Pulsed Nd:YAG Laser Micro-turning of Alumina to Study the Effect of Overlap Factors on Surface Roughness Performance

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Abstract. Laser micro-turning is one of the latest micromachining technologies for processing cylindrical shaped work material. Utilizing this novel micromachining process, micron size depth of desired length along the cylindrical axis of the workpiece can be micro-turned using highly intense laser beam. In this process, there are two important overlap factors i.e. spot overlap and circumferential overlap play important role for achieving the desired quality of micro-turning surface. The present paper deals with the effect of overlap factors on roughness of laser micro-turning surface. By varying the pulse frequency, workpiece rotating speed and workpiece axial feed rate, a range of spot overlap and circumferential overlap can be achieved and experiments have been conducted at different process parametric combinations. Parametric effects and detailed analysis have been carried out using different graphical plots. Scanning electron microscopic (SEM) images of the machined surface were also analysed for the qualitative assessment and parametric effects of the process.

1. Introduction
In last two decades, laser micromachining processes finds huge potentials for effective applications in several important fields such as aerospace, electronics and instrumentation, biomedical, jet engines and automotive etc. This enormous success of applications of laser micromachining processes has been achieved due to several advantages of the processes such as higher productivity, less processing time, adaptability to automation, minimization of secondary finishing operations, less material wastage and improved geometrical accuracy and surface finish [1, 2]. Furthermore, there are significant demand of difficult-to-machine engineering ceramic and composite materials which are high strength and temperature resisting (HSTR) type. To machine these type of materials, laser micromachining processes can be effectively and efficiently utilized. Engineering ceramics such as zirconium oxide, magnesium oxide, silicon carbide, aluminium oxide, aluminium titanate etc has some outstanding thermos-physical properties which include high corrosion resistance, high hardness, low thermal coefficient, high temperature resistant and low weight-to-strength ratio [3]. Furthermore, laser micromachining processes has the capabilities of producing accurate geometry of 2D as well as 3D microstructures on different engineering materials mentioned above [4].
Amongst several laser micromachining processes, laser micro-turning is recently developed micromachining process for removing small layer of material from cylindrical shaped workpiece with accurate micro-turn depth and desired length along the sample length [5]. In this process, a high intense laser beam is used to irradiate onto the rotating workpiece and feed rate is given to the workpiece along the workpiece axis so that micro-turning can be carried out for a specific length of job. This novel micromachining process has been developed utilizing the laser micro-grooving process in which several micro-groove of specific geometry and dimensions is achieved one after another onto the cylindrical workpiece material. In laser micro-turning, the rotational speed and axial feed of the job is so controlled in their values that multiple micro-groove are generated side-by-side onto the workpiece surface and also, most important is that there must be some amount of overlap between two consecutive micro-groove widths. Therefore, if such condition occurs, then there will be removal of very thin planar layer of material from the workpiece surface. For obtaining a desired value of micro-turning depth on the machined area, multiple number of such type of laser scanning can be carried out by providing continuous rotation of job and to and fro nonstop feed motion of rotating workpiece. For successful achievement of desired condition of surface integrity as well as dimensional tolerance of the machined surface, two overlap factors i.e. spot overlap and circumferential overlap play vital role. The common area between two successive laser spot is called as spot overlap whereas the overlap between two consecutive laser scan widths for successive rotation of cylindrical workpiece is known as circumferential overlap [6]. The relationships between the process parameters and these overlaps are mentioned in the following equations.

\[
\text{Spot Overlap Percentage (SOP)} = \left(1 - \frac{0.5238 \times N}{D \times F_p}\right)
\]

(1)

\[
\text{Circumferential Overlap Percentage (COP)} = \left(1 - \frac{60 \times f}{D \times N}\right)
\]

(2)

In the above-mentioned equations, N, D, Fp and f represent workpiece rotating speed in rpm, laser spot diameter in mm, laser pulse frequency in Hz and axial feed rate of sample (Y feed rate) in mm/s. For removal of bulk form (like a ring shape or tapered groove) of material from workpiece, laser micro-turning process is applied by using two intersecting laser beams [7]. However, for carrying out micromachining process such as laser micro-turning, a single laser beam should be used to remove very thin planer layer from work material surface by irradiating and focusing the laser beam onto the machining surface of rotating workpiece through the desired length of turn along the axis of work sample. There are few research works reported by researchers in the area of laser micro-turning. The effect of variation of different process parameters such as laser power, laser pulse frequency and scanning speed on depth of cut and surface characteristics [5]. The results revealed that the surface roughness (Ra) was achieved in the range of 6.45 to 11.48 µm and range of depth of cut obtained in the range of 38 to 223 µm. Another research study of the same group of authors has been carried out for studying the effect of process parameters on surface roughness (Ra) and depth deviation using different surface plots [8]. Furthermore, multi-objective optimization has been done for obtaining simultaneous minimization of responses. The same group of authors also carried out experiments on laser micro-turning on alumina ceramics to study the process parameters and their significance in achieving the desired surface criteria and geometrical dimensions of machined parts [9]. Furthermore, sensitivity analysis of process parameters was carried out to investigate of amount of variation in process performance in small changes in input process parameters. The authors also carried out experiments in laser micro-turning process on alumina ceramics based on Taguchi based experimentation and analysis of process parameters were done based on S/N ratio plots [10]. Multi-performance optimization parametric combination has been obtained based on GRA based optimization technique. From these research investigation, it is revealed that experiments have been done without considering the overlap factors which is one of the significant keys in laser micro-turning process. Therefore, to explore the effect of these overlap factors, which is controlled by different process parameters, in the present research study, experiments have been conducted in laser
micro-turning process on 99% pure alumina ceramics using pulsed Nd:YAG laser micromachining system.

