Microstructure characterization is of great value to understanding nuclear graphite's properties and irradiation behavior. However, graphite is soft and could be easily damaged during sample preparation. A three-step polishing method involving mechanical polishing, ion milling, and rapid oxidation is proposed for graphite. Ion milling is adopted to remove the broken graphite pieces produced by mechanical polishing. Rapid oxidation is then adopted to remove irradiation-induced damage layer during ion milling. The Raman spectra show very small G peak width and very low $I_D/I_G$ ratio after rapid oxidation. The microcracks that were conventionally observed via a transmission electron microscope can be observed on rapid-oxidized surface in a scanning electron microscope. By digital image processing, the microcracks along with the gas-escape pores in nuclear graphite IG-110 are statistically analyzed. Porosity's distributions on crack (pore) size (spanning from 10 nm to 100 μm) are given, which could help to understand and simulate graphite's performances in reactors.

**KEYWORDS**
ion milling, microcracks, microstructure, nuclear graphite

---

**1 | INTRODUCTION**

Graphite materials have a variety of applications in many fields of industry and engineering. Particularly, highly purified graphite is proposed to be the core structural material in two types of Generation IV reactors: molten salt reactors and very high temperature reactors. The artificial graphite is usually manufactured from a filler coke and pitch binder. The release of volatile content of binder region during carbonization leaves gas-escape pores in the graphite product. Cooling down from high-temperature graphitization creates microcracks between graphite basal planes. Both gas-escape pores and microcracks have a great influence on nuclear graphite's properties and performances.

Graphite microstructures are very complicated. The gas-escape pores and microcracks show various shapes, orientations, and sizes in nuclear graphite. Direct observation and statistical analysis of graphite gas-escape pores have been achieved for pristine graphite,1–3 oxidized graphite,4,5 and irradiated graphite.6 X-ray tomography has been used to compare pore structures of several graphite grades3 and to investigate porosity changes induced by oxidation.5 The best resolution of X-ray tomography is around 1 μm. A technique combining optical microscopy and digital image processing has also been adopted to analyze pore structures of various graphite grades.1,2,4 It has been demonstrated that X-ray tomography and optical micrograph processing give consistent pore-size distributions for IG-110 graphite.6 Microcracks in graphite conventionally were observed via transmission electron microscope (TEM). It is very difficult to achieve a statistical analysis of microcracks based on TEM characterization because of its very limited field of view. Therefore, the differences in microcracks between graphite grades and the changes in microcracks induced by irradiation or oxidation cannot be readily found via TEM characterization. In recent years, the focused ion beam-scanning electron microscopy (FIB-SEM) tomography7,8 and electron tomography9 have been used to reconstruct the 3-D structure of graphite microcracks. Neutron irradiation-induced significant development of mesopores with volume <0.1 μm$^3$ has been demonstrated using the FIB-SEM tomography.7 However, the sizes of samples for FIB-SEM tomography and electron tomography are limited to several microns. A statistical analysis of graphite microcracks is still a challenge.
Appropriate specimens have to be prepared for microstructural characterizations. Graphite materials are soft and could be changed during specimen preparation, which may bring some uncertainties to the analysis of graphite microstructures. The TEM specimens are usually prepared by argon ion beam milling or focused gallium ion beam milling. Ion-milling-induced damage in alloys have been studied and successfully removed by an electropolishing method. As for graphite, ion milling's influence to the microstructures has not been identified. A low-density carbon material has been found and studied during TEM observation of nuclear graphite specimens prepared by argon ion milling\textsuperscript{11,12} or focused gallium ion milling.\textsuperscript{7,13} But the origin of this carbon material has not been well explained. When observed in an optical microscope or a scanning electron microscope (SEM), the graphite specimen requires polishing, usually mechanical polishing. It was reported that mechanical polishing could greatly enhance the intensity of Raman D mode, indicating a remarkable increase of defects in graphite.\textsuperscript{14} The submicron-sized structures (such as microcracks) cannot be seen on mechanically polished graphite surface.

In this study, the damages induced by mechanical polishing and ion milling are identified and effectively removed to produce a graphite surface without artificial defects, so that the graphite microcracks on the sample's surface can be observed in an SEM. A statistical analysis of graphite microcracks is then achieved.

