euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016

www.euspen.eu

A closed loop quality control system for laser chemical machining

Peiran Zhang, Axel von Freyberg

BIMAQ – Bremen Institute for Metrology, Automation and Quality Science at the University of Bremen, Germany

Email: Zha@bimaq.de

Abstract

Laser induced chemical machining (LCM) combines the advantages of electro-chemical machining and laser ablation. It could be used for producing a flexible surface on hard metal in the micro range. Due to low energy consumption, this method avoids material stressing and produces high precision surfaces without micro cracks and debris. A desired geometry is usually resulting from a sequence of overlapping Gaussian removal paths. In order to achieve the required geometry at minimal costs, a closed loop quality control system is developed to design the profiles of the individual removal paths as well as the corresponding process parameters producing the removal, and to compensate the interactions among the paths. In this report, a rectangular die was produced by the LCM process with a quality control system.

Keywords: Quality control; Laser micro machining; Material removal

1. Introduction

An increased miniaturization and functionality of the industrial products demands a micro metal machining with high geometrical accuracy and optimal surface quality. The laser chemical machining (LCM) combines advantages of both laser machining and electro-chemical machining (ECM) [1]. It realizes a localized material removal at low laser power in specified areas without causing micro-cracks and debris [2]. LCM is based on laser induced thermo-chemical reactions between an etchant and metal atoms on the surface of the work piece (Eq. 1, [3]). All metals with a material specific passivation layer could be machined by this process. Sulfuric acid or 5 molar phosphoric acid (H_3PO_4) could be used as etchant for different metals. The chemical reaction takes place in a laser heated area at a temperature of 90°C [4].

$$Me + 2H^+ \rightarrow Me^{2+} + H_2 \qquad (1)$$

However, the form and quality of the workpiece surface, the injection of the etchant, the movement of the workpiece, the chemical reaction and other disturbances result in turbulence and gas bubbles, which could cause a deviant resulting geometry. Therefore, applying this machining method presupposes a quality control system of the process.

The main components of the LCM setup are a fibre-laser, an *xyz*-linear stage and a liquid-phase etching cell. The continuous wave (CW) fibre-laser source is operating at a wavelength of 1080 nm with a maximum power of 300 W and a minimum of 10 W. By using a gradient lens, the CW laser can be set to the required power *p* in the finishing area from 3 to 20 W. The laser beam is focused by a lens system and guided coaxially to the etchant jet-stream through a nozzle onto the workpiece surface. The focus diameter *D* of the laser beam can be varied with a motorized beam expansion from 24 to 74 µm. The liquid-phase etching cell consists of two parts, a basin and a coaxial nozzle assembly. An adjustable pump enables flow rates *Q* of the etchant jet-stream between 300 and 700 ml/min. The workpiece is fixed in the basin and can be positioned by an *xyz*-linear stage with an accuracy of 0.1 µm in the finishing area. For the LCM process, a required feed rate of the workpiece *υ* amounts to 3 to 30 µm/s.

2. Quality control system

In order to produce the desired geometry and achieve a smooth removal surface, a quality control system is designed. The controlled quantity features are the form variables in a cross section of a single removal path. This cross section could be approximated by a Gaussian curve in the defined process window [3, 4]. The form variables of the Gaussian curve ***a*** could be varied by adjusting the process parameters ***P***, which are the actuating variables of the control system.

This control system consists of a block for path planning, a comparison algorithm, a quality controller based on an inverse process model, a post-process measurement by using a 3D-laser scanning microscope and the finishing process (Figure 1). The details about this system are presented in the following paragraphs.

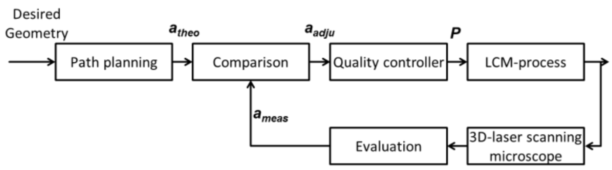

Figure 1. A closed loop quality control system for LCM

2.1. Path planning

In the LCM process, the surface geometry usually results from a sequence of overlapping removal paths, which are oriented parallel to the feed direction along the workpiece. Due to the effective thermal energy distribution, the resulting geometry is considered as a superposition of single removals [4]. In theory, a removal path with constant parameters has identical cross sections along the whole path in feed direction. Therefore, a path planning could be simplified by a 2D cross section. Under consideration of the process window for smooth Gaussian removal, the path planning calculates an optimal superposition of removal paths close to the desired cross section of a surface profile. Each path *i* is characterized by its depth $a_{i,1}$ and its width $a_{i,2}$. Figure 2a) illustrates for example a path plan for a rectangular die. The line 3 shows a desired contour and the line 2 is the theoretic resulting removal cross section from four Gaussian removal paths (line 1).

2.2. Quality controller

According to the form variables ***a*** from path plan, combination of process parameters ***P*** are calculated by the quality controller for realizing the path plan (Eq. 2).

$$P = h(a) \qquad (2)$$
$$with: \quad P = [p, \upsilon, Q, D]; \quad a = [a_1, a_2]$$

The controller is realized by a forward process model based on radial basis functions (RBF) and an iterative optimization algorithm applying the simplex method [4]. However, the angle-dependent laser energy absorption as well as the thermal and the hydrodynamic conditions cause deviations to the theoretical superposition. In order to analyze the interactions among the removal paths and the influence of the flank angle, the produced rectangular die was taken out of the LCM-machine after two removal paths and measured by a 3D-laser scanning microscope. The average removal depths of 300 measurements in the feed direction are calculated and illustrated as a cross section of the path profile with the line 3 in Figure 2b).

