Study on Dry-Ice Particle Jet Polishing Process of 316L Stainless Steel Electrode

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Abstract: Dry-ice particle jet technique has the advantages of rapid sublimation, easy drying, and without residues after striking onto the surface, which has been applied in the field of optical coating and the polishing and cleaning of integrated circuit. However, the process mechanism of this technique on stainless steel is not clear and the application research is not in-depth, which restricts the development and application of dry-ice particle jet technique in electrode polishing. In this work, the influence of the processing parameters such as spraying pressure, spraying angle, spraying distance, and spraying time on the micro-morphology and roughness of the stainless steel electrode surface was studied by single factor experiments. In addition, the characterization methods for the surface roughness, surface defects, surface micro-morphology, surface micro-unevenness, and surface chemical composition of the stainless steel electrodes were developed. Comprehensive characterization technology of the electrode surface was established.

1.Introduction
The surface roughness and cleanliness of the electrodes of accelerators, high-voltage devices and special electric vacuum devices have a great influence on the voltage withstand ability of the electrode vacuum gap. The polishing and cleaning are often required to improve the voltage withstand ability of the electrode vacuum gap. The traditional polishing and cleaning technologies of electrode surface, includes mechanical polishing⁴, electrochemical polishing⁵, and chemical cleaning techniques⁶, but they all have great disadvantages. For the mechanical polishing technique, the residual abrasives and organic pollutants requires to further cleaning and fine polishing; for the electrochemical polishing technique, the use of strong acid with high temperature would do great harm to the environments and operators; in addition, an oil-containing, alkali-containing or alcohol-containing cleaning agent must be used in the chemical cleaning technique, resulting in that the cleaning agent is harmful to human bodies, waste liquid need to be purified and then discharged, and the cost is high. Therefore, in order to further improve the vacuum gap pressure resistance of the electrode, it is urgent to develop a polishing and cleaning technology with high efficiency and no pollution.

In order to solve the aforementioned problems, a polishing and cleaning technology based on dry-ice particle jet was proposed in this research. The influence of its main parameters on the polishing and cleaning process of 316L stainless steel electrodes was studied through experiments and the relevant
mechanism was revealed.

2. Experimental

2.1. Experimental process

The dry-ice particle jet system includes a dry-ice particle sprayer, air compressor and gasholder, as shown in Fig. 1. The rated power, the rated pressure, and the rated flow of the air compressor are 22 kW, 0.8 MPa, and 3.6 m$^3$/s, respectively. The initial size of the dry-ice is 1-3 mm in length and 1 mm in diameter. The dry-ice is easily sublimated in the air, and absorbs a large amount of heat during the transformation form solid state to gas state, resulting in the reduction of ambient temperature and the white fog can be observed.

![Fig. 1 Schematic of dry-ice particle jet system](Image)

2.2. Characterization

The roughness of stainless steel electrode surface before and after polishing was measured using Taylor three-dimensional Topograph instrument (Talysurf CLI2000). The element compositions and phase distribution of stainless steel electrode surface before and after polishing were characterised using energy-dispersive X-ray spectroscopy (EDS, INCAs Energy, Oxford Instruments) and X-ray diffraction (XRD, D/MAX3BX, RIGAKU), respectively. The micro-morphology of the electrode surface was characterized using scanning electron microscopy (SEM, JSM-6360LV, Japan). The micro-unevenness of stainless steel electrode surface before and after polishing was detected using three-dimensional surface topography instrument (Zygo, NewView5022).

3. Results & discussion

The influence of the processing parameters on the surface roughness was carefully studied by single factor experiments. The variation of the surface roughness reduction percentage with the spraying pressure is shown in Fig. 2(a). Dry-ice particle jet polishing experiments were carried out at spraying pressure of 0.2, 0.3, 0.4, 0.5, and 0.6 MPa, respectively (spraying angle, spraying distance, spraying time were 30°, 4 cm, and 60 s, respectively). It can be seen that the surface roughness reduction percentage increased to 44.2% when the spraying pressure was 0.4 MPa and then decreased with the further increasing of spraying pressure. Due to the fact that the dry-ice particles acquired more energy and velocity with the increasing of the spraying pressure, the impact force increased when the dry-ice particles struck onto the samples, and the removal effect of the surface microstructures was more effective. However, when the spraying pressure higher than its suitable processing pressure, excessive kinetic energy and impact force, in turn, produce new micropits on the surface, resulting in a decreasing of the surface roughness reduction percentage.