2 \hspace{1cm} EXPERIMENTAL

One typical nuclear grade of graphite, IG-110, is used in this study. The IG-110 graphite, from Toyo Tanso Inc., is produced from a petroleum coke with an average grain size of 20 μm. A sample with sizes of 15 × 15 × 15 mm was used in this study. The mass and dimensions of the samples were measured using a balance and micrometer, respectively, in order to calculate the apparent density and total porosity.

A three-step polishing method is proposed in this study. The first step is mechanical polishing. In order to prevent the pores being blocked by graphite dust and polishing medium, a thermoplastic resin was used to fill the graphite pores before mechanical polishing. One facet of the sample was ground on a grit 600 silicon carbide abrasive paper and then was polished successively on cloth using 3-μm diamond and 20-nm silica suspensions for several minutes. After that, the sample was washed in acetone to remove the resin.

The second step is ion beam milling. A small sample with sizes of 3 × 3 × 2 mm was cut from the mechanically polished sample. The mechanically polished surface of the small sample was then bombarded by glancing-incident (6°) argon ion beams with energies of 4.5 and 3 keV successively in a Gatan Model 691 system. The sample size is limited by this ion milling system.

The third step is rapid oxidation. A furnace was electrically heated in air to 680°C. Then the ion-milled sample was put into the furnace as quick as possible. The ion-milled graphite surface was oxidized in air for 3 min. The sample was then taken out and cooled down in air. (It should be noted that the temperature was not specifically selected in this study. The furnace temperature was set to 750°C. Due to its bad temperature probe, the actual temperature was calibrated by a thermal couple and was 680°C. Besides, the temperature was not strictly controlled during oxidation because opening the furnace lid disturbed the temperature inside the furnace. The above mentioned operation of rapid oxidation is not rigid but very convenient and is good enough for the purpose of oxidation in this study.)

In order to analyze the gas-escape pores, the mechanically polished surface of the sample was observed using an optical microscope with a magnification of 100 ×. The pixel resolution was measured in Photoshop software and is 0.54 μm. In total, 63 micrographs were recorded for the sample and were stitched together to form a large grayscale image of the polished surface. An 8 × 8 mm micrograph was then cut from the large grayscale image with the help of Photoshop. The pores in the optical images are shown as dark regions. Then, the pores were extracted from the optical images and were statistically analyzed.

The graphite surface was observed in an SEM after performing each polishing step. The element on the surface was measured by using the energy dispersive x-ray (EDX) spectroscopy. Especially, after rapid oxidation, the surface was observed in SEM with a magnification of 5000 ×. The pixel resolution was measured in Photoshop software and is 7.5 nm. In total, 48 micrographs were recorded for the sample and were stitched together to form a large grayscale image (0.13 × 0.13 mm). Similar to the pores in optical image, the microcracks are shown as dark regions in the SEM image. The microcracks then were extracted from the image and were statistically analyzed.

In order to investigate the low-density carbon material reported in previous studies, a thin disk specimen of IG-110 graphite was also prepared for TEM observation. A hole in the middle of the specimen was achieved by argon ion milling, which used the same ion energies as the second polishing step given above. The very thin area of the TEM specimen was also observed via SEM.

To study the damage induced by each polishing step, the Raman spectra were measured on sample’s surface after mechanical polishing, ion beam milling, and rapid oxidation. A Bruker SPECTRUM confocal Raman microscope was used. The excitation light is a He–Ne laser with a wavelength of 633 nm. Five spots were randomly selected on the samples’ surface for Raman spectra measurements.

3 \hspace{1cm} RESULTS AND DISCUSSION

3.1 \hspace{1cm} Identifying damage induced by mechanical polishing and ion milling

Figure 1A shows an SEM image of mechanically polished surface of IG-110 graphite. The widespread microcracks cannot be seen, and the fillers cannot be readily distinguished from the binder regions on the surface. One typical area is magnified in the inset image, which shows small broken graphite pieces induced by friction between graphite surface and silica particles during mechanical polishing.
Figure 1B shows an SEM image of ion-milled IG-110 graphite. The broken graphite pieces have been completely removed. More importantly, microcracks (indicated by the white arrows in Figure 1B) are observed on the ion-milled surface. However, it is observed that the very thin cracks are not empty after ion beam milling.

