Research Article

Grzegorz Witkowski*, Szymon Tofil, and Krystian Mulczyk

Effect of laser beam trajectory on pocket geometry in laser micromachining

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Abstract: The article presents the problem of planning the laser beam trajectory for the laser micromachining process. The article concerns on the ablative laser micromachining issues. Different effects of laser beam trajectory on pocket geometry in laser micromachining were investigated. The results of experimental tests are presented. Based on the research, potential causes of different effects of the laser beam for various trajectories were formulated. Several different types of trajectories for the assumed shape were developed for the purposes of the research. Laser micromachining was performed with fixed parameters of the laser device using different trajectories. The article indicates the significant impact of the laser beam trajectory on the effect of interaction on matter during the laser milling process, which is not often mentioned in scientific reports. The article presents the basic geometrical measurements indicating the need to determine the leading of the laser beam. Studies were conducted using the microscopic observation methods and interferometric methods for estimating the surface condition. The article indicates the need for extensive research focusing on the mechanism of the impact of the laser beam scan strategy on the effect on the material during ablative laser machining. The article summarizes the analysis and discussion of research results.

Keywords: laser micromachining, scan strategy, microstructures, geometry quality

1 Introduction

Laser milling is fast emerging as an important technology for material micro manufacturing. Compared to other competing methods, such as micro electrical discharge machining, laser milling is the most versatile method of milling or micro texturing all types of materials [1–5]. An important advantage of the laser micromachining method is the ability to process dielectric materials, unlike EDM method. As well as in traditional milling, laser milling technology can be implement in layer-by-layer material removal technology with constant tool penetration into the work-piece body and ability to changing of layer thickness to be removed [6]. Precise material removal is possible due to the phenomenon of cold ablation, consisting in the rapid evaporation of laser-illuminated material [3]. It is well known that short pulse, usually pico and femtosecond lasers are used for laser micromachining technology. Single pulse duration oscillates between tens of femtoseconds and several picoseconds. Depending on the type of material, appropriate light wavelengths of lasers are used. Typically, lasers with wavelengths in the UV (343 nm) and near infrared (1064 nm) range are used. To obtain the assumed machining effects, the parameters such power, frequency the number of repetition and scanning speed are adequate modulated. Analyzing the available literature sources for laser milling, it can be concluded that the effects of these parameters is partially and sufficiently recognized. However, very little attention is paid to issues related to the influence of the shape of the scanning path on the final effect of laser micro machining. It has been observed that the use of fixed laser device parameters for different trajectories brings different end results.

Nowadays, miniaturization is an important trend in an increasingly fast-growing industry. That is why we are increasingly micro machining various construction materials. It may seem that the micro machining process is analogous to the conventional macro machining process, and knowing the given procedure, we can easily do the same on a micro scale. Nothing more confusing. Micro machining requires a different approach to issues and processes related to it. Of course, at the micro scale, some problems are similar to the macro scale, but you must also pay special attention to the error tolerance of the process being performed. Even small deviations in the correctness of the performed process can have a significant impact on the final result, which may differ from expectations.
In the literature we can find works on the issues of micro-machining of various materials using ultrashort pulse lasers [7, 8]. Surface texturing, also known as surface structuring, is the process of giving a surface a specific geometric structure to achieve specific surface properties. Structures obtained on the surface using ultra short laser pulses can be made in a way unattainable for other surface forming technologies. The scale of the textures obtained is often from nanometers to millimeters. Laser surface structuring technology can be used for almost all materials with flat and curved surfaces.

There are two main approaches to laser texturing of surfaces with ultra-short laser pulses: obtaining textures through direct laser engraving [9] and using the effect of self-assembly surface under the action of a laser radiation pulse [10]. The effects of self-assembly caused by the influence of the laser beam on the material can be used to create textures in an indirect way. The dimensions of the texture obtained are independent of the dimensions of the laser beam focus, typical sizes may be even smaller than the wavelength of the radiation used [10]. They can be made on various materials such as metals, ceramics and glass. Important parameters for this type of treatment is the wavelength, polarization, and the fluence of the laser radiation.

