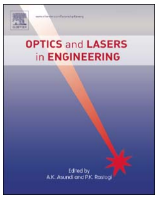
Optics and Lasers in Engineering 91 (2017) 160–168

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Laser milling of martensitic stainless steels using spiral trajectories

L. Romoli[a,*], F. Tantussi[b], F. Fuso[b,c]

[a] Department of Industrial Engineering, University of Parma, Italy
[b] Department of Physics "Enrico Fermi" and CNISM, University of Pisa, Italy
[c] INO-CNR, Pisa, Italy

ARTICLE INFO

Keywords:
Laser
Micro machining
Stainless steel
Roughness

ABSTRACT

A laser beam with sub-picosecond pulse duration was driven in spiral trajectories to perform micro-milling of martensitic stainless steel. The geometry of the machined micro-grooves channels was investigated by a specifically conceived Scanning Probe Microscopy instrument and linked to laser parameters by using an experimental approach combining the beam energy distribution profile and the absorption phenomena in the material. Preliminary analysis shows that, despite the numerous parameters involved in the process, layer removal obtained by spiral trajectories, varying the radial overlap, allows for a controllable depth of cut combined to a flattening effect of surface roughness. Combining the developed machining strategy to a feed motion of the work stage, could represent a method to obtain three-dimensional structures with a resolution of few microns, with an areal roughness S_a below 100 nm.

1. Introduction

The increasing concern for the micro-fabrication of moulds, sensors, actuators, micro optics, micro-fluidic components and other micro-system devices, has pushed companies towards innovative and versatile machining methods. Among all, laser milling has demonstrated to be a flexible process suitable for machining difficult-to-machine materials like ceramics, dielectrics, carbide and hardened steel with high productivity and surface quality. Compared with other conventional mechanical processes, laser micro-machining is a non-contact material removal process that removes much less material, involves highly localized heat input to the workpiece, minimizes distortion, and offers no tool wear. Therefore, the process is not limited by constraints such as maximum tool force, build up edge formation, or tool chatter [1].

In laser milling a focused laser beam is scanned over the workpiece, removing material layer by layer. As for conventional milling, the scanning pattern can be different for each layer, and as a result this 2.5D machining method can produce 3D shaped surface structures [2]. The key-factor of such a process resides mainly in the control of the ablation depth per layer [3]. This parameter represents the thickness of the single removed layer irradiated by the laser and it is opposed to the surface roughness in the definition of the process robustness. The ablation depth, and consequently the surface roughness, are determined by the laser beam characteristics (wavelength, pulse duration, peak power, repetition rate), by the strategy on which the surface is irradiated (scan speed, scan strategy per layer) and obviously by the chemistry and physical properties of the workpiece.

The trade-off between productivity and surface quality (e.g. roughness, burrs, melt deposits, etc.) is frequently argued in the literature. Representative examples can be found in [4] where the performance of micromilling of AISI H13 can be obtained as a balance between the conditions for minimum surface roughness and maximum ablation depth. Multi-objective process parameters optimization is also a frequent tool used to perform a statistical optimization of laser micro-milling: in [5] it was used to enhance the ablation capability of T-shaped features on tool steels while in [6] it was adopted to derive the best set of process parameters for the micromilling of aluminium 5754.

A possible way to mitigate such a trade-off resides in shortening the laser pulse duration below the characteristic time for which the pulse energy is transformed into heat on the workpiece. The combination of pulse peak power and pulse duration significantly influences the material removal mechanism: for long pulses (micro- and nano-second) and peak power density ranging between 10^9–10^{11} W/cm^2, the material is removed by melt expulsion, combining material vaporization and melting. Those sources show high production rates against low quality generated by melt accretions and thermal damage of the workpiece [7]. Due to the large amount of melt ejection and spatter formation involved in the process, the quality and reproducibility of the micromilled cavity is rather low [8]. If higher precision is needed, short and ultrashort laser pulses have to be applied. According to [9], a pulse is ultrashort when the diffusion depth during the pulse is in the same order or smaller than the skin layer depth in the Beer-Lambert absorption law.

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* Corresponding author.
E-mail address: luca.romoli@unipr.it (L. Romoli).

http://dx.doi.org/10.1016/j.optlaseng.2016.11.016
Received 28 September 2016; Accepted 17 November 2016

With ultrashort laser pulses and high power density (above 10^9 W/cm^2) the material is removed with minimized heat impact: the laser interacts with the material in the solid state only, and direct solid-vapour transition occurs. In case of metals, 1 ps can be retained a threshold value for transition from short to ultrashort [7]. As a result, no heat related defects occur – e.g., no burrs, thermal stress, melt, chipping, or cracking – and very thin substrates can be processed without breaking or deformation. The small ablation rate (tens of µm^3 per pulse) can be significantly increased using repetition rate in the order of 100 kHz or even higher, as reported in [10]. Using high repetition rates is also beneficial in terms of surface roughness since a much higher pulse overlap can be obtained at scan speeds of several meters per second. A more uniform removal over the scanned beam trajectory avoids an alternation of peak and valley which strongly lowers surface quality [11].