In order to understand the non-empty cracks, a thin disk specimen with a hole in the middle was prepared by argon ion milling. Figure 2A shows a TEM image of one filler in IG-110 graphite. The low-density carbon material, which has been reported in previous studies, also appears in cracks shown in Figure 2A. If this carbon material is inherent in as-manufactured graphite, it should be found inside the cracks. The TEM image does show that the carbon material seems to reside inside the cracks. However, the cracks look different when observing them via SEM. The SEM image (Figure 2B) shows that the cracks are highly likely to be covered by a thin layer of carbon material. The narrow cracks are fully covered, and the wide cracks are partly covered. Especially the wide crack on the left is observed to be empty and partly covered by two thin layers of carbon material on the upper surface and the lower surface (indicated by arrows), respectively. Both sides of the thin specimen were processed by argon ion milling. Except for sputtering, another important effect is irradiation during argon ion milling. It is well-known that irradiation induces swelling of graphite along the c axis. The irradiation-induced c-axis swelling could be as high as 200% at room temperature. Therefore, this carbon material should be caused by irradiation-induced c-axis swelling of graphite crystallites. The argon ion irradiation process was simulated by using “The Stopping and Range of Ions in Matter” program. The irradiation damage induced by 3-keV argon ions at a glancing angle of 6° is deposited in a 2-nm-thick surface layer. Thus, the cracks shown in Figure 2 should be covered by a 2-nm-thick layer of carbon material.

The artificial carbon material induced by irradiation damage is apparently much more defective than the underlying graphite structures and is believed to be more susceptible to oxidation. Therefore, a rapid oxidation process was adopted to remove this artificial carbon material. Figure 1C shows an SEM image of IG-110 graphite after oxidation at 680°C for 3 min. The artificial carbon material induced by argon ion milling is completely removed by rapid oxidation, and the microcracks can be clearly seen on the sample's surface. It is proved that 3 min is too short to cause an obvious damage to surface morphology and pore structures but is long enough to remove the very thin irradiation layer.

Figure 3A–C shows the EDX spectra of as-machined graphite surface and graphite surface after ion milling and rapid oxidation, respectively. Oxygen, either chemically absorbed (C–O or C=O) or physically absorbed (C(O2)), always can be detected on graphite surface even after ion milling. The reason is that the ion-milled sample was exposed to air for a short period of time before characterization in an SEM. After rapid oxidation, a lot of oxygen atoms were chemically absorbed on the specimen. The chemical bonding of carbon atoms on the very surface has been changed. However, the pore structures with sizes >10 nm should not be influenced by the local chemical bonding.

After ion milling, a strong signal of argon can be seen in Figure 3B, indicating that the argon ions were implanted into graphite surface. Argon implantation has been found in highly ordered pyrolytic graphite sputtered with 5-keV argon ions. As the argon ions slowed down and settled in graphite, argon–carbon collisions happened and induced irradiation damage. After rapid oxidation, the
artificial carbon thin layer was removed, and the argon was released. No argon signal was detected in Figure 3C.

It is worth mentioning that silicon has been found after ion milling and rapid oxidation. The reason is that the sample was mechanically polished with silica suspensions before ion milling. We did not use ultrasonic cleaning to remove the residual silica particles in order to prevent ultrasound-induced damage to graphite structures. The silica particles adhering to the surface were sputtered and redeposited in pores and then were detected during EDX spectrum measurements. Because the microcracks were covered by an irradiation damage layer during ion milling, silica should not be deposited in cracks. Therefore, the presence of silicon element would not influence the analysis of pores and cracks.

Figure 4A shows the typical Raman spectra measured on IG-110 graphite surface after mechanical polishing, ion milling, and rapid oxidation. Each spectrum has three peaks (the D peak located at \( \sim 1340 \text{ cm}^{-1} \), G peak at 1583 cm\(^{-1}\), and the D' peak at 1619 cm\(^{-1}\)). The intrinsic G peak originated from the in-plane symmetric stretching motion of C–C sp\(^2\) bond and is the only peak that can be detected from defect-free graphite crystal. The D peak involves a breathing mode of sixfold rings of carbon atoms and only can be excited in the presence of in-plane defects.
Fitting of the Raman spectra was achieved by using three Lorentzian lines for the G, D, and D' peaks. The peaks in the spectrum of ion-milled graphite seem to be raised up by a “bump” of the spectrum. Based on above discussion, ion beam milling introduced irradiation damage at surface and produced a highly damaged surface layer with a thickness of ~2 nm. The Raman spectrum of ion-milled graphite is composed of signals from the highly damaged thin layer (responsible for the “bump” of the spectrum) and the graphite structure underneath this layer. Therefore, one Gaussian line was added to fit the “bump” of the spectrum.