As with laser drilling or milling, a concentrated laser beam can be used to remove material with a specific pattern to create surface textures [11]. The textures resulting from this method are determined by the laser scanning pattern and focused spot size [8]. It is noteworthy that such textures are clearly thought out, while the formation of self-organizing textures is an implicit process. Typical peak spacing between direct write textures start at about 10 µm, and the structure depth is usually in the same order of magnitude [9].

A type of texture commonly used is the texture of a pockets, which consists of a pattern of laser drilled pockets or holes. Typical hole diameters range from less than ten micrometers to several dozen micrometers [12]. Laser ablation is a process in which chemical bonds of macromolecules of a modified material break under the influence of concentrated laser beam [13]. Then fragments of these macromolecules are detached from its surface layer. The phenomenon of ablation occurs especially during erosive machining of materials. This applies to all materials used, including metals, hard-melt alloys (e.g. titanium, iridium, platinum or tantalum) and metals with a high heat transfer coefficient (copper, silver) [14].

In the case of processing materials with a high thermal conductivity coefficient, laser ablation is used in the processes of manufacturing micro modules of micro modules (microlithography), miniaturized machine elements and components used for their cooling, as well as for very precise correction of the shape of miniature objects.

There are two mechanisms of ablation which can occur separately or simultaneously: photochemical and photothermal. The thermal ablation of a copper occurs as a result of the excitation of molecules into the high energy state by laser radiation. This results in generation and, at a later stage, in heat accumulation and an increase in material temperature. The thermal ablation occurs after exceeding the temperature value of the material called the threshold ablation temperature ($T_T$). The energy initiating the thermal ablation is expressed by the following relation:

$$E_i^{th} = \frac{c_v (T_D - T_R)}{\alpha (1 - R)}$$  \hspace{1cm} (1)

where: $T_R$ - initial temperature of polymer material, $c_v$ - specific heat of polymeric material, $\alpha$ - radiation absorption coefficient, $R$ - reflectivity factor of laser radiation [3].

The mechanism of photochemical ablation consists in the photolytic breaking of chemical bonds. Ablation achieves its full degree of development when a large number of (n) chemical bonds simultaneously break as a result of a laser pulse. The value of the energy that initiates ablation (the threshold value of ablation energy) describes the dependence: with automatic axis:

$$E_i^{th} = n \frac{h \nu}{\phi \alpha (1 - R)}$$  \hspace{1cm} (2)

where: $\phi$ - quantum yield of breaking bonds (value from 0-1 range), $h \nu$ - photon energy [3].

## 2 Test stand

Experimental research was carried out on a test bench existing at the Laser Processing Research Center of the Kielce University of Technology. A test stand consists of a laser machine for micromachining, automatic axis and galvo head. The scheme of the test stand is shown in Figure 1.

The characteristics of the basic units of the laser machine for micromachining are as follows: Laser TruMicro 5325c · type of laser: pulsed diode impulse laser disk with 3 harmonic generation; · wavelength: 343 nm, · average power: 5 W, · minimum pulse duration: 6.2 ps, · 400 kHz pulse frequency with the possibility of dividing by natural numbers from 1 to 10000, · maximum pulse energy: 12.6 µJ, · mod: TM00, · $M^2 = 1.3$ · maximum fluency: 4.8 J/cm².

The TruMICRO 5325c laser has been equipped with a SCANLAB "galvo" scanning head with a 90 mm square machining area and a scanning speed of up to 2000 mm/s.
with a 160 mm lens. The scanner head has been integrated with the AEROTECH axles driven by a linear motor. Positioning accuracy is \( \pm 1 \) \( \mu \)m and positioning repeatability \( \pm 0.5 \) \( \mu \)m.

