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ORIGINAL ARTICLE

Experimental analysis on Nd:YAG laser micro-turning of alumina ceramic

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Abstract Laser micro-turning is a micro-machining strategy to machine cylindrical workpiece of hard-to-process materials such as ceramics. Laser micro-turning method is in high demand in the present high-precision manufacturing industries because of its wide and potential uses in various engineering fields such as automobile, electronics, aerospace, and biomedical applications, etc. In the present research, the experimental analysis of Nd:YAG laser micro-turning of cylindrical-shaped ceramic material has been made to explore the desired laser output responses, i.e., depth of cut and surface roughness by varying laser micro-turning process parameters such as lamp current, pulse frequency, and laser beam scanning speed. Single laser beam has been utilized for successful micro-turning operation. Experimental results revealed that the laser machining process parameters have great influences for achieving desired laser micro-turned depth and surface roughness characteristics during laser micro-turning of alumina ceramics. SEM and optical photographs have also been analyzed for better understanding of the laser micro-turning process for different parametric settings.

Keywords Laser micro-turning · Surface roughness · Depth of cut, alumina (Al_2O_3)

1 Introduction

Laser machining processes transport photon energy into the target material in the form of thermal energy or photochemical energy; they remove material by melting and blow away, or by direct vaporization/ablation. On the other hand, traditional machining processes rely on mechanical stresses induced by tools to break the bonds of materials. Also, the superior hardness characteristics of most advanced materials like ceramics made them ineffective in machining which further reduces the economical aspect during conventional mechanical-type micro-machining processes. To get desired surface characteristics and also economic productivity, several nontraditional micro-machining processes such as laser beam machining [1], electrical discharge machining [2], abrasive flow machining [3], ultrasonic machining [4] as well as hybrid micro-manufacturing processes such as electrochemical discharge machining [5], ultrasonic assisted EDM [6], etc. have been developed. Laser beam machining is one of the most effective micro-machining methods applied for efficient micro-removal of material from difficult-to-process advanced ceramics [1, 7–9]. Laser beam machining has a great potential to manufacture intricate-shaped micro-products with its unique process features such as high flexibility and productivity, elimination of finishing operation, improved product quality, greater material utilization, and processing of material irrespective of electrical conductivity, etc. [10, 11]. In laser beam machining method, several material processing techniques such as laser micro-drilling, cutting, micro-grooving, micro-turning, marking, or scribing, etc. can be done [12]. These processes have huge potential uses in respective field of applications in modern manufacturing industries. Laser micro-turning operation deals with the layer-by-layer material removal from rotating cylindrical surface of material by high-density laser beam through some desired length along the cylindrical axis by controlling the rotational speed and as well as the axial movement speed of workpiece material simultaneously. Laser micro-turning is mostly applied to generate desired

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micro-grooves or slots for a specific depth and length on cylindrical surface and also micro-finished surface required for assembly purpose of different micro-components. However, to produce laser micro-turning operation on advanced ceramic material, one must find a set of process parameters, which provide the desired output results under particular processing constraints [13]. The different process parameters which can be varied during laser micro-turning process are laser pulse energy, i.e., laser lamp current, pulse frequency, pulse duration, feed rate, and assist-gas pressure [14, 15]. Experimentations on pulsed Nd:YAG laser in computational prediction for single dimensional laser beam machining of advanced ceramics such as alumina (Al_2O_3), silicon nitride (Si_3N_4), silicon carbide (SiC), and magnesia (MgO) have been done [16–20]. Research work includes fabrication of cavities of advanced ceramics with high aspect ratio to predict the cavity depth based on thermal modeling. The authors also successfully predicted absorptivity transitions during the low-aspect ratio 1.06-μm wavelength laser cutting of structural ceramics such as Al_2O_3, Si_3N_4, SiC, and MgO by an integrated approach based on experiments and a computational thermal model [21, 22]. Study on the effect of multiple laser passes on cavities was done for structural ceramics incorporating thermal model based on temperature-dependent absorptivity and thermophysical properties along with defocusing of laser beam, multiple track-induced preheating effect, and heat transfer [23]. However, research in the direction of laser micro-turning of alumina ceramic has not been done across the globe. Although, an investigation is found to turn a square Si_3N_4 ceramic rod into a cylinder using an acoustic-optical Q-switched yttrium aluminum garnet (YAG) pulsed laser system, and the results showed that a roundness error of 13 μm was obtained [24].

