Journal of Manufacturing Processes 19 (2015) 49–58

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

Surface topography in three-dimensional laser machining of structural alumina

Hitesh D. Vora [1], Narendra B. Dahotre *

Laboratory for Laser Aided Additive and Subtractive Manufacturing, Department of Materials Science and Engineering, University of North Texas, 1155 Union Circle # 305310, Denton, TX 76203-5017, USA

A R T I C L E I N F O

Article history:
Received 18 July 2014
Received in revised form 10 February 2015
Accepted 13 April 2015

Keywords:
Nd:YAG laser
Laser machining
Moving laser beam
Structural ceramics
Alumina (Al_2O_3)
Multiphysics computational model
Surface roughness

A B S T R A C T

An integrated experimental and computational approach was adopted to study the influence of moving laser beam (with lateral and transverse overlap) on the generation of corresponding surface finish//profile/roughness during three-dimensional laser machining of structural alumina. A multiphysics-multistep computational model was developed to understand the influence of various physical phenomena such as recoil pressure, Marangoni convection, surface tension, and cooling rates over the surface morphology of alumina and eventually establish the relationship between the surface finish and process parameters of laser machining. Both experimental and computational results evidently revealed that the selection of appropriate laser machining conditions can machine the structural ceramics with higher material removal rates ($60 \pm 2.70\ mm^3/min$) for initial rough cuts as well as produced higher surface finish ($39.9 \pm 2.29\ \mu m$) for final finishing. The results of the computational model are also validated by experimental observations with reasonably close agreement (±6%).

1. Introduction

Structural ceramics (alumina, magnesia, zirconia, silicon carbide, and silicon nitride), can be considered as an effective solution in a variety of industries including automobile, aerospace, medical, printing, textile, and electronic because of their ability to resist deformation at elevated temperature, excellent wear and thermal shock resistance, chemical inertness, superior electrical properties, and lower density [1–5]. On contrary, hard and brittle nature (~1200–2200 Knoop hardness and ~3–5 MPa-m½ fracture toughness) of structural ceramics causes serious limitations toward machining into desirable components using conventional machining techniques such as grinding, cutting, polishing, and their derivative processes [5–11]. In addition, these processes are inherently associated with several disadvantages such as undesirable tool wear, inadequate dimensional accuracy, mechanical or thermal damage to workpieces, lower material removal rates, and surface and subsurface micro-cracks [5,12–16]. Among these conventional machining techniques, grinding is the most popular method to fabricate structural ceramics with good surface finish and higher dimensional accuracy regardless of their longer machining time and higher operating costs [6–8,17]. Hence, for various industrial applications a more efficient and economical machining technique is sought.

In this regard, laser based unconventional machining (non-contact laser beam) can be considered as an effective solution to manufacture complex components from the structural ceramics [1,2,5,17–29]. The main characteristics of laser machining, which are practically not possible to attain by conventional techniques, are (i) laser beam is highly directional, coherent, and monochromatic (same wavelength), (ii) laser beam delivers a high energy/power in a small concentrated area (~$0.1\ mm^3$), (iii) generates higher temperatures (>5000 K) in a very short laser-material interaction time (<1 ms), (iv) higher heating and cooling rates (~10^4 K/s) due to absorption of high energy laser beam and self-quenching by bulk material, respectively [17–21].

To improve the quality of laser machining, the considerable amount of experimental and numerical/computational works [1,2,5,15,21–23,30–46] were carried out by employing various types of lasers (CO_2, excimer, and Nd:YAG) and their operating modes (continuous wave (CW) or pulse mode (PM)). Especially, for structural ceramics, the PM lasers (pulse width in millisecond range) are more suitable since the lasers concentrate their output energy into series of shorter time high-power (~$10^7\ J/m^2$) pulses at regular intervals (1–100 Hz) [1,2]. As a result, significant volume

* Corresponding author. Tel.: +1 940 565 2031; fax: +1 940 565 4824.
E-mail address: Narendra.Dahotre@unt.edu (N.B. Dahotre).
URL: http://mtse.unt.edu/Dahotre/ (N.B. Dahotre).
[1] Current address: Mechanical Engineering Technology, Oklahoma State University, Stillwater, OK 74078, USA.

http://dx.doi.org/10.1016/j.jmapro.2015.04.002
1526-6125/

of material is removed at higher material removal rates predominantly by evaporation and partly by melt ejection and dissociation [1,2]. However, to achieve higher material removal rate along with the desired surface finish is still a challenging task. In the past, many researchers [1,2,5,30,31] used the experimental and computational approaches to investigate the mechanisms of material removal during laser machining of various structural ceramics [1,2,9,35,47]. Although, the main focus of their works was to increase the material removal rates by selecting optimal laser processing parameters, they have completely disregarded the issues related to surface finish. Hence, the undesirable surface finish produced during PM laser machining is still one of the critical issues to be resolved.

