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Material selection for mirror substrate compatible with high-power laser beam utilized by Tritium-monitor diagnostic in ITER

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The ITER (International Thermonuclear Experimental Reactor) project [1], a pioneering initiative in fusion energy research, requires precise diagnostic systems to monitor and control the plasma behaviour within the reactor. Among the various diagnostic systems, T-monitor diagnostics [2] play a crucial role in providing in-situ measurements of the tritium content inside the vacuum vessel. One essential component of this diagnostic is the optical system, which employs mirrors to introduce the high-power laser beam into the vessel and enable coaxial Visible/Near-Infrared (VIS/NIR) observation of the laser heated divertor target. The materials selected for these mirrors are critical as they must withstand the extreme conditions within the ITER environment, including high temperatures, nuclear radiation, and magnetic fields, on top of the high power density of the laser spot on the mirror. In this discussion, we will explore the key characteristics and requirements for selecting mirror materials suited for the T-monitor diagnostic systems in ITER.

High-power laser irradiation can cause transient surface heating, inducing significant stresses in the mirrors. These stresses may lead to surface roughening, yielding (plastic deformation when the stress exceeds the yield strength), or fracture. An accurate stress determination for specific materials and loads often requires time-dependent, 3D analysis. However, in many cases, a simplified one-dimensional model provides a good estimate of the peak stress.

This work introduces a simplified model that accounts for finite heat penetration depths based on the infinite half-space approximation to estimate the stress and deformation of different mirror material options. The transverse stresses are expressed as $\sigma = -\frac{E\alpha_L \Delta T}{1-\nu}$ [3], where E is the elastic modulus, α_L is the linear coefficient of thermal expansion, ΔT is the temperature difference at the surface from a stress-free reference temperature and ν is Poisson's ratio. Using temperature equations [4], the temperature increase ΔT at the end of the heating pulse can be defined as: $\Delta T = \frac{2}{\kappa}\sqrt{\frac{\alpha}{\pi}}Q_f$, where $Q_f = q\sqrt{\tau}$ is the heat flux factor, q - heat flux on the surface and τ - heating pulse duration $\alpha = \frac{k}{C_p\,\rho}$ is the thermal diffusivity, κ is the thermal conductivity, C_p is specific heat capacity and ρ is the density of the material. The critical heat factor for mirrors can be expressed as: $Q_{f,[\sigma]} = \frac{\kappa[\sigma]\,(1-\nu)}{2E\alpha_L}\sqrt{\pi/\alpha}$, where $[\sigma]$ is the allowable stress: yield stress for ductile materials and ultimate compressive stress for brittle materials. This value represents the threshold at which the mirror experiences permanent damage at the central point of the laser heated area. Note while $Q_{f,[\sigma]}$ is an exact upper bound for the peak stress for most mirror geometries made of ductile materials, it serves only as an indicative value for mirrors made of brittle materials due to the presence of tensile stress at the border of the laser spot. On top of that to prevent delamination of the Au layer from the substrate, which would lead to the failure of the reflective surface, the surface temperature of the gold coating must stay below

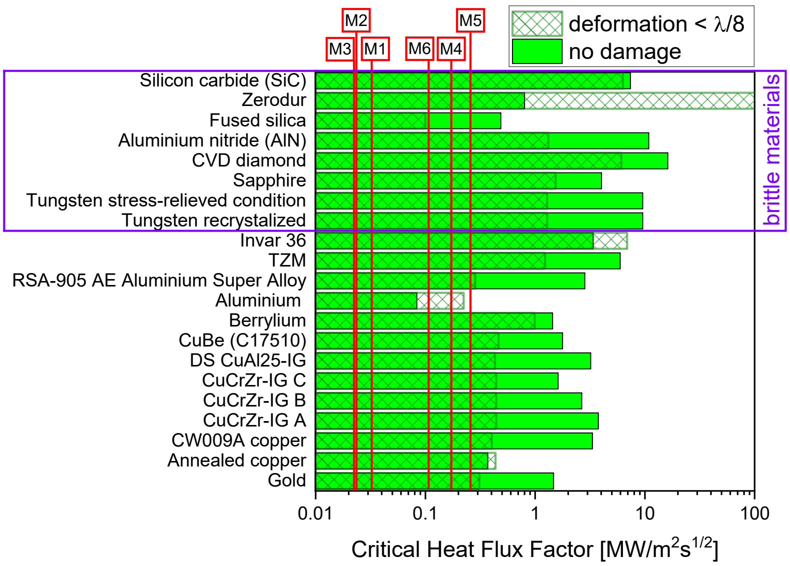

Fig. 1: Critical heat flux factors for various materials suitable as mirrors substrate for high power laser beam transportation. Green lines show maximum heat flux factors for the mirrors M1-M6 with gold coating in the Port Plug.

