Laser Damage Studies of Mirrors

The pulsed temperature rise is estimated to be[1]

$$\Delta T = \frac{p_d}{A}\sqrt{\frac{T_p}{KC}}$$

where p_d/A is the power dissipated per unit area, K and C are the thermal conductivity and heat capacity of the material, respectively, and T_p is the pulse length.

Figueira & Thomas, "Damage Threshold at Metal Surfaces for Short Pulse IR Lasers"[2]

Figueira and Thomas have an expression for surface melting

$$(IT_p)_m = \frac{T_m - T_0}{2A_0}\sqrt{\pi KCT_p}$$

where $(IT_p)_m$ is the laser fluence, incident energy per unit area, T_m and T_0 are the melting and ambient temperatures, respectively, and A_0 is the room temperature surface absorption. This equation has the same pulse length dependence and must be based on the same physics - diffusion of heat after having been absorbed on the surface. They also present a more complex model that accounts for the temperature dependence of the optical absorption coefficient.

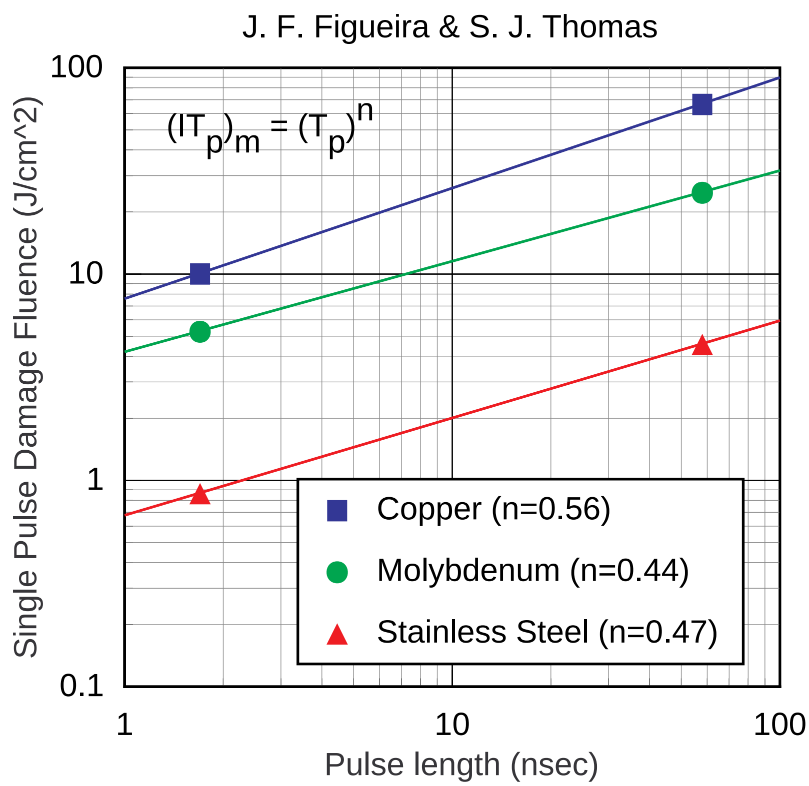
They performed an experiment studying single pulse and multiple pulse optical damage for different materials. Mirrors were illuminated in vacuum with 1.7 nsec long CO_2 laser pulses (10.6 μm). The definition of optical damage was visible damage observable through an optical microscope. A summary of their results, which seem in reasonable agreement with the estimates except for the case of 6061 aluminum, is in the table below.

Material	**Preparation**	**1 - R**	**$(IT_p)_m$ (const) J/cm^2**	**$(IT_p)_m$ (variable) J/cm^2**	**$(IT_p)_v$ J/cm^2**	**F_1 J/cm^2**
Cu	Polished	0.009	15.8	6.5	9.1	10.1 ± 0.5
Molybdenum	Polished	0.019	8.5	-	-	5.3 ± 0.3
SS-304	Polished	0.102	0.56	-	-	0.87 ± 0.08
Al6061	Polished	0.104	2.7	1.8	4.56	0.34 ± 0.02
Al 6061	Single Pt Diamond Turned	0.021	2.7	1.8	4.56	0.62 ± 0.04

$(IT_p)_m$ (const) = melting fluence with constant absorption; $(IT_p)_m$ (variable) = melting fluence with variable absorption; $(IT_p)_v$ = vaporization threshold; F_1 = single shot damage threshold.

