Electro-chemical polishing: a technique for surface improvements after laser milling

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Abstract

Electro-chemical polishing is a process of improving micro smoothness, micro topology, and material brightness by anodic dissolving of the substrate in an electrolyte with an external source of electricity. The resulting surface improvements depend on the uniformity of the material microstructure, the lack of surface inclusions, and the consistency of the surface finish all over the target area. In contrast, laser milled structures are mostly concave features; their roughness is usually higher than that achieved on the other surfaces of the component, and also there is a significant presence of foreign or recast particles on them. Thus, it is important to investigate systematically the effects of electro-chemical polishing on microstructures machined by laser milling. The paper discusses the effects of electro-chemical polishing on the surface finish of laser milled features. Although ECP displayed some limitations when polishing micro features, it still managed to achieve almost 30% improvements in comparison to the initial roughness after laser milling. Another benefit is that the process also improves the edge quality of the laser machined structures by removing the burrs.

Keywords: electro-chemical polishing, laser milling, surface quality

1. Introduction

Laser milling with long pulses, e.g. in the microsecond range, is primarily a thermal material removal process. The target material is heated up due to the incident laser light, and a crater full of molten material is formed. When the material reaches its boiling temperature some of the molten material is evaporated and some is ejected from the crater together with the vapour. The amount of expulsion could be quite high, accounting for more than 50% of the total crater volume [1]. This material then lands back on the machined surface in the form of debris, causing contamination which is detrimental to the surface quality resulting after laser milling. Furthermore, the molten material that remains in the crater cools down and re-solidifies, generating a recast layer.

The presence of such formations is disadvantageous to the overall result of the laser milling process, especially when it is applied for microstructuring. Thus, it is important to study systematically the capabilities of available techniques for cleaning debris, removing recast layers, and improving the surface roughness after laser milling. The techniques to achieve this can be grouped under two main categories. The first group includes techniques for post-process cleaning, for example by ultrasonic cleaning, de-oxidisation through pickling, or electro-chemical polishing (ECP). The second group includes techniques for on-the-machine surface improvements [2]. In this paper, the ECP process belonging to the second group is investigated.

2. Process descriptions

The ECM process is based on the principle of anode metal dissolution in an electrolyte [3]. The process was first introduced in 1929 and proved to be exceedingly advantageous for processing high-strength and high-melting point alloys. The Industrial applications of this technology have broadened to include electro-chemical drilling, deburring, grinding and electro-chemical polishing (ECP) [4].

ECP is a process of improving micro smoothness, micro topology, and material brightness by anodic dissolving of the substrate in an electrolyte with an external source of electricity [5]. Basically, the process mechanism involves immersing a metal target in a chemical solution, and making it the anode in a direct current circuit. ECP is highly dependent on the ability of the solution to polish uniformly the surface of the material without the occurrence of corrosion pits that penetrate the substrate as a result of the etching process.

The equipment setup for ECP could be used for electroplating by reversing the polarity. In particular, the components are made the anode in the circuit in the case of electro-polishing, while in electroplating they are the cathode. The setup is relatively simple and requires a tank, a solution, and a low voltage direct current provided by a rectifier.

As with electroplating, ECP is generally applied on macro-scale components, and its application for improving the surface finish of laser milled surfaces poses a considerable challenge. The macro-scale electro-polishing process depends on the uniformity of the material microstructure, the lack of surface inclusions, and the consistency of the surface finish all over the component. In contrast, laser milled structures are mostly concave features. Their roughness is usually higher than that achieved on the other surfaces of the component, and also there is a significant presence of foreign or recast particles on them. Thus, it is important to investigate systematically the effects of electrochemical polishing on microstructures machined by laser milling.

In this research, an experimental study is reported to identify important factors affecting the process’s efficiency. The main objective is to prove the feasibility of using ECP for improving the surface quality after laser milling.
3. Factors affecting the process efficiency

ECP is a process that has the potential to improve considerably the surface finish that could be obtained after laser milling. There are a number of factors affecting the process efficiency, in particular the surface improvements that could be achieved by its application. In addition, the effects that the polishing could have on the surface topography should also be studied.

The main factors influencing the ECP process are feature sizes, especially those of microstructures, together with the applied temperature control, the existence of solution agitation, and the process duration.

