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Nanosecond Laser-Induced Shock Waves of Polymer Surfaces

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Abstract

Nanosecond pulsed lasers interacting with polymer surfaces generate ablation, plasma formation, and rapidly expanding vapor/plasma plumes that launch shock waves into the surrounding medium and substrate. These laser-induced shock waves (LISWs) produce high pressures and ultrahigh strain rates at the surface, enabling surface texturing, microstructuring, delamination, and dynamic mechanical modification of polymers. This paper reviews the physics of nanosecond laser–polymer interactions leading to shock formation, summarizes experimental diagnostics and characteristic pressure/time scales, and presents an experimentally-oriented methodology for investigating LISWs on polymer foils. Expected results, measurement strategies (optical shadowgraphy, beam-deflection, hydrophones, and fiber-optic probes), and a discussion of mechanisms (ablation pressure, plasma confinement, and material response) are presented. Applications and implications for laser shock processing, microfabrication, and polymer functionalization are discussed. Key gaps and recommendations for future experimental and modeling work are highlighted [1-3].

Keywords: Nanosecond Laser, Shock Wave, Polymer Surface, Laser Ablation, Plasma, High Strain Rate, Surface Structuring

1. Introduction

Pulsed lasers with nanosecond durations are widely used to modify surfaces by thermal ablation, melting, and plasma formation. When irradiance is sufficiently high, rapid vaporization and plasma formation launch compressive shock waves into the ambient medium and the target. In metals and ceramics this phenomenon has been extensively exploited (e.g., laser shock peening); for polymers, the combination of lower thermal conductivity, complex viscoelastic response, and lower ablation thresholds gives rise to distinctive shock-generation physics and morphological outcomes such as wrinkling, delamination, blistering, and micro-bubbling [4, 5].

Understanding the pressure amplitude, temporal evolution, and spatial distribution of LISWs is essential both for controlled micro/nano structuring and for preventing undesirable damage. Recent instrument advances (ultrafast fiber probes, ICCD imaging, high-bandwidth hydrophones) have improved temporal resolution for shock diagnostics and modeling validation [2, 6].

2. Theoretical Background

2.1 Mechanisms of shock generation

When an intense nanosecond laser pulse (>10^7–10^9 W/cm² depending on wavelength and absorption) irradiates a polymer surface, energy is deposited within an optical penetration depth. Rapid heating leads to vaporization and plasma formation. The plasma expands supersonically, generating a shock front in the surrounding medium and launching pressure waves into the polymer. The instantaneous ablation pressure PaP_aPa scales approximately with absorbed fluence and ablation coupling efficiency; semi-empirical models (e.g., Fabbro model) are often used to relate laser parameters to peak pressure [3, 7].

Key timescales include: laser pulse duration (~ns), plasma expansion (~10–100 ns), and shock transit (ns–µs). Peak pressures in nanosecond LISWs can range from a few MPa to several GPa depending on fluence, confinement, and absorbing layer [8, 9].

2.2 Polymer response

Polymers subjected to LISWs exhibit viscoelastic/plastic response, phase changes, delamination, and fracture. Strain rates of 10^4–10^7 s^-1 often induce brittle-like fracture in ductile polymers and can produce micro-textures by spallation or blistering

[10, 11].

3. Literature Review

- Lorenz *et al*. demonstrated nanosecond excimer lasers generating shock waves that deform polymer foils and enable micropatterning down to sub-µm scales [1].
- Radziejewska *et al*. measured temporal evolution of laser-induced shock pressure, showing plasma expansion and shock formation dynamics [3].
- Nguyen *et al*. reported selective removal of polystyrene microspheres via controlled LISWs [12].
- Yang *et al*. investigated nanosecond ablation of polymers, analyzing plume and shock behavior [13].
- Jia reviewed the mechanisms and applications of laser shock peening, including polymers [4].

4. Materials and Methods

Materials

Polystyrene (PS), polycarbonate (PC), PET foils (25–250 µm), plus PDMS elastomer for comparison. Absorbing layers (graphite/Al) can be used for confinement [4].

Laser system

Nd:YAG (1064/532 nm), Q-switched nanosecond pulses (5–12 ns), fluence 0.1–5 J/cm², spot 0.2–2 mm, single-pulse tests under air and confinement (glass/water overlay) [1, 4].

Diagnostics

- Shadowgraphy/ICCD for shock imaging [2].
- Probe-beam deflection [14].
- Hydrophones/pressure transducers in water confinement [3, 6].
- Fiber-optic probes for ultrafast pressure [2].
- Post-irradiation SEM, AFM, Raman/FTIR [10].

5. Expected Results and Discussion

- **Pressure trends:** Peak pressure increases nonlinearly with fluence and confinement, with confined ablation reaching hundreds of MPa or more [4, 8].
- **Surface morphology:** Low fluence yields roughening; moderate fluence produces craters, blistering, delamination; high fluence yields spallation and microsphere removal [1, 12].
- **Material response:** Brittle fracture, melting, or chemical decomposition (detected by FTIR/Raman) expected at high strain rates [10].
- **Modeling:** Rankine–Hugoniot and Fabbro model can be used to correlate experimental data with shock predictions [7, 8].

6. Conclusion

Nanosecond laser pulses on polymer surfaces generate laser-induced shock waves with pressures ranging from MPa to GPa. Diagnostic tools (ICCD, hydrophones, fiber probes) allow quantitative analysis of peak pressures and waveforms. Controlled use of LISWs enables surface texturing, selective removal, and mechanical testing of polymers, while excessive fluence may cause damage. Future research should combine high-bandwidth experiments with multiphysics simulations for predictive control [2, 4, 8].

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