Pulse length dependence was measured by comparing these results with a 58 nsec long pulse. The results are shown in the figure below. The exponent ranges from 0.44 for molybdenum to 0.56 for copper. Other experiments have also observed the $\sqrt{T_p}$ dependence.

[1] R. Siemann, ARDB-1
[2] Joseph F. Figueira & S. J. Thomas, IEEE Jour. of Quantum Electronics **QE-18**, 1381 (1982).



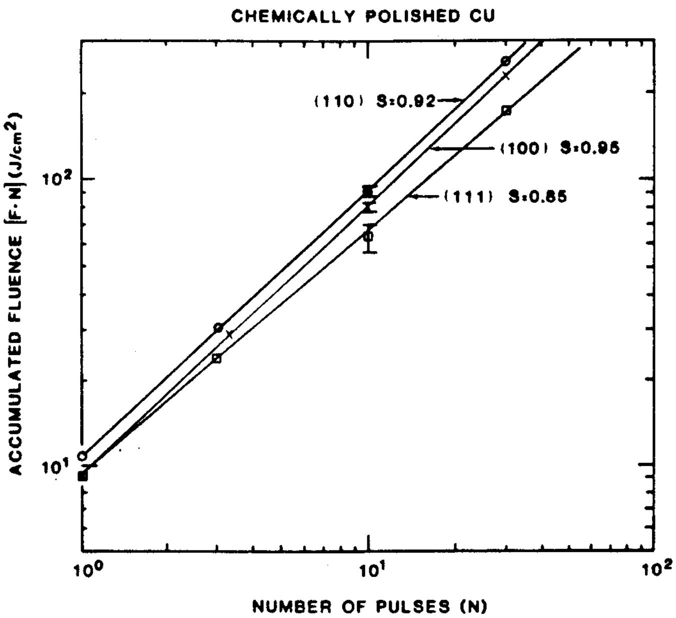
This was based on 100 pulses and extrapolation to a larger number is not meaningful. They measured this same dependence for mirrors prepared by different manufacturers using different surface preparation techniques and concluded that the failure was determined by intrinsic properties of copper.

My conclusion from this paper is that scalings with pulse length, heat capacity and thermal conductivity are appropriate for estimating both short and long term damage to structures for the pulse lengths of interest to us.

Jee, Becker & Walser, "Multiple-Pulse Laser-Induced Damage to Metal Mirror Surfaces"[3]

They studied the damage of single crystal, chemically polished copper with a 10 nsec, 10 Hz Nd:Yag laser (1064 nm). Damage is defined as any permanent changed observed on the surface when viewed under a 200X optical microscope. They parameterize the results in terms of an "accumulation curve", and example of which is shown below. The accumulation curve is a plot of the product of the single pulse fluence times the number of pulses versus the number of pulses. Values for the slope, S, and the single shot damage fluence are given in the table above. The single pulse damage fluence is ~ 10 J/cm^2. Since the pulse length is longer than in the Figueira &

[3] Y. Jee, M. F. Becker & R. M. Walser, SPIE vol. 895 **Laser Optics for Intracavity and Extracavity Applications**, 236 (1988).



Crystal Orientation	Slope of Accumulation Curve, S	F_1, Damage Threshold (J/cm^2)
(100)	0.95	9.2
(110)	0.92	10.8
(111)	0.85	9.2

