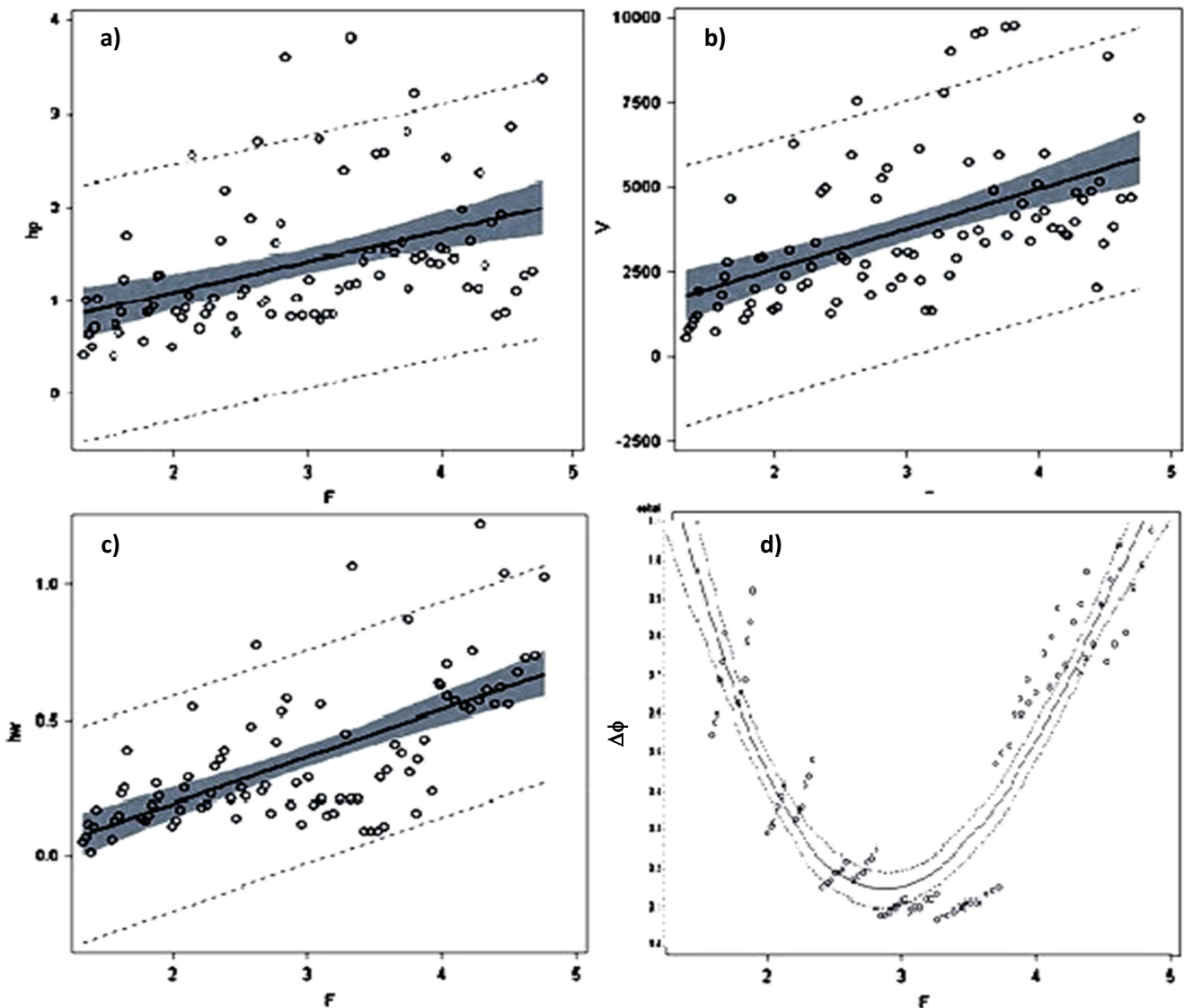
Fig. 3. Charts of matching with confidence intervals for regression dependences: a) h_p, b) V, c) h_w, d) $\Delta\phi$; on the fluence of laser radiation

$$\Delta\phi = 0.282\ F^2 + 2.373 \tag{1}$$
$$h_w = 0.173\ F - 0.152 \tag{2}$$
$$V = 1188.7\ F + 209.4 \tag{3}$$
$$h_p = 0.327\ F + 0.432 \tag{4}$$

to the surface of the processed material . Microcavities made using these values F were made imprecisely and their diameter is much smaller than the set value. For the processing of the fluence greater than 3.57 J/cm² microcavities with an irregular shape resulting from the melting of the material are observed. The diameter of microcavities made at the value F greater than the J/cm² was higher than the set value.

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