Lasers Beam Micromachining

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Micromachining processes are used for creating micro features (1-999µm size) by selective controlled removal of excess material.

**Micromachining Processes**

**Conventional Micromachining**
(HT > HW, Wedge Tool, Direct Contact)
- μ-Turning
- μ-Drilling
- μ-Milling
- μ-Abrasive Grinding
- μ-Abrasive Finishing

**Unconventional Micromachining**
(HT < HW, Image Tool, Non Contact)
- μ-Electro-Discharge Machining
- μ-Beam Machining Processes
- μ- Electro-Chemical Machining
- μ- Chemical Machining Processes
- μ- Ultra-Sonic Machining
- μ- Jet Machining Processes
**Laser:** Light Amplification by Stimulated Emission of Radiations

Interaction of Photon with Material

- **Absorption:**
  - $hv = E_2 - E_1$

- **Spontaneous Emission**
- **Stimulated Emission**

Limited class of materials (mainly admixtures) have ability to show Stimulated Emission Phenomenon (Lasing Action). Materials showing Lasing action are called as Lasing Materials.
Properties of Normal Light and Laser Light

**Normal Light**
- Non-Monochromatic
- Non-Coherent
- Non-Collimated

Power Density = 8 W/m²

**Laser Light**
- Monochromatic
- Coherent
- Collimated

Power Density = 8 X 10⁹ W/m²
Types of Industrial Laser:

Depending on the followings:

1. The state of Lasing Material
   (Solid OR Gas)

2. The range of the laser wavelength
   (Short OR Large Wavelength)

3. The mode of operation
   (CW-Laser OR PW-Laser)

4. The pumping method
   (Optical Pumped OR Discharge Pumped)
Laser System:

Beam Generation Unit  Beam Delivery Unit  Workpiece Positioning Unit
Beam Generation Unit

- Lasing Medium Unit
- Energy Pumping Unit
- Feedback Unit
- Chiller Unit

Feedback System

100% Reflective Mirror

Lasing Medium

95% Reflective Mirror

Energy Source
Beam Delivery Unit

- Beam Splitter
- Mirrors
- Focusing Lens

\[ d = \frac{8 \lambda f}{\pi W} \]
\[ b = \frac{8 \lambda f^2}{\pi W} \]
Lasers for Micromachining

Solid Lasers

PW (ns/ps/fs) Solid Lasers

- Nd: YAG laser
- Nd: YVO4 laser
- Er: Fibre laser
- Ti: Sapphire laser
- Yb: YAG laser
- Yb: KGW laser
- Yb: KYW laser

Gas Lasers

PW (ns) Excimer laser

- ArF (193 nm)
- KrF (248 nm)
- XeCl (308 nm)
- XeF (351 nm)

CW Diode Lasers

- AlGaAs (750-900 nm)
- InGaAs (980 nm)
- AlGaInP (630-680 nm)
- InGaAsP (1200-1600 nm)
Laser Micromachining Processes

- Laser Microdrilling (1-D)
- Laser Microcutting (2-D)
- Laser Microgrooving (3-D)
- Laser Microturning (3-D)
- Laser Micromilling (3-D)
Laser Micromachining

**Laser Microdrilling**
- Holes with eccentricity value below 5% and surface roughness below 5μm
- The erosion front, located at the bottom of the drilled hole, propagates in the direction of the laser beam in order to remove material
- *Laser Percussion Micro Drilling is used to make small holes* < 0.6mm
Overview of laser beam drilling methods
50 μm diameter hole in steel

125 μm diameter holes in 0.5 mm alumina

Injector holes, 60 Deg
Laser Microcutting

Laser is used for Cutting micro thickness sheets by giving X-Y motion to the table over which sheet form of workpiece is placed and controlled by CNC controller.