Thomas experiment, the absorption must be greater by ~ 2.5 (= √10/1.7). The parametrization of the N cycle damage fluence, F_N, in terms of the one cycle fluence is

$$F_N = F_1 N^{S-1} .$$

The paper includes a model of this multi pulse fatigue failure from the cumulative effect of repeated cycling due to the laser pulses. The thermally induced stress is

$$\sigma = -\frac{E\alpha\Delta T}{1-\nu}$$

where ν is Poisson's ratio, E is Young's modulus, and α is the coefficient of thermal expansion. The plastic yield point is at $|\sigma| = Y$ where Y is the yield stress of the material. Using the metal properties in Marrs *et al*[4] ($\alpha = 16.7\times10^{-6}K^{-1}$, $E = 1.23\times10^5$ N/mm^2, $Y = 35.9$ N/mm^2, $\nu = 0.345$) gives a maximum $\Delta T = 11.5$ K. A single pulse damage fluence of $F_1 = 10$ J/cm^2 gives a temperature rise

$$\Delta T(K) = \frac{2F_1A_0}{\sqrt{\pi KCT_p}} = 3.05\times10^4 A_0$$

for copper and a pulse length of 10 nsec. They do not give a value for the absorption, so using $A_0 = 0.0225$ (the Figueira & Thomas value, $A_0 = 0.009$, multiplied by 2.5 for the lower single pulse damage fluence) $\Delta T = 690$ K, and the thermally induced stress is $\sigma = 2.2\times10^3$ N/mm^2. The ΔT

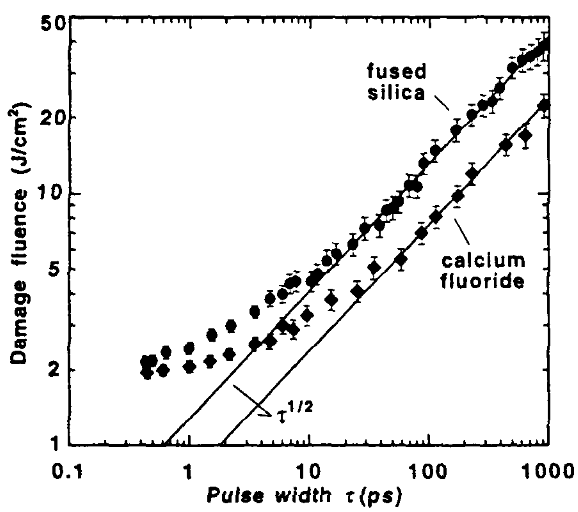
[4] C. D. Marrs *et al*, Applied Optics **21**, 4063 (1982)

could be consistent with melting given the uncertainty about absorption versus temperature, and the stress is about fifty times the yield strength. The material is stressed well beyond the plastic yield point. Their model is that the cumulative damage that is observed is due to hysteresis as the surfaces is repeatedly strained and then relaxes.

These results can be compared with the estimate based on Goodman stress curve in ARDB -1. Using σ_E = 75.8 N/mm^2 and σ_U = 221 N/mm^2 gives σ_{cyc} = 65 N/mm^2 which would imply a material failure for temperature rise of 21 K.

B. C. Stuart *et al*, "Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses"[5]

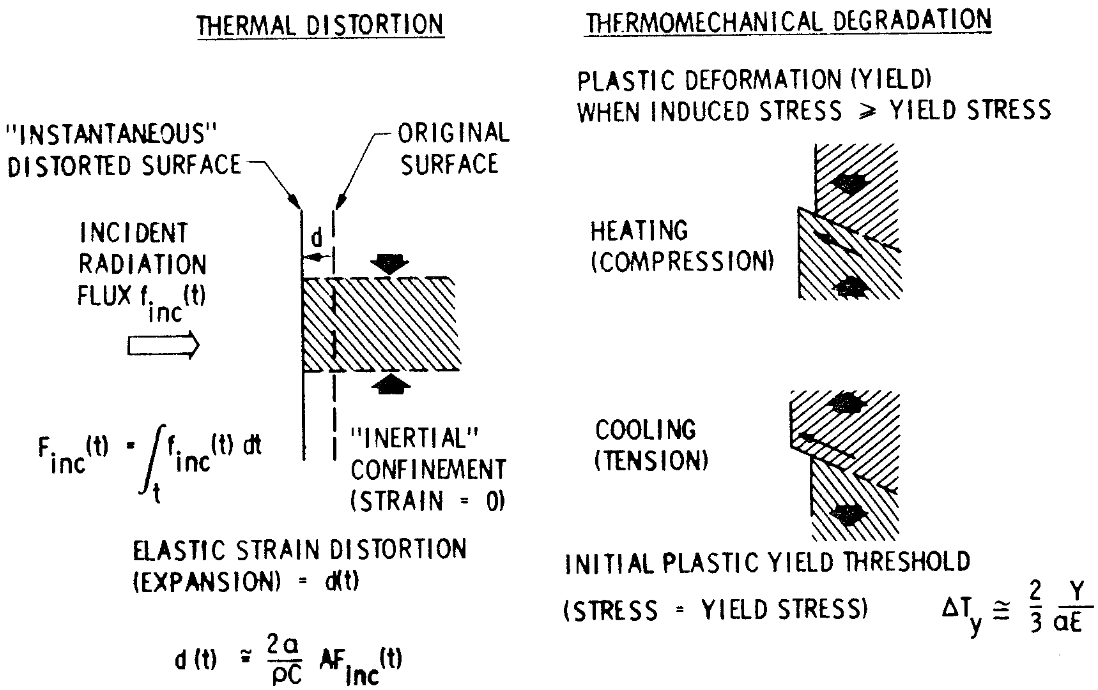
This paper discusses damage to fused silica and calcium fluoride due to short pulsed lasers. The experiment was performed with multiple pulses (number unknown) and probably was done with transmission optics. These details of the measurement are missing from the paper. The main result is the figure below. For pulse lengths less than ~20 psec the damage no longer follows a $\sqrt{T_p}$ dependence. Above 20 psec the damage is thermal in nature while for shorter pulses the damage is characteristic of material removed by ablation.