The full width at half maximum (FWHM) of the G peak and the ratio of the intensities of D and G peaks ($I_D/I_G$) have been widely used to analyze the microstructures of graphitic materials after various treatments. The average value and the standard deviation (the error bar) of the FWHM and $I_D/I_G$ ratio are shown in Figure 4B,C, respectively.

The Raman spectra clearly show the damage induced by each polishing step. Mechanical polishing induced broken graphite sheets with abundant boundaries, which could raise the D peak intensity. Figure 4C shows that the mechanically polished graphite surface shows the highest $I_D/I_G$ ratio (~1.4). Ion beam milling induced crystal disordering, which causes a strong coupling between discrete G mode and a continuum of phonon states, resulting in peak broadening.

Therefore, the ion-milled graphite surfaces show the highest G peak width (Figure 4B). After rapid oxidation, the G peak width and $I_D/I_G$ ratio reduced to 19 cm⁻¹ and 0.28, respectively. It is worth mentioning that the $I_D/I_G$ ratio was reported to be inversely proportional to the in-plane graphite crystal size ($L_a$) and this relationship has been used to obtain $L_a$ from the Raman spectra measured on graphite sample’s surface. However, Figure 4 shows that the mechanical machining, grinding, or polishing could raise the $I_D/I_G$ ratio and thus underestimate the real $L_a$ of graphite crystallites inside the sample. The Raman spectra measured on rapid-oxidized surface are believed to be more appropriate for calculating the $L_a$ value.

3.2 Analysis of IG-110 graphite pores and microcracks

Figure 5A is an SEM image of rapid-oxidized surface showing a typical filler particle in IG-110 graphite. There are abundant microcracks in this filler region. Some cracks are bridged by small graphite sheets (indicated by the two arrows). The graphite sheets are curved, deflected, and folded in the filler. It is found that IG-110 is very rich in microcracks, which is consistent with its low coefficient of thermal expansion ($4 \times 10^{-6} \text{ K}^{-1}$) and deep volume shrinkage (~5% at 750°C) during neutron irradiation.

The quinoline insoluble (QI) particles can also be clearly seen on graphite’s surface after rapid oxidation. Figure 5B shows several QI particles observed at a magnification of 40 000×. The nanosized graphite sheets with their c axis directing radially toward the center of the QI particles are clearly seen. There was an attempt to identify the QI particles on mechanically polished graphite surface. It was observed that the typical structure of QI particles was damaged by mechanical polishing. The IG-110 graphite is characterized to have a limited number of QI particles. The agglomeration of QI particles, which was reported in another nuclear graphite (NBG-18), is rare to see in IG-110.

In order to make a statistical analysis of gas-escape pores and microcracks, images were stitched together to form a micrograph with a wide field of view and a high resolution. An 8 × 8 mm optical micrograph (pixel resolution of 0.54 μm) of mechanically polished graphite surface was obtained for pore structure analysis. A 0.13 × 0.13 mm SEM micrograph (pixel resolution of 7.5 nm) of rapid-oxidized graphite surface was obtained for microcrack analysis.

The pores and microcracks are shown as dark regions in the micrographs. A grayscale threshold value was selected to extract the pores and microcracks from the micrographs. Figure 6A shows the distribution of the pore (crack) area. In total, over 49 000 cracks and over 200 000 pores were identified. The number of cracks shown in Figure 6A was multiplied by 5. There is much more tiny pores (cracks) than large pores (cracks). However, some pixel noise could be misidentified as tiny pores (or cracks). Furthermore, it is reported that the number of tiny pores could be easily altered by changing the grayscale threshold value. Therefore, the number of tiny pores (cracks) shown in Figure 6A could be misleading. Fortunately, these tiny pores are reported to have a limited contribution to porosity.

The porosity’s distribution on pore (crack) area (A) is shown in Figure 6B. In this study, the porosity (S) is defined as the ratio of sum of each pore’s (crack’s) area to the whole image area. Because the pore (crack) area varied from 0.0001 to 10 000 μm², the vertical
coordinate of Figure 6B uses $dS/d (\log A)$ instead of $dS/d A$. It can be seen that the porosity's distribution has peaks at $\sim 0.1$ and $\sim 300 \, \mu m^2$ for microcracks and pores, respectively, far away from the peaks of pore numbers shown in Figure 6A. Because the porosity is mainly contributed by relatively large pores (cracks), the porosity's distribution was proved to be not sensitive to the change of the grayscale threshold value.\textsuperscript{2} Although the micro images of one graphite grade may be recorded by different microscopes and analyzed by different researchers, a stable and convincing porosity distribution can be obtained.