A second possible alternative to increase the surface quality concerns the scan strategy per layer: being an intensified source of energy, the laser beam is used as a sharp-edged tool which produces grooves to be flanked and partially superimposed to determine the removal of a layer. The surface roughness can be then predicted by knowing the spacing between the groove, also defined as hatch distance parameter and the ablated depth per groove (which is in turn function of process parameters) [12]. More complex but semi-empirical models have been proposed in [13] for the laser milling of PMMA obtained by flanking parallel grooves of Gaussian profile.

A similar strategy of layer removal was used in laser micro-turning [14]: also in this case the surface roughness is determined by flanking of surface peaks and valleys generated by superimposed grooves along the spiral trajectory of the beam on the cylindrical surface of the specimen. Average values of R_a were found in the range of 2–6 µm, corresponding to a finishing procedure in conventional machining with chip removal.

The literature testifies that despite the already existing applications of ultrashort pulse laser milling (e.g. the shaping of micro moulds [15] and micro cutting tools [16], machining of complex lab-on-a-chip structures [17]) the topic of the surface finishing obtainable at the bottom of the removed layer is still a main concern for a machining technique which should enable the high accuracy to fulfil the requirements of precision engineering.

The accuracy obtainable on the working plane is typically in the micrometer range and it depends on the positioning stages but also on the optics adopted. On the other hand, the accuracy and the surface quality in the depth direction depend not only on the process settings, but also on the composition and finish of the material used. The best results are usually obtained with a fine grain or amorphous material structure and a polished surface to begin with. Therefore the first objective of the present research is to investigate the laser micro-milling process in real industrial conditions performing experiments using a production fs-laser source and stainless-steel samples in as-delivered conditions. This will allow to determine if the initial surface roughness, which has almost the same scale of the removal depth per layer, influences the material removal and the formation of the new surface topography.

With the objective of increasing the surface quality with respect to the available literature, a new set-up was established in this study to perform laser micro-milling. The engraving strategy can be pinpointed as follows:

- The laser beam was firstly moved along circular trajectories varying process parameters in order to define the cross profile of each groove (depth and width) as a preliminary step in determining the ablation depth;
- Once the groove profile was established, the beam was then moved in spiral trajectories to perform the removal of a layer. The radial overlap was varied and the obtained surface investigated, in view of the removal of circular pockets.
- Laser parameters and scanning strategies were studied in order to ascertain their role in determining a controllable ablation depth per layer and a surface roughness lower than that available in the literature for similar processes.
- Final ambition of the present article is to give fundamentals for the micro-milling of three-dimensional structures ranging from ten to several hundreds microns with a controlled roughness well below 1 µm.

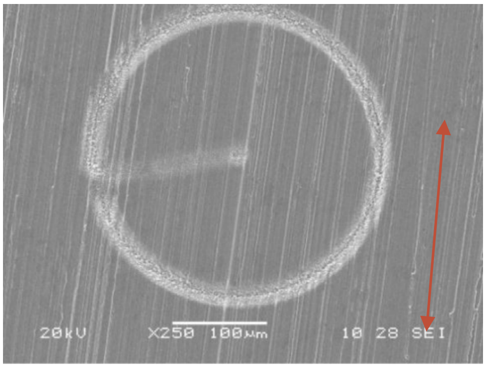

Fig. 1. SEM micrograph of a laser-machined sample. Red arrows highlight the anisotropic roughness due to mechanical machining.

2. Materials and methods

2.1. *Sample preparation*

Experiments were carried out on AISI 440 C stainless steel, 0.35 mm thick, circular plates with a diameter of 14 mm and an arithmetical mean roughness R_a in the range 0.2–0.3 µm. Plates at as-delivered conditions present an anisotropic roughness due to the final grinding procedure, as highlighted in Fig. 1. The AISI 440 C is a martensitic stainless steel (composition given in Table 1) that presents high resistance to corrosion and to wear, massively used in automotive industry.

Each plate was milled in order to create two planar surfaces used as reference to define the position of the workpiece during the laser processing.

2.2. *Experimental setup*

A fibre fs-laser system (Raydiance Starfemto R-100) was used to generate linearly polarized laser pulses with a duration $\tau = 800$ fs, a central wavelength $\lambda = 1552$ nm and a maximum pulse energy $E_P = 50$ µJ at a repetition rate $f = 100$ kHz. The laser source was equipped with a 3D scan head (Arges Precession Elephant) with up to five axes, schematically represented in Fig. 2.

The attenuator unit allowed the variation of laser power while the rotator, consisting in a λ/4 plate, was used to obtain circularly polarized pulses. The angle of incidence can be modified by means of the precession unit with a maximum inclination of about 7° with respect to the ablated surface. The Z-translator was used to adjust the focus distance while the XY scan system consisted in two mirrors mounted onto galvanometers, providing the possibility to draw desired shapes on the workpiece. Therefore, the scan head allowed to realize circular, elliptical, spiral and helicoidal paths with a range of incidence angles.

Table 1
Chemical composition of AISI 440 C stainless steel.

	Element						
	C	Cr	Mn	S	Si	Mo	Se
Composition in wt%	0.95–1.2	17.2	1.00	0.015	1.0	0.75	0.20