### 3 Experiment preparation

In order to verify the possible effect of various laser beam trajectories on the final treatment effect, a series of experiments were performed. The experiments consisted of carrying out laser treatment with constant, fixed laser source parameters. Electrotechnical copper – M1E samples were chosen as the processed material. Copper was used because of its specific properties and application in industry, in particular for the construction of micro heat sinks and integrated circuits. Copper is a material with high reflectivity, which significantly hinders its processing using laser techniques. The laser source parameters were respectively: pulse frequency \( f = 200 \) kHz, pulse energy \( 12.6 \) \( \mu \)J and pulse duration \( 6.2 \) ps. The galvo head was responsible for the correct positioning of the laser beam. The laser scanning speed was fixed at \( V = 200 \) mm/s. Laser treatment was carried out in the X, Y plane. The single-layer scanning process was repeated fifty times. It was expected to obtain a defect in the form of a cylinder with a base diameter of \( d = 1 \) mm and height \( h = 0.24 \) mm. Nine experiments were conducted, three for each trajectory. The laser beam moved along the material according to three programmed motion trajectories. The first trajectory assumed the movement of the laser beam along straight lines one after another in a circle area with a diameter of \( d = 1 \) mm. The distance between lines was fixed at \( \delta d = 0.01 \) mm. Graphic interpretation of programmed trajectory No. 1 is shown in Figure 2.

The second trajectory predicted the movement of the laser beam along the Archimedean spiral also known as

![Figure 1: The scheme of the test stand with TruMicro 5325c laser.](image)

![Figure 2: Graphical interpretation of prepared trajectories (1 – trajectory 1, 2 – trajectory 2 and 3 – trajectory 3).](image)
the arithmetic spiral. The movement of the laser beam began at the end point of the spiral at its intersection with a circle with a diameter of $d = 1\text{mm}$. The end point of the movement was in the centre of the spiral. The approximate distance between successive arches was fixed at $\delta d = 0.01\text{mm}$. Graphic interpretation of the programmed trajectory No. 2 is shown in Figure 2.

The third trajectory predicted movement along the Archimedean spirals same as second trajectory. However, in this case the starting point of the movement was at the centre of spiral. It can be said that trajectory 3 and trajectory 2 predict the same path but in the opposite movement direction. Graphic interpretation of the programmed trajectory No. 3 is shown in Figure 2.

4 Results and discussion

As a result of the conducted experiments, nine micro pockets of three for each variant of the trajectory were obtained. The geometrical dimensions of obtained micro pockets, angles of inclination of side surfaces, cross section profile and roughness of the bottom of pockets were analysed. The method of performing geometric measurements of obtained micro pockets - diameters and angles of the inclination of the side edges, is presented on the Figure 3. Figures 4, 5 and 6 shows 3D profiles of pockets made according to trajectory 1. Diameter measurements were carried out for a number of cross-sections. The measured diameter indicated in the article is the average of these measurements.

![Figure 4: 3D profile of the first sample for trajectory No. 1.](image)

![Figure 5: 3D profile of the second sample for trajectory No. 1.](image)

![Figure 6: 3D profile of the third sample for trajectory No. 1.](image)

Figure 3: Scheme of the measurement method.

The outline of the top (green line) and bottom (red line) surface was determined on the basis of approximated average theoretical lines, for which the sum of squares deviations is the smallest. Side edge outlines (blue lines) were estimated in the same way. The characteristic points of intersection of theoretical lines allowed to estimate the diameters ($d_1$, $d_2$) and the angle of inclination of the side surfaces. These measurements were made on the basis of a series of ten cross-sections for each sample using the stan-
Table 1: List of measurement results for trajectory 1.

| Trajectory | Diameter d1, µm (σ – stand. dev.) | Diameter d2, µm (σ – stand. dev.) | Depth H, µm (σ – stand. dev.) | Angle α, deg (σ – stand. dev.) | Ra  | Sa  |
|------------|----------------------------------|----------------------------------|-------------------------------|--------------------------------|-----|-----|
| sample 1   | 1000 (1.9436)                    | 839 (1.4907)                     | 240.1 (0.7771)                | 2.44                            | 3.42|
| sample 2   | 1005 (2.0248)                    | 849 (1.8257)                     | 239.8 (0.768)                 | 2.72                            | 3.44|
| sample 3   | 1004 (1.6330)                    | 835 (1.6996)                     | 238.9 (0.7724)                | 2.42                            | 3.38|

During the experiment, deviations in shape including roundness tolerance were not studied. The main emphasis was placed on the impact of the type of trajectory on the bottom surface shape expressed quantitatively by Sa parameter and obtained diameter d2. The obtained diameter d1 was also compared with the assumed diameter. The Ra parameter in selected cross-sections was analysed and the roughness parameter Sa for the bottom surface was examined. Geometric and roughness measurements were conducted on two devices Hirox KH-8700 confocal microscope and Talysurf CCI interference profilometer.

