Analytical modeling for prediction of temperature field and micro-crack depth during laser treatment of alumina for LAM

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Thermal Modelling,
Crack Depth Prediction.

ABSTRACT

Industrial applications of structural ceramics like alumina have increased with time, due to some of their properties being superior to other metals and alloys. But machine ceramics, through conventional machining, is very difficult and expensive, while keeping its properties and integrity under control. Preheating of ceramics, prior to machining, forms thermal micro-cracks on the surface due to severe thermal stress induced which may make the machining easier by reducing the cutting force requirements. Prediction of the crack depth can be very helpful to select the appropriate depth of cut during machining of alumina for efficient machining. An analytical model has been developed for the profile prediction of temperature induced and rate of cooling during laser scanning of alumina. Further, this temperature distribution data has been used to predict the thermal stress distribution in the work piece, which can be used to predict the crack depth develop in alumina ceramic.

1. Introduction

Ceramic materials e.g. Al_2O_3 and SiC etc. are finding their application in a number of engineering products due to their inherent properties link low density, corrosion resistance, superior wear and high refractoriness. But, due to the brittle nature of ceramic materials, the most commonly used machining methods like grinding and diamond machining, are the only options to machine such materials in order to achieve the accuracy required. Though conventional machining may meet the required surface finish and dimensional accuracy, the issue remains the high cost associated with these methods. So, there is a natural demand of efficient processing methods to machine ceramics at high MRR, while achieving reduced wear and enhanced surface integrity. In recent years, Laser-assisted machining (LAM) has emerged as an efficient technique to machining ceramics at high MRR with enhanced surface quality.

Laser treatment of ceramic prior to the machining represents an alternative technique for the above said problems. LAM is a hybrid machining process where a small area on the workpiece just in front of the cutting edge of the tool is targeted with collimated laser beam to increase the temperature of the workpiece subsurface region. This increment in the temperature of the work-piece makes the material removal easier as it induces micro-cracks and reduces hardness of such treated ceramic.

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2. Literature Review

Due to inherent hardness and brittle nature of ceramics it is difficult to machine these materials by conventional methods of machining (Samant & Dahotre, 2019). Due to high tool cost and as well as high tool wear the overall cost of machining is very high. In addition to that, the surface integrity issues like sub surface damage and cracks also occur during conventional machining. Due to these researchers have attempted to machine the ceramic materials with laser assist. Due to laser heating, the ceramics like silicon nitride become relatively softer (Lei et al., 2000 & 2001) and due to their decreased strength material removal occurs due to plastic deformation combined with brittle fracture instead of only brittle fracture. Pfefferkorn et al. (2004) have observed that after laser treatment, micro-cracks were present in PSZ ceramics in the heat affected zone. It indicates that laser heating of ceramics introduced higher thermal stresses resulting in these cracks. This crack depth was found to be increasing with attained surface temperature (depending on laser power). If a smaller depth of cut is selected than this crack depth, the remaining crack depth after machining would detrimental for the mechanical properties of the machined work piece. It calls for a controlled material temperature that in turn will produce controlled crack depth that will make the material removal easier without any damage remaining in the component machined using LAM. In another work (Tian & Shin, 2006) related to laser assisted machined Si_3N_4, compressive residual stresses were observed both in the hoop and axial directions. Though, the magnitude of such stress was found to be smaller than that produced during grinding process as the softened glassy phase in ceramic material relieved the stress significantly in the machining zone. During processing of fused silica, Song et al. (2019) have shown that as compared to conventional machining, a better surface integrity can be achieved with LAM. The distribution of micro-cracks for different process parameters during laser assisted turning of alumina have been investigated (Xiaohong et al., 2014). It was found that the crack formation mechanism and crack types were different. The cracks were formed due to thermal and mechanical stress, separately. A neural network model with back propagation was used to define the nonlinear relationship among the process parameters and processing requirements. The model was found to be effective in predicting ceramic surface integrity after machining. A two-step laser-assisted wet grinding of alumina with laser-induced thermal cracks was performed and compared with the wet grinding (Zhang et al. (2014). The higher material removal rates along with lower forces could be achieved for LAWG.