An ellipse with the same moments of Orders 1 and 2 as the gas-escape pore or microcrack was used to define the sizes of the pores or cracks. The lengths of major axis and minor axis of the ellipse are denoted as $D_{\text{max}}$ and $D_{\text{min}}$ of the pore (crack), respectively. The porosity's distributions on $D_{\text{max}}$ and $D_{\text{min}}$ are shown in Figure 7. The peaks are located at $\sim 0.15$ and $\sim 13 \, \mu m$ for $D_{\text{min}}$, whereas the peaks are located at $\sim 0.7$ and $\sim 30 \, \mu m$ for $D_{\text{max}}$. As for microcracks, the $D_{\text{max}}$ and $D_{\text{min}}$ represent the length and width of the crack, respectively. As for pores with irregular shapes, the $D_{\text{max}}$ and $D_{\text{min}}$ only approximately represent the pore sizes. In the analysis of 3-D pore structures reconstructed from X-ray tomography, the diameter of inscribed sphere of one pore was defined as the pore size and was used to produce the porosity's distribution on pore size.\textsuperscript{3} Using $D_{\text{min}}$ defined in this study, the $dS/d (\log D_{\text{min}})$ of IG-110 graphite has been demonstrated to be consistent with porosity's distribution derived from X-ray tomography.\textsuperscript{2} In other words, the $D_{\text{min}}$ is comparable with the diameter of inscribed sphere of graphite pores.

The aspect ratio ($\delta$) of a pore (crack) is defined as $D_{\text{max}}/D_{\text{min}}$. The aspect ratio versus $D_{\text{min}}$ is shown in Figure 8. In order to explicitly show the distribution of aspect ratio, only one in seven cracks and one in 20 pores were randomly selected and are shown in Figure 8. Most of the pores have aspect ratio smaller than 4. In contrast, the aspect ratio of microcracks could be as high as 40. The inset of Figure 8 shows the distribution of aspect ratio of pores and cracks.

At last, a porosity of 14.2% is obtained in this study for IG-110 gas-escape pores, which is consistent with previous studies.\textsuperscript{1,2} A porosity of 3.0% is obtained for IG-110 microcracks. The apparent density of the IG-110 sample was measured to be 1.771 g/cm$^3$. Given the ideal graphite density of 2.26 g/cm$^3$, the total porosity is calculated to be 21.6%. There is a gap between the total porosity (21.6%) and the sum (17.2%) of derived porosity values for pores and microcracks. This gap can be explained as follows. If the graphite sheets in one crystallite are happened to be nearly parallel to the sample's surface, the lenticular microcracks will be shown as very shallow dishes on the surface and cannot be identified in the surface image. These missing microcracks exposed large cross-sectional area on the sample's surface and have a considerable contribution to the calculated porosity. In addition, only large QI particles can be seen at the

![Figure 6](image1.png)  
**Figure 6** (A) Distribution of pore (crack) area. (B) The porosity's distribution on pore (crack) area

![Figure 7](image2.png)  
**Figure 7** The porosity's distribution on pore (crack) size
The aspect ratio ($\delta$) of pore (crack) versus $D_{\text{min}}$. The inset shows the distribution of the aspect ratio.

**FIGURE 8**

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

Qing Huang performed the conceptualization, methodology, writing—original draft, investigation, and funding acquisition. Hui Tang performed the formal analysis, investigation, and writing—review and editing.

DATA AVAILABILITY STATEMENT

The raw/processed data required to reproduce these findings are available from the authors upon request.