- **Feature sizes.** The recesses of microstructures produced by laser milling are of prime importance. They inhibit the polishing process by preventing the access of a fresh solution to the target area, and thus lead to an adverse concentration of dissolved material around the feature surfaces. In particular, the higher the concentration of target ions in the solution, the less effective the polishing process becomes. In addition, this could result in local overheating of the workpiece.

- **Temperature control.** The electrolyte of every electro-chemical polishing system has a defined range of optimum operating temperatures. A temperature below this range could lead to an increase of the electrolyte viscosity, and thus obstruct the diffusion of the dissolved particles into the electrolyte, and obstruct the supply of fresh electrolyte.

- **Solution agitation.** The existence of any solution agitation has a multiple effect on the process efficiency, especially when polishing micro features. In particular, it can affect the process efficiency in the following ways [5]: 1) improve the supply of fresh electrolyte to micro recesses; 2) eliminate the undesirable concentration of the dissolved material in the vicinity of micro features; 3) stimulate the release of gas bubbles from the polished substrate which may cause problems, e.g. pitting; and 4) prevent local overheating of the workpiece.

- **Process duration.** The duration of the ECP process depends on the workpiece material, its initial conditions, and the electrolyte composition. Excessive electro-polishing does not always result in surface quality improvements. Actually, sometimes it may even produce an opposite effect. This is because the processing time should always be set taking into account the current density. Typically, an increase of the current density shortens the electro-polishing time.

4. Experimental setup

Figure 1 presents the setup used for the ECP experiments. The DC power supply provides a variable voltage from 0 to 32V with a direct current up to 12 A.

In practice, ECP is controlled by the current density provided by an external power source. The anodic current density is given as c.d. = I/S, where I is the electric current in [A], and S is the surface of the anode workpiece in [cm²]. A voltmeter was used to set the operational current, and thus to control the current density applied to the anodic workpiece. Regarding the surface area of the anode, there are a number of methods to control it. One is to selectively cover the workpiece with an acid-resistant compound, leaving open only the target area. In this study, in order to mimic the processing of a component incorporating micro features as closely as possible, the workpiece was not covered, but through the selection of its dimensions an optimum current density was achieved.

The material selected for the cathode was industrial copper. A sheet of copper was shaped in a 3-cm wide strip and then rolled to obtain a tube with a smaller diameter than the beaker. In this way, the workpiece could be placed in the middle of...
the beaker and thus be surrounded by the cathode to provide a uniform electrical potential from all sides. Also, the shaped cathode provided space for better agitation in the vicinity of the AISI 316 workpiece.

The test structure was machined on a single AISI 316 workpiece by laser milling. The machining was carried out on a commercial laser milling system with a microsecond Nd:YAG laser (λ = 1064 nm). The process parameters are provided in Table 1. After machining, the workpiece was cleaned in an ultrasonic bath for 6 min at room temperature.

Table 1 Laser milling process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AISI 316</th>
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<tr>
<td>Laser flashlamp current / [%]</td>
<td>68.8</td>
</tr>
<tr>
<td>Frequency / [kHz]</td>
<td>40</td>
</tr>
<tr>
<td>Scanning speed / [mm/s]</td>
<td>400</td>
</tr>
<tr>
<td>Pulse duration / [µs]</td>
<td>10</td>
</tr>
<tr>
<td>Hatching distance / [µm]</td>
<td>10</td>
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</table>

The next step was to remove the oxides and other contaminants by immersing the workpiece in a pickling solution [6]. The chemicals, nitric acid HNO₃: 20 %; Hydrofluoric acid HF: 7 %, and additives were obtained in ready to use form. The setup employed was the same as with the electrochemical polishing (see Figure 1) except for the use of electrical current. The duration of the pickling process was set to 10 minutes at room temperature. Subsequently, the test piece was rinsed and air-dried prior to all measurements. Surface roughness measurements were taken from the experimental structures for comparison. The measurements were performed on an interferometric profiling microscope. Three consecutive measurements were taken from each target surface.

For the ECP process, the workpiece was submerged in a ready to use solution with the following composition: sulphuric acid: 15% to 50%, and phosphoric acid: 25% to 60%. The solution was at 55°C during the polishing experiment. The duration of the process was set to 10 mins, and at a voltage providing anodic current density of 0.2 A/cm². The duration of the ECP operation was selected after conducting some initial trials to identify the processing window for AISI 316. After completing the operation, the workpiece was again rinsed and air-dried. Consequently, a new set of measurements were taken from the experimental surfaces using the same interferometric profiling microscope. Again, three measurements were taken from each test area.