For trajectory No. 1, pockets with 1000, 1005 and 1004 µm diameters were obtained with a nominal pocket diameter of 1000 µm. The inclination of the side surface of the pockets was 77.0, 77.24 and 76.8 degrees, respectively. The depth of the beams for the first trajectory was 240.1 239.8 and 238.9 µm, respectively. Smooth pocket bottom with Sa 3.42 3.44 and 3.38, respectively, was observed for all three tests. The summary of measurement results for the pocket geometry carried out according to trajectory 1 are presented in Table 1. Figures 7, 8 and 9 shows 3D profiles of pockets made according to trajectory 2.

For trajectory No. 2, pockets with diameters of 1014 1025 and 1008 µm with a nominal pocket diameter of 1000 µm. The inclination of the side surface of the pockets was 77.4, 75.95 and 76.7 degrees, respectively. The pocket depth for the second trajectory was 244.240 and 243.6 µm, respectively. For all three tests, the bottom of the pocket was observed with distinct depressions around the centre point and near the inside diameter of the pocket. The Sa values were 4.21, 4.26 and 4.38, respectively. The summary of
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Table 2: List of measurement results for trajectory 2.

| Trajectory 2 | Diameter d1, µm (σ – stand. dev.) | Diameter d2, µm (σ – stand. dev.) | Depth H, µm (σ – stand. dev.) | Angle α, deg (σ – stand. dev.) | Ra | Sa |
|--------------|-----------------------------------|-----------------------------------|-------------------------------|-------------------------------|----|----|
| sample 1     | 1014 (8.4721)                     | 860 (3.5590)                      | 244                           | 77.4                          | 1.8 | 4.21 |
| sample 2     | 1025 (9.6378)                     | 856 (3.6817)                      | 240                           | 75.95                         | 2.05| 4.26 |
| sample 3     | 1008 (8.7305)                     | 850 (2.3570)                      | 243.6                         | 76.7                          | 2.21| 4.38 |

Figure 10: 3D profile of the first sample for trajectory No. 3.

Figure 11: 3D profile of the second sample for trajectory No. 3.

Figure 12: 3D profile of the third sample for trajectory No. 3.

measurement results for the pocket geometry carried out according to trajectory No. 2 is presented in Table 2. Figures 10, 11 and 12 shows 3D profiles of pockets made according to trajectory 3.

For trajectory No. 3, pockets with 1008 999 and 998 µm diameters were obtained with a nominal pocket diameter of 1000 µm. The inclination of the side surface of the pockets was of 73, 77.89 and 78 degrees, respectively. The pocket depth for the third trajectory was 250, 261 and 270 µm, respectively. An irregular profile of the bottom of the pocket was observed for all three tests with disturbances in the area of the pocket diameter. The Sa parameter values were 798, 754 and 723, respectively. The summary of measurement results for the geometry of defects made according to trajectory No. 3 is presented in Table 3. Statistical analyses for all diameters and angles measurements are shown on Figure 13–15.