Three-dimensional laser beam machining using two intersecting laser beams was introduced in 1988 [25]. In this process, each laser produces the corresponding blind cutting kerfs which converges and results in the solid stock removal. However, two intersecting laser beam cannot turn-out micro-thin layer from large length of cylindrical workpiece materials. An attempt has been made to utilize single-laser beam for effective micro-turning operation of ceramic work sample. In laser micro-turning using single-laser beam, the primary concept of material removal is vaporization. In this process, a continuous feed motion is given to the workpiece perpendicular to the laser scanning direction. This causes the removal of planar surface layer with orthogonal or cylindrical boundaries. To remove the additional micro-layers of material, intermittent feed motion perpendicular to the previously machined surface is given. Owing to the requirement of removal of very thin layer using single-laser beam and also to achieve desired output characteristics such as depth of cut and surface quality and accuracy, in the present investigation, micro-turning of cylindrical-shaped alumina ceramic material (Al_2O_3) by pulsed Nd:YAG laser have been performed varying different laser micro-turning process parameters such as lamp current, pulse frequency, and laser beam scanning speed. Optical photographs of the micro-turned surface at different machining parametric settings have also been analyzed for better understanding of the machined surface topography.

2 Nd:YAG laser experimental setup details

CNC pulsed Nd:YAG laser system that includes various subsystems such as beam delivery unit, power supply unit, radio frequency (RF) Q-switched driver unit, cooling unit, CNC controller (ACCUPOS S–14 CNC Controller driven by Multisawing software) for *X*–*Y*–*Z*-axis movement etc. was used during this experimental investigation. The schematic representation of CNC Nd:YAG laser system with laser turning set-up is shown in Fig. 1. A krypton (Kr) arc lamp was used to act as the pumping source of YAG crystal host. The energy of the laser beam was controlled by the current supply to the lamp. The laser machining set-up is having the capability of delivering maximum of 50 W of average power with pulse repetition rate of 20 kHz. The Q-switch driver unit converts the beam from continuous wave to pulsed mode. The laser beam diameter achieved at the focal position is 100 μm. A workpiece holding fixture was indigenously developed and used to fix the cylindrical workpiece on the CNC *X*–*Y* table. To obtain different rotational speeds of the cylindrical workpiece, a micro-processor-based stepper motor drive system was developed to control accurately the rotation of cylindrical job during laser micro-turning operation. The workpiece holding device attached with steeper motor rotates simultaneously. For laser-turning operation on cylindrical shaped job, the rotation of job holding device must be free from eccentric movement as eccentricity will result in nonuniform focusing of workpiece surface to be turned. The feed is given along the axis to the rotational work piece with the help of CNC *X*–*Y* table control unit for laser-turning operation. The desired depth of cut was set by the laser system software MULTISAW, which focused the laser beam after each pass by controlling the movement of lens with CNC *Z*-axis motion control unit. A CCD camera together with a CCTV monitor was used to check correct focusing condition of laser beam to the material surface for effective utilization of the energy of pulsed Nd:YAG laser beam and also for viewing the exact location of laser turning operation. To avoid thermal damage of laser cavity, lamp, Nd:YAG rod, and Q-switch, cooling system was used to circulate deionized water into them for removing the heat generated due to production of high-energy laser beam. Compressed

