研究速報

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Observation of Thermal Stresses Induced by Laser Irradiation in Transparent Optical Materials

透明光学材料におけるレーザー誘起熱応力の観測

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Damage in optical materials has become a serious problem for high power laser systems. Thermal stress degradation and failure is one of the most probable causes in cw infra-red transparent materials. We have observed temporal and spatial dependence of the stress field subject to CO_2 laser beam, by using stress-birefringence effect. Stress-birefringence arises because the value of the refractive index change varies according to the direction when a uniaxial stress is applied to the isotropic transparent materials.[1-3] If we analyze a fringe distribution caused by a birefringence, we can obtain a stress distribution in a sample and also predict a stress failure limitation.

Experimental setup is shown in Fig. 1. We can make a circular polarized light by diffusive plate (D), linear polarizer (P) and quarter-wave plate (Q_1). Anisotropic phase shift is added while a probe laser light of He-Ne laser beam passes the sample (S), which absorbs a CO_2 laser energy. The phase delay is observed by a quarter-wave plate (Q_2) and cross polarized analyser (A). Spatial distribution of the bimefringent fringes after 60 seconds irradiation of CO_2 laser is shown in Figs. 2 and 3. The samples are $L_x=L_y=L_z=10$mm cubes, which have two pairs of optically polished surfaces. Figure 2 is the birefringent fringes of BaF_2 where axially symmetric stress field is observed along the optical axis of CO_2 laser beam, and concentric stress field near the front and the rear surfaces. We also observed a more complicated stress field in KRS-5 sample (Fig. 3). Although the sample initially has a residual inner stress because the sample is not made completely uniform, we can obtain the stress concentration near the sample surfaces at the CO_2 laser irradiation from the divergence of fringes from surface.

After we obtain themperature distribution in the sample by solving the partial differential equation of the heat conduction, we can calculate the internal stresses. The stress distribution results in the anisotropic change in reflactive indeces. The ralation between birefringent fringe movement (χ) and phase delay of the two direction of the polarized light (δ) is written as follows;

$$\chi=\sin^2(\delta) \quad (1)$$

The phase delay is proportional to the absorption coefficient (β) and the insident laser power (P). The

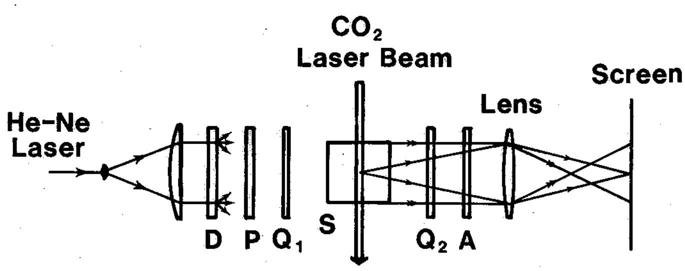

Fig. 1. Experimental Setup.

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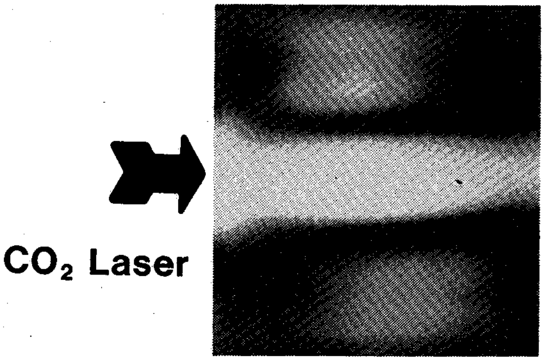

Fig. 2. Birefringent fringes of BaF_2 during the irradiation of CO_2 laser beam.

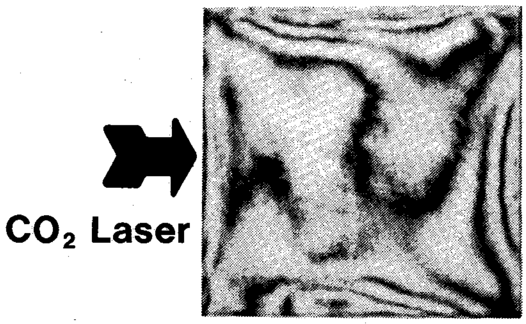

Fig. 3. Birefringent fringes of KRS-5 during the irradiation of CO_2 laser beam.

analysis of a stress field in three dimentional sample is too complex. We use a simple model of axially symmetrical adiabatic heat load in plane strain approximation.[4] The expression of the phase delay along the y-axis at the center of the sample is;

$$\delta=\frac{4\pi aE}{\lambda}(q_{\parallel}-q_{\perp})\int_0^{L_y}\Big[\frac{1}{L_y^2}\int_0^{L_y}Ty\,dy-\frac{1}{y^2}\int_0^{y}Ty\,dy-T\Big]dy, \qquad (2)$$

where a is the thermal expantion coefficent, E is the Young's modulus, λ is the wavelength of the probe laser beam (633 nm), and $q_{\parallel}$ and $q_{\perp}$ is the piezo-optic coefficients of the two poralized light. The temperature distribution (T) is;

$$T=\frac{P\beta}{\rho c}\frac{1}{4}\Big\{w^2-y^2+\frac{2w^2}{hR}+2w^2\ln\Big(\frac{L_y}{w}\Big)\Big\} \qquad 0\leqq y\leqq w,$$

$$T=\frac{P\beta}{\rho c}\frac{w^2}{4}\Big\{\frac{1}{hL_y}+\ln\Big(\frac{L_y}{y}\Big)\Big\} \qquad w<y\leqq L_y, \qquad (3)$$

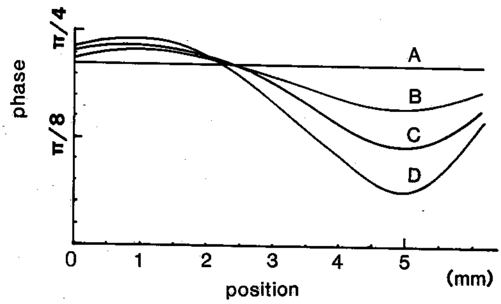

Fig. 4. Spatial and temporal birefringent phase shift of BaF_2 crystal (experiment). Curve A : t=0 sec., B : t=5 sec., C : t=20 sec. and D : t=60sec..

where P is the incident laser power, w is the spot size, β is the absorption coefficient, ρ is the density, c is the specific heat, and h is the heat transfer coefficient.[5] We can obtain the relation at the center of the sample as follows;

$$\delta=-4.57\times10^7\times\frac{P\beta}{\rho c}aE(q_{\parallel}-q_{\perp}). \qquad (4)$$

Figure 4 shows the spatial and temporal distribution of the phase shift. At the power of 160 W/cm^2 BAF_2 is fractured. The critical stress is estimated as 3.41×10^5 Pa.

The stress birefringence result from not only thermal stress caused by the optical absorption of the sample but also residual internal stress and holding external stress. So the measurement of the stress birefringence will be the direct method to estimate the damage threshold of the transparent optical materials for high power laser.

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