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Abstract:

The use of femtosecond pulses for materials processing results in very precise cutting and drilling with high efficiency. Energy deposited in the electrons is not coupled into the bulk during the pulse, resulting in negligible shock or thermal loading to adjacent areas.

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The use of femtosecond lasers allows materials processing of practically any material with extremely high precision and minimal collateral damage. Advantages over conventional laser machining (>ns pulses) are realized by depositing the laser energy into the electrons of the material on a time scale short compared to the transfer time of this energy to the bulk of the material, resulting in increased ablation efficiency and negligible shock or thermal stress.

In dielectric materials irradiated with femtosecond pulses[1], initial free electrons are produced by multiphoton ionization. These electrons are accelerated in the laser field and produce additional free electrons by collisional ionization (the relative ratio of the two mechanisms is pulse width dependent). A critical density plasma is formed in a thin layer (≈1 μm) at the surface of the dielectric and ablation occurs by expansion of the 1-1000 eV plasma away from the surface. Very little energy (shock or thermal) is coupled into the bulk material because the pulse duration is shorter than the characteristic energy transfer time (a few ps for most dielectrics) of the electrons to the lattice.

From the standpoint of this mechanism of laser interaction, enamel, bone, etc. are simply dielectrics and exhibit the same behavior as materials examined in the initial experiments (SiO_2, CaF_2, etc.). Shown in figure 1 are electron micrographs of the surface of a tooth following material removal by a 1.4-ns laser pulses and 350-fs pulses. The pulses are produced by a variable pulse duration laser operating at 1054 nm. Cracking of the surrounding material and the uncontrollable nature of material removal by thermal shock are readily apparent in the enamel irradiated by nanosecond pulses. In this regime, thermal stresses build up causing ablation first from the point with the least material strength. By contrast, the morphology in the femtosecond case is characteristic of internal enamel and there is no evidence of heat transfer into the surrounding material. Extreme precision in the position of material removal is possible due to the strong intensity dependence of the multiphoton initiation step. Figure 2 shows the cross section of a conical hole drilled in a tooth by subpicosecond laser pulses. There is no collateral damage evident in the bulk tissue.

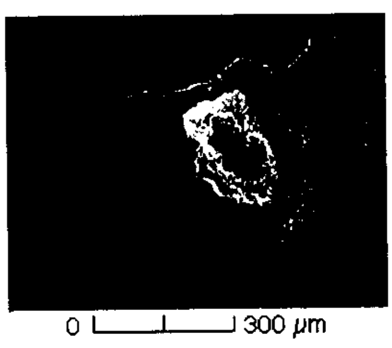

Figure 1(a): Drilling of enamel with 1.4 ns, 30 J/cm^2 laser pulses. Enamel is removed by a conventional thermal mechanism resulting in cracking and collateral damage from temperature rise and thermal shock.

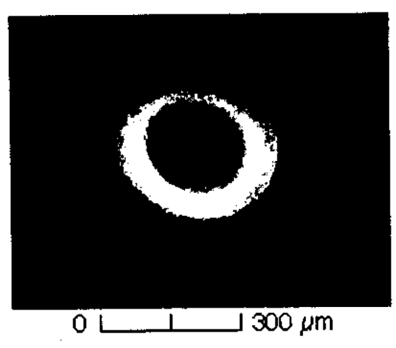

Figure 1(b): Drilling of enamel with 350 fs, 3 J/cm^2 laser pulses. Enamel is removed by a nonthermal mechanism which eliminates collateral damage and leaves the surface in its natural state.

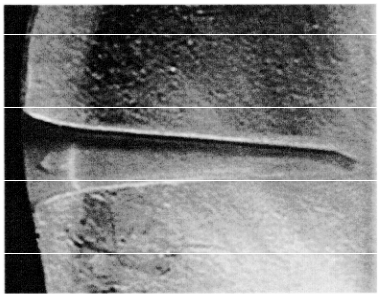

Figure 2: Cross section of a conical hole drilled in tooth with femtosecond laser pulses. With no thermal shock, there is no collateral damage to adjacent tissue.

