CIRP Annals - Manufacturing Technology 62 (2013) 195–198

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Disturbance of material removal in laser-chemical machining by emerging gas

S. Mehrafsun*, F. Vollertsen (1)

BIAS-Bremer Institut fuer angewandte Strahltechnik, Klagenfurter Str. 2, 28359 Bremen, Germany

ARTICLE INFO

Keywords:
Laser micro machining
Material removal
Process stability

ABSTRACT

Using laser-chemical machining allows a localized and precise processing of metallic work pieces. The temperature distribution on the surface is the primary factor of this selective and gentle machining method. Investigations regarding temperature and material removal related surface effects like locally induced gas bubbles and reduced material removal are shown. It is shown that the processing feed rates only have a negligible impact on the resulting temperature field and thus the width of the cavity, while laser intensity appears to be the dominant parameter. Furthermore, it is shown that emerging gas bubbles caused reduced material removal resulting in irregular cavities.

1. Introduction

For micro structuring materials with high strength and hardness, laser machining is a flexible tool and one of the machining methods of increasing importance. But often micro-cracks, distortion, and stress can result when using short pulsed laser ablation. Another useful approach for structuring and producing small parts is electrochemical machining (ECM) [1]. One of the main benefits of ECM is that it does not cause any heat affected zones or thermal stresses to the work piece. This fact is the basis for many hybridisations of ECM with other processes such as EDM and laser aspiring to combine advantages of accuracy with good surface quality and machining speed [2]. In electrolyte jet machining the work piece is machined locally in the area contacted by an electrolyte jet through which an electric current is applied [3]. In laser assisted jet ECM the purpose of the laser is to localize machining to specified areas so that precision is improved [4]. Using high power laser machining within a salt solution results in a reduced recast layer and a reduced heat affected zone [5].

In laser-chemical machining (LCM) the advantages of both laser machining and ECM are combined using an etching liquid which is injected coaxially to the laser beam, enhancing the machining quality [6]. However, the dynamics of the laser light absorption, heat, chemical reactions, hydrodynamics and transport phenomena cause within a certain range of parameters a disturbance of material removal. External and internal sources could be responsible for the disturbances which can be explained due to interface instabilities [7].

Since LCM is a temperature driven process, increased laser power results in increased material removal rates [6]. This effect is used to machine work pieces with a higher processing speed. However, high reaction rates lead to increased formation of hydrogen which could result in gas bubbles. Furthermore, high laser power results in high surface temperature which could cause etchant boiling and again result in gas bubbles too [4]. Thus disturbance of material removal can occur. As higher removal rates are relevant for industrial application the aim of this paper is to explain the nature of this disturbance as a basis for counter-measure.

2. Laser-chemical machining

2.1. Experimental

For the results presented here a fibre-laser source the "TruFiber 300" made by Trumpf was used. Its TEM_{00} cw laser radiation is emitting 1080 nm. Fig. 1 schematically illustrates the setup and mechanisms of LCM whereby Table 1 shows the specifications of

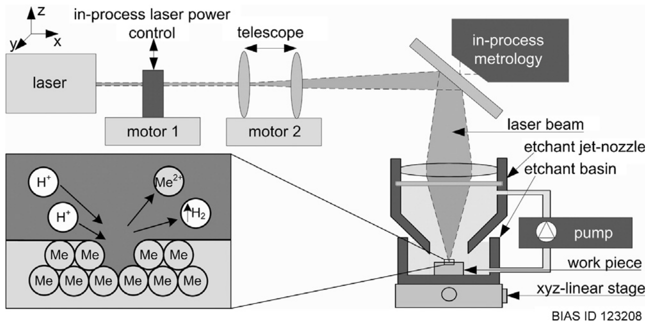

Fig. 1. Laser-chemical machining principle and mechanisms.

Table 1
Experimental setup specifications.

Setup	Version 1	Version 2
Telescope design	2 Lenses	5 Lenses
Laser spot diameter	59 μm[§]	24 μm[§§]
Optical path	App. 3040 mm	App. 1171 mm
Etchant jet velocity	1.8 m/s and 2.3 m/s	3.5 m/s

[§] Calculated.
[§§] Measured with Primes Micro Spot Monitor.

* Corresponding author. Tel.: +49 421 218 58081.
E-mail address: mehrafsun@bias.de (S. Mehrafsun).

0007-8506/$ – see front matter © 2013 CIRP.
http://dx.doi.org/10.1016/j.cirp.2013.03.030

the setup before (version 1) and after (version 2) setup remodelling. The new setup was created in order to minimize the effects of external triggered disturbance of material removal and loss of power due to the long optical path.

For the presented investigations as work piece material titanium and Stellite 21 were used. While processing the work pieces were immersed in an etching liquid consisting of 5 M phosphoric acid at room temperature.

2.2. Mechanisms

Selective material removal using LCM is based on the laser-induced thermochemical reactions between an etchant and metal atoms on the surface of the work piece and is possible for all metals with material specific passivation layer. The passivation layer is locally reduced under formation of hydrogen and water soluble metallic salts caused by thermal influence of the laser. According to Eq. (1) the chemical material removal within the reactive fluid is driven by the temperature-dependent proton activity of the redox reaction, and is mainly responsible for the formation of the electrochemical potential [6].