Most of the studies have reported only few parametric effect on machining like laser power, cutting speed, feed and DOC, however, simultaneous influence of various other parameters (e.g. pre laser scanning, cutting tool parameters, and material coatings etc.) also need to be explored. Also, Simulation based models need to be developed to analyse the temperature distribution profile and cooling rate and its effect on material and surface integrity. The objective of the present work is to formulate an analytical model for temperature and thermal stress prediction to predict temperature and cooling rate prediction in the depth direction. This will help to calculate the thermal stress generated due to temperature profile, and to predict the depth of crack formation.

3. Model Development

The model predicts the temperature profile on the surface and beneath. Further it is extended to find the temperature at the same spot during cooling period. Here alumina (95%) taken as a work piece on which fibre laser has been irradiated.

3.1. Temperature prediction module

This module considered some assumption. The laser beam is considered to be flat. Heat conduction is considered to be one dimensional (in depth direction) because of very low interaction time due to high cutting speed. Heat input is considered to be uniform during the laser irradiation time. The convection and radiation losses from the surface are considered to be negligible. At each step during the iteration value of C_p, K has been taken at the average temperature of surface and the surrounding while density (ρ) is assumed to be constant during the process

The governing equation for one dimensional heat conduction is

$$\frac{\partial T(z,t)}{\partial t} = \propto \frac{\partial^2 T(z,t)}{\partial z^2} \qquad \text{..................(1)}$$

The initial condition is considered as: $T(z,0) = T_0$, for $0 \leq z \leq \infty$, t = 0, means the temperature at the surface at the time t=0 is room temperature i.e. T_0

All the heat absorbed is considered to be conducted. So the boundary condition at the surface (z = 0) becomes:

$$-k\frac{\partial T(0,t)}{\partial z} = \delta H \qquad \text{....................(2)}$$

Where H is the absorbed laser energy density. Further, solving the 1D heat conduction equation by applying the before said boundary condition and initial condition for temperature rise during laser heating at any depth z from the surface becomes (Carslaw and Jaeger 1959):

$$T(z) = T_r + \left[\frac{H}{K}\right]\delta \cdot ierfc\left({}^{z}/_{\delta}\right) \qquad \text{.....................(3)}$$

Similarly, for equation for temperature drop during cooling at any time 't', larger than laser interaction time, becomes:

$$\Delta T(z, t \geq \tau) = \left[\frac{H}{K}\right]\left[\delta \cdot ierfc\left(z/_{\delta}\right) - \delta^{*} \cdot ierfc\left(z/_{\delta^{*}}\right)\right] \qquad \text{.....................(4)}$$

Further, the diffusion length, δ and δ^* can be expressed as,

$$\delta = 2\sqrt{\frac{K\tau}{\rho \cdot C_p}} \text{ and } \delta^{*} = 2\sqrt{\frac{K(t-\tau)}{\rho \cdot C_p}} \qquad \text{.....................(5)}$$

Where, H is absorbed laser power density at z=0, which is $H = \frac{P_l \cdot (1-R)}{\pi \cdot a^2}$, P_l is the laser Power, R is the reflectivity of the material, 2a is Beam spot diameter, τ is Laser interaction time (2a/v), v is the cutting velocity, z is depth from the surface, ρ is density of the material, C_p is Specific heat at constant pressure, K is Thermal conductivity of the material.

The flow chart for the analytical model is given in Fig 1.

From the temperature dependent material data provided by a referred work (Chang & Kuo, 2010). The curve fitting has been done for the temperature dependent properties like specific heat and thermal conductivity (C_p and K) of alumina which will be used as input in the temperature prediction modelling. Equations 5 and 6 show the polynomial curve fitting of the specific heat and thermal conductivity.

$$C_p = 4 \times 10^{-7}T^3 - 0.0013T^2 + 1.4002T + 728.16 \quad (R^2 = 0.9992) \qquad \text{...............(6)}$$

$$K = -2 \times 10^{-8}T^3 + 7 \times 10^{-5}T^2 - 0.0737T + 34.422 \quad (R^2 = 0.9995) \qquad \text{...............(7)}$$

Where T is the absolute temperature.

