Micromachining of cold-worked tool steel by nanosecond laser

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Abstract. The paper brings the results of experimental study of the laser beam milling applying the industrial grade fiber nanosecond laser operating at wavelength of 1064 nm and 62SiMnCr4 cold-work tool steel as working material. The laser pulse intensity and both lateral and transverse pulse overlaps influence on the material removal rate (MRR) and surface roughness are analysed and discussed. The experimental results reveal that for high ablation efficiency in combination with good surface finish the higher values of laser pulse intensities and lower to moderate lateral pulse overlap distances should be applied.

1. Introduction

In recent years, we have seen progress and development trends in micromachining technologies that are characterized by a wide range of applications, with the ability to machine almost all kinds of materials with high precision, good surface quality and relatively low cost. One of the most common micromachining technologies is the Laser Beam Machining (LBM). It has, among other things, a wide range of applications in the field of machining of materials used in tooling industry. The successful application of laser beam machining operations (laser beam drilling, laser beam milling and laser beam texturing) of these materials requires the perfect knowledge of material ablation mechanisms and the generation of new surfaces. Therefore this topic is of the interest of several academic and research centers in the world. Some of them put emphasis on the research of laser machining of different types of advanced tool materials, including cemented carbides, ceramics and polycrystalline diamond as well. A lot of earlier works were carried out also on tool steel used in the production of dies and molds [1 – 10].

Texidor et al. [1], using statistical analysis, evaluated the effects of parameters (scanning speed, pulse intensity and pulses frequency) on surface roughness and dimensional accuracy of machined micro-channels. In this case a pulsed, Nd:YAG laser was used for machining hardened tool steel AISI H13.

The study [9] focuses on Cr12MoV alloy steel, with high carbon content, machined by a picosecond, pulsed Nd:YVO4 laser. The authors reported the effect of laser beam energy density on ablation and morphology of the machined surface for wavelengths 1064 nm, 532 nm and 355 nm. A logarithmic increase of the ablation intensity up to 41 nm per pulse was recorded using the wavelengths of 1064 nm
and 355 nm. For the wavelength of 532 nm, the material ablation rate with increased beam energy density increased up to a level of 54 nm per pulse at laser fluency of $25 \times 10^5 \text{ J} \cdot \text{cm}^{-2}$ and then dropped to almost zero as the energy density increase above $25 \times 10^5 \text{ J} \cdot \text{cm}^{-2}$. With increased energy density, the roughness of the machined surface deteriorated exponentially.

The changes of the laser drilled surface microstructure of the M2 tool steel surface depending on the different wavelengths and pulse intensity, were analyzed in [10]. Based on the SEM, the authors found that the greatest material removal rate (MRR) and ablation occurred at higher pulse intensities. At a wavelength 1064 nm, using a shielding gas, typical structures of the hardened material were generated on machined surface due to the plasma effect. The direction of flow of the molten material, was identical with the direction of flow of the shielding gas above the surface of the workpiece.

Fleischer et al. [11] examined a similar field for tool steel X38CrMoV5-1 and reported that pulse energy and pulse overlaps have the greatest influence on the machined surface quality.

The laser machining parameters influences on roughness and depth of micro-channels were investigated in [12] at 30 W power on tool steel AISI H13. The results showed, that scanning speed has high impact on surface roughness and the depth of the machined micro-channels. Frequency does not affect both the surface roughness and the depth of micro-channels.

The influence of pulse overlaps on AISI H13 steel surface roughness was analyzed in [13]. By applying higher levels of pulse overlap the surface roughness parameter $S_a$ was improved by 86.7 % from the initial roughness $1.35 \mu m$ to polished $0.18 \mu m$.

A literature review shows, that exploring and improving the quality of laser-machined tool surfaces is a field, where it is still necessary to examine input process parameters, and optimize them for different materials, in order to achieve the best possible results. Therefore, the aim of this work is to investigate laser beam machining of the 62SiMnCr4 tool steel, designed for cold-worked molds and dies production. As the tool, a fiber nanosecond laser beam, with a wavelength of 1064 nm is used. The goal is to analyze the influence of pulse intensity and pulse overlaps on surface morphology, basic roughness parameters of machined surface and MRR.