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

Another fundamental influence on material removal beside the thermal activation of chemical reactions is the mass transport limitation. These transport limitation of the etching processes leads to a reduced removal rate [6]. The etchant jet-stream provides a fast exchange of the reactants, which results in increased removal rates. Thus a continuous wetting of the surface with fresh etchant is the basic requirement for the chemical removal reaction. On the other hand it should be kept in mind that the etchant is also cooling the surface, which might reduce the etching speed or inhibit the chemical reaction.

It is a well-accepted assumption that the shape of the cavity is determined by the etching action, having the temperature field as primary influence factor. The thermal conductivity determines the achievable processing speeds via the temperature field.

3. Characteristics of the resulting cavities

3.1. Classification

LCM is strongly influenced by four main process variables:

- laser power P
- feed velocity of the work piece v (or in combination with laser power: line energy E_l)
- etchant flow velocity v_{flow}
- focus diameter d_f or more general: fluence distribution Φ of the laser beam spot at the work piece surface.

The machining result of a single path can be classified with respect to quality as follows. Appropriate combination of process parameters allows a successful material removal which is named *Class A* (see Fig. 2). A laser beam having a Gaussian intensity distribution was used is that example. The shape of the cavity can be approximated by a Gaussian bell curve.

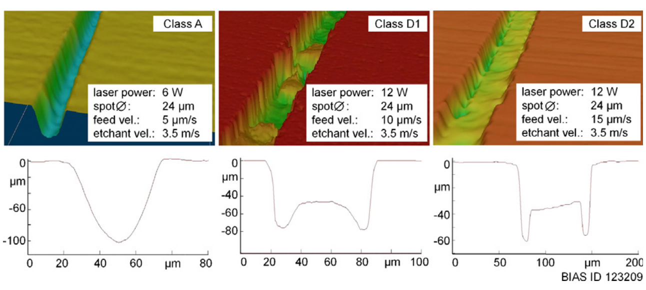

Fig. 2. 3D-laser scanning microscope images of a removal path in Stellite 21 with successful (*Class A*) and erroneous removal (*Class D1* and *Class D2*) using LCM setup version 2.

Other ranges of laser power, feed velocity and etchant flow velocity might lead to a local disruption or discontinuation of the chemical removal reaction [7]. This results in an erroneous removal path with insufficient material removal in the centre of the cavity which reflects not only the shape of the intensity distribution e.g. that of a Gaussian bell curve [8]. This disturbance of material removal could be interrupted along the processing path. That case is named *Class D1* (Fig. 2 centre). It can also happen that disruption is constant, leading to a continuous shape along the machining path. This case is named *Class D2* (Fig. 2 right). Please note that the inclination of the centre plane in the cross section of *Class D2* could be an artefact due to improper clamping of the sample during the measurement.

3.2. Process windows

The resulting process boundaries for machining of Stellite 21 were determined experimentally. Fig. 3 (left and centre) shows the resulting process windows using LCM setup version 1.

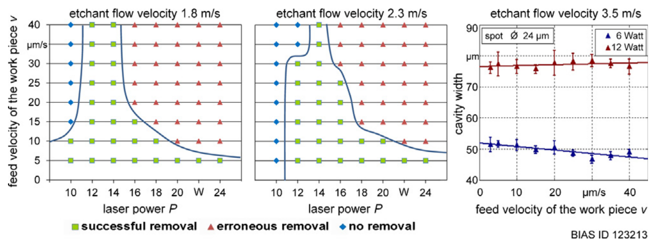

Fig. 3. Process windows for Stellite 21 for LCM setup version 1 with an etchant flow velocity of 1.8 m/s and 2.3 m/s showing successful (*Class A*), erroneous (*Class D1* and *Class D2*) and no material removal [8] (left and centre), measured cavity width in dependence to feed velocity using LCM setup version 2 and Stellite 21 as work piece material (right).

It is shown that increasing flow velocities of the etchant determines higher laser powers in order to guarantee a successful removal of material. Increased flow velocity leads to increased cooling of the work piece surface. No material removal is detected when laser power is too low. Due to this cooling effect the boundary between no removal and successful removal (Fig. 3 centre blue and green symbols) is shifted. Higher laser powers and in part lower feed velocities are necessary to guarantee a successful removal. Furthermore the boundary between successful removal and erroneous removal (Fig. 3 centre green and red symbols) is shifted too. It is shown that with an increased etchant flow velocity the range of erroneous removal paths decrease and it is possible to machine successful removal paths using higher feed velocities.

Furthermore investigations regarding the width of a material removal path using LCM setup version 2 (Fig. 3 right) show that a variation of the feed velocity has only a small influence on the width of cavities. With increasing laser power at constant other parameters the width of the kerfs is increasing. In LCM velocities of 40 μm/s or less are used and thus are very low and therefore have a negligible impact on temperature distribution.

4. Disturbance of material removal by emerging gas

4.1. Hypothesis

The following is postulated as a working hypothesis: high removal rates achieved by using high laser power lead to local disturbance of material removal by emerging gas. These gas bubbles act like a protective layer and shield the surface of the work piece against the etchant, thus the dissolving chemical reaction is inhibited. Formation of gas bubbles could emerge firstly by the chemical reaction and on the other due to high surface temperature resulting in etchant boiling.