Fig. 2a shows the variation of temperature in the depth direction during laser heating. The surface temperature of the work-piece is about 1180 °C with 90 W laser power and 15mm/s scanning velocity. The reflectivity of the alumina is considered to be 80% obtained from the literature review. The temperature sharply goes down in the depth direction more or less in a linear fashion. The temperature come down from 1180 °C at the surface to 700 °C at a depth of 250 µm. This is probably due to the non-conducting nature of the alumina ceramics.

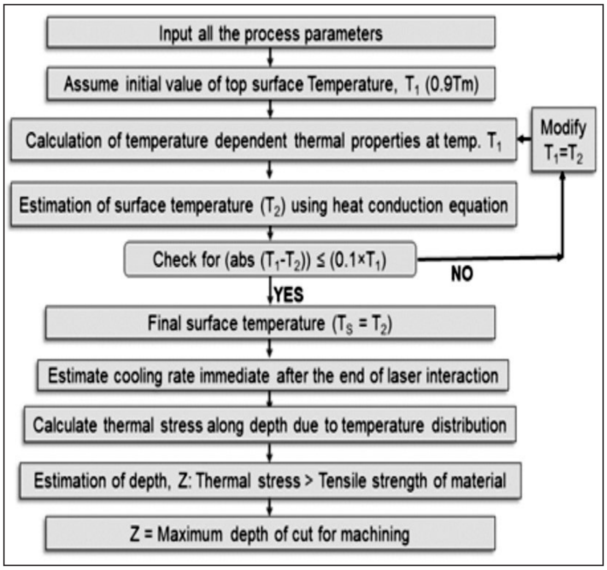

Fig. 1. Model flow chart for the prediction of surface temperature, cooling rate and thermal stress.

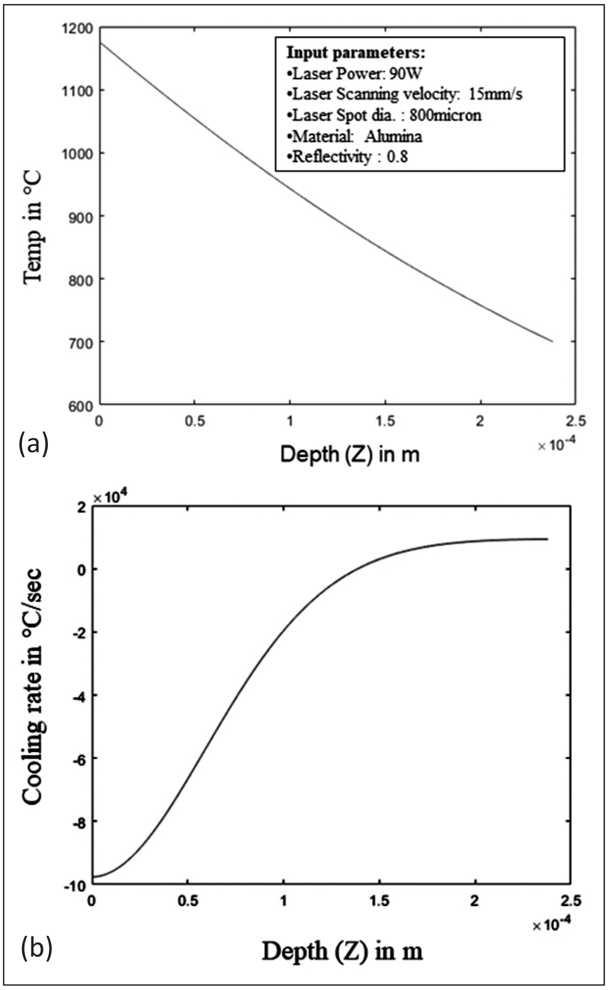

Fig. 2. Variation of temperature in depth direction (a) during heating cycle (b) cooling rate in the depth direction.

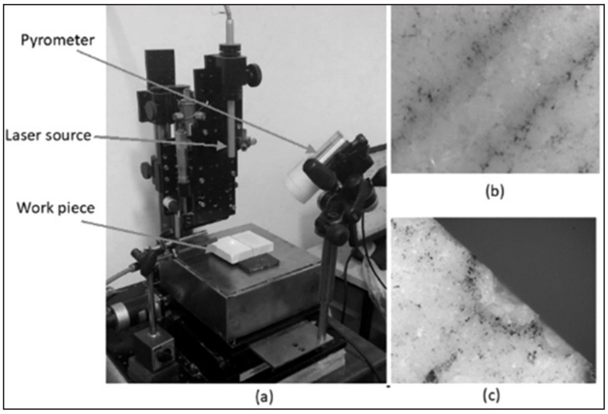

Fig. 3. Laser preheating with fiber laser
(a) Experimental setup (b) and
(c) Longitudinal and cross sectional view of scanning track under microscope.