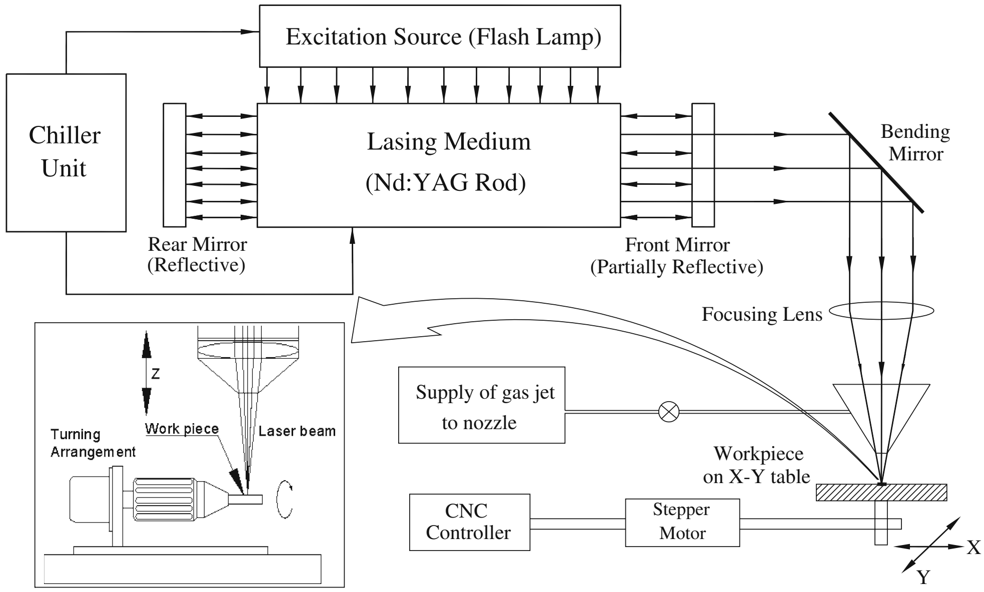


Fig. 1 Schematic representation of Nd:YAG laser turning system

assist air was delivered at the machining zone during laser micro-turning operation for easy removal of molten material from workpiece surface.

3 Experimental planning

Experimental set-up which has been used in this research investigation is SLT-SP-2000 Laser Machine manufactured by M/s Sahajanand Laser Technology, India. The workpiece used during laser micro-turning was cylindrical-shaped aluminum oxide material of size 10 mm in diameter and 40 mm in length. The major properties of aluminum oxide job samples are similar to the authors earlier published paper [26]. During experimentation, the laser processing parameters which have been kept constant are laser pulse width at 38% of duty cycle, *Z*-axis feed rate at 0.001 mm/s, *Y*-axis feed rate at 0.007 mm/s, and assist-compressed air pressure at 2 kgf/cm^2. These constant values were chosen after conducting extensive trial experimentations with randomization during laser micro-turning operation. The higher value of air pressure was chosen to make sure that most of the melted portion of work material can be completely removed from its surface and minimize the surface irregularities due to recast material. The rotating speed of the workpiece was chosen as 4, 7, 11, and 18 rpm, and corresponding values of laser scanning speed (v) were calculated using Eq. 1, where D is diameter of workpiece in millimeter and N is rotational speed of workpiece in revolutions per minute.

$$\text{Laser scanning speed, } v = \frac{\pi \times D \times N}{60} \quad (1)$$

The actual ranges of different laser processing parametric settings have been selected after performing some pilot experiments. Various laser turning process parameters with respective parametric levels considered during experimentation are listed in Table 1. The schematic drawing of the targeted shape of the alumina material to be generated by laser turning is shown in Fig. 2. The depth of cut of the laser micro-turned surface was measured at 10× magnification with the help of optical measuring microscope (Olympus STM6, minimum measurable dimension= 0.5 μm). The surface roughness (Ra) was measured by SURFCOM 120A-TSK roughness measuring instrument. During roughness measurement, the cutoff length (λc) was chosen so that variations due to wavinesss or form errors are excluded, and surface finish related to the closely spaced irregularities can be measured correctly. The surface roughness of the micro-turned surface was measured along the length parallel to the axis of the cylindrical job. The cutoff length was set as 0.8 mm, and total length of measurement (L) was 2.7 mm (L=λc×3).

4 Parametric analysis of Nd:YAG laser micro-turning

The influence of important process parameters such as lamp current, pulse frequency, and laser scanning speed on the workpiece for Nd:YAG laser micro-turning characteristics such as laser-turned depth and machined surface finish have been analyzed based on experimental results obtained through various measurements. Experiments for each parameter settings were repeated three times, and the results of average of values were plotted in the corresponding graphs. The plotted graphs also show errors in measure-

Table 1 Experimental conditions during micro-turning using Nd:YAG laser

Condition	Description
Machine details	
Laser type	Nd:YAG laser
Wavelength	1,064 nm
Mode of operation	Q-switched (pulsed)
Type of Q-switch	Acousto optic
Mode of laser beam	Fundamental mode (TEM_{00})
Mirror reflectivity	Rear mirror 100% and front mirror 80%
Parameter details	
Lamp current, A	22, 23, 24, 25
Pulse frequency, Hz	200, 400, 600, 800
Laser scanning speed, mm/s	2.2, 3.85, 6.06, 9.9
Pulse width,% of duty cycle	38
Air pressure, kgf cm^{-2}	2
Z feed rate, mm s^{-1}	0.001
Y feed rate, mm s^{-1}	0.007

ments in depth of cut (3% error) and in surface roughness (5% error) during experimentation. Moreover, optical and SEM views of Nd:YAG laser micro-turned surface of Al_2O_3 ceramic workpiece have been observed for laser turning at various laser process parametric settings.