The variation of the surface roughness reduction percentage with the spraying angle is shown in Fig. 2(b). Dry-ice particle spraying polishing experiments were carried out at spraying angle of 30°, 45°, 60°, and 90°, respectively (spraying pressure, spraying distance, spraying time were 0.4 MPa, 4 cm, and 60 s, respectively). It can be seen that the surface roughness reduction percentage decreased with the increasing of the spraying angle. As a result of the work piece before polishing is obtained by turning, the surface textures of the stainless steel electrode were micro-protrusions distributed in a ring-shape.
The impact force of the dry-ice spraying can be decomposed into vertical impact force and horizontal shear force. The principle of the polishing process is that the microprotrusions were removed by the horizontal shear force and squeezed by the vertical impact force. Note that compared with the vertical impact force, the horizontal shear force removed the microprotrusions more effectively. Meanwhile, a smaller spraying angle means a larger horizontal shear force. Thus, the surface roughness reduction percentage decreased almost linearly with the increasing of the spraying angle.

The variation of the surface roughness reduction percentage with the spraying distance is shown in Fig. 2(c). Dry-ice particle spraying polishing experiments were carried out at spraying distance of 1, 2, 3, 4, and 5 cm, respectively (spraying pressure, spraying angle, spraying time were 0.4 MPa, 30°, and 60 s, respectively). It can be seen that the surface roughness reduction percentage increased to the maximum when the spraying distance was 4 cm and then decreased with the further increasing of spraying distance. As a result of the velocity of the dry-ice particles increased first and then decreased after leaving the Laval-type nozzle, resulting in an increasing and then decreasing of the impact force when the struck onto the samples. Thus, the surface roughness reduction percentage increased first and then decreased.

The variation of the surface roughness reduction percentage with the spraying time is shown in Fig. 2(d). Dry-ice particle spraying polishing experiments were carried out at spraying distance of 30, 60, 90, and 120 s, respectively (spraying pressure, spraying angle, spraying distance were 0.4 MPa, 30°, and 4 cm, respectively). It can be seen that the surface roughness reduction percentage increased to the maximum when the spraying time was 60 s and then decreased with the further increasing of spraying time. As a result of a prolonged spraying time, dry-ice particles continued to strike onto the substrate after the microprotrusions were removed, causing new damage on the surface and thereby the surface roughness reduction percentage decreased.

**Fig. 2** Influence of the process parameters on the surface roughness of the stainless steel. (a) Variation of the surface roughness reduction percentage with the spraying distance. (b) Variation of the surface roughness reduction percentage with the spraying angle. (c) Variation of the surface roughness reduction percentage with the spraying distance. (d) Variation of the surface roughness reduction percentage with the spraying time.

**Fig. 3** shows the Zygo images, SEM images, and digital images of the stainless steel before and after polishing, respectively. The electrode was polished at the spraying pressure of 0.4 MPa, spraying angle of 30°, spraying distance of 4 cm, and spraying time of 60 s. The roughness of the samples decreased from 0.0708 μm to 0.0395 μm after polishing, as shown in Fig. 3(a1)-(a2). In addition, it can be seen
form Fig. 3(b2)-(b2) that the turning scratches on the surface of the electrode after polishing were significantly reduced. Form the digital images before and after polishing, the mirror effect and the reflection ratio of the polished surface were greatly enhanced (shown in Fig. 3(c1)-(c2)).

![Zygo images](image1)

![SEM images](image2)

![Digital images](image3)

Fig. 3 The Zygo images (a1)-(a2), SEM images (b1)-(b2), and digital images of (c1)-(c2) of the stainless steel before and after dry-ice particle jet polishing.

In order to explore whether new elements or pollutants were introduced into the surface of the electrode after polishing, EDS and XRD analysis were conducted. It can be seen from Fig. 4(a-b) that Fe, Cr, Ni, Mn, Mo, Si, and Al were all detected before and after polishing, and the contents of all elements changed little. Meanwhile, we can find that the peaks on the surface of the electrode before and after polishing were same, which is Cr-Ni-C-Fe, demonstrating that the chemical compositions of the polished surface did not change. The EDS and XRD analysis results show that dry-ice particle jet and polishing technique only affected the surface roughness of the electrode and would not introduce new elements or pollutants.
Fig. 4 Chemical compositions before and after polishing. (a) EDS spectra before polishing; (b) EDS spectra after polishing; (c) XRD pattern before and after polishing.

4. Conclusions
In this paper, the influence of dry-ice particle jet polishing parameters on the surface roughness reduction percentage of stainless steel electrode was studied. The optimum parameters were determined, that is the spraying pressure, spraying angle, spraying distance, and spraying time were 0.4 MPa, 30°, 4 cm, and 60 s, respectively. Furthermore, when the other three parameters were constant, the surface roughness reduction percentage increased first and then decreased with the increasing of spraying pressure, spraying distance, and spraying time, respectively. By contrast, the surface roughness reduction percentage decreased with the increasing of the spraying angle. In addition, the EDS and XRD analysis results show that dry-ice particle jet polishing technique only affected the surface roughness of the electrode and had little influence on the chemical compositions.

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