**Background**

**Classification: Structural Materials**
- Metal
- Polymer
- Ceramic
- **Strong & tough**
- High-temperature strength
- High wear resistance
- **Light & cheap**
- Chemically inactive
- Easy to fabricate
- **Limitations on max operating temperature**
- Used at temperatures below 300°C only
- **Still hindered from several applications because of its limitations towards machining into desirable components**
- Examples: Alumina (Al₂O₃), ZrO₂, B₄C, SiC, Si₃N₄

**Defence and space exploration**
- Machining and fabrication of high-temperature materials
- Insulating tiles for space shuttle, ceramic coatings, engine components, and windshields of glass in airplanes

**Machining and fabrication**
- Excellent hardness & heat resistance properties ideal for drilling, shaping, grinding, and forming metal workpieces

**Reference:** Google images

**Motivation**

**Conventional machining** techniques (grinding)
- Unacceptable tool wear & insufficient accuracy
- Mechanical or thermal damage
- Lower material removal rate or machining time
- Higher operating costs

**Potential solution: Laser Machining**
- Innovative and potential tool for bulk material removal and shaping of structural ceramics
- Non-contact process - eliminates tool wear
- Efficient, reliable, cost effective solution to fabricate complex structures at large scales

**Need:** Obtaining desired surface finish at much higher material removal rate

**Solution:** Better understanding of various physical phenomena (heat transfer & fluid flow) and its influence on the evolution of surface finish during laser machining of ceramics

**Objective**

Current research aims at presenting the state of the art in the field of **laser machining** of alumina and emphasizes on **experimental and computational approaches** in understanding physical nature of the complex phenomena.

**Laser-Material Interaction**

**Schematic of laser-material interaction**

- Plasma
- Heat conduction
- Surface melting
- Surface vaporization
- Plume formation
- Recoil pressure
- Liquid pile-up
- Rapid solidification

**All explained physical phenomena happened**
- within the small interval of time
- very difficult to observed physically
- Solution — **finite element method**

**Numerical Study**

A COMSOL® multiphysics based two-step numerical model **coupled with heat transfer and fluid flow** was developed

**Step-1: Heat transfer model**

(a) Heat flux boundary condition

(b) Melt depth

(c) Crater depth

**Step-2: Fluid flow model coupled with heat transfer model**

(a) prediction of solid, liquid & vapor interface by Level-set method
(b) prediction of crater and melt pool dimensions
(c) flow of molten material due to various boundary conditions
(d) prediction of surface profile after solidification

**Governing Equations**

- Laser power density in **Gaussian distribution**
  \[
  P_\text{g} = A \exp\left(-\frac{(x - \text{loc})^2}{2\sigma^2}\right)
  \]
  \[
  \text{Recall pressure} (P) \text{ at the evaporating surface depends on the incident laser energy density and is given by the following equation}
  \]
  \[
  P_r = \left( \frac{P_g}{\kappa} \right) \left( \frac{1}{\sqrt{1 + 2.2 \left( \frac{L}{T_v} \right)}} \right)
  \]
  \[
  \text{Navier-Stokes equations} \text{ was used to model the movement of the liquid under the action of the recoil pressure}
  \]

**Experimental Study**

**Path to multidimensional model**

Ongoing efforts include the **extension** of one-dimensional numerical model into two- and three-dimensional with inclusion of effects of multiple laser pulses on the surface morphology during laser machining of alumina

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