Underwater Laser Micromilling of Commercially-Pure Titanium Using Different Scan Overlaps

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Abstract. Underwater laser milling process is a technique for minimizing the thermal damage and gaining a higher material removal rate than processing in air. This paper presents the effect of laser scan overlap on cavity width, depth and surface roughness in the laser milling of commercially-pure titanium in water. The effects of laser pulse energy and pulse repetition rate were also examined, in which a nanosecond pulse laser emitting a 1064-nm wavelength was used in this study. The experimental results indicated that a wide and deep cavity was achievable under high laser energy and large scan overlap. According to the surface roughness, the use of high pulse repetition rate together with low laser energy can promote a smooth laser-milled surface particularly at 50% scan overlap. These findings can further suggest a suitable laser micromilling condition for titanium in roughing and finishing operations.

1. Introduction

Fabrication of micro/nano-components has become a significant attention in many fields of manufacturing industries. Lasers have been recognized as a highly potential tool to produce micro parts due to their high resolution and low processing cost compared to other technologies. However, heat generated and accumulated in work material during laser machining processes adversely introduces side effects to the workpiece in terms of heat-affected zone and recast deposition. These undesired features are usually found alongside the machined area [1, 2]. Underwater laser machining process is therefore an alternative technique to reduce such problems and also gain better cut quality as well as higher machining rate than the laser ablation in ambient air [3]. Laser milling process in water has comprehensively been studied in recent years with an attempt to understand the underlying process mechanics and its potential to fabricate the accurate and smooth micro cavities [4, 5]. However, these studies have still not provided in-depth discussion on the influence of scan overlap, especially when flowing water is applied over the workpiece surface during the ablation. Hence, this paper aims at investigating the effects of the laser scan overlap as well as other laser parameters on the cavity dimensions and surface roughness obtained in the underwater laser micromilling process.

2. Experimental Design and Procedure

A commercially-pure titanium (cp-Ti) sheet having the thickness of 1.0 mm was used as a workpiece sample in this study. The chemical compositions of cp-Ti are listed in Table 1. The whole workpiece
was held in a stainless steel chamber as shown in Fig. 1(a). This chamber had a window on the top side allowing a laser beam to reach the workpiece surface for ablation. Inlet and outlet channels positioned on each side of the chamber introduced a directional flow of water across the top workpiece surface. The distance between the window and specimen was kept constant at 5 mm. A centrifugal pump was used to supply water into the chamber with the rate of 4 l/min.

**Table 1.** Chemical compositions of cp-Ti sheet

| Element | Content (%) |
|---------|-------------|
| C       | 0.10        |
| Fe      | 0.30        |
| H       | 0.015       |
| N       | 0.03        |
| O       | 0.25        |
| Ti      | 99.20       |

**Figure 1.** Schematic of (a) underwater laser milling process; (b) top view of laser milling paths; (c) pulse overlap and scan overlap

A nanosecond pulse laser providing the wavelength of 1064 nm and pulse duration of 120 ns was used in this study. The maximum laser pulse energy was 1 mJ, and the pulse repetition rate can be varied from 30 to 250 kHz. A collimated laser beam having the diameter of 10.2 mm was focused at the top workpiece surface by a 67.27-mm focusing lens. As the laser beam travelled through air, window and water before reaching the target surface, the refracted beam in water consequently caused the spot diameter of 27.11 µm at the surface [6]. This optical setup was identically employed for all tests in this study.
Process parameters considered in this research were laser scan overlap, laser pulse energy and laser pulse repetition rate. Three levels of scan overlap and two levels of laser energy and pulse repetition rate were tested in this work as shown in Table 2. A laser beam scanned over the workpiece surface with a constant traverse speed of 100 mm/min to create a 2×2 mm cavity. Each laser path overlapped the other regarding the scan overlap value, while the pulse overlap was dependent on the scan speed as illustrated in Fig. 1(c). Cavity width and depth including surface roughness were quantified from each cavity by using a high magnification confocal laser microscope (Olympus LEXT OLS4000). Surface morphology of milled cavity was qualitatively observed by a scanning electron microscope (SEM).