2. Experimental conditions and planning
A CNC controlled pulsed Nd:YAG laser beam micromachining system was used to conduct experimentation on laser micro-turning process of alumina ceramics. In the present experimental investigation, the process parameters, which have been considered are laser pulse frequency, workpiece rotating speed and Y feed rate. The laser beam micromachining system has a laser focusing lens of 50 mm focal length and focal spot size of laser beam was 100 µm. The workpiece rotating system was indigenously developed using an AC servo motor with an AC servo amplifier. The schematic view of developed workpiece rotating system can be viewed in Fig. 1. To minimize the error in eccentricity during rotation of workpiece, the collet which hold the cylindrical workpiece was accurately and precisely attached with the motor axis. To focus the laser beam onto the workpiece surface correctly, a CCD camera and CCTV were utilized. The Y feed rate was given to the workpiece by moving the Y axis of the work table of laser machine.

![Figure 1. Schematic representation of workpiece holding and rotating system](image1)

![Figure 2. Schematic diagram of the surface texture realized for different circumferential overlaps](image2)
### Table 1. Experimental conditions for laser micro-turning process

| Conditions          | Description                                      |
|--------------------|--------------------------------------------------|
| Laser type         | Nd:YAG Laser (pulsed)                            |
| Wavelength         | 1064 nm                                          |
| Mode of operation  | Q-switched (pulsed)                              |
| Mode of laser beam | Fundamental mode (TEM<sub>00</sub>)              |
| Mirror reflectivity| Rear mirror 100% and front mirror 80%            |
| Pulse width, % of duty cycle | Variable                        |
| Beam average power | 8 W                                              |
| Pulse frequency    | 3000, 5000, 7000 Hz                              |
| Workpiece rotating speed | 200, 400, 600 rpm                        |
| Y feed rate        | 0.1, 0.3, 0.5 mm/s                              |
| Air pressure, kgf/cm² | 1.3                                             |
| Z feed rate, mm/s  | 0.01                                             |

If the distance between two consecutive laser spots increases (with the increase in laser scanning speed or decrease in pulse frequency), the spot overlap achieved is low and therefore, wavy surface along with several peaks and valleys is generated. Thus, it is desirable to select parametric setting during laser micro-turning in which high value of spot overlap is obtained. On the other hand, as shown in Fig. 2, with the increase in circumferential overlap (with the decrease in Y feed rate or increase in workpiece rotating speed), the overlap between two successive scan widths increases and as a result, uniform surface can be achieved in laser micro-turning process. Thus, these two overlap factors are vital for achieving desired value of surface roughness and other dimensional accuracies. In the present experimentation, the values of process parameters such as pulse frequency, workpiece rotating speed and Y feed rate were selected in such a way that there is defined ranges of spot overlap and circumferential overlap. The details of the laser machine setup are enlisted in Table 1. It also shows the values of the various process parameters considered during experimentation. The workpiece was taken as 99% pure alumina ceramics of diameter 10 mm and length of 40 mm. After conducting experiments, surface roughness (Ra) was measured for each laser micro-turning surface. A surface roughness measuring instrument, SURFCOM 120A-TSK was used to measure surface roughness values. Surface roughness was measured six times for each experiment by rotating the work sample for 60° turn. The cut-off length and total length of measurement were 0.25 and 2.5 mm, respectively.

3. Results and Discussions

In this section, the influence of the spot overlapping percentage (SO<sub>p</sub>) and circumferential overlap percentage (CO<sub>p</sub>) on surface roughness (Ra) has been analysed through various plots. It is already described that the spot overlap percentage can be varied by two methods, (i) by varying work sample rotating speed keeping the pulse frequency at a constant value, and (ii) by varying pulse frequency keeping the workpiece rotating speed at constant value. For the results shown in Fig. 3, the beam average power and Y feed rate were kept constant as 8 W and 0.3 mm/s, respectively. From this figure, it is observed that roughness of the micro-turned surface reduces with the increase of spot overlap for each of the pulse frequency settings. From equation 1, it is obvious that the reduction in rotating speed of work sample results in high overlap value between successive laser spots. This high amount of overlap results in even machined surface and reduces the surface roughness. It is also seen from the same plot that the surface roughness value increases with pulse frequency at any particular spot overlap percentage value. With the increase of pulse frequency, according to equation 1, the spot overlap percentage increases. However, at high pulse frequency condition, the time duration between two successive pulses is very less. Therefore, the material at the focused zone on the sample gets adequate thermal energy for melting and vaporization instantly. Thus, ultimately, the total amount of
irradiated laser beam energy is high enough and it results in more depth of crater formed on the surface, which results higher value of surface roughness.