4.1 Effect of laser micro-turning process parameters on depth of cut

When the laser beam interacts with alumina ceramic particles, the material undergoes mainly two governing phenomena, namely melting and evaporation. As amount of material melting and evaporation depends mainly on energy of laser beam, different process parametric settings result in variation in laser micro-turned depth on ceramic job surface. Figure 3 shows the effect of variation in laser scanning speed on laser micro-turned depth for laser pulse frequency of 400 Hz and 800 Hz keeping other process parameters, i.e., pulse width as 38% of duty cycle, lamp current as 23 A, and air pressure as 2 kgf/cm^2. It is observed that there is a great influence of laser scanning speed on micro-turned depth. The depth of cut is seen to be decreased sharply with the increase of scanning speed for both values of pulse frequencies. At lower scanning speed, the absorbed energy of the laser beam is higher due to longer interaction time between laser beam and alumina particles, which cause more material to melt and evaporate from the focused surface. However, at higher scanning speed, the incident energy per unit scanned area is reduced, which further reduces the turned depth. Moreover, higher pulse frequency, i.e., 800 Hz results in more depth of cut compared to lower pulse frequency, i.e., 400 Hz at any fixed laser scanning speed in the considered range. Higher pulse frequency results in high percentage of overlap of the laser beam on the work surface, which further increases the depth of cut of laser-turned surface of alumina ceramic.

In Fig. 4, the variation of laser micro-turned depth of cut is shown with the variation of lamp current for laser pulse frequency settings of 400 and 800 Hz at constant parameters of pulse width as 38% of duty cycle, laser scanning speed as 6.06 mm/s, and air pressure as 2 kgf/cm^2. It is revealed from this figure that the depth of cut of laser micro-turned surface increases with the increase of lamp current within the considered range of values. At lower lamp current setting, the laser beam delivers lower amount of energy, which generates insufficient surface temperature to melt and evaporate the surface of workpiece material and results in lower penetration of laser beam into the material.

