FLORIDA STATE UNIVERSITY

COLLEGE OF ENGINEERING

# ULTRAFAST LASER MACHINING OF DIELECTRICS:

# A SHARP INTERFACE MODEL



By

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# ABSTRACT

High temperature pressure sensing is desirable for a broad range of applications related to reentry of space vehicles and control of combustion processes; however, limited materials can sustain temperatures above 1000°C while under time-varying pressure. A sapphire based optical pressure transducer has been proposed for measuring pressure at temperatures approaching 1600°C. Manufacturing such sensors has focused on picosecond laser machining. Current research has produced models which can predict material ablation for longer (ns) pulses and shorter (fs) pulses but there is an underwhelming amount of research focusing on predicting and understanding the mechanics of picosecond pulses. This is partially because of transitions in the mode of ablation processes associated with photothermal versus photochemical behavior. We put forth a general model for laser ablation using Maxwell's equations and a sharp interface equation and compare different constitutive laws which couple the two equations together. The proposed modeling results are compared to laser machining experimental data on sapphire from the literature to illustrate key material parameter uncertainty and sensitivity to the laser machining process. Bayesian uncertainty quantification is used to help validate the approximations within the constitutive equations.

# CHAPTER 1

# BACKGROUND

## 1.1 Theoretical Background

High powered laser-sapphire interactions have long been of interest to those studying fundamental physics. This research has found numerous engineering applications including microfluidics, microsensors, optical windows, abrasion resistant mechanical contacts, buffer materials and high power laser construction. Therefore, numerous computational and experimental studies have been performed regarding milli-, micro-, nano-, pico- and femtosecond laser ablation. The first step of light-matter interaction is non-thermal absorption (electron excitation) through either multiphoton ionization, defect allowed single-photon ionization or inverse Bremsstrahlung[9] [26]. Only multiphoton ionization is allowed in pristine equilibrium sapphire on the basis of sapphire's large bandgap energy of $\approx 8.8$eV[17]. Absorption is followed by complex material processes. In general this secondary process is classified as either photothermal (pyrolytic), photochemical (photolytic) or photophysical (both thermal and chemical). This classification is difficult because it can depend on many different parameters including laser pulse duration, fluence, material properties and material defects[18]. Conventionally, pulse length is considered the leading determinant of classification. However, experimental measurements have shown that sapphire is unconventional. Millisecond pulses have been quantified to produce thermal melting[17]. Nanosecond pulse measurements are believed to generate to electron sputtering[3], a photochemical process. This is concluded from temperature measurements of the ablation plume[12][13]. Faster pico- and femtosecond pulsed laser-sapphire interactions have proven to be more complex.

The complexity of pico- and femtosecond pulsed laser interaction is strongly dependent on material defects. Defects play a large role in laser induced damage of dielectrics[21]. Nowhere can this be seen more clearly than in sapphire's two ablation phases: the gentle phase and the strong phase[3]. Experimental results have suggested that the transition from the gentle to strong phase is due to the number of defects and inclusions in the material[3]. The gentle phase is characterized by a lower rate of removal and a polishing surface effect while the strong phase has a significantly larger rate of removal and tends to have a rough surface finish [4]. Although separate gentle and strong phases do not generally exist in other dielectrics[2], these materials still see huge

variability in ablation depth and threshold due to defects[21]. The gentle phase is considered to be a photochemical effect: either Coulomb explosion or particle vaporization. The strong phase is considered to be a photothermal effect, specifically phase explosion[4][20]. This separation into gentle and strong phases works well when $\tau_{pulse} \lesssim 4$ps, however the physical characteristics begin to blend together when $\tau_{pulse} \gtrsim 4$ps[4]. This leaves classification of picosecond lasers an open question.

## 1.2 Machining Characteristics

Collaborators at the University of Florida have pursued three desirable types of cuts for laser processing of sapphire: through, face and pocket[6]. Through-milling produces a cut through the entire material with a desired profile. Face-milling is used to reduce the thickness of a workpiece. Pocket-milling is used to produce a given depth feature[6]. These different cuts can have an effect on the processing strategy and laser parameters. Therefore, it is imperative to properly model the physics and material response for different laser parameters.

The modeling research presented here is primarily meant to provide a fundamental approach to predicting picosecond laser ablation. A key question pertains to excessive pulsing that produces undesirable material removal and machining defects. Excessive pulsing can occur due to starting/stopping, small radius turns and command delays. As seen in Figure 1.1, excessive pulsing in H-bar test cuts at the University of Florida have produced undesirable microcracks[6].

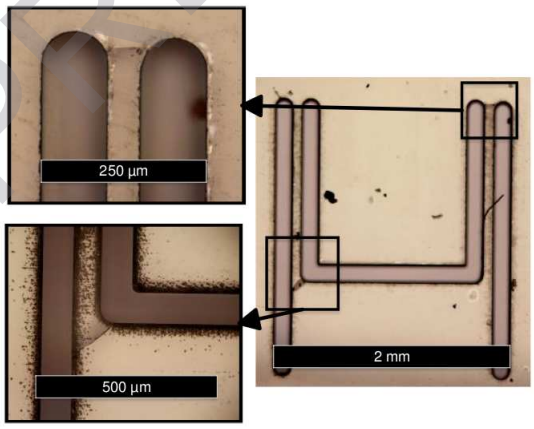


Figure 1.1: Visible cracks in machined sapphire. Includes blown up views to show greater details of damage. Credit Daniel Blood[6]

There are also other mechanics of material issues to address. Nanoscale indentation on laser machined specimens have an unexplained toughening of the material on the laser ablation surface.