2. Materials and methods

A laser machining centre Lasertec 80 Shape equipped with the low-power nanosecond ytterbium-doped fiber laser (wavelength of 1064 nm, maximal average output power of 100 W, pulse duration of 120 ns) was used for laser machining of cold-work tool steel 62SiMnCr4 without using a shielding gas. The working material is a low-alloy tool steel suitable for cold-worked forming tool components, with very good toughness, relatively high hardness, good resistance to dynamic alternating stress and impact stress and very good wear resistance. The chemical composition and selected physical properties of this material are specified in Table 1 and Table 2, respectively.

| Table 1. Chemical composition of 62SiMnCr4 steel (wt %) |
|------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C | Si | Mn | P | S | Cr | Ni |
| 0.55 – 0.65 | 1.5 – 1.9 | 0.6 – 0.9 | $\leq 0.03$ | $\leq 0.035$ | 0.7 – 1.0 | $\leq 0.35$ |

| Table 2. Selected physical properties of 62SiMnCr4 steel |
|--------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Specific heat capacity | Thermal conductivity | Linear expansion coefficient | Density |
| 460 J · kg$^{-1}$ · K$^{-1}$ | 31.0 W · m$^{-1}$ · K$^{-1}$ | $12.7 \times 10^6$ K$^{-1}$ | 7.8 g · cm$^{-3}$ |

27 cavities (with square shape and 5 mm long sides) (Fig. 1) were machined by cross hatching milling strategy, according to the full factorial experimental plan (3$^3$ trials). The surfaces to be machined have been prepared by grinding and polishing so that the roughness was $Ra 0.02$. The layer-by-layer method
of material removal during laser beam machining was used with total number of 10 layers.

The influence of laser pulse intensity and lateral and transverse pulse overlap on the surface roughness of machined surface and MRR has been studied. The experimental factors and their levels are listed in Table 3. For each experimental design the pulse frequency was set at 80 kHz. Laser beam with spot size of 50 µm was focused on the top of surface to be machined.

The principle of lines and machined areas formation applying the lateral and transverse pulse overlap is illustrated in Figure 2.

Roughness parameters of machined surfaces were measured using a contact-gauge profilometer Zeiss Surfcom 5000. The profile parameters Ra and the Abbotte-Firestone curve parameters Rpk, Rvk were elaborated and reported in the perpendicular direction to the direction of laser beam movement in the last machined layer. The measurements were taken according to the standards [14], [15], [16].

Table 3. Factors of the experiment and their levels

| Experimental factor | Level       |
|---------------------|-------------|
|                     | 1           | 2           | 3           |
| Laser pulse intensity (PI) [× 10^8 W · cm²] | 2.12        | 3.18        | 4.25        |
| Lateral overlap distance (DL) [µm]         | 12.5        | 20          | 27.5         |
| Transverse overlap distance (DT) [µm]      | 12.5        | 20          | 27.5         |

Figure 1. Experimental sample
a – before machining, b – after machining

Figure 2. Schematic of lateral and transverse pulse overlap
(D – spot diameter, DL – lateral overlap distance, DT – transverse overlap distance)
The MRR for each experimental trial has been calculated based on the dimensions of the machined cavities (the depth of cavities was measured by Z-measurement probe installed on the laser machine tool) and the total time of machining, recorded by the machine tool control system.

In order to quantify the effects of the studied factors and interactive influences among them on the surface profile parameters and MRR, the analysis of variance (ANOVA) using Minitab v. 17 software was performed. The significance of factors has been evaluated at the significance level of 0.5.

3. Experimental results and discussion

The statistical significance and the main effect of the process parameters were detected by ANOVA tables and main effect plots. Because ANOVA assumes that the analysed data are normally and independently distributed with the same variance for each treatment or factor level, therefore these hypotheses were checked by normality test and test for equal variances.