ORCID

Qing Huang https://orcid.org/0000-0001-7253-3496

REFERENCES

1. Kane J, Karthik C, Butt DP, Windes WE, Ubic R. Microstructural characterization and pore structure analysis of nuclear graphite. *J Nucl Mater*. 2011;415(2):189-197.
2. Huang Q, Tang H. Porosity analysis of superfine-grain graphite IG-110 and ultrafine-grain graphite T220. *Mater Sci Technol*. 2019;35(8):962-968.
3. Jing SP, Zhang C, Pu J, et al. 3D microstructures of nuclear graphite: IG-110, NBG-18 and NG-CT-10. *Nuclear Sci Tech*. 2016;27:66.
4. Wang P, Contescu CI, Yu S, Burchell TD. Pore structure development in oxidized IG-110 nuclear graphite. *J Nucl Mater*. 2012;430(1-3):229-238.
5. Kane JJ, Matthews AC, Swank WD, Windes WE. Effects of air oxidation on the evolution of surface area within nuclear graphite and the contribution of macropores. *Carbon*. 2020;166:291-306.
6. Wade-Zhu J, Krishna R, Bodey AJ, et al. 4D synchrotron X-ray microtomography of fracture in nuclear graphite after neutron irradiation and radiolytic oxidation. *Carbon*. 2020;168:230-244.
7. Contescu CI, Arregui-Mena JD, Campbell AA, et al. Development of mesopores in superfine grain graphite neutron-irradiated at high fluence. *Carbon*. 2019;141:663-675.
8. Arregui-Mena JD, Edmondson PD, Campbell AA, Katoh Y. Site specific, high-resolution characterisation of porosity in graphite using FIB-SEM tomography. *J Nucl Mater*. 2018;511:164-173.
9. Arregui-Mena JD, Cullen DA, Worth RN, et al. Electron tomography of unirradiated and irradiated nuclear graphite. *J Nucl Mater*. 2021;545:152649.
10. Lu C, Jin K, Béland LK, et al. Direct observation of defect range and evolution in ion-irradiated single crystalline Ni and Ni binary alloys. *Sci Rep*. 2016;6:19994.
11. Wu N, Marrow J, Marsden B. Microcracks in nuclear graphite and highly oriented pyrolytic graphite (HOPG). *J Nucl Mater*. 2008;381(1-2):199-203.
12. Karthik C, Kane J, Butt DP, Windes WE, Ubic R. Neutron irradiation induced microstructural changes in NBG-18 and IG-110 nuclear graphite. *Carbon*. 2015;86:124-131.
13. Freeman HM, Jones AN, Ward MB, et al. On the nature of cracks and voids in nuclear graphite. *Carbon*. 2016;103:45-55.
14. Lasithiotakis M, Marsden BJ, Marrow TJ. Annealing of ion irradiation damage in nuclear graphite. *J Nucl Mater*. 2013;434(1-2):334-346.
15. Kolke J, Pedraza DF. Dimensional changes in highly oriented pyrolytic graphite due to electron-irradiation. *J Mater Res*. 1994;9(7):1899-1907.
16. Theodosiou A, Spencer BF, Counsell J, et al. An XPS/UPS study of the surface/near-surface bonding in nuclear grade graphites: a comparison of monatomic and cluster depth-profiling techniques. Appl Surf Sci. 2020;508:144764.
17. Tuinstra F, Koenig JL. Raman spectrum of graphite. J Chem Phys. 1970;53(3):1126-1130.
18. Ferrari AC, Robertson J. Interpretation of Raman spectra of disordered and amorphous carbon. Phys Rev B. 2000;61(20):14095-14107.
19. Huang Q, Lei Q, Deng Q, et al. Raman spectra and modulus measurement on the cross section of proton-irradiated graphite. Nucl Instrum Meth B. 2017;412:221-226.
20. Elman BS, Dresselhaus MS, Dresselhaus G, Maby EW, Mazurek H. Raman scattering from ion-implanted graphite. Phys Rev B. 1981;24(2):1027-1034.
21. Cancado LG, Takai K, Enoki T, et al. General equation for the determination of the crystallite size La of nanographite by Raman spectroscopy. Appl Phys Lett. 2006;88:163106.
22. El-Genk MS, Tournier JMP. Comparison of oxidation model predictions with gasification data of IG-110, IG-430 and NBG-25 nuclear graphite. J Nucl Mater. 2012;420(1-3):141-158.
23. Heijna MCR, de Groot S, Vreeling JA. Comparison of irradiation behaviour of HTR graphite grades. J Nucl Mater. 2017;492:148-156.
24. Huang Q, Han XQ, Liu P, et al. Ion-beam-assisted characterization of quinoline-insoluble particles in nuclear graphite. Nucl Sci Tech. 2020;31:98.
25. Karthik C, Kane J, Butt DP, Windes WE, Ubic R. Microstructural characterization of next generation nuclear graphites. Microsc Microanal. 2012;18(2):272-278.

How to cite this article: Huang Q, Tang H. A statistical analysis of pores and microcracks in nuclear graphite. Surf Interface Anal. 2022;54(1):37-44. doi:10.1002/sia.7013