5. Results and discussion

The experiment was carried out in accordance with the preset plan. By applying ultrasonic cleaning debris and contaminants were removed from the laser milled surfaces without any of the detrimental effects usually associated with mechanical cleaning or brushing. This could be seen clearly in Figure 2. Then, through pickling, the target surfaces were cleaned chemically of various types of surface inclusions. As a result, the workpiece was free from any traces of oxides before undergoing the ECP operation. Also, the pickling process proved to be the best option for cleaning the hard and difficult to remove recast layers on the feature’s surfaces that were formed by the laser machining.

Table 2 provides the results from the surface roughness measurements of the test features after ECP. The equipment used was MicroXAM white light interferometer. In particular, standard 2D and 3D surface statistics involving S-parameters and summit and valley analyses are applied [7]. There were three sets of measurements performed on: non-machined surface (mechanically polished), 5 mm, and 0.5 mm square pockets.

It is important to emphasise the results obtained on the mechanically polished surface. In particular, the surface roughness in this case did not improve, and in fact it showed a slight increase. The initial roughness was equal to Ra 0.11µm and then it rose to Ra 0.17µm after the pickling process. The ECP operation improved the surface quality to Ra 0.14µm. The reason for this should be sought in the two cleaning processes. First, it should be expected that the pickling process would not improve the surface roughness but would only remove scales and oxides. Thus, it would “reveal” the surface asperities, and in this way would lead to a marginal worsening of the initial polishing results. The ECP process on the other hand, is effective only in a given range of surface finish, and given the relatively low roughness achieved by the preceding mechanical polishing process, it could provide only a little improvement.

In contrast, the 5 mm square pocket that was laser milled, showed a significant improvement of the surface finish resulting from the ECP operation. Although there were some marginal improvements
after the pickling process, the real reduction of the surface roughness should be attributed to ECP. In particular, the surface finish improved by 53% in total compared to that of the laser milled surface. Table 2 Results from surface roughness measurements, $R_a$ \(\mu m\)

<table>
<thead>
<tr>
<th></th>
<th>5 x 5 mm</th>
<th>0.5 x 0.5 mm</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Pickling</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>1.83</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>1.76</td>
<td>1.69</td>
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<td></td>
<td>1.86</td>
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<td></td>
<td>2.43</td>
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<td></td>
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<td>2.63</td>
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<td>2.54</td>
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The initial average roughness of the laser milled 0.5 x 0.5 mm pocket was $R_a$ 2.52µm. Compared to the average roughness of $R_a$ 1.83 µm achieved for the larger feature, it represented a worsening of the initial surface finish by almost 30%. This time there were no improvements after the pickling operation as had been the case with the bigger pocket. Also, the surface roughness reduction was approximately 30% after ECP in comparison to the original laser milled surface.

The beneficial effect of the ECP operation on the laser milled features is also noticeable in Figure 3b. The process removed completely the burrs that were present along the top edge of the pockets after the machining, thus eliminating this undesirable side effect from the laser milling process.

6. Conclusions

This paper discusses the effects of ECP on the surface roughness of laser milled surfaces. The ECP process is directed mainly at improving the surface quality. Although ECP displayed some limitations when polishing micro features, it still managed to achieve almost 30% improvement in comparison to the initial roughness after laser milling. Another benefit is that the process also improves the edge quality of the laser machined structures by removing the burrs that typically are left after the machining.

Thus, ECP is a viable finishing process that in combination with the continuous improvements of the laser ablation technology, e.g. the use of shorter pulse durations, new machining strategies, and laser polishing techniques, could deliver surface improvements that are necessary for broadening the application area of laser milling, especially when utilised for micro structuring.

Acknowledgements

The authors would like to thank the UK Engineering and Physical Sciences Research Council (EPSRC) for funding this research under the EPSRC Programme "The Cardiff Innovative Manufacture Research Centre". Also, this work was carried out within the framework of the EC FP6 Network of Excellence "Multi-Material Micro Manufacture: Technologies and Applications (4M)".

References