Pulse mode (PM) laser machining can be categorized for one-, two-, or three-dimensional machining (Fig. 1a) to replicate a generic drilling, cutting, and milling (and/or turning) processes, respectively. Although, this classification is just for simplicity, the applications of laser machining are not kept limited to these processes only. In the past, the present authors have already employed an integrated experimental and computational methodology for PM one- and two-dimensional laser machining of structural alumina to investigate the influence of stationary (single [48] or multiple laser pulses [49]) and moving (multiple laser pulses with lateral overlap [50]) laser beam and its effects on evolving surface topography/physical texture/roughness (Fig. 1a). The detailed discussion of laser–material interaction and physical phenomena involved during one-dimensional (stationary laser beam with single [48] or multiple laser pulses [49]) and two-dimensional laser machining (moving laser beam, multiple laser pulses with lateral distance/overlap or center-to-center distance between two laser pulses [50]) and their combined influence on the process of generating surface topography can be found in the authors' previous publications [48–50]. Based on the results of these works, the surface roughness was found to increase with an increase in average laser energy density [48], pulse rate (10, 20, 30, 40, and 50 Hz) [49], and lateral distance (dist = 0.6, 0.5, 0.4, 0.3, 0.2, 0.1 mm) or laser beam overlap (0, 17, 33, 50, 67, and 83%) [50]. It was also observed that the increase in crater depth and pile-up height of the machined material around the machined cavity was mainly due to the evaporation induced material lost and recoil pressure-induced fluid flow, respectively.

In an extension of these works and to complete the final category of three-dimensional (3D) laser machining, the present article presents the study on the effect of PM moving laser beam (multiple laser pulses) on the surface topography (finish/roughness) during three-dimensional laser machining to mimic/replicate a generic three-dimensional milling process (Fig. 1a). Particularly, the 3D laser machining is specifically intended to process large area or volume and complex geometries. However, due to the smaller beam diameter (~0.6 mm), the laser machining of large area or volume is carried out by successive laser racks with the combination of lateral overlap distance (center-to-center distance between two consecutive laser pulses, D_L) and transverse overlap distance (transverse distance between two laser tracks, D_T) with various scanning configurations (long run, sort run, cross run, spiral run, etc.) (Fig. 1a and b).

In light of this, the present article investigated the influence of PM moving laser beam (multiple laser pulses) with combination of both lateral overlap distance (D_L) and transverse overlap distance (D_T) and its corresponding lateral overlap $\left(O_L = \frac{D-D_L}{D} \times 100\right)$ and transverse overlap $\left(O_T = \frac{D-D_T}{D} \times 100\right)$, in % respectively, on the surface topography (physical texture/roughness) during 3D laser machining (Fig. 1b) via an integrated experimental and computational approach. This integrated approach can overcome the difficulties associated with the in situ measurements of thermophysical properties (temperature, cooling rates, surface roughness, etc.) during laser machining because heating/melting/vaporization occurs in a small confined zone for very short time duration. In this way, this approach can provide more insight into understanding the laser-material interactions during subsequent laser tracks and their consequent effects on evolving surface roughness/topography/profile/physical texture. Hence in this work, unlike authors' previous two-dimensional laser machining computational model [50], an advanced computational model was designed and developed to incorporate the combine effect of both lateral and transverse overlaps (Fig. 1b) with incorporation of temporal and spatial heat built up during multiple laser tracks by using the multiphysics finite-element modeling approach followed by its validation with the experimental observations.

2. Multistep computational model

As explained earlier, 3D laser machining can be carried out with various scanning configurations. However for simplicity, in the present case, the PM 3D laser machining, the laser beam is moving continuously along the principle longitudinal axis (*X*-axis) with predefined scanning speed (Vin) and pulse rate or pulses per second (*f*) to complete each laser track (1st laser track – A, laser beam is ON in forward direction) (Fig. 1). The laser beam overlap or lateral overlap distance ($D_L = \text{Vin}/f$) is the center-to-center distance between two consecutive laser pulses, which is estimated based on the selected scanning speed (Vin) and pulse rate or pulses per second (*f*). Once the laser beam completes the laser track, the laser beam is turned OFF and the focusing head or workpiece is programmed to index along *Z*-axis by the preset transverse overlap distance (D_T) followed by the consecutive laser track (2nd laser track – B, laser beam is ON in forward direction) (Fig. 1). Similarly, this cycle continuously runs for '*n*' number of laser tracks along the surface profile to machine the large surface area and therefore resultant surface topography is evolved (Fig. 1).

Based on the selected transverse overlap value, the interaction of these consecutive laser tracks (e.g. 1st laser track – A and 2nd laser track – B, or successive laser tracks) dramatically influence the resultant surface topography (Fig. 1b). In this regard, the selection of laser machining parameters and their effect on overlapping region caused by lateral overlap distance (D_L) and transverse overlap distance (D_T) and its corresponding lateral overlap (O_L) and transverse overlap (O_T), in % respectively, are very crucial and they play a significant role in generating the resultant surface roughness. Therefore, in 3D laser machining, both lateral overlap (D_L) and transverse overlap (D_T) can be appropriately varied by selecting appropriate laser parameters (scanning speed and pulse rate) to achieve the desired surface topography.

In view of this, a computational model was designed and developed on the basis of a multiphysics approach on commercially available COMSOL^{TM} finite-element platform to precisely mimic the moving PM 3D laser machining process for structural alumina by incorporating both lateral (O_L) and transverse (O_T) overlaps (in %). To achieve higher modeling accuracy, the present multiphysics (heat transfer and computational fluid dynamics) computational model incorporated temperature-dependent material properties of structural alumina available in the open literature, the phase change effects due to temperature along with body force (gravitational force with Boussinesq approximation) and surface forces (shear and normal stresses). The shear stresses (tangential component) took into account the temperature dependent surface tension and viscosity whereas the effect of recoil pressure due to vaporized substrate material as function of temperature on normal stresses was considered. The other modeling assumptions are: (i) laser beam profile is in Gaussian distribution (TEM_{00} mode), (ii) material is isotropic and opaque, (iii) evaporated/ablated material is