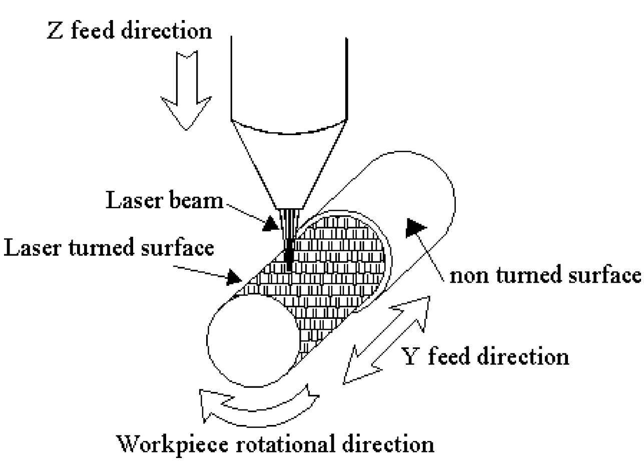


Fig. 2 Schematic diagram of targeted shape of laser-turned surface on alumina

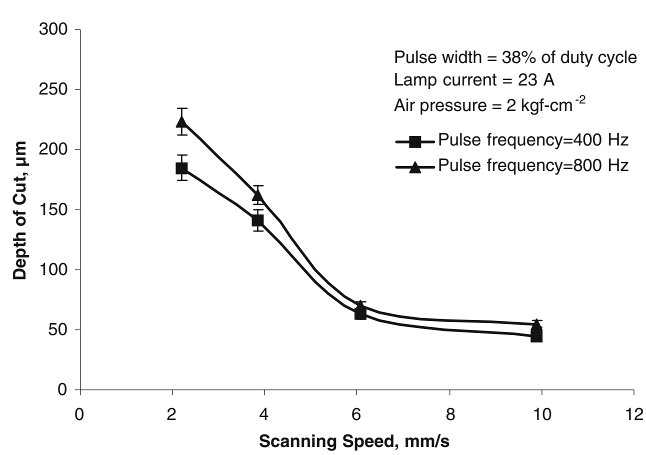


Fig. 3 Variation of depth of cut with laser scanning speed

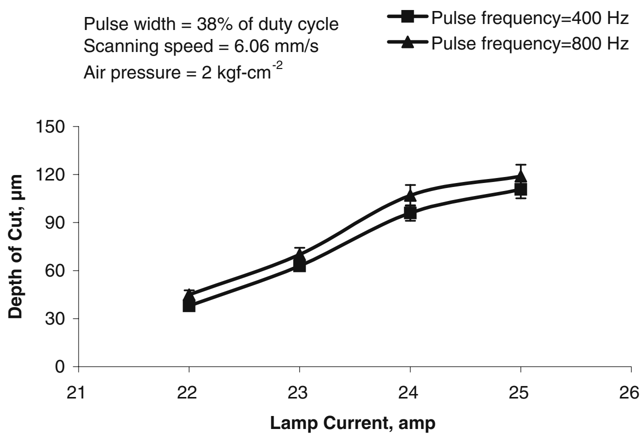


Fig. 4 Variation of depth of cut with lamp current

However, higher lamp current results in more energy of the laser beam interacting with alumina which generates sufficient temperature to vaporize the material directly without melting from workpiece. This removal of vaporized material results in higher turned depth. It is also observed from the same graph that laser pulse frequency has less effect on laser-turned depth. However, it is seen that higher pulse frequency results in slightly more turned depth compared to lower value of pulse frequency.

Figure 5 shows the variation of laser micro-turned depth of cut with pulse frequency of laser beam for two different lamp current settings, i.e., 23 and 25 A while keeping other process parameters as pulse width of 38% of duty cycle, laser beam scanning speed of 6.06 mm/s, and assist air pressure of 2 kgf/cm^2. It is observed from this graph that the variation of laser pulse frequency on laser-turned depth is very low. However, it is seen that higher lamp current, i.e., 25 A produces higher depth of laser micro-turned surface compared to lamp current setting of 23 A.

4.2 Effect of laser micro-turning process parameters on surface roughness

One of the important responses of the laser beam turning process is roughness of the micro-turned surface of cylindrical workpiece. This section describes the effect of most significant laser micro-turned process parameters such as lamp current, laser pulse frequency, and beam scanning speed over the workpiece on surface roughness characteristic during laser turning of alumina ceramic. In Fig. 6, the variation of surface roughness of laser-turned surface is shown with respect to variation of laser beam scanning speed on cylindrical workpiece surface for two different values of pulse frequency settings, i.e., 400 and 800 Hz. This figure shows that the roughness of the laser micro-turned surface increases with the increase of scanning speed of cylindrical work material. However, for a fixed beam scanning speed of workpiece, higher pulse frequency value, i.e., 800 Hz results in lower value of surface roughness compared to lower frequency, i.e., 400 Hz. As the beam scanning speed over the workpiece increases, the percentage of overlapping of the consecutive laser beam spots decreases. This phenomenon makes the laser-turned surface more irregular and high value of surface roughness. Moreover, as laser pulse frequency increases, the overlapping percentage increases, and as a result the roughness of the turned surface decreases. The relationship of percentage of laser spot overlap (O_p) with pulse frequency (P_f) and scanning speed (v) of the workpiece surface is expressed in Eq. 2 where D is laser beam spot diameter at focused position [27].

$$\text{Overlapping percentage } \left(O_p\right) = \frac{D - v/P_f}{D} \times 100\ \% \qquad (2)$$

In Fig. 7, various percentages of spot overlapping can be viewed with varying consecutive spots distances (d).