H. M. Musal, Jr., "Thermomechanical Stress Degradation of Metal Mirror Surfaces Under Pulsed Laser Irradiation"[6]

This paper is a theoretical treatment of the laser damage problem. The situation is summarized in the figure below. The laser pulse deposits energy in the metal surface which expands freely. The dimensions parallel to the surface also want to expand due to heating, but they are confined by the inertia of the material around them and they cannot move (=> strain = 0). The dominant stresses are parallel to the free surface, and the stress normal to the free surface is equal

[5] B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore, and M. D. Perry, Phys. Rev. Letters **74**, 2248 (1995).
[6] H. M. Musal, Jr., Laser Induced Damage in Optical Materials 1979, Nat. Bur. Standards Spec. Pub 568, 159, 1980.



$$F_{inc}(t) = \int_t f_{inc}(t)\,dt$$

$$d(t) \approx \frac{2\alpha}{\rho C} AF_{inc}(t)$$

$$\Delta T_y \cong \frac{2}{3}\frac{Y}{\alpha E}$$

to zero. Musal develops equations for the strain normal to the surface, ε_N and the stress parallel to the surface τ_T

$$\varepsilon_N(x,t) \cong \frac{1+\nu}{1-\nu}\alpha\Delta T(x,t)$$

$$\tau_T(x,t) \cong -\frac{E}{1-\nu}\alpha\Delta T(x,t)$$

where x is the distance into the surface, E, ν, and α are Young's modulus, Poisson's ratio, and the coefficient of thermal expansion.

During the initial part of the pulse, the stress is compressive, and if it is sufficiently large, the material will yield plastically. The result will be the extrusion of material as shown in the figure above. The maximum shear stress is at 45^o with respect to the free surface, so the slip will be along crystal planes or grain boundaries oriented at about that direction. Upon cooling, the material will relax elastically and will be under tension when cooled to the initial temperature. If the compressive stress was large, the material will yield during cooldown also. The threshold for plastic deformation is

$$\Delta T_Y \cong \frac{(1-\nu)Y}{E\alpha}$$

where Y is the yield strength. For pure copper, ΔT_Y (K) = 3.18×10^{-7} Y(N/m^2) $\approx$ 20 K.

