Effect of Glaze Composition on the Impact Resistance of Glass Lining of Glass-Lined Vessels

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Abstract—Glass-lined pressure vessels are widely used in various corrosion conditions because of their excellent corrosion resistance. However, mechanical impact is the most common failure mode of glass linings due to its brittleness. Under the same firing process condition, the impact-resistant properties of glass-lined vessels are largely dependent upon the glaze composition. In this paper, three kinds of glazes were selected to study the impact resistance of the glass lining. Based on the glaze composition analysis, the impact energy measurement and the micromorphology observations of the impact surfaces, the effect of glaze composition on the impact resistance of glass lining was discussed. The results showed that the low content of refractory oxides such as SiO₂, ZrO₂ and Al₂O₃ made the glaze easy to melt and with high-temperature fluidity. Therefore, the structure of the glass lining was dense, and glass lining exhibited good resistance to impact.

1. INTRODUCTION

Glass lining is made by coating the glaze with high silicon content on the metal surface and firing it at 880-950 °C for several times to form the dense coating on the metal surface [1]. Therefore, the glass-lined equipment has both the high strength of metal and the excellent corrosion resistance of glass lining [2]. The surface is smooth and easy to clean. Therefore, it is suitable for the service environment of high temperature, high pressure and strong corrosion, and it has been widely used in chemical, pharmaceutical, energy, pesticide, petroleum, food and other industries [3-5].

Mechanical impact is the most common failure mode of glass linings. The glass lining which is similar to glass is brittle, with low elongation, poor elasticity, and low tensile strength. Any hard metal object may cause damage to the glass lining [6].

The chemical composition of glaze and firing process are very important for physical-chemical properties of glass lining. Under the same firing process condition, the performance of the glass lining is mainly determined by the glaze composition. Different chemical compositions of glaze result in obvious difference in the microstructure of glass lining, which affects the mechanical properties. Therefore, it is of significance to study the relationship between the properties of glass liner and its chemical composition for improving the physical and chemical properties of the glass lining and designing and developing high-quality glaze. In this paper, three kinds of glass linings were selected to study the impact resistance of the glass lining. Based on the glaze composition analysis, the impact
energy measurement and the micromorphology analysis of the impacted surface, the influence of the chemical composition of the glaze on the impact resistance of the glass lining was discussed.

2. EXPERIMENTAL PROCEDURES

2.1. Material and specimen preparation

The substrate material used was a commercial special steel for enamel with specification BTC340 and was cut to yield 80×80×5.5 mm specimens. Three kinds of surface glazes were selected to prepare glass lined specimens, named K, M, N.

The specimens were coated with 1.2 mm thick glass lining layers on the surface of the substrate by the following steps.

1. The substrate plate was cleaned with acetone.
2. The ground glazes were mixed with water and sprayed on the substrate surface. The sprayed specimens were dried and then fired at 930 °C for 13-15 minutes in enameling furnace.
3. The surface glazes were mixed with water and sprayed on the specimen surface. The thickness of surface glazes was kept to be 0.2-0.25 mm. After being dried, the specimens were fired at 880 °C for 8 minutes. The thickness of the formed glass lining layer was measured.
4. The third step was repeated until the thickness of glass lining layer reached to 1.2 mm. But the firing temperature was reduced by 20 °C for each layer in turn.

2.2. Impact test

The impact tests were conducted based on the Chinese national standard GB/T 7990-2013 <Vitreous and porcelain enamels - Determination of resistance to impact>. The impact tester was shown in Figure 1. The specimen was placed on the sand bed. The ball holder/releaser was adjusted to a certain height. The ball placed in the holder/releaser was released to impact the glass lined surface freely. The impacted surface was observed with 60W light. If there were no cracks, spelling and chipping, the height of the ball holder/releaser was raised, and the specimen was moved to ensure that the distance between the two impact points is more than 10 mm. The impact and observation steps were repeated until the obvious defects could be seen on the impacted surface. The impact energy W was calculated by the following formula.

\[ W = m \cdot g \cdot h \]

where m was the mass of the ball. The h was the distance between the starting point of the drop and the glass lined surface.

Figure 1. Schematic of the impact tester. (1. Leveling nut, 2. Support, 3. Position bolt, 4. Laser range finder, 5. Ball holder/releaser, 6. Ball, 7. Specimen, 8. Sand bed, 9. Chassis, 10. Base).
3. RESULTS AND DISCUSSIONS

3.1. Chemical composition analysis of the glass glaze
The phase in the surface glazes was identified by means of X-ray diffraction (XRD) on a BRURER AXS SRS 3400 apparatus. The chemical composition analysis results of the three glazes are shown in Table 1.