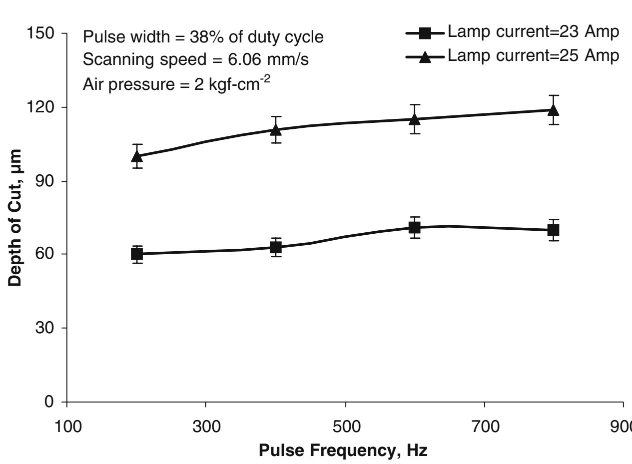


Fig. 5 Variation of depth of cut with laser pulse frequency

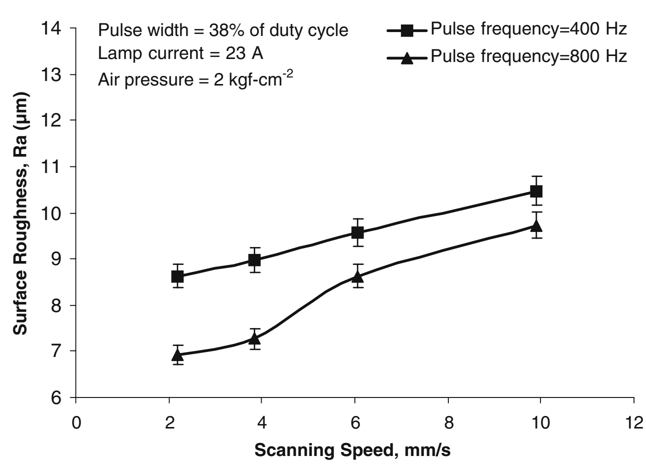


Fig. 6 Variation of surface roughness with laser scanning speed

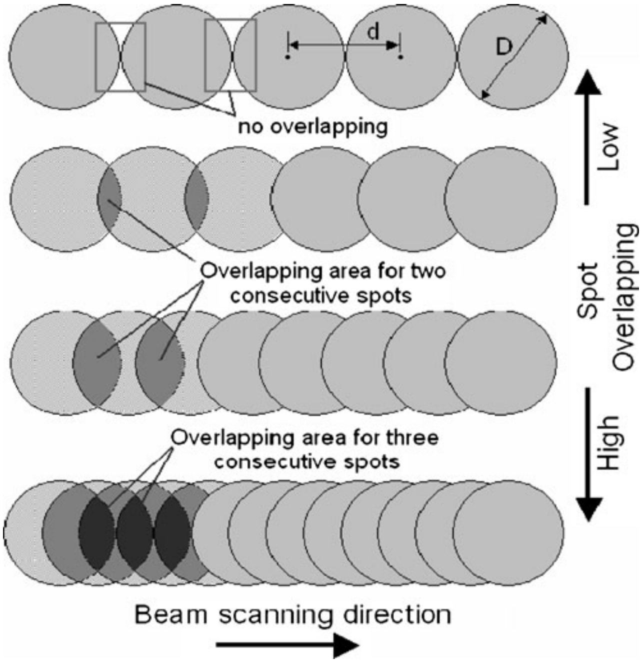


Fig. 7 Various percentage of overlap of laser spots at different laser scanning speed

The variation of micro-turned surface roughness with laser lamp current is shown in Fig. 8 for pulse frequency values of 400 and 800 Hz. This figure shows that the surface roughness sharply decreases with the increase of lamp current for both frequencies. At lower lamp current, the energy of the laser beam is less, and during micro-turning, all the portion of the material cannot be melted and removed from the machining zone. Some portion of melted material also remains on the top surface of cylindrical work material, which is called recast layer. This phenomenon increases the roughness of the turned surface. However, at higher lamp current settings, the energy of laser beam is high. This huge amount of energy instantaneously melt and vaporize all the material from the spotted zone as well as surrounding portion of laser scanning area. This phenomenon reduces the variation of peak and valley distance of the laser-turned surface and inturn reduces the surface roughness. In the same figure, it is also seen that higher pulse frequency of 800 Hz results in lower surface roughness, i.e., high-quality surface compared to 400 Hz pulse frequency setting.

In Fig. 9, the variation of laser-turned surface roughness with changing in pulse frequency values are plotted for two different settings of lamp current, i.e., 23 and 25 A. It is observed that for both the values of lamp current, the measured surface roughness decreases with the increase of pulse frequency. This decrement of surface roughness with the increase of pulse frequency is already discussed in Fig. 6. However, it is observed that for a fixed value of pulse frequency setting and higher value of lamp current setting, i.e., 25 A, better quality surface is obtained compared to that at lamp current setting of 23 A.

