ISSN 1063-7745, Crystallography Reports, 2012, Vol. 57, No. 6, pp. 792–797. © Pleiades Publishing, Inc., 2012.
Original Russian Text © A.N. Serdyukov, E.B. Shershnev, Yu.V. Nikityuk, V.F. Sholokh, S.I. Sokolov, 2012, published in Kristallografiya, 2012, Vol. 57, No. 6, pp. 879–885.

PHYSICAL PROPERTIES OF CRYSTALS

Features of Controlled Laser Thermal Cleavage of Crystal Quartz

A. N. Serdyukov, E. B. Shershnev, Yu. V. Nikityuk, V. F. Sholokh, and S. I. Sokolov

Francisk Skorina Gomel State University, Gomel, 246019 Belarus
e-mail:nikitjuk@gsu.by

Received April 17, 2012

Abstract—Controlled laser thermal cleavage of crystalline quartz has been simulated. The thermoelastic fields formed in a square single-crystal quartz plate as a result of successive laser heating and exposure to coolant have been calculated for five different versions specified by the crystal cut orientation and direction of laser beam displacement. The results have been verified experimentally using a CO_2 laser. The simulation results can be used in the electronics industry to optimize laser cutting of quartz crystals.

DOI: 10.1134/S1063774512060120

Controlled laser thermal cleavage is one of the most efficient methods for high-precision treatment of brittle nonmetallic materials. Its essence is the division of a material into parts as a result of the formation of a thermally induced crack upon successive laser heating and exposure the processed surface to a coolant [1]. The main advantages of controlled laser thermal cleavage are a high precision and high division rate, low energy consumption, and minimal waste. The main features of this method as applied to isotropic brittle nonmetallic materials were studied in [2–5] (primarily, for silicate glasses and alumina ceramics).

Currently, much attention is paid to the features of laser thermal cleavage of various crystals [6, 7]. The interest in this technique stems from the significant drawbacks of conventional methods used to cut crystals, in particular, significant loss of material and contamination of working surfaces.

Among the publications on this subject, the studies devoted to controlled laser thermal cleavage of quartz crystals [8, 9] are of special interest. The study of the specific features of this technique as applied to quartz crystals is very important, because quartz crystal elements are widely used in industry: the annual quartz consumption cost exceeds 1 bln USD [10]. It was shown in [8–10] that the consideration of the crystallographic orientation of material processed is of fundamental importance when choosing the parameters of laser thermal cleavage. However, the focus of the aforementioned studies was on the anisotropy of thermal expansion of quartz crystals, while the dependence of other quartz properties on the crystallographic direction was disregarded. In this context, we find it expedient to analyze the features of controlled laser thermal cleavage of quartz crystals with allowance for the anisotropy of not only thermal expansion but also thermal conductivity and elastic properties.

Laser thermal cleavage of quartz plates was simulated by the finite-element method [11]. In the first stage we calculated the temperature fields and then determined the thermoelastic stresses formed as a result of laser irradiation and effect of coolant on a crystalline quartz plate. With this simulation algorithm, the results are obtained within the unbound quasistatic thermoelasticity problem [12]. The simulation results were analyzed using the maximum tensile stress criterion [13].

Calculations were performed for square plates 20 × 20 × 1.5 and 20 × 20 × 0.75 mm in size, exposed to 10.6 μm laser radiation with a power $P = 50$ W; the laser spot radius was $R = 1.5$ mm. The velocity of plate motion with respect to the laser beam and coolant was chosen as $v = 5$ or 15 mm/s.

Simulation was carried out for standard initial orientations of crystalline squared samples [14]. For each of three cuts under study the directions of laser beam motion were aligned with the crystallographic axes lying in the corresponding plane processed (Fig. 1). In accordance with [14], the cuts are denoted by two letters, indicating the crystallographic axes along which the crystalline element is oriented. The first letter indicates the axis to be directed along the sample thickness and the second letter corresponds to the axis oriented along the sample length.

Obviously, when square samples are used, it is sufficient to consider processing only along the X axis in the case of *zy* cut. Thus, the thermoelastic fields formed in a single-crystal quartz plate as a result of successive laser heating and exposure to a coolant were calculated for five different versions:

(I) analysis of the *zy* cut with laser beam displacement along the X axis;

(II) analysis of the *yx* cut with laser beam displacement along the X axis;

(III) analysis of the *yx* cut with laser beam displacement along the Z axis;

(IV) analysis of the *xy* cut with laser beam displacement along the Z axis;

