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Surface cracking of soda lime glass under pulsed high-current electron radiation

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Abstract

Electron beam radiation has been widely used to modify the surface properties of materials such as metals, ceramics, and glasses. However, a few investigations of surface topology of glasses after electron irradiation can be found. In contrast to the surface cracking by bending, indentation, and thermally induced stress in soda lime glasses a 2 μs pulsed high-current electron beam was used to modify the surfaces of soda lime glass. Surface topology of irradiated samples was studied by using traditional optical microscopy and atomic force microscopy. Parallel to and perpendicular to surface cracks were observed. The depth of crack can be obtained by electron penetration, Newton's ring and AFM. The stress to produce the crack by electron radiation was calculated using three obtained depths. The observed surface crack is explained in terms of radiation-induced thermal stress and high local electric field-induced by deposited charges from pulsed electrons.

Keywords: Surface crack; Soda lime; Electron radiation

1. Introduction

One unique feature of glasses is brittleness. They break abruptly without macroscopic deformation; however, the nano-scale deformation, i.e., micro-cavities, at the crack site was recently observed by atomic force microscopy [1]. Electron beam technology has been developed since the 1970s from a welding source to a multiple purpose tool in industrial applications [2–9]. Electron radiation modified the surfaces of metallic materials by enhancing the surface hardness due to the surface phase transformations, forming alloys on thin metallic films due to mixing of metal atoms at the interfaces, and oversaturated metallic components in alloys [10,11]. Electron radiation has also been used in food sterilization where electrons were accelerated to a desired speed or energy and then bombarded onto a target material in which the chemical reactions such as bond breaking and forming take place. Furthermore, electron beam radiation was applied to ceramics and glasses to improve the biological affinity and to prevent the formation of water vapor and condensation on glass surfaces [12]. Previous study of electron radiation effects on surface of lead silicate glass indicated that permanent metallic lead accumulated on the surface due to the Pb–O bond breaking and nucleation of metallic Pb [13,14] while the relative concentrations of bridging and non-bridging oxygen species changed accordingly during the radiation.

Surface cracks produced by bending [15], indentation [16], and thermally induced stress, [17] in soda lime glasses were previously reported. Although there has been an extensive application of electron beam technology, few studies of glass surface crack induced by pulsed high-current electron beam have been reported. It is of interest to investigate the

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surface topology changes of soda lime glasses after pulsed high-current electron irradiation. In this paper we report radiation-induced surface cracks under pulsed high-current electrons onto the surfaces of soda lime since it has limited resistance to thermal shock [18]. From the measured depths of the crack by optical microscope and AFM, the stresses to produce the crack under electron radiation were calculated.

2. Experimental

The pulsed high-current electron beam was produced by an accelerator manufactured by the Tomsk Institute of Nuclear Science. The schematic drawing of the setup is shown in Fig. 1. The pulse duration and beam homogeneity are accomplished by using a plasma to form and deliver the electron beam to the sample target. When the cathode/anode and the beam drift space are filled by plasma, the electric field at the cathode and the electron drift distance can be increased substantially as compared to the traditional electron emission in vacuum diodes. The plasma is produced from the spark sources as shown in parts labeled by 5 and 6 where region 5 contains positively charged plasma near the cathode and region 6 has negatively charged plasma near the anode and sample. The electron energy produced by this setup can reach up to 40 keV at beam currents of 10^4 A, while the pulse width of the beam is 2.0 μs. The beam cross-section is approximately 20 cm^2 and the electron energy density is 5–10 $J\,cm^{-2}$.

The glass sample is commercially available soda lime glass with the following weight percentages: 72.6 SiO_2, 1.63 Al_2O_3, 0.2 Fe_2O_3, 6.3 CaO, 3.83 MgO, and 15.4 Na_2O. Samples are 40 mm × 40 mm × 1 mm, cleaned by acetone, methanol, de-ionized water, and then blown dry with nitrogen. The experiments were performed under vacuum at about 4.5×10^{-5} Torr during irradiation. Samples were investigated by optical microscope and atomic force microscopy, Nanoscope IIIa manufactured by Digital Instruments, after bombarded by 24 keV electrons. A white light was used to obtain the optical images with 100× and 400× magnifications.

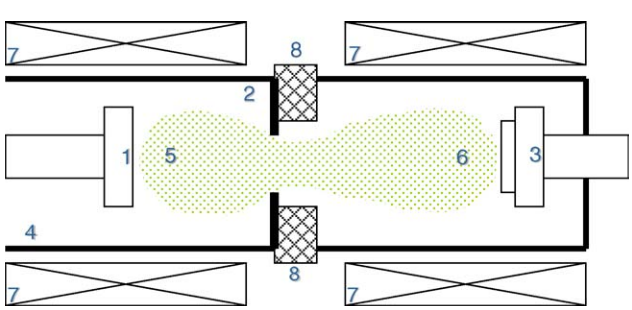

Fig. 1. Schematic drawing of the experimental setup, cathode (1), anode (2), sample (3), vacuum chamber (4), positively charged plasma (5), negatively charged plasma (6), coils (7), and spark sources (8).

Fig. 2. Optical picture (100×) of sample surface after radiation. Dark lines and parts indicated cracks/peelings on the surface.

3. Results and discussion

The optical microscope results of sample after radiation are shown in Figs. 2–4 where Figs. 2 and 3 with a magnification of 100 and Fig. 4 400 times magnification. Two kinds of crack appeared under the microscope. One is perpendicular to the surface and the other is approximately parallel to the surface. The first kind cracks were seen as dark lines in Figs. 2 and 3 and the second type cracks were deduced from the Newton rings in Fig. 4. Some line cracks are caused by the radiation-induced bond breaking and thermal stress on the radiation layer. Some other line cracks are due to the interaction between crack fronts produced by bond breaking/thermal stress due to the energy lose of electron and surface defects. Field [19] illustrated how the crack reacts with other surface defects to form these line cracks so called Wallner lines [20]. Since these two kinds of line cracks interwoven so much that

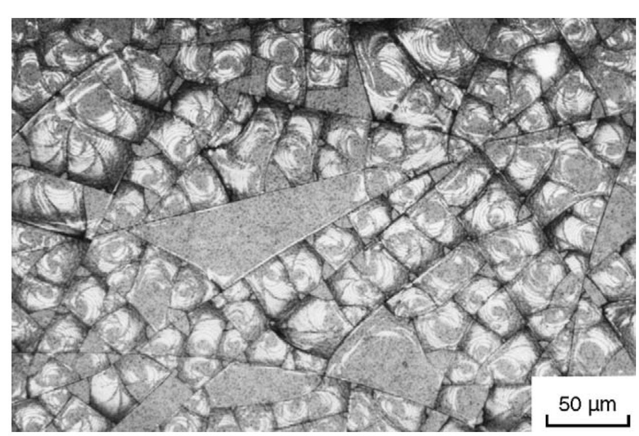

Fig. 3. Optical picture of sample surface after radiation. Partial arcs and complete dark circles, Newton's rings, were seen. Evidently some parts of surface, e.g. a big flat triangular piece, did not show surface damage. Once the stress released around this piece by forming the cracks and peeling there is nothing to induce a stress on it. Therefore there will not be any further damage.