This is also called as Two-Dimensional Cutting

It may be either of the following:

Laser Straight Cutting
Laser Curved Cutting
Laser Trepan Cutting
Laser Micromarking

- Laser marking is the world's largest laser application
- Relevant to all sectors
- Virtually any material can be laser marked to produce robust images, texts and codes
Laser Microturning

(a) Helix Removal

(b) Ring Removal
Laser Micromilling

- In Laser Micro Milling two laser beams are positioned at oblique angles.
- Small incidence angle is made between the laser beam direction and perpendicular direction to the surface.
- For large incidence angles, the material removal rate is reduced, but the surface quality improves.
Mechanism of Material Removal in Laser Micromachining

- The Laser is absorbed in a skin layer of workpiece surface by the free electrons within 1 fs.

- Electrons start to convert laser energy into heat energy after 1 ps which is the relaxation time for electron and phonon.

- Heat energy diffuses from skin layer to the bulk material by conduction.
  Laser energy diffuses (heats) up to 10 nm depth in 1 ps time.

- The material properties and laser parameters decides whether Fusion and Ejection, Vaporization, or Ablation dominate in the material removal process.
Mechanism of Material Removal in CW Laser Micromachining

- The CW laser removes material primarily by Fusion and Ejection.
- Resolidified layer and Micro cracks are significantly visible on the machined surface.
Mechanism of Material Removal in Nanosecond Laser Micromachining (Long Pulse)

- In ns-Pulse Laser Micromachining the pulse duration is larger than the time required for transfer of laser energy for absorption and conversion to heat energy which is responsible for laser machining (1 fs +1 ps).

- This heat energy diffuses from skin layer to the significant thickness of bulk material by conduction.

- Material is mainly removed by fusion and ejection.

- Re-solidified layer and Micro cracks are normally visible on the machined surface.
Nanosecond Laser Micromachining
Mechanism of Material Removal in Picosecond Laser Micromachining (Short Pulses)

Pulse duration lies between 1 ps to 10 ps (Near the electron-phonon relaxation time of around 1 ps)

- The Laser energy focused on the material surface is absorbed in a skin layer by the free electrons within 1 fs.
- Very little or negligible heat conduction takes place and hence very little or negligible melt depth is formed.
- Hence very small or negligible amount is melted which is easily ejected leading to negligible re-solidified layer and micro cracks.
- Suitable for micromachining of hard and transparent materials such as Diamond, Ceramics, and Glasses.
Advantages
No thermal damage: High machining quality, heat sensitive material machining
Unmatched accuracy: Down to 100 nm can be machined
Mechanism of Femtosecond Laser Micromachining (Ultrashort Pulse)

- Here the pulse duration is very short (fs) in comparison to electron-phonon relaxation time (1 ps) as well as Laser Intensity is also very High.
- Only electrons within the thin surface layer are heated.
- No energy is transferred to the lattice. All energy is stored in a thin surface layer only.
- No melt depth is formed hence it is a very precise machining operation.
- Non recast layer or HAZ is formed.
- Capable to create 3D feature inside a transparent material.
CW laser

ns laser

ps/fs laser

Target material

Target material

Target material

Dark area: Heat affected zone

Blue line: Shock waves
Studies in Laser Micromachining

- Development of Set-Up of the Machine for
  - Feasibility Study of the Process
  - Performance Study of the Process
- Development of Mathematical Model for
  - Simulation of the Process
  - Optimization of the Process
Development of Set-Up of the Machine

Knowledge of Mechanical, Electronics and Computer Technology are required
Development of Mathematical Model

- Mathematical Modeling is the mathematical representation of the process behavior
- Mathematical model establishes relationship between input and output parameters to represent the performance of the process

\[ Y_i = f(X_j) \]
Analytical Modeling

- Analytical model can be derived from basic physical and chemical phenomenon of manufacturing process in terms of Mathematical Equations (Normally Differential Equations). It gives generalized solution under varied operating conditions using Exact Method OR Numerical Method.