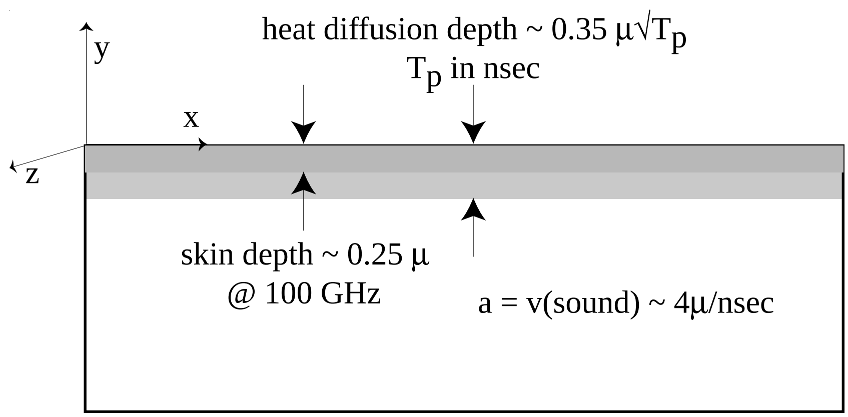
Assume the material has yielded slightly on the first pulse. After cooling down it is under elastic tension. A second pulse of the same fluence will put the material under compression, but by an amount below the yield strength. All the damage has been done on the first pulse, and there is no subsequent damage. The criterion for further damage is that the temperature rise exceed $2\Delta T_Y$. Musal gives this as the incremental strain after the first pulse; it is

$$\Delta\varepsilon = \alpha(\Delta T_{max} - 2\Delta T_y)$$

The conclusions of this paper are

- The surface temperature rise at which a metal surface under short-pulse large-spot laser irradiation will begin to yield plastically due to thermomechanical stress is relatively small. This plastic yield threshold temperature rise (ΔT_Y) is of order 20K for pure copper.
- A simple scaling relationship, namely $FT_p^{-1/2}$ = constant, expresses the plastic yield threshold in terms of pulse parameters. For a high-quality copper mirror irradiated with a rectangular (constant-flux) CO_2 laser pulse, the numerical value of the constant is approximately 1×10^4 J/cm^{2}-s$^{1/2}$.
- Repetitive pulse irradiation will cause accumulation of plastic strain on each successive pulse if $2\Delta T_Y$ is exceeded during the pulse. The increment of plastic strain accumulated during a pulsed heating-cooling cycle is proportional to the temperature rise in excess of $2\Delta T_Y$, and consists of both contraction and extension in both of two orthogonal directions along the surface. It will be manifest as progressive surface degradation in the form of slip bands, intergranular slip, and fatigue cracks.

Presentation Made at the July 31, 1996 ARDB Meeting



The pulsed heating situation is illustrated above: the inside of the cavity is at y = 0; the skin depth is a fraction of a micron and heat diffuses a few microns into the material (depending on the pulse length T_p); the speed of sound in the material is ~ 4μ/nsec. When heat is deposited, sound waves are generated. The wave in the +y direction is reflected from the free surface at y = 0. The heat deposition and skin depths are narrow, and sound propagates across those regions in a fraction of a nanosecond. As a result, stress in the y-direction is relaxed during the RF pulse.

In the transverse directions the characteristic distance over which sound propagates during the pulse is $L_p = aT_p$. The spatial variation of the RF power is small

$$\frac{\Delta P_{RF}}{P_{RF}} = \frac{aT_p\, dP_{RF}/dx}{P_{RF}} << 1$$

and stress build-up is not relieved during the RF pulse.

In the absence of sound propagation the stresses in the x, y, and z directions are

$$\sigma_x = \sigma_y = \sigma_z = 3B\alpha\Delta T$$

where B is the bulk modulus, α is the linear expansion coefficient, and ΔT is the temperature rise (see the discussion of W. P. Mason's article below). Including the propagation of sound the equations are

$$\sigma_x = 3B\alpha\Delta T + (\lambda + 2\mu)\varepsilon_x + \mu(\varepsilon_y + \varepsilon_z)$$
$$\sigma_y = 3B\alpha\Delta T + (\lambda + 2\mu)\varepsilon_y + \mu(\varepsilon_x + \varepsilon_z)$$
$$\sigma_z = 3B\alpha\Delta T + (\lambda + 2\mu)\varepsilon_z + \mu(\varepsilon_y + \varepsilon_x)$$