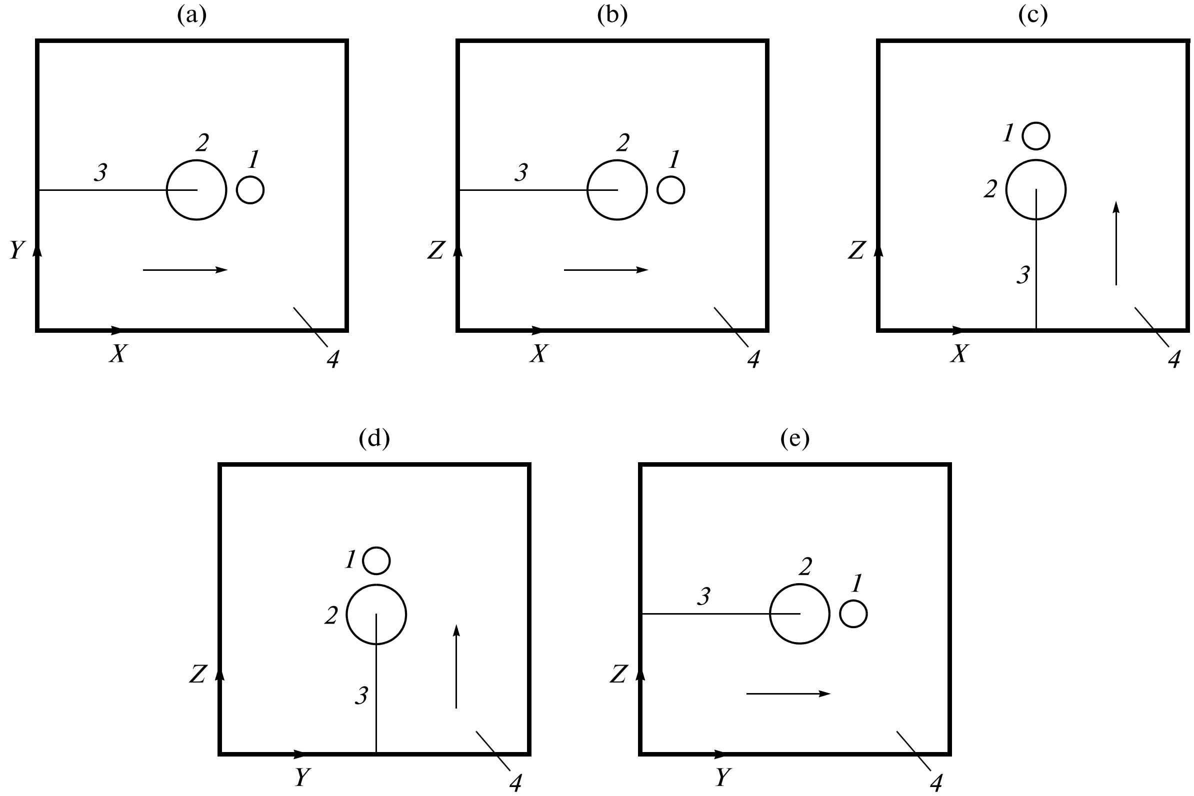

Fig. 1. Schematic arrangements of the regions exposed to laser radiation and coolant in the treatment plane for versions (a) I, (b) II, (c) III, (d) IV, and (e) V: (*1*) laser beam, (*2*) coolant, (*3*) laser-induced crack, and (*4*) quartz plate. The horizontal arrow indicates the direction of displacement of element processed with respect to the laser beam and coolant.

(V) analysis of the *xy* cut with laser beam displacement along the *Y* axis.

Figure 1 shows schematic arrangements of the regions exposed to laser radiation and coolant in the treatment plane for the five treatment versions under consideration.

The density and specific heat of crystalline quartz in the calculations were assumed to be, respectively, $\rho = 2643$ kg/m^3 and $C = 741$ J/(kg K). The differences in the physical properties of crystalline quartz in different crystallographic directions were taken into account. The thermal conductivity and linear thermal expansion of crystalline quartz were taken as, respectively, $\lambda_{\parallel} = 12.3$ W/(m K) and $\alpha_{\parallel} = 9 \times 10^{-6}$ K^{-1} along the threefold symmetry axis Z and $\lambda_{\perp} = 6.8$ W/m K and $\alpha_{\perp} = 14.8 \times 10^{-6}$ K^{-1} in the direction perpendicular to the Z axis [15, 16].

The Hooke law for anisotropic materials can be written in matrix form [17, 18]:

$$\sigma_i = \sum_{k=1}^{6} C_{ik}(\varepsilon_k - \varepsilon_k^t), \tag{1}$$

where the stresses

$$\sigma_1 = \sigma_{xx}, \quad \sigma_2 = \sigma_{yy}, \quad \sigma_3 = \sigma_{zz},$$
$$\sigma_4 = \sigma_{yz}, \quad \sigma_5 = \sigma_{zx}, \quad \sigma_6 = \sigma_{xy}; \tag{2}$$

elastic strains

$$\varepsilon_1 = \varepsilon_{xx}, \quad \varepsilon_2 = \varepsilon_{yy}, \quad \varepsilon_3 = \varepsilon_{zz},$$
$$\varepsilon_4 = 2\varepsilon_{yz}, \quad \varepsilon_5 = 2\varepsilon_{zx}, \quad \varepsilon_6 = 2\varepsilon_{xy}; \tag{3}$$

and thermal strains

$$\varepsilon_1^t = \alpha_x \Delta T, \quad \varepsilon_2^t = \alpha_y \Delta T, \quad \varepsilon_3^t = \alpha_y \Delta T,$$
$$\varepsilon_4^t = 0, \quad \varepsilon_5^t = 0, \quad \varepsilon_6^t = 0. \tag{4}$$

Low-temperature quartz belongs to the trigonal system; therefore, its elastic properties are described by six independent components of the elasticity tensor, which can be written in matrix form for the *zy* cut as [19]

$$\{C_{ik}\} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} & 0 & 0 \\ C_{12} & C_{11} & C_{12} & -C_{14} & 0 & 0 \\ C_{13} & C_{12} & C_{33} & 0 & 0 & 0 \\ C_{14} & -C_{14} & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & C_{14} \\ 0 & 0 & 0 & 0 & C_{14} & \dfrac{C_{11} - C_{12}}{2} \end{pmatrix}. \tag{5}$$

The matrix $\{C_{ik}\}$ for the *yx* cut can be written as