- A large number of unrealistic assumptions are taken for making model solvable are the major limitations of analytical modeling.
Experimental Modeling

- Experiments are conducted to get Input-Output data and then Mathematical Model is developed using any one of the following method:
  - Regression Analysis Modeling (RAM) (OPAT)
  - Response Surface Modeling (RSM) (MPAT)
  - Neural Network Modeling (NNM) (MPAT)

- Every experimental model can be used for accurate description of process behavior for the limited range of manufacturing conditions only
- High experimentation cost and large experimentation time are the major limitations of experimental modeling.
Mathematical models are used for

- Simulation of the process

- Optimization of the process
Simulation of LBMM

Using mathematical Model finding Output Parameters for a given set of Input Parameters
Optimization of LBMM

Using mathematical Model finding appropriate set of Input Parameters for Desired Output Parameters (Optimum)

Single Objective Optimization (SOO) Multi-Objective Optimization (MOO)
Differential Equations are used to describe the behavior in terms of primary variable in some enclosed domain (D) surrounded by a boundary (B) on which certain boundary conditions are specified.

Governing Equation: \( L(\phi) + f = 0 \) \quad \text{in D}

Boundary condition: \( M(\phi) + r = 0 \) \quad \text{on B}
GENERAL FINITE ELEMENT FORMULATION

- Weak Formulation
- Discretization and Finite Element Approximation
- Development and Evaluation of Elemental Equations
- Assembly
- Application of Boundary Conditions
- Solutions
ANN based Modeling of LBMM

ANN based Modelling is gaining popularity due to its generalization capabilities from imprecise and noisy data and its ability to approximate non-linear and complex relationship between process parameters and performance characteristics.

Capability of ANN are governed by

- Characteristics of Neuron
- Network Architecture
- Training Algorithm
ANN acquires the knowledge through a learning process and interneuron connection strength known as synaptic weights are used to store the knowledge.

The procedure used to perform the learning process is called learning algorithm which modify the synaptic weights of the network in a systematic way to attain the desired objective.
FEM-ANN Hybrid Approach Modelling and
GRA-PCA Hybrid Approach Optimization of
Laser Beam Percussion Micro Drilling Process
FEM -ANN Hybrid Approach Modeling

Simulated results for data generation

FEM Model

\[ X_1, X_2, X_3, \ldots, X_j \]

\[ Y_1, Y_2, Y_3, \ldots, Y_i \]

Generated data for Training and Testing

ANN Model

\[ X_j \]

\[ Y_1, Y_2, Y_3, \ldots, Y_i \]
GRA-PCA Hybrid Approach of Multi Objective Optimization

1. Predicted values of each quality characteristics from developed ANN based process model

2. Grey relational generating

3. Calculation of grey relational coefficients for each quality characteristics

4. Determination of grey relational grades on the basis of weights obtained for each quality characteristics using PCA

5. Finding the optimum values of each process parameters using the response table of grey relational grade

6. Determination of percentage contribution of each input process parameter using Analysis of Variance (ANOVA)

7. Performing conformance test
Hole Quality

Salient geometrical features of laser drilled hole
Steps in Modeling and Optimization of LBPM

- To develop a 2-D axisymmetric Finite Element Method (FEM) based transient thermal model incorporating the temperature dependent thermal properties, optical properties, phase change phenomena and change of laser beam radius with depth.

- To simulate and predict Hole Taper ($T_a$), Heat Affected Zone (HAZ) and Material Removal Rate (MRR) during Nd:YAG LBPD of difficult to laser drill thin sheet of Aluminium and Nickel superalloy.

- To conduct experiments on pulsed Nd: YAG laser beam machining system to validate the values predicted by the model.

- To investigate the effect of pulse width, pulse frequency, peak power and sheet thickness on, $T_a$, HAZ and MRR during Nd: YAG LBPD using the developed model.

- To develop soft computing based intelligent prediction model of Nd: YAG LBPD using coupled approach of FEM and ANN.