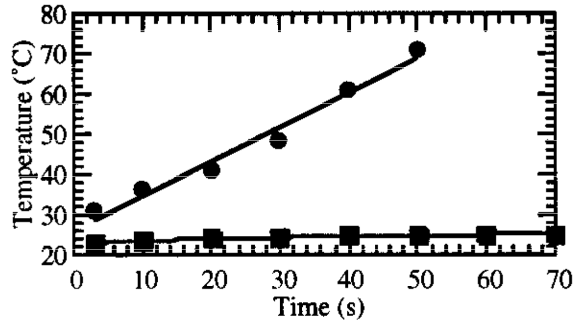

Figure 3: Temperature increase of bulk tooth due to drilling with nanosecond (circles) and femtosecond (squares) laser pulses. In both cases, the laser wavelength was 1054 nm and the material removal rate was 1 μm/pulse at 10 Hz

The change in material removal mechanism away from a thermal process results in a minimal increase in temperature of the surrounding material and a significant reduction in the shock to the bulk material. Thermal measurements show that in the case of nanosecond pulse ablation, the bulk temperature of a 1-mm slice of tooth increased by over 40 °C while for femtosecond pulses the temperature rise was less than 2 °C (Figure 3). The fluence in each case was set to remove 1 μm depth of material per pulse. This required 30 J/cm^2 for the ns pulses and only 3 J/cm^2 for the fs pulses. The practical consequences in dentistry are substantial. In the case of existing laser systems, active cooling of the tooth is necessary to prevent permanent damage to the pulp (5°C increase) while no cooling is necessary with femtosecond laser pulses.

In metals, by choosing the laser pulse duration such that the thermal penetration depth is on the order of the optical skin depth, very small amounts of material (0.01-1 μm) can be precisely removed with minimal transport of energy by either shock or thermal conduction away from the volume of interest. Extremely high aspect ratio cuts (Fig. 4) are possible with no heat affected zone. This allows cutting of materials with minimal material removal and no damage to surrounding areas. Slots of various shapes can be cut by tailoring the spatial beam profile (Fig. 5).

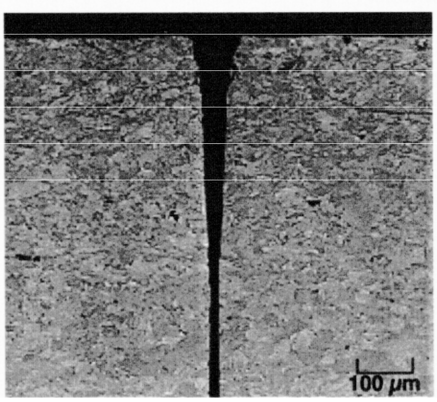

Figure 4. High aspect ratio kerfs can be produced in metals with no heat-affected zone.

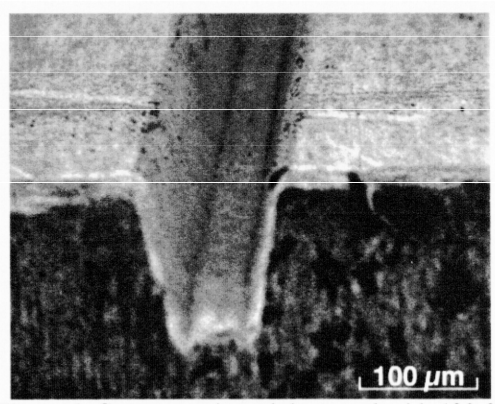

Figure 5. Groove cut in stainless steel with 130-fs flat-top beam.

[1]B.C. Stuart, M.D. Feit, A.M. Rubenchik, B.W. Shore, and M.D. Perry, "Nanosecond to femtosecond laser-induced breakdown in dielectrics", Phys. Rev. B **53**, 1749-1761 (1996).

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