Figure 3. Effect of spot overlapping on surface roughness (Ra) at different pulse frequency

Figure 4. Effect of spot overlapping on surface roughness (Ra) at different rotating speed

For the experimental results shown in Figure 4, the average power of laser beam and Y feed rate were kept constant at 8 W and 0.3 mm/s, respectively. The figure clearly indicates that with the increase of spot overlap percentage for any constant value of workpiece rotating speed, surface roughness (Ra) decreases. Due to high percentage of spot overlap, the material removal from the workpiece surface occurs uniformly and therefore, high quality machining surface is achieved. Furthermore, for same spot overlap percentage value, the micro-turned roughness is more for higher value of rotating speed. At higher setting of sample rotating speed, consecutive spot overlap is less, resulting uneven micro-turning surface.

In Figure 5, the surface roughness has been plotted keeping laser beam average power at 8 W and laser pulse frequency at 5000 Hz. From equation 2, it is obvious that the circumferential overlap percentage mainly depends onto two process parameters i.e. Y feed rate and rotational speed of workpiece. It is clear from this plot that the increase in circumferential overlap percentages i.e. increase in workpiece rotating speed with constant Y feed rate setting results in slight decrease in surface roughness values. From equation 2, it is clear that circumferential overlap percentage increases with decreasing work rotating speed and this phenomenon has directly resulted for reduction of roughness of laser micro-turned surface. High percentage of circumferential overlap results in uniform removal of material from laser irradiated surface and high finish surface is achieved. Moreover, it is also clearly seen from Figure 5 that for a constant value of circumferential overlap, the increase in Y feed rate results in rougher micro-turned surface. Increase in Y feed rate of sample is resulted more null and void spacing between two successive scan widths and this phenomenon consequently results uneven and rough micro-turning surface.
Figure 5. Effect of circumferential overlapping on surface roughness (Ra) at different Y feed rate

Figure 6. Effect of circumferential overlapping on surface roughness (Ra) at different rotating speed

In Figure 6, the influence of circumferential overlap on surface roughness is shown at laser beam average power of 8 W and pulse frequency of 5000 Hz, respectively. It is observed from this plot that with the increase in circumferential overlap, roughness of the machined surface decreases for each workpiece rotating speed setting. Due to high circumferential overlap, the laser scan widths for successive rotation of workpiece come closer to each other and in turn, this phenomenon results in even and regular micro-turning surface. It shows that at higher rotating speed settings, the amount of circumferential overlap is high and further it results lower value of surface roughness of the surface profile produced during laser micro-turning operation.

4. Analysis of SEM Images for Assessment of Machined Surface

For qualitative assessment of the machined surface in laser micro-turning process of alumina workpiece, Scanning Electron Microscopic (SEM) images were taken to study the influence of various predominant process parameters. Fig. 7 (a) and (b) shows the SEM micrographs of the machined surface obtained at parametric combinations of workpiece rotating speed and Y feed rate of 600 rpm/0.30 mm/s and 400 rpm/0.50 mm/s. At these parameters settings (at constant value of pulse frequency at 5000 Hz), the spot overlap and circumferential overlap values were calculated as 37 and 70% (at 600 rpm/0.30 mm/s) and 58 and 25% (at 400 rpm/0.50 mm/s). By comparing these micrographs, it is concluded that with higher values of circumferential overlap in Fig. 7 (a), quite regular and even surface is achieved than lower value of circumferential overlap in Fig. 7 (b). At these two parametric combinations, the values of surface roughness (Ra) were obtained as 6.63 µm and 7.77 µm, respectively. Thus, it is concluded that the values of predominant process parameters have vital and significance influences on achieving the desired quality of surface characteristics.
5. Conclusions
In the present research work, experimental investigation and analysis of laser micro-turning of 99% pure alumina ceramics was carried out using a pulsed Nd:YAG laser micromachining system. By varying the predominant process parameters, a range of spot overlap and circumferential overlap was calculated. Based on the different values of these overlaps, surface roughness (Ra) values were measured of machined surface. It was observed from various plots of spot overlap versus surface roughness that with the increase of spot overlap percentages, the roughness of micro-turning surface decreases at various parametric settings of pulse frequency and workpiece rotating speed. Moreover, it was observed that circumferential overlap factor mainly depends on Y feed rate and workpiece rotating speed and it has significant influences on surface roughness criterion. Thus, by proper controlling of these process parameters, desirable quality of surface can be obtained. The results achieved in the present paper can be effectively utilize to produce quality surface and to predict the surface patterns during machining of cylindrical alumina ceramics with pulsed Nd:YAG laser.

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