3.1 Material removal rate

The results of ANOVA and main effect plots of the MRR are depicted in Fig. 3. It shows that pulse energy (PI) of laser beam has strong, directly proportional effect on the material removal rate. The effect of the lateral overlap distance, that is controlled by pulse frequency and scanning speed, is also statistically significant, but with lower effect on the response variable, compared with the pulse intensity. The opposite effect is produced regarding the transverse pulse overlap distance, where no significant impact on the volume of removed material was documented. Also no significant influence of process parameter interactions on the MRR was observed.

| Source   | Sum of squares | DF  | Mean square | F - value |
|----------|----------------|-----|-------------|-----------|
| PI       | 20.247         | 2   | 10.124      | *28.57    |
| DL       | 4.167          | 2   | 2.084       | *5.88     |
| DT       | 0.18           | 2   | 0.09        | 0.25      |
| PI*DL    | 0.359          | 4   | 0.0897      | 0.25      |
| PI*DT    | 0.652          | 4   | 0.163       | 0.46      |
| DL*DT    | 0.982          | 4   | 0.246       | 0.69      |
| Error    | 2.835          | 8   | 0.354       |           |
| Total    | 29.2422        | 26  |             |           |

Tabulated F-test values at 95% confidence level: F (0.05; 2.8) = 4.46; F (0.05; 4.8) = 3.84; R²adj = 68.69%

* significant parameter

Figure 3. ANOVA table and main effect plots for MRR

3.2 Surface roughness

The results of the evaluation of the response variables Ra, Rpk and Rvk as a function of the process parameters are summarized in Figs. 4 – 6. The arithmetical mean deviation of the assessed profile Ra was documented due to its simplicity of its geometrical meaning and because it is the most common acceptation by researchers and production engineers. The surface roughness parameters Rpk and Rvk were assessed because these parameters brings information about the tribological properties of the surface - Rpk characterizes protruding peaks that might be eliminated during function and Rvk characterizes the valleys that will retain lubricant or worn-out materials.

As can be seen, the increasing of pulse energy reveals increasing of all evaluated surface parameters. On the other hand the roughness decreases when both lateral and transversal overlap distance increase, i.e. the pulse overlap decreases. The significant influence of the process parameters interactions has not been observed for all evaluated response variables.
### Table 1: ANOVA table for Ra

| Source    | Sum of squares | DF | Mean square | F - value |
|-----------|---------------|----|-------------|-----------|
| PI        | 9.442         | 2  | 4.721       | **38.86** |
| DL        | 12.457        | 2  | 6.228       | **51.27** |
| DT        | 6.799         | 2  | 3.400       | **27.99** |
| PI*DL     | 1.779         | 4  | 0.448       | 3.66      |
| PI*DT     | 0.653         | 4  | 0.163       | 1.34      |
| DL*DT     | 0.356         | 4  | 0.089       | 0.73      |
| Error     | 0.972         | 8  | 0.121       |           |
| Total     | 32.458        | 26 |             |           |

Tabulated F-test values at 95% confidence level: F (0.05; 2.8) = 4.46; F (0.05; 4.8) = 3.84; $R^2_{adj} = 90.27\%$

* significant parameter

**Figure 4. ANOVA table and main effect plots for Ra**

### Table 2: ANOVA table for Rvk

| Source    | Sum of squares | DF | Mean square | F - value |
|-----------|---------------|----|-------------|-----------|
| PI        | 3.215         | 2  | 1.608       | **3.34**  |
| DL        | 6.423         | 2  | 3.212       | **6.67**  |
| DT        | 3.790         | 2  | 1.895       | **3.93**  |
| PI*DL     | 2.404         | 4  | 0.601       | 1.25      |
| PI*DT     | 0.982         | 4  | 0.245       | 0.51      |
| DL*DT     | 2.783         | 4  | 0.696       | 1.44      |
| Error     | 3.854         | 8  | 0.482       |           |
| Total     | 23.450        | 26 |             |           |

Tabulated F-test values at 95% confidence level: F(0.05; 2.8) = 4.46; F(0.05; 4.8) = 3.84; $R^2_{adj} = 46.59\%$