- To apply the coupled approach of Grey Relational Analysis (GRA) and Principal Component Analysis (PCA) for the MOO of pulsed Nd:YAG LBPD.
## Reasons for Selecting the Input Parameters

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Reasons for selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse width</td>
<td>Determine the duration of laser–workpiece interaction and amount of molten material and thus control the size of hole.</td>
</tr>
<tr>
<td>Pulse frequency</td>
<td>It control the shape of hole</td>
</tr>
<tr>
<td>Peak power</td>
<td>Determine the amount of heat flux entering the workpiece</td>
</tr>
<tr>
<td>Sheet thickness</td>
<td>To analyse the change in interaction mechanism between laser beam and workpiece due to dimensional variation of the target material.</td>
</tr>
<tr>
<td>Output Parameters</td>
<td>Reasons for selection</td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Hole Taper</td>
<td>Predicts the geometrical accuracy of the drilled hole.</td>
</tr>
<tr>
<td>Heat-affected Zone</td>
<td>Show the extent of metallurgical distortion surrounding the hole due to high power density of laser.</td>
</tr>
<tr>
<td>Material Removal Rate</td>
<td>Helps to increase the cost effectiveness of the process or its productivity.</td>
</tr>
</tbody>
</table>
Reasons for Selecting the Sheet Materials

- Thickness: 0.7 mm, 1.0 mm, and 1.3 mm

<table>
<thead>
<tr>
<th>Aluminium alloy (Grade 40800)</th>
<th>Nickel superalloy (Inconel 718)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser drilling is difficult due to high thermal conductivity, low thermal diffusivity and high optical reflectivity.</td>
<td>One of the most difficult materials to drill by conventional method due to its high hardness, high strength at high temperature, tendency to react with the tool.</td>
</tr>
</tbody>
</table>

Finds wide application in Aerospace and aircraft industry due to high specific strength and specific rigidity of Aluminium.

Finds wide application in Air craft gas turbines e.g. combustion chamber, blades, vanes etc.
Steam turbine power plants e.g. blades, stack gas reheaters
Reciprocating engines e.g. turbochargers, exhaust valves etc
Nuclear power systems.

- To get the distinctive effect of thermophysical properties on hole characteristics and material removal during Nd:YAG LBPD
## Average thermo-physical properties of Aluminium alloy (Grade 40800) and Inconel 718.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Unit</th>
<th>Aluminium alloy</th>
<th>Inconel 718</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting range (T_m)</td>
<td>K</td>
<td>933</td>
<td>1533-1628</td>
</tr>
<tr>
<td>Density (\rho)</td>
<td>kgm(^{-3})</td>
<td>2702</td>
<td>8240</td>
</tr>
<tr>
<td>Specific Heat (C_p)</td>
<td>Jkg(^{-1})K(^{-1})</td>
<td>903</td>
<td>439</td>
</tr>
<tr>
<td>Conductivity (k)</td>
<td>Wm(^{-1})K(^{-1})</td>
<td>237</td>
<td>10.3</td>
</tr>
<tr>
<td>Latent Heat Fusion (H_m)</td>
<td>Jkg(^{-1})</td>
<td>360 x (10^3)</td>
<td>231 x (10^3)</td>
</tr>
<tr>
<td>Latent Heat boiling (H_v)</td>
<td>Jkg(^{-1})</td>
<td>10900 x (10^3)</td>
<td>6444 x (10^3)</td>
</tr>
<tr>
<td>Vapourisation Temperature (T_v)</td>
<td>K</td>
<td>2793</td>
<td>3100</td>
</tr>
<tr>
<td>Thermal Diffusivity</td>
<td>m(^2)s(^{-1})</td>
<td>0.000097</td>
<td>2.85</td>
</tr>
<tr>
<td>Density (\rho_l) (liquid phase)</td>
<td>kgm(^{-3})</td>
<td>2385</td>
<td>7420</td>
</tr>
<tr>
<td>Specific Heat (C_{pl}) (liquid phase)</td>
<td>Jkg(^{-1})K(^{-1})</td>
<td>1080</td>
<td>677</td>
</tr>
<tr>
<td>Conductivity (k_l) (liquid phase)</td>
<td>Wm(^{-1})K(^{-1})</td>
<td>100</td>
<td>29</td>
</tr>
<tr>
<td>Recrystallization temperature</td>
<td>K</td>
<td>473</td>
<td>1293</td>
</tr>
</tbody>
</table>
Thermal Modeling and Finite Element Simulation of Nd:YAG LBPD