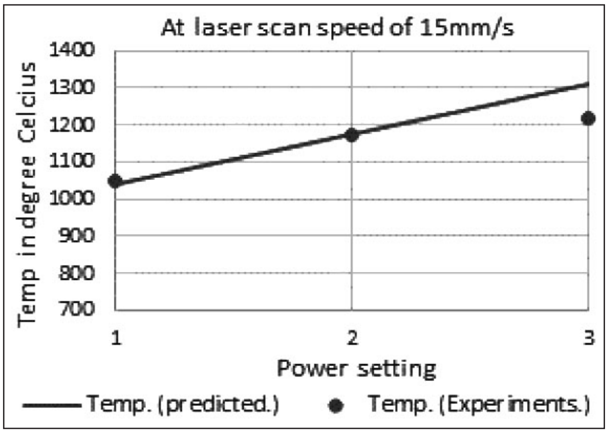

Fig. 4. Comparison of experimental and simulation results of surface temperature.

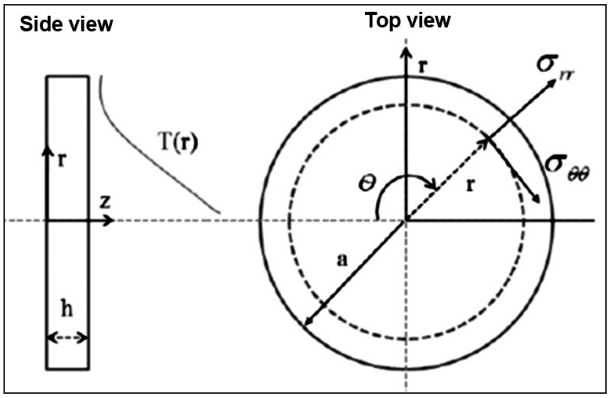

Fig. 5. A circular disc model of thickness 'h' and radius 'a', exposed to a temperature distribution T(r), showing tangential and radial stresses (Boley & Jerome, 2012).

Variation of cooling rate in the depth direction is shown in Fig. 2b. At z=0 means at the surface the cooling rate is extremely high i.e. 10×10^4 °C/sec. As there is heat removal during cooling the heat transfer is in negative values. This high cooling rate suggests that there must be severe thermal tensile stress. As a result, the material must have failed and micro-cracks must have generated at the surface as well as in the depth direction of the alumina work piece. Which will help in reduction of cutting forces due to easy removal of the chips.

3.2. Experimental validation of temperature module

Fig. 3 shows the laser scanning setup having a fiber laser (wavelength 1064 nm, Continuous wave type)) generating unit of maximum power 400 W, from which laser get transmitted through the optical fiber cable to the collimator.

The beam profile is Gaussian intensity profile with beam diameter of 800µm. A pressurized air outlet is provided at the opening of the collimator to protect the lens from blown particle of the work piece. The platform on which the work piece is placed can move in X and Y directions with the help of stepper motors and a microcontroller. A computer system is there to control the motion of the platform through programming as well as manually. An IR-pyrometer has been used to measure the temperature.

Here alumina (95%) work piece of size 80mmX 52mmX 18mm is taken as a work piece for the laser treatment. Laser is scanned on this rectangular surface at three power settings i.e. 80, 90 and 100 W at constant scanning speed of 15 mm/sec. Three laser scanning are done for each laser power setting. The average temperature of these three scanning are reported as the result. Fig. 4 shows the comparison between the simulation and experimental results for above three power setting at 15 mm/s laser scan speed. As it can be seen in the graph, the predicted temperatures are found to have a good match with the experiments, though at higher power settings there is a small deviation (around 8.5%) between experimental and simulated temperatures predictions which may be due to system inherent losses or pyrometer accuracy limits (±5%).

