Fracture toughness, hardness, and elastic modulus of kyanite investigated by a depth-sensing indentation technique

ALEXANDRE MIKOWSKI,1 PAULO SOARES,2 FERNANDO WYPYCH,3 AND CARLOS M. LEPIENSKI1,*

1Department of Physics, Universidade Federal do Paraná, Curitiba (PR) 81531-990, Brazil
2Department of Mechanical Engineering, Pontifícia Universidade Católica do Paraná, Curitiba (PR) 80215-901, Brazil
3Department of Chemistry, Universidade Federal do Paraná, Curitiba (PR) 81531-990, Brazil

ABSTRACT

Macroscopically bladed kyanite crystals of blue and glassy luster were cleaved along two planes, and the mechanical properties were measured through depth-sensing indentation (DSI). The conventional method to determine fracture toughness (Kc) from indentation is based on radial crack lengths measurements, which is difficult to estimate owing to the ease with which kyanite cleaves. An alternative method is proposed to determine the Kc for the perfect cleavage plane (100) of kyanite based on the estimation of the crack nucleation threshold load from a discontinuity or “pop-in” in the DSI load-unload curve. The toughness value for kyanite in the plane of perfect cleavage (100) determined by the proposed method is Kc = 2.1 MPa m1/2. The hardness of 10.7 ± 1.6 GPa for the perfect cleavage plane is lower than the one measured in a plane (010), 18.0 ± 2.9 GPa. The measured elastic modulus for the perfect cleavage plane (100) and for the plane (010) are 297 ± 11 and 405 ± 31 GPa, respectively. These values are in agreement with the published mechanical properties of kyanite, obtained by other techniques. The mechanical behavior is discussed and correlated to fracture patterns during indentation for both crystallographic directions of this mineral.

Keywords: Kyanite, fracture toughness, hardness, elastic modulus, depth-sensing indentation, mechanical properties

INTRODUCTION

Kyanite, with an ideal composition of Al2SiO5, is the high-pressure polymorph of the aluminosilicate group, which includes two other minerals, andalusite, and sillimanite. The three polymorphs are very important in metamorphic and experimental petrology due to their abundance and relatively simple chemistry, providing an exemplary crystal-chemical system to study mineral transformations (Yang et al. 1997a). Kyanite is classified as an orthosilicate (isolated SiO4 tetrahedra; i.e., no O atoms bridging to other Si tetrahedra) (Hatman and Sherriff 1991) with AlO6 octahedra forming chains parallel to [001]. It occurs in metamorphic rocks and its color is variable, with blue, white, green, yellow, pink, gray, or black varieties known to occur, depending on the contaminant elements; Fe3+, Cr3+, and Ti4+ being the most important ones and generally substituting for octahedral Al. Kyanite is primarily used in refractory and ceramic products, including porcelain plumbing fixtures and dinnerware, as electrical insulators and abrasives, and as a gemstone, though this last application is limited by its anisotropic characteristic (Karaus and Moore 2003).

The structure of kyanite is triclinic with cell parameters: a = 7.1262 Å, b = 7.8520 Å, c = 5.5724 Å, α = 89.99°, β = 101.11°, and γ = 106.03° (Winter and Ghose 1979). Kyanite is strongly anisotropic, and its hardness varies depending on crystallographic direction, which is considered an identifying characteristic. The Mohs scale hardness of kyanite is ~4.5–5 when scratched in the direction of [001] (the octahedra chains) and ~6.5–7 when scratched perpendicular to this direction (Klein and Hurlbut 1999).

Aiming to study this anisotropic characteristic of the kyanite, Winchell (1945) measured the Knoop hardness (HK) using an applied load of 1 N. Due to the Knoop indenter geometry, the largest diagonal was oriented along the planes [001], [010], and (100) in combination with the directions [100], [010], and [001]. No cracks were observed for all the impressions. From the work of Winchell (1945), the averages Knoop hardness (HK) are 7.8 GPa for the cleavage plane (100) and 10.6 GPa for the other planes.

Recently, Whitney et al. (2007) carried out mechanical experiments using the Vickers indentation and depth-sensing indentation (Berkovich indenter) in some common metamorphic minerals with a single loading-unloading cycle with applied loads of 2 N and 100 mN, respectively. The three Al2SiO5 polymorphs (kyanite, andalusite, and sillimanite) were measured and presented Vickers hardness (HV) of 10–12 GPa and depth sensing indentation hardness (DSI) of 12–16 GPa, independent of the indented plane orientation.

The bulk modulus of kyanite was obtained through compress-