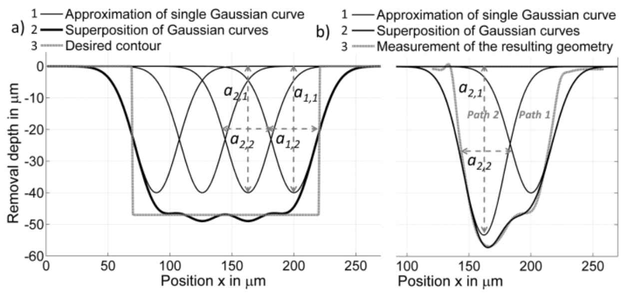

Figure 2. Comparison of the theoretical path plan and the produced profile: a) The Gaussian path plan for a rectangular die with a depth of 47±1 µm; b) Approximation of the measured profile by Gaussian curves for analyzing the interactions among the individual removal paths

The measurements could be also characterized with the superposition of a sequence of Gaussian curves (line 2 in Figure 2b). The relative deviations ***η*** between the form variables of the approximated Gaussian curves for the measured profile a_{meas} and of the theoretical path plan a_{theo} are calculated and listed in Table 1. According to these deviations, the adjusted form variables of the second path a_{adju} are calculated by the comparison algorithm with Eq. 3 for the subsequent production process. The calculated form variables a_{adju} are fed to the quality controller, and thereby the corresponding process parameters ***P*** are adjusted for a subsequent production process (see Figure 1 and Eq. 2).

$$a_{adju} = \frac{a_{theo}}{\eta} \qquad with \quad \eta = \frac{a_{meas}}{a_{theo}} \qquad (3)$$

Table 1 The form variables of the theoretical path plan and of the approximated Gaussian curves for the measured profile

Theoretical a_{theo} in µm	$a_{2,1}$	40	$a_{2,2}$	25
Mearsurement a_{meas} in µm	$a_{2,1}$	52	$a_{2,2}$	25
Relative deviation η	η_1	1.30	η_2	1
Adjusted a_{adju} in µm	$a_{2,1}$	31	$a_{2,2}$	25

3. Experimental results

Both the third and the fourth path are processed next to a previously machined inclined surface. This means similar boundary conditions as the manufacturing of the second path. Therefore, the process parameters of the second path are also used for path 3 and 4. The combinations of the process parameters of all paths for producing a rectangular die are listed in Table 2. A resulting geometry is shown in Figure 3a). The averaged cross section of 500 removal profiles is plotted in Figure 3b). The results show an over ablation of the second removal. It could be resulting from gas bubbles or the inhomogeneity of the material Stellite 21. For high requirements on the surface quality, the over ablation can be compensated by iteratively using Eq. 3. Furthermore, due to the Gaussian-shaped removal, the deviations at the flanks are already existent in the path plan. The production of flanks with exact 90° requires the studies of further process windows with non-Gaussian removal profiles.

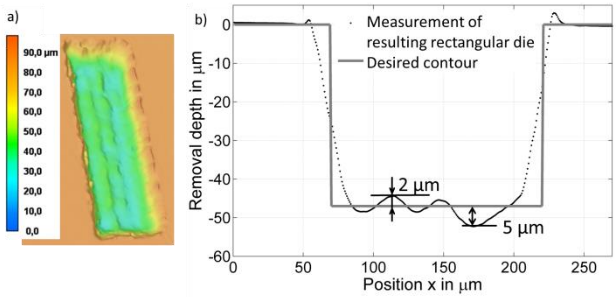

Figure 3. Measurement of a produced rectangular die: a) Measurement by 3D-laser scanning microscope; b) Averaged cross section of 500 measured profiles

Table 2 The process parameters for producing a rectangular die

	Path 1: Removal without interaction of path	Path 2, 3, 4: Removal with interaction of path
Laser power *p*	5 W	5 W
Feed rate of the workpiece *υ*	10 µm/s	11 µm/s
Flow rates of the etchant *Q*	500 ml/min	500 ml/min
Focus diameter of the laser beam *D*	24 µm	24 µm

4. Summary

A closed loop quality control system was developed for a LCM process. It calculates the optimal combination of Gaussian removal paths as well as the corresponding process parameters for realizing such a path plan. Furthermore, it compensates the interactions among the removal paths. The further studies of process windows could be realized by another removal profile, and thereby provide the production of more flexible geometries, for example producing vertical flanks.

Acknowledgment

The authors thank the German Research Foundation (DFG) for funding the subproject A5 of the Collaborative Research Centre 747 (SFB747) and Ms. O. Hauser for her support.

References

[1] Stephen A and Vollertsen F 2010 Mechanisms and processing limits in laser thermochemical machining *J. CIRP Annals* **59** 1 251–254

[2] De Silva A, Pajak P, Mc Geough J and Harrison D 2011 Thermal Effects in Laser Assisted Jet Electrochemical Machining *J. CIRP Annals* **60** 1 243-246

[3] Mehrafsun S and Vollertsen F 2013 Disturbance of material removal in laser-chemical machining by emerging gas *J. CIRP Annals* **62** 1 195-198

[4] Zhang P and Goch G 2015 A quality controlled laser-chemical process for micro metal machining *J. Production Engineering* **9** 5 577-583