3.3. Stress and crack prediction module

As shown in the Fig. 5, the circular disc is subjected to a temperature distribution of T(r) due to laser irradiation at the centre.

With some assumption stated below, the tangential and radial stresses at a distance 'r' from the centre of a solid circular disc of radius 'a', being exposed to a temperature distribution, T(r), can be given as below (Boley and Weiner, 2012).

$$\sigma_{rr} = E\left[\frac{1}{a^2}\int_0^a \alpha T(r) r dr - \frac{1}{r^2}\int_0^r \alpha T(r) r dr\right] \quad ....(8)$$

$$\sigma_{\theta\theta} = E\left[-\alpha T + \frac{1}{a^2}\int_0^a \alpha T(r) r dr + \frac{1}{r^2}\int_0^r \alpha T(r) r dr\right] \quad ....(9)$$

Where, E is the young's modulus, and α is the thermal expansion coefficient.

Assumptions taken are: The disc is considered to be very thin (h/2a <<1). i.e. the stresses are assumed to be of plane stress. The interaction between the stresses in different planes has been neglected in the depth direction. The value of α, i.e. coefficient of thermal expansion is taken as negative. This is because when the heat source is taken off, the material begins to contract. This thermal contraction generates tensile stresses in the material.

For thermal stress prediction the scanning track can be considered to be a parallel array circular plates. The temperature variation in the depth direction is considered to be the variation of temperature in radial direction for the half circle. The temperature distribution T(r) on the circular disc is obtained from the curve fitting of the results obtained from the previous temperature prediction simulation. Resulted temperature profile from the analytical modelling get fitted with fifth order polynomial as shown in the Fig. 6.

$T=-31.499z^5 + 310.23z^4 - 1188.8Z^3 + 2275.7z^2 - 2328.1z + 1153.6$ ($R^2 = 0.9994$) ....(10)

4. Results and Discussion

Fig. 7 shows the variation of the thermal stress obtained from the simulation in the depth direction for a laser scanning speed of 15 mm/s and a laser power of 90 W. The tensile stress comes to near about zero from 1700 MPa at the surface within the depth span of 3mm. Initially it decreases rapidly up to 1 mm then it gets slower.

Heating during laser scanning generates rapid material expansion followed by rapid contraction during subsequent cooling. During heating, the expansion is constrained by the surrounding rigid material, which induces compressive stresses. Whereas during subsequent cooling, tensile residual stresses get generated. Fracture occurs when (Thermal stress generated due to temp gradient) > (Critical Thermal fracture stress).

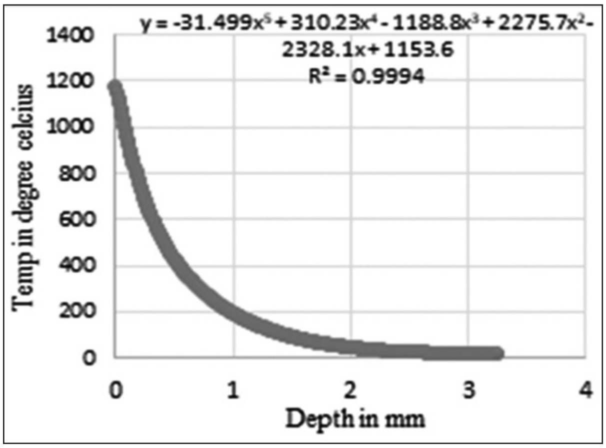

Fig. 6. Curve fitting of the obtained temperature data from simulation.

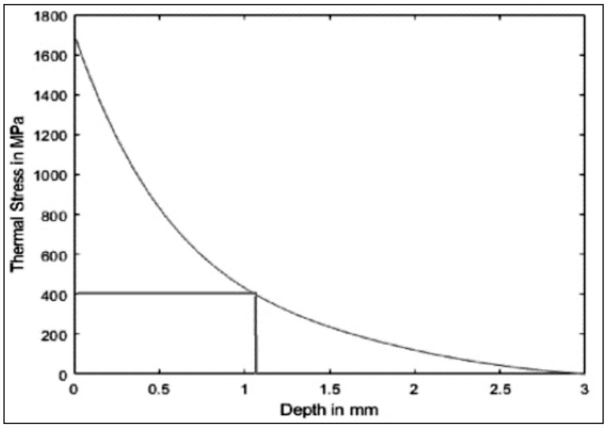

Fig. 7. Resulting radial thermal stress σ_{rr} in depth direction due to laser scanning of alumina at 90W and 15 mm/s scanning speed and comparison with tensile strength.