The material is constrained in the x and z directions because of the uniformity of the power deposition, and the strains in those two directions are zero, $\varepsilon_x = \varepsilon_z = 0$. Also, stresses are relieved in the thin y layer during the RF pulse, $\sigma_y \cong 0$. The equations above become

$$\sigma_x = 3B\alpha\Delta T + \mu\varepsilon_y$$
$$0 = 3B\alpha\Delta T + (\lambda + 2\mu)\varepsilon_y$$
$$\sigma_z = 3B\alpha\Delta T + \mu\varepsilon_y$$

Using the relations between the Bulk modulus, Young's modulus, Poisson's ratio and the Lamè coefficients gives

$$\varepsilon_y = -\frac{3B\alpha\Delta T}{\lambda + 2\mu}$$
$$\sigma_x = \sigma_z = \frac{E}{1-\nu}\alpha\Delta T$$

The second of these is Musal's equation for the stress build-up during pulsed laser irradiation. The essential assumption was that the plate was wide, $\Delta P_{RF}/P_{RF} << 1$, which is what Musal calls "inertial confinement". Following his paper the threshold for surface damage and fatigue cracks is expected to be ~ 40^oK in copper.

The conclusions are that surface roughening and fatigue cracks will appear when the temperature rise exceeds this value. There have been some reports of substantially higher temperature rises in RF cavities.[7] This would imply that this surface damage does not affect RF performance. Alternatively, the surface roughening could break the planar symmetry and relieve stress in the x and z directions. This seems unlikely since the same mechanism would apply to the laser damage case also.

W. P. Mason, "Elasticity"[8]

The encyclopedia article gives a summary of equations and definitions of variables that appear in elasticity theory. **Stresses** (τ) and **strains** (ε) are related by **Hooke's law equations**

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7 J. Wang and T. Chen, private communication, ARDB meeting July 24, 1996.

8 W. P. Mason, Encyclopaedic Dictionary of Physics (Pergamon Press, 1962; edited by J. Thewlis, R. C. Glass, D. J. Hughes and A. R. Meetham) page 617.

$$\tau_1 = (\lambda + 2\mu)\varepsilon_1 + \lambda(\varepsilon_2 + \varepsilon_3); \quad \tau_2 = (\lambda + 2\mu)\varepsilon_2 + \lambda(\varepsilon_1 + \varepsilon_3)$$

$$\tau_3 = (\lambda + 2\mu)\varepsilon_3 + \lambda(\varepsilon_1 + \varepsilon_2); \quad \tau_4 = \mu\varepsilon_4; \quad \tau_5 = \mu\varepsilon_5; \quad \tau_6 = \mu\varepsilon_6$$

For τ_i and ε_i i = 4, ..., 6 apply to shear. The coefficients λ and μ are the **Lamé coefficients**.

For a wide plate the strains ε_2 and ε_3 are zero when a stress τ_1 is applied, and the elastic constant relating the stress and strain is the **plate modulus** is $\lambda + 2\mu$. (This is the "inertial confinement" condition in Musal's paper.)

For a narrow rod if stress τ_1 is applied, the material will move sideward to relieve the transverse stress, τ_2, $\tau_3 = 0$. The results is

$$\tau_1 = \mu\left(\frac{3\lambda + 2\mu}{\lambda + \mu}\right)\varepsilon_1 = E\varepsilon_1$$

$$\varepsilon_2 = \varepsilon_3 = \left(\frac{-\lambda}{2(\lambda + \mu)}\right)\varepsilon_1 = -\nu\varepsilon_1$$

where E is **Young's modulus** and ν is **Poisson's ratio**.

If a hydrostatic pressure p is applied

$$\tau_1 = \tau_2 = \tau_3 = \left(\frac{3\lambda + 2\mu}{3}\right)(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) = B(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)$$

where B is the **Bulk modulus**.

A summary of the relationships is

$$E = \mu\left(\frac{3\lambda + 2\mu}{\lambda + \mu}\right); \quad \nu = \frac{\lambda}{2(\lambda + \mu)}; \quad B = \frac{3\lambda + 2\mu}{3} = \frac{E}{3(1 - 2\nu)};$$

$$\lambda = \frac{E\nu}{(1 + \nu)(1 - 2\nu)}; \quad \mu = \frac{E}{2(1 + \nu)}$$