Analysis of obtained micro pockets profiles shows geometrical incompatibility with the planned reference geometry. In each case, obtained micro pocket had the shape of an inverted truncated cone in relation to the assumed cylindrical shape. Figure 16 presents 2D profiles of chosen samples for each trajectory. For each type of trajectory used there is a visible trace of laser beam movement which is an undesirable phenomenon. For linear trajectory (trajectory 1) there are noticeable depressions of the bottom surface near the side edges (Figure 16 A) which is probably caused by instability of the beam parameters during re-emission of the beam for subsequent passes. For spiral trajectory 2, depression in the center of the profile (Figure 16 B) is noticeable due to the concentration of heat in a small area of the material during last passes of laser beam.
Table 3: List of measurement results for trajectory 3.

| Trajectory 3 | Diameter d1, µm (σ – stand. dev.) | Diameter d2, µm (σ – stand. dev.) | Depth H, µm | Angle α, deg (σ – stand. dev.) | Ra | Sa |
|--------------|----------------------------------|----------------------------------|-------------|----------------------------------|----|----|
| sample 1     | 1008 (7.7888)                    | 835 (5.1424)                     | 250         | 73.0 (0.7472)                    | 5.6 | 7.98 |
| sample 2     | 999 (7.6303)                     | 844 (4.5946)                     | 261         | 77.89 (0.6674)                   | 5   | 7.54 |
| sample 3     | 998 (7.9442)                     | 844 (5.2068)                     | 270         | 78.0 (0.5868)                    | 4.17| 7.23 |

Figure 13: Statistical analysis of d1 diameter value measurements for all trajectories.

Figure 14: Statistical analysis of d2 diameter value measurements for all trajectories.

Figure 15: Statistical analysis of angle value measurements for all trajectories.

Figure 16: 2D profiles of chosen samples for each trajectory (A – trajectory 1, B – trajectory 2, C – trajectory 3).

Considering the measurement of diameter d1, the highest convergence was obtained for trajectory 1 (1000, 1005, 1004 µm) with the smallest measurement data dispersion (1.9436, 2.0548, 1.6330). The diameter measurements d1 for trajectory 1 also had a symmetrical distribution around the mean values. The angles of inclination of the side surfaces for all types of trajectories used were in the range of 73 to 78 degrees. The highest concordance of the pocket depth was obtained for the first trajectory, which was on average 239.6 µm against the assumed 240 µm.

The biggest differences concerned the shape of the bottom of the pocket. The most uniform bottom shape (Sa 3.42, 3.44, 3.48) was obtained for the first trajectory. Micro pockets made according to the third trajectory were characterized by significant distortions in the bottom shape of the pocket (Sa 798, 754, 723) and clearly visible remelts.

The processes that occur during the laser ablation process are highly complex. Studies show a strong dependence of the bottom roughness on the type of trajectory.
used for the same, fixed machining parameters. This is particularly evident when measuring $S_a$ values while $R_a$ measurements do not show large differences. The observed differences in the shape and roughness of the bottom surface of the micro pockets are related to the heat accumulation in the processed material. Heat accumulation occurs when the time between successive heat inputs on the same spot is too short for the processed material to cool down to the initial temperature. The thus occurring gradual temperature increase eventually causes the temperature of the workpiece to exceed a given critical value e.g., the melting temperature [15]. Figure 17 presents a schematic illustration of heat accumulation during laser ablation process for the first trajectory.

![Figure 17: Schematic illustration of the multiple interactions of the laser beam (indicated by the red circles) on a given point (white cross) which leads to heat accumulation between passes [15].](image)

This is especially noticeable in the case of the third trajectory, where the laser beam was moving from the inside of the pocket in the direction of heat conduction. To accurately recognize the impact of trajectories and describe the impact of heat conduction on the process, it is reasonable to perform computer simulations. However, available calculation packages do not fully describe processes such as ablation pressure, shock wave, which are very important during ablation laser micro machining.

5 Conclusions

The research shows a significant relationship between the laser beam trajectory and the effects of ablative processing. Analysis of the data from the experiment indicates that for the first and third trajectories, good diameter dimension match is obtained, but in case of first trajectory the dispersion of measurements is the smallest. Tests of the $S_a$ parameter show that the most uniform bottom shape was obtained for the first trajectory. Information provided by researchers such as power, frequency, pulse time, etc. are not enough. There should also be added the information about the beam trajectory used. Only such complex data will help repeat the experiment. On the basis of the results obtained, the authors believe that it is necessary to conduct advanced tests to determine the analytical relationship between the shape of the beam path and the condition of the treated surface and dimensional compatibility.

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