Thus the crack nucleates. Severe thermal stress will generate micro-cracks which will break the continuity and reduces the strength at the locality of the material. Prediction of the depth up to which crack might have generated is important for selecting the depth of cut during machining. Here in this modelling crack is assumed to occur at a point when the resulting thermal stress exceeds the tensile strength of the material. Considering the tensile strength value of the alumina to be 400 MPa (red line in Fig 7), the depth of crack prediction can be seen as 1.1mm from the surface approximately.

4.1. Micro-hardness test of laser scanned region

Due to the development of cracks, the micro hardness of the scanned track might have got reduced. To check for the same reason, the micro hardness tests have been done on the

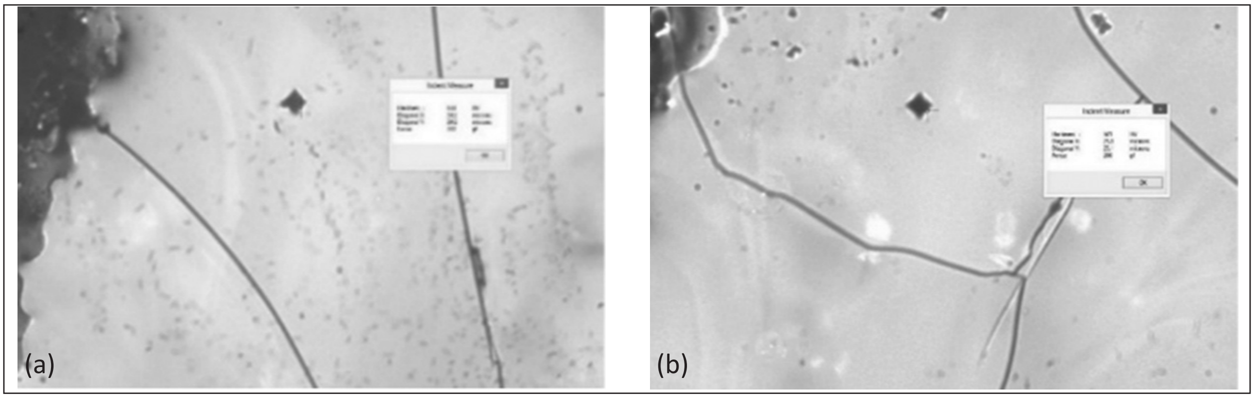

Fig. 8. Micro-hardness tests done on the laser scanned tracks.

laser scanned tracks at three different regions, as shown in the Fig. 8a & 8b with the help of a ZHVµ micro Vickers hardness tester. The average of these three tests are taken for the comparison with the theoretical hardness value of the untreated surface. Mean hardness was found to be 612hv, which is the equivalent to 6.002 GPa. When comparing this altered hardness value with the untreated material hardness i.e. around 15 GPa (Chang & Kuo, 2007), there is more than 50% reduction in the theoretical hardness value of alumina. The visibility of indentation marks during hardness test makes a clear idea that there is a brittle to ductile transition in the surface. As a deduction from this result it can be stated that the laser treated surface can be further be machined with relative ease.

5. Conclusion

Laser treatment, specifically pre-heating has been implemented by many researchers to increase the machinability of hard materials like ceramics. In the present work an analytical model has been developed to predict the interaction of laser with the ceramic material in terms of heating and cooling rates and stresses generated therein. The following are the conclusions form the work done:

- Surface temperature predicted was found to have a good match with the experimental results
- Variation of temperature in depth direction is predicted and based upon that the variation of thermal stress along the depth direction is also predicted.
- At 90 W and 15 mm/s scanning speed the depth of crack formation is predicted to be approximately 1.1 mm.
- Micro-hardness at the laser scanned track is found to be reduced by approximately 50%. Which would result in easier machining of Alumina ceramic.

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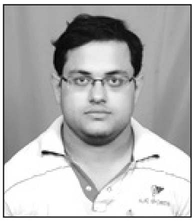

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