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DEVELOPMENT OF AN IMPROVED TECHNOLOGY FOR ENAMELING TEMPERED GLASS SAMPLES AND INVESTIGATION OF THE TECHNOLOGICAL PROPERTIES OF THE OBTAINED SAMPLES

Abstract. This article presents the results of developing an improved technology for enameling the surface of tempered glass, determining the optimal parameters of the technological process, and evaluating the physical and mechanical properties of the obtained samples. In the study, the processes of thermal tempering and enamel coating formation were investigated under laboratory conditions using flat sheet glass samples. The tempering temperature was determined based on the viscosity characteristics of glass and the Vogel–Fulcher–Tammann equation. According to the experimental results, the optimal tempering temperature was found to be 693 °C, with a holding time of 4 minutes. During the cooling stage, the use of compressed air at a pressure of 6 kPa enabled the formation of the required internal stresses within the glass body. The bending strength of the tempered samples increased significantly compared to non-tempered samples, reaching values in the range of 310–340 MPa. In addition, the physical and mechanical properties of the enameled tempered glass samples were determined, confirming their compliance with GOST standards. The obtained results demonstrate the feasibility of producing high-quality enameled tempered glass based on locally available raw materials.

Keywords: tempered glass, glass enamel, thermal treatment, tempering temperature, physical and mechanical properties, enamel coating, sheet glass, technological scheme.

1. Introduction

Today, tempered glass is widely used in construction, architecture, interior design, mechanical engineering, furniture manufacturing, household appliances, and culinary equipment production. Its widespread application is primarily due to its high mechanical strength, resistance to thermal effects, and its ability to break into small, non-sharp fragments, ensuring safety. In this regard, tempered glass is considered a significantly superior material compared to conventional sheet glass [1, 2].

Tempered glass is produced by subjecting ordinary sheet glass to a special thermal treatment. During this process, specific internal stresses are generated throughout the glass volume, which are responsible for its enhanced mechanical strength [7, 8]. From a technological perspective, this process is complex and requires precise coordination of heating, rapid cooling, and final cooling stages. Therefore, combining the tempering process with surface enameling represents not only an innovative technological solution but also enables the production of high value-added products [9].

The objective of this study is to develop an improved technology for enameling tempered glass samples, optimize the technological regimes, and evaluate the main technological as well as physical and mechanical properties of the obtained samples.

2. Research Methods

Experimental studies to determine the physical and mechanical properties of the obtained products were carried out in accordance with the requirements of GOST 30698-2014 [26]. According to this standard, the geometric parameters of the samples, the equality of diagonals, the condition of edges, and mechanical strength characteristics were evaluated. To determine impact resistance, tests were conducted for both hard-body and soft-body impacts.

In the hard-body impact test, the samples were mounted in a horizontal position on a специаль steel frame. To ensure uniform fixation from all four sides, a clamping frame equipped with a 12 mm thick rubber strip was used. As a test body, a polished steel ball with a mass of 227±2 g and a diameter of 38 mm was applied. This method made it possible to assess the minimum strength level of the samples [19–29].

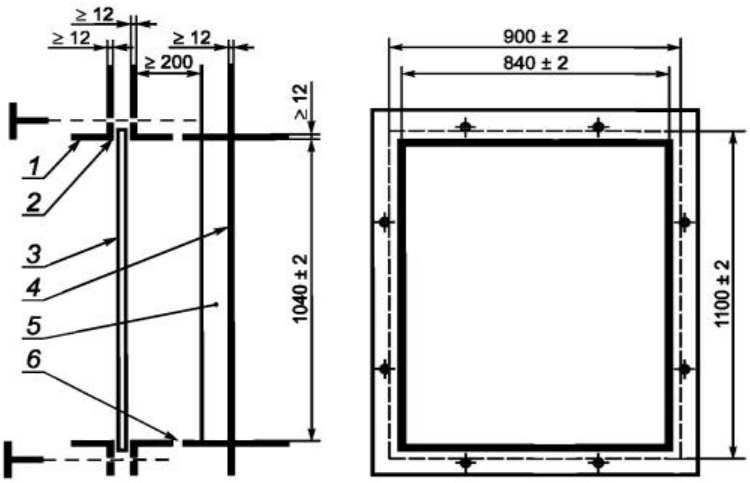


Figure 1.
Apparatus for determining the mechanical strength of tempered glass samples under hard-body impact:

1 – clamping frame; 2 – rubber strip; 3 – test sample; 4 – frame made of rigid steel; 5 – soft layer (impact-absorbing material); 6 – holes.

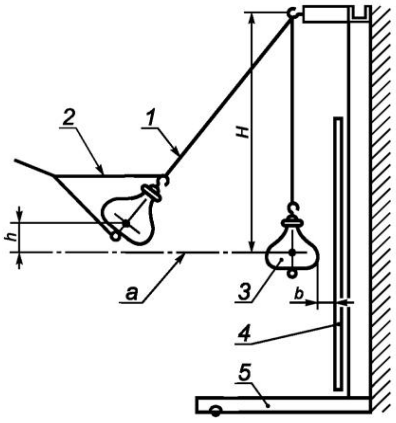


Figure 2. Apparatus for determining the mechanical strength of tempered glass samples under soft-body impact:

1 – cable; 2 – lifting strap (harness) for the bag; 3 – leather bag (soft body); 4 – test sample; 5 – support base; H – height to the center of the bag in its free (initial) position; h – drop height of the bag; a – central axis of the test sample; b – distance between the sample and the freely suspended bag.

To determine resistance to soft-body impact, a special apparatus equipped with a leather bag