| Process parameters     | Value |
|------------------------|-------|
| Laser scan overlap (%) | 25    |
|                        | 50    |
|                        | 75    |
| Laser pulse energy (mJ)| 0.1   |
|                        | 0.5   |
| Pulse repetition rate (kHz) | 30  |
|                        | 60    |
| Traverse speed (mm/min) | 100  |
| Water flow rate (l/min) | 4    |

### 3. Results and Discussion

Fig. 2 presents the average width and depth of laser-milled cavity obtained from each test. The increase in laser pulse energy and scan overlap was found to increase the cavity width and depth. This is due to the fact that high laser energy can introduce rapid melting and vaporization of work material being irradiated, which in turn causes a large ablated area. In addition, when a laser beam scans back and forth over a workpiece surface with a large track overlap in the laser milling process, the work material located in the overlapped region undergoes reheating and more evaporation during the ablation. This consequently makes the laser-milled cavity wider and deeper under a larger scan overlap particularly with the combination of high laser energy operation. As for Fig. 2(c) and (d), the maximum depth seems to be about 175 µm. The off-focusing of laser beam could be responsible for this feature, and the light absorption in water can also attenuate the laser intensity at the workpiece surface to some extent, thus limiting the laser energy to further deepen the cut. Besides the influence of the laser energy and scan overlap, the pulse repetition rate also provided different cavity dimensions. As presented in Fig. 2, the low repetition rate can result in a slightly large and deep cut. This is on account of long pulse-off time in the low repetition rate setup that allows water to completely flush away the cut debris from the laser ablated area before firing the next laser pulse. A wider and deeper cavity can be expected in the laser ablation with low pulse repetition rate, and the similar results can be found in [4, 6, 7].
Average surface roughness (Ra) of cavity was also quantified in this study as shown in Fig. 3, indicating that the use of low pulse repetition rate and high laser energy produced rough cavity surface. This is because high heat input induced by such conditions can cause large bubble formation at the laser-irradiated area in water, so that shock waves generated during the formation and collapse of bubbles can impinge toward the laser-ablated surface[8] and thereby make the surface roughened [4,9]. Since the shock waves were occurred while the laser-irradiated surface was still being the liquid or soft-solid status, the mechanical shock pressure was therefore of high potential to deform the work material or even create small holes in the cavity surface as shown in Fig. 4. With regard to the experimental results, the scan overlap of 50% was able to provide the smoothest cavity surface among the others. When too small overlap is applied in the laser milling process, the large distance between consecutive milling tracks and weak laser intensity around the rim of Gaussian laser spot cannot effectively facilitate the ablation of material elements in-between milling tracks. This thus leads to a significant peak-to-valley surface roughness so as the average roughness value. On the contrary, too large overlap causes more amount of molten material at the cavity surface whose morphology can easily be altered by the mechanical shock pressure induced by bubbles in water, thus deteriorating the laser-milled surface quality. The average surface roughness of about 0.4 μm was achievable when 50% scan overlap was applied together with 0.1-mJ laser pulse energy and 60-kHz repetition rate. This condition can be used for surface finishing in the underwater laser milling process.

Figure 2. Effects of process parameters on cavity width and depth

Figure 3. Effect of process parameters on surface roughness
Figure 4. Surface morphology of titanium induced by the underwater laser milling process with the (a,d) scan overlaps of 25%, (b,e) 50% and (c,f) 75% when the laser pulse energy of 0.1 mJ and pulse repetition rate of 30 kHz were used.

4. Conclusions
This study investigated the influence of laser scan overlap as well as laser pulse energy and laser pulse repetition rate in the underwater laser milling of commercially-pure titanium in flowing water. The width, depth and surface roughness of cavities were measured and discussed in this paper. The major findings and implications of this work can be concluded as follows:

- A wide and deep cavity was obtained when high laser pulse energy, low pulse repetition rate and large scan overlap were applied in the laser micromachining process in water. This condition could be used for rough cutting operation, which the high material removal rate is the primary concern. However, the compensation of milling paths is a must to yield the accurate cavity’s dimensions.
- The smooth milled surface can be produced by using 50% scan overlap together with low laser pulse energy and high pulse repetition rate. Though this setup is likely suitable for finishing operation, the decreased ablation rate is to be sacrificed.
- Laser-milled surface improvement and micro-fabrication of three dimensional features in biomedical materials will further be investigated to unlock the potential of underwater laser micromilling process for manufacturing practice.

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6. References
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