5 Analysis of laser-turned surface using micrographs

This section describes the Nd:YAG laser micro-turned surface characteristics of Al_2O_3 ceramic through some optical and SEM micrographs for different laser process parametric settings. In Fig. 10, the exhibited photograph shows the maximum depth of 0.223 mm and surface profile obtained through laser micro-turning on alumina at parametric setting of 23 A of lamp current, 800 Hz of pulse frequency and workpiece scanning speed of 2.2 mm/s. Figure 11 shows optical views as well as corresponding SEM micrographs of laser micro-turned surface topography obtained at different parametric settings, i.e., lamp current/pulse frequency/laser scanning speed of (a) 23 A/400

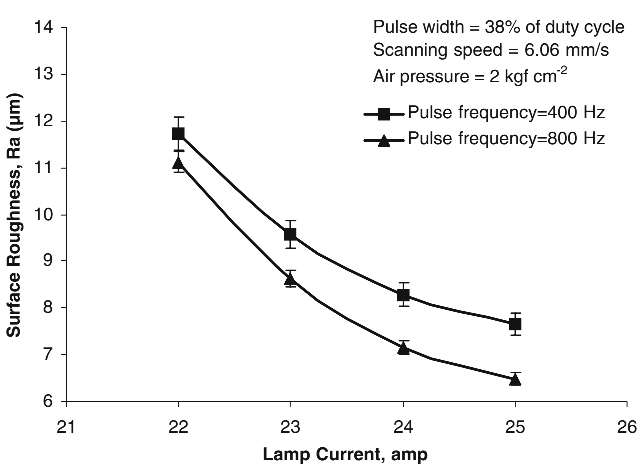


Fig. 8 Variation of surface roughness with lamp current

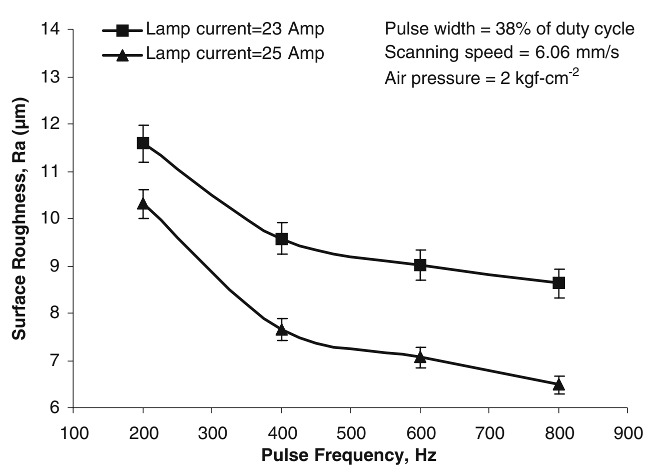


Fig. 9 Variation of surface roughness with laser pulse frequency

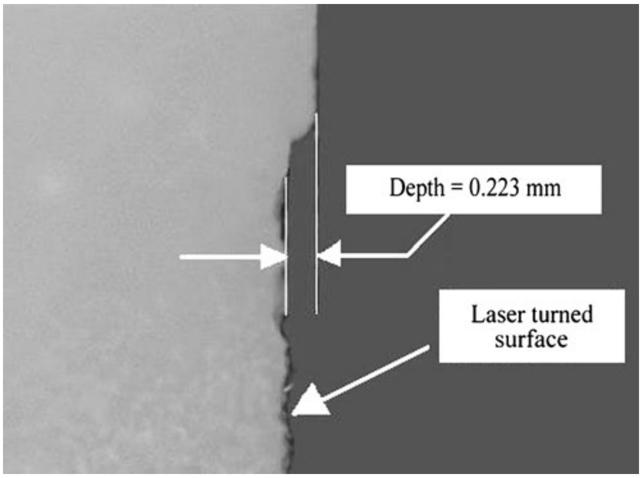


Fig. 10 Optical microscopic view of maximum laser micro-turned depth

Hz/9.9 mm/s, (b) 23 A/800 Hz/6.06 mm/s, and (c) 23 A/400 Hz/6.06 mm/s. The surface roughness values obtained in these experimental settings are 10.47, 8.63, and 9.57 µm. From these SEM micrographs, a comparison can be drawn for the surface topography of the laser-turned surface. Comparing the process parameters settings and surface roughness values of Fig. 11a and c, it can be concluded that by decreasing the laser scanning speed, better micro-turned surface can be achieved. Moreover, from Fig. 11b and c, it is seen that higher pulse frequency setting, i.e., 800 Hz has resulted better surface quality compared to pulse frequency of 400 Hz. Furthermore, recast layers are formed due to interaction of laser beam with alumina ceramic material and viewed in some regions of the workpiece surface in the SEM micrographs. It is known that the physical and mechanical properties of the recast portion are different from the parent alumina material. So, it is very important that material removal mechanism during Nd:YAG laser micro-turning should be based on evaporation phenomena rather than melting to avoid recast layer formation. To avail this, the laser turning process parameters like lamp current, pulse frequency, and scanning speed, etc. should be properly controlled.