3.2. Resistance to impact
The impact energy is an important parameter to evaluate the impact resistance of glass lining. The results measured by the impact test are shown in Table 2. The impact energies of the three specimens are all larger than 20×10⁻³ J, which meets the requirement of Chinese national standard GB 25025-2010 <Specification of glass-lined equipment for industry>. The measured value of specimen M is larger than that of specimen K and N, which shows that specimen M has the best resistance to impact. The specimen N exhibits the worst resistance to impact.

**TABLE 1. COMPOSITION OF THE GLASS GLAZES**

| Composition | Content (%) |
|-------------|-------------|
|             | K           | M           | N           |
| SiO₂        | 68.30       | 67.00       | 70          |
| B₂O₃        | 4.70        | 3.24        | 7.14        |
| Na₂O        | 14.20       | 14.20       | 14.10       |
| K₂O        | 2.95        | 2.02        | 0.46        |
| Al₂O₃        | 4.20        | 1.51        | 2.33        |
| CaO        | 2.26        | 1.98        | 1.53        |
| MgO        | 0.14        | 0.11        | 0.10        |
| ZrO₂        | 0.52        | <0.1        | 1.05        |
| TiO₂        | 0.45        | 8.45        | <0.1        |
| CoO        | 0.40        | 0.52        | 0.67        |
| MnO        | 0.22        | 0.21        | <0.1        |
| Fe₂O₃        | 0.20        | 0.12        | 0.12        |
| P₂O₅        | 0.17        | <0.1        | <0.1        |

**TABLE 2. COMPOSITION OF THE GLASS GLAZES**

| Specimen | Impact Energy (J) |
|----------|-------------------|
| K        | 254×10⁻³          |
| M        | 299×10⁻³          |
| N        | 238×10⁻³          |
3.3. Surface morphology analysis
The surfaces of the impacted specimens are shown in Figure 2. It can be seen that there are no macroscopic cracks on the impacted surface. The microstructures and morphologies of the failure zone were observed by using a ZEISS EVO® MA 15 scanning electron microscope (SEM), as seen in Figure 3. Microscopic crack is the main form of impact failure of glass lining. There is a ring-shaped main crack on each specimen surface. No branch crack is found on the surface of the specimens K and M, as seen in Figure 3(a)–(d). Figure 3(e) and 3(f) show the surface morphology of the specimen N. It can be seen that the step-like drop on both sides of the main crack is larger than that of the other two specimens, and some branch cracks can be found.

3.4. Effect of glaze composition on the impact resistance of glass lining
Glass lining is a typical brittle material. The failure of brittle materials is generally the propagation of microcracks. Therefore, the resistance to mechanical impact is the ability of the glass lining to resist the formation and propagation of microcracks under the action of external mechanical impact. This
property is related to the surface hardness and smoothness of the glass lining and the interface bond strength between the lining and the substrate. Generally, the glass lining with high density, low surface roughness and strong interface bond exhibits high resistance to mechanical impact [7].

During the firing process, a large amount of gas is generated. When the gas escapes the glass layer, some pits will be left on the surface. The enamel melt will gradually level the pits to form a flat surface. If the high-temperature viscosity of the glaze is too large, the gas stays in the glass layer and form some small gas cavities, which significantly reduce the density and the surface smoothness, thus decreasing the impact resistance of the glass lining. However, the fundamental influence factor of these properties is the chemical composition of the glaze.

It can be seen from Table I that the content of the refractory oxides such as SiO₂, ZrO₂ and Al₂O₃ in specimen M glaze is relatively small compared with the other two specimen glaze, which makes the glaze easy to melt and with high-temperature fluidity and strong mutual diffusion ability between the glass lining and the substrate. After firing, there are fewer pores in the glass lining of the specimen M, the integrity and smoothness are better, and the structure of the glass lining is denser. Therefore, the specimen M shows the best resistance to impact.

4. CONCLUSION
The composition of the glaze is one of the important factors affecting the impact resistance of glass lining. The low content of refractory oxides such as SiO₂, ZrO₂ and Al₂O₃ makes the glaze easy to melt and with high-temperature fluidity. Therefore, the structure of the glass lining is dense, and glass lining exhibits good resistance to impact.

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