- Temperature dependent thermal properties
- Temperature dependent optical property (absorptivity)
- Phase change
- Change of laser beam radius with change of depth

Thermal Model of LBPD

Temperature distribution using melt isotherm

1. Hole taper
2. HAZ
3. MRR
Assumptions

- The zone of influence of laser beam in workpiece is considered to be axisymmetric.

- The workpiece material is homogeneous and isotropic in nature.

- On-time of pulsed laser is considered to be much shorter than the pulse-off time and therefore plasma generation does not take place in the laser drilled hole.

- Gaussian spatial distribution of laser heat flux is assumed due to smooth drop of irradiance from the beam center towards radial direction.

- Multiple reflections of the laser radiation within the hole are neglected.
Governing Equation

\[
k(T) \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial T(r,z,t)}{\partial r} \right) + \frac{\partial^2 T(r,z,t)}{\partial z^2} \right] = \rho(T)C(T) \frac{\partial T(r,z,t)}{\partial t}
\]

where,

\[T = \text{transient temperature},\]
\[t = \text{time},\]
\[k(T) = \text{temperature dependent thermal conductivity},\]
\[\rho(T) = \text{is the temperature dependent density},\]
\[C(T) = \text{is the temperature dependent specific heat},\]
\[r = \text{radial distance}\]
\[z = \text{distance across the depth}\]

Thermal model of pulsed Nd: YAG LBPD
Boundary conditions

When \( t > 0 \)

\[
k(T) \frac{\partial T(r,0,t)}{\partial z} = \begin{cases} 
    h_c (T(r,0,t) - T_0) & \text{if } r > R \text{ on } B_1 \\
    q_{in} & \text{if } r \leq R \text{ on } B_1 \\
    0 & \text{during off-time}
\end{cases}
\]

\[
\frac{\partial T(r, z, t)}{\partial n} = 0 \quad \text{on } B_2, B_3, \text{and } B_4
\]

\( q_{in} \) = heat flux
\( R \) = radius of laser pulse
\( h_c \) = heat transfer coefficient
\( T_0 \) = room temperature

When \( t = 0 \)

\[
T(r, z, 0) = T_0 \quad \text{in } ABCD
\]
Flux at a distance $r$ from the beam axis

$$q_{in} = A_s \frac{2P_p}{\pi R^2} \exp\left(-\frac{2r^2}{R^2}\right)$$

$A_s =$ absorptivity of sheet material

$P_p =$ peak power of laser pulse

Peak power

$$P_p (W) = \frac{Average\ laser\ Power \ (W) \times 1000}{Repetition\ rate\ (Hz) \times Pulsewidth\ (ms)}$$

The change of laser beam radius with the depth

$$R = \frac{d}{2} \left[ 1 + \left( \frac{4\lambda(z_m + f_c)}{\pi d^2} \right)^2 \right]^{\frac{1}{2}}$$

$R =$ effective beam radius, $d =$ beam diameter, $f_c =$ focal length of lens, $z_m =$ the melt depth, $\lambda =$ wavelength of the laser beam.
Temperature dependent absorptivity

\[ A_s = \sqrt{\frac{4\pi c \varepsilon_0 \left[ 1 + \alpha_r (T(r,t) - T_0(r,t)) \right]}{\lambda \sigma_0}} \]

where,

\( \varepsilon_0 \) = the permittivity of vacuum,
\( \alpha_r \) = coefficient of resistance of the sheet,
\( \lambda \) = wavelength of Nd:YAG laser beam,
\( c \) = velocity of light
\( \sigma_0 \) = the target conductance at initial temperature.