550°C. The critical heat flux factor for a temperature increase to 550°C is: $Q_{f,\Delta T=550°C} = \frac{\kappa}{2}\sqrt{\frac{\pi}{\alpha}}\Delta T_{max} = \frac{\sqrt{\pi\,\kappa\, C_p\,\rho}}{2}\Delta T_{max}$.

However, optical quality may degrade before the permanent damage occurs. For T-monitor mirrors to maintain an acceptable optical performance the surface deformation must remain below λ/8 for laser operation at λ = 1.07 µm to avoid the optical distortion. As an optimistic estimation the shift the surface of an infinite half-space $u_z = \frac{1+v}{1-v}\frac{\alpha_L}{C_p\,\rho} q\tau$ is taken. Then the critical heat flux factor for achieving λ/8 deformation is: $Q_{f,\lambda/8} = \frac{1-v}{1+v}\frac{C_p\,\rho\,\lambda}{8\,\alpha_L\sqrt{\tau}}$.. Fig. 1 shows the critical heat flux factor for different materials $Q_{f,crit} = min\{Q_{f,[\sigma]}, Q_{f,\Delta T=500°C}\}$ that can be used as mirror substrate for the optical system. The vertical lines represent the maximum heat flux factors for in-vessel mirrors (M1-M6), which have a gold reflective coating.

For most materials, $Q_{f,\lambda/8}$ is lower than the permanent damage threshold for a single-pulse operation mode. However, materials like recrystallized tungsten, annealed copper and aluminium experience plastic deformation before reaching λ/8. The laser in the T-monitor project will operate in different modes. In the most critical mode, the laser has a pulse duration of 3 ms, a frequency of 64 Hz, and a total of 192 laser pulses. The total measurement time for each mode must remain under 3 seconds, requiring an increasing laser pulse frequency as the laser pulse number progress.

The in-vessel mirrors, designated M1 through M6, absorb varying levels of power per 3 ms laser pulse. This ranges from 579 W for the M1 mirror to 710 W for the M6 mirror, based on a surface reflectivity of 96%. However, the most critical parameter is the maximal power density. The M4 mirror, which has the smallest laser spot footprint, experiences the highest incident power density, approximately 7.85 kW/cm². For M4, the

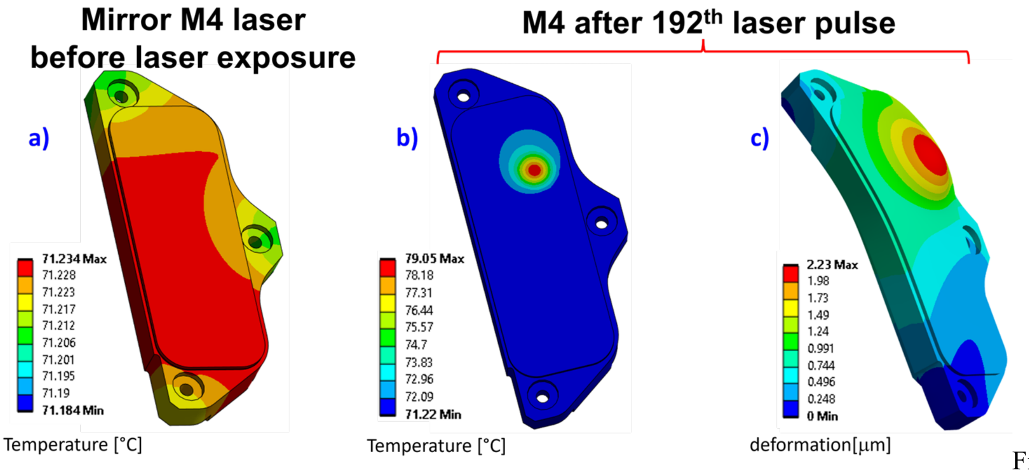

Figure 2: (a) Temperature distribution after a 6-hour cooldown following plasma operation; (b) Temperature distribution after the 192nd pulse for M4; (c) Total deformation after the 192nd pulse (in micrometers, considering only laser load).

absorbed power per 3 ms laser pulse is 655 W, resulting in a cumulative absorption of 377 J over the 192 pulses. Figure 2a illustrates the temperature distribution after a 6-hour cooldown following plasma operation, while Figure 2b presents the resulting temperature distribution for M4 at the end of the 192nd pulse. Before the T-monitor measurements, the temperature of the M4 mirror is nearly uniformly distributed, with a temperature deviation of less than 0.1°C. After the 192nd laser pulse, the maximum temperature increase is less than 8°C, remaining below the threshold for plastic deformation of annealed copper ($\Delta T_{threshold} \approx 11.3$°C). Additionally, Figure 2c depicts the total deformation after the 192nd pulse (in micrometers, considering only the laser load). Ray-tracing analysis conducted in Zemax, using the distorted mirror surface of M4, indicates that the deformation does not significantly affect image quality compared to the nominal case. Minor spot position shifts caused by surface deformation can be corrected through readjustment (corrected focusing) before the next laser pulse is issued.

References

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