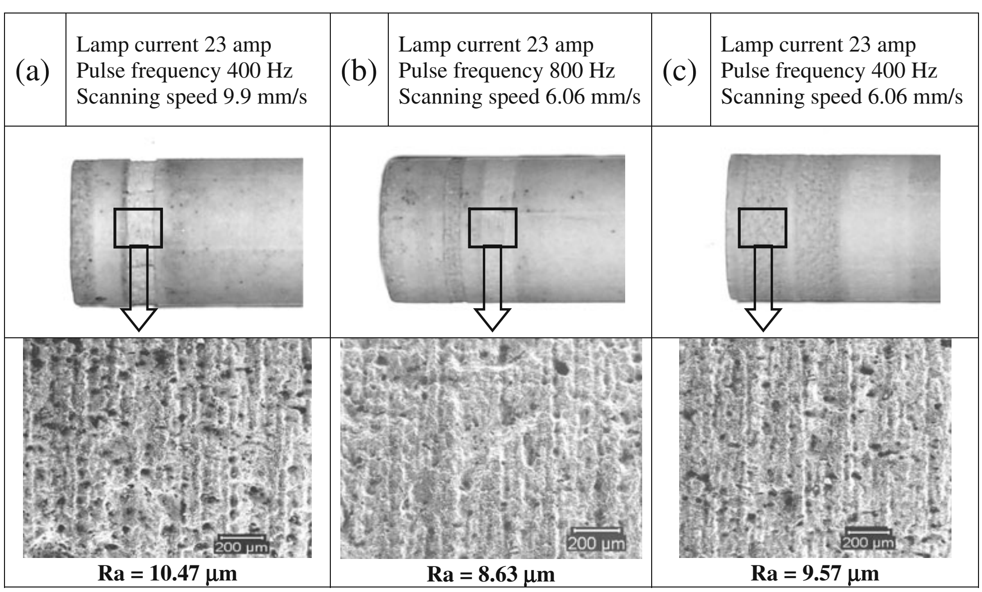
6 Conclusions

Experimentation in laser micro-turning operation using single-laser beam is done by a pulsed Nd:YAG laser of cylindrical alumina ceramic. It can be concluded that using single-laser beam, desired turned depth with quality surface can be generated through proper controlling of the micro-turning process parameters such as lamp current, pulse frequency, and laser scanning speed and also varying the overlapping percentage of consecutive laser spots during laser micro-turning. From experimental analysis on Nd:YAG laser micro-turning, the following conclusions can be drawn:

(a) Laser lamp current and laser scanning speed have very predominant effect on varying depth of cut of laser micro-turned ceramic. However, it is observed that laser pulse frequency has moderate effect on laser-turned depth. The maximum depth of cut achieved in this experimentation is 0.223 mm micro-turned at parametric setting of 23 A/800 Hz/2.2 mm/s.

(b) Surface roughness value increases with the increase of laser scanning speed, whereas the increase of lamp current and pulse frequency result in lower surface roughness, i.e., higher quality surface. The better

Fig. 11 SEM views of laser-turned surface processed at various process parametric settings



surface quality, i.e., minimum surface roughness value obtained at micro-turned parametric setting of 25 A/800 Hz/6.06 mm/s.

(c) Based on the micrographs of the laser-turned surface utilizing single-laser beam, it can be concluded that lower scanning speed and higher pulse frequency will generate better surface topography.

(d) The percentage of overlapping of laser beam spots has predominant effect on surface topography and roughness values as spot overlapping has direct effect on irregularities of micro-turned surface.

The present research will be useful for getting into further research in the area of laser micro-turning and also will open up challenging possibilities for exploring effective applications of laser technology for single-laser beam micro-turning of advanced ceramics for fulfilling the demand of micro-components in the field of high-precision micro-engineering applications. The experimental result obtained during laser micro-turning of alumina ceramic may also be utilized for its application in the area of grinding wheel dressing.

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