* significant parameter

**Figure 5. ANOVA table and main effect plots for Rvk**

### Table 3: ANOVA table for Rpk

| Source    | Sum of squares | DF | Mean square | F - value |
|-----------|---------------|----|-------------|-----------|
| PI        | 7.441         | 2  | 3.705       | **46.09** |
| DL        | 11.091        | 2  | 5.545       | **68.99** |
| DT        | 3.700         | 2  | 1.850       | **23.02** |
| PI*DL     | 0.120         | 4  | 0.030       | 0.37      |
| PI*DT     | 0.566         | 4  | 0.142       | 1.76      |
| DL*DT     | 0.378         | 4  | 0.095       | 1.18      |
| Error     | 0.643         | 8  | 0.080       |           |
| Total     | 23.909        | 26 |             |           |

Tabulated F-test values at 95% confidence level: F (0.05; 2.8) = 4.46; F (0.05; 4.8) = 3.84; $R^2_{adj} = 91.26\%$

* significant parameter

**Figure 6. ANOVA table and main effect plots for Rpk**
**Figure 7.** Machined surface microprofiles (DL = DT = 20 µm)

a – low level of energy (PI = 2.12 × 10^8 W · cm^2): Ra 1.80 µm, Rpk 2.30 µm, Rvk 2.17 µm

b – high level of energy (PI = 4.25 × 10^8 W · cm^2): Ra 2.83 µm, Rpk 4.15 µm, Rvk 2.23 µm

**Figure 8.** Machined surface microprofiles (PI = 4.25 × 10^8 W · cm^2, DT = 12,5 µm),

a – low level of lateral overlap (DL = 27.5 µm): Ra 2.99 µm, Rpk 4.39 µm, Rvk 2.81 µm

b – high level of lateral overlap (DL = 12.5 µm): Ra 18.28 µm, Rpk 34.85 µm, Rvk 10.51 µm
The strong effect of pulse intensity and lateral overlap distance on the surface finish is visible in the Figs. 7 – 8, where the significantly different surface microprofiles, affecting the surface tribology properties are seen.

The combinations of the process parameters for achieving the maximal MRR and good surface finish are obvious from the 4D bubble plot (Fig. 9). The high MRR and low Ra area is associated with higher level of laser pulse intensities and low to moderate lateral overlap distances.

**Figure. 9** A 4D bubble plot showing the design points obtained with variables of MRR, surface roughness Ra, lateral overlap distance DL (represented by color) and laser pulse intensity PI (represented by bubble size)

**Conclusions**

The effect of nanosecond laser pulse intensity, lateral and transverse pulse overlap on ablation efficiency and machined surface quality of 62SiMnCr4 cold work steel have been studied. On the basis of results obtained from this investigation and statistical analysis, the following conclusions can be drawn:

(1) Significant effect of the laser pulse intensity on the MRR and surface morphology and surface roughness has been observed. It was confirmed that high laser pulse intensities lead to the worst surface finish. The head accumulated in the irradiated region in the case of higher values of pulse intensities causes a rapid increase in temperature which in turn increases the ablation efficiency. However, the phenomena such as stronger plasma irradiation and explosions of molten material during machining by high pulse intensities resulted in worst surface finish.

(2) The lower values of lateral pulse overlap, given by scanning speed and pulse frequency, lead to decreasing the material ablation efficiency and also surface roughness. Strong effect of both type of pulse overlaps on surface roughness parameters Ra and Rpk has been recorded while the roughness parameter Rvk has been slightly affected only by lateral pulse overlap. Similar trend has been observed in [17] during laser machining of the similar workpiece material by picosecond laser using frequencies lower than 1 MHz. However, according to this study, when the higher pulse frequencies (above 1 MHz) in combination with ultra-short pulses are applied, the increasing of lateral pulse overlap leads to better surface roughness.

(3) The only minimal effect of transverse pulse overlap on MRR has been reported.

(4) For high ablation efficiency and good surface finish the higher values of laser pulse intensities in combination with lower lateral pulse overlap should be applied.
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