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Numerical simulation of thermal stress damage in 1064 nm anti-reflection fused silica by millisecond pulsed laser

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ABSTRACT

In this paper, we study and establish the theoretical model of thermal stress damage of 1064 nm anti-reflection fused silica, based on which transient distributions of temperature field and thermal stress field are simulated using the finite element method (FEM) and then analyze the mechanism of the damage. The main results show that: there is a cumulative effect in the process of 1064 nm anti-reflection fused silica damaged by the laser, its effect is to make the material damage degree increased. The radial temperature gradient is bigger and the axial temperature gradient is smaller in the fused silica internal. In thermal stress damage process which circumferential stress acts a primary role, 1064 nm anti-reflection fused silica damaged by the laser often occurs at the action center or the edge near the spot radius.

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1. Introduction

Laser irradiation on fused silica and its surface coating material is a complex physical process, which is decided by the nature of the two aspects: one is the laser properties, for example: laser pulse width, energy density, repetition rate and effective laser radius, the second is its material properties. Different laser conditions can produce different effects on the same material, and different materials can produce effects of different types of damage under the same laser condition [1]. According to the different effect of the damage, it is divided into thermal damage, stress and strain damage, burning damage, laser supported detonation wave(LSDW) damage and the coupling effects of multiple damage. All of them have a very short period of time, which brings great difficulties to the research work. 1064 nm anti-reflection fused silica is a common window material in optical system, and the damage of any window material in the optical path can cause great loss, even causes the whole system can't run stably. Therefore, it is of great significance and application value to study the damage characteristics of 1064 nm anti-reflection fused silica, especially for the study of the damage effect and damage mechanism of fused silica [2].

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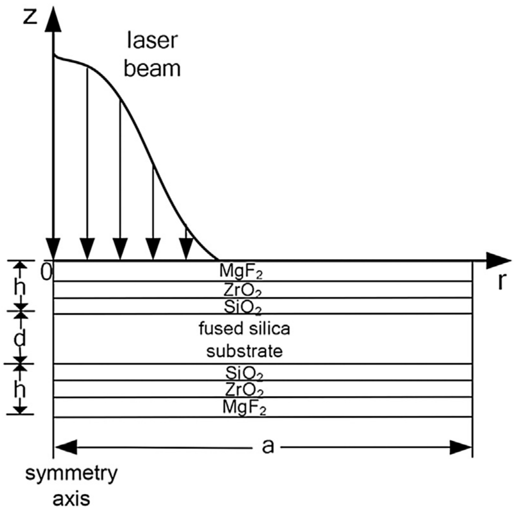

Fig. 1. Geometric model.

2. Theoretical model

2.1. Geometric model

Due to the laser in space is Gaussian distribution, so calculation by cylindrical coordinates, hypothesis of fused silica and its surface coating material are isotropic continuum, Energy absorption that laser irradiation on the material surface is volume absorption [3], a geometric model of 1064 nm fused silica with laser damage is established as shown in Fig. 1, film thickness $h = 5.5 \times 10^{-4}$mm, fused silica substrate thickness $d = 4$ mm, material radius $a = 11.25$ mm.

2.2. Mathematical model

2.2.1. Heat conduction equation

Due to the millisecond pulsed laser and the 1064 nm anti- reflection fused silica energy exchange process is mainly reflected as the heat exchange, and ignoring the material with the surrounding space radiation and convection process, the heat conduction equation can be expressed as the following form [4]:

$$\frac{\partial T_i(r,z,t)}{\partial t} = \frac{k_i}{\rho_i c_i}\left(\frac{\partial^2 T_i(r,z,t)}{\partial r^2} + \frac{1}{r}\frac{\partial T_i(r,z,t)}{\partial r} + \frac{\partial^2 T_i(r,z,t)}{\partial z^2} + \frac{q_i(r,z,t)}{k_i}\right) \tag{1}$$

Where, T_i *(r, z, t)*at time t is the temperature distribution. k_i, r_i and c_i respectively represent heat conduction coefficient, density and specific heat. $i = f$、s respectively represent film and fused silica substrate, the heat source of the heat conduction equation can expressed as [5]:

$$q_i(r,z,t) = \alpha_i(1 - R_i)I_0 f(r)m(z)g(t) \tag{2}$$

$$f(r) = \exp\left(-\frac{2r^2}{r_0^2}\right) \tag{3}$$

$$m(z) = \exp(-\alpha_i z) \tag{4}$$

$$g(t) = 1(0 \le t \le \tau_p(ms)) \tag{5}$$

Where, *f(r)* and *g(t)* respectively represent the laser spatial and temporal distribution. r and z respectively represent the radial and axial coordinates of cylindrical coordinate system, r_0 represent the laser spot radius, a_i represent the absorption coefficient of film and fused silica, t_p represent laser pulse width, R_i represent the reflectivity of film and fused silica. I_0 represent the laser power density [6].

2.2.2. Elastic mechanics equation

Under the cylindrical coordinate system, the coupled equations of elasticity can be expressed as follows:

$$\nabla^2 u_{ri} - \frac{u_{ri}}{r^2} + \frac{1}{1-2\mu_i}\frac{\partial \varepsilon_i}{\partial r} - \frac{2(1+\mu_i)}{1-2\mu_i}\beta_i\frac{\partial T_i}{\partial r} = 0 \tag{6}$$

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