Phase change consideration

\[ C(T) = \begin{cases} 
C_o + \frac{\Delta H_m}{\Delta T_m} & \text{from } T_m \leq T \leq T_m + \Delta T_m \\
C_o + \frac{\Delta H_v}{\Delta T_v} & \text{from } T_v \leq T \leq T_v + \Delta T_v 
\end{cases} \]

where,

\( C_o \) = normal constant specific heat
\( \Delta H_m \) = latent heats of fusion
\( \Delta H_v \) = latent heats of boiling
\( \Delta T, \Delta T_m \) = temperature bands over which the transition occurs
Modeling for $T_a$, HAZ and MRR

- FEM based MATLAB code has been developed for simulation of Nd:YAG LBPD process.

- In order to determine the temperature distribution in the workpiece, domain of thickness 700 µm, 1000 µm and 1300 µm with radius of 2500 µm is respectively used for sheet thickness of 0.7 mm, 1.0 mm and 1.3 mm.

- The profile of melt-isotherm is obtained from the results of temperature distribution in the sheet material.

- Due to the removal of material during LBPD, the domain correspondingly changes for each consecutive strike of laser pulse, therefore re-meshing of the remaining domain (using ANSYS 10 software) and corresponding prediction of new melt-isotherm (using MATLAB code) were repetitively performed until a through hole was obtained.

- The nodal temperature obtained for each preceding step has been used as the initial temperature to determine temperature distribution due to successive laser pulses. After the formation of a through hole the diameter at the entry ($d_{\text{entry}}$) and exit side ($d_{\text{exit}}$) of the hole was finally obtained from the final melt-isotherm and the $T_a$. 
The width of isotherm corresponding to melting point and recrystallization temperature of the respective sheet material is used to evaluate the extent of HAZ.

\[
\text{Extent of HAZ} = R_{\text{recrystallization}} - R_{\text{melt}}
\]

\[
T_a (\text{degree} ) = \tan^{-1} \left[ \frac{d_{\text{entry}} - d_{\text{exit}}}{2t_h} \right] \times \frac{180}{\pi}
\]
The total volume of material removed ($V_T$) after ‘$n$’ pulses

$$V_T = \sum_{p=1}^{n} V_P$$

where

$$V_P = \sum_{i=0}^{c-1} V_i$$

where

$$V_i = \pi \left( \frac{r_i + r_{i+1}}{2} \right)^2 \left( z_{i+1} - z_i \right)$$

**Predicted MRR ($MRR_{th}$) after ‘$n$’ pulses**

$$MRR_{th} (mm^3 / s) = \frac{V_i \times 1000}{\sum_{i=1}^{n} t_p}$$

**Schematic to determine theoretical MRR**
Experiment was performed on SIL-200 solid state pulsed Nd: YAG laser beam system.

All the experiments were carried without assist gas in the percussion drilling mode.

The diameter of all the laser drilled holes at the entry and exit side was measured using an Optical Measuring Microscope (Model SDM-TR-MSU, Sipcon Instrument Industries, India) at 10x magnifications.

Percent difference is determined to find the uncertainty of the experiment

\[
\% \text{ difference} = \frac{d_{\text{entry}1} - d_{\text{entry}2}}{\frac{d_{\text{entry}1} + d_{\text{entry}2}}{2}}
\]

where, \(d_{\text{entry}1}\) and \(d_{\text{entry}2}\) are the first and second observations of the entrance hole diameter.
Due to hole taper the final geometry of the hole is considered to be a frustum of cone

\[ V_{\text{exp}} = \frac{\pi t}{3} \left( r_{\text{entry}}^2 + r_{\text{exit}}^2 + r_{\text{entry}} r_{\text{exit}} \right) \]

\( V_{\text{exp}} = \) Volume of material removed during LBPD

\[ MRR = \frac{V_{\text{exp}} \times 1000}{\text{Pulse frequency} \times \text{time of drilling operation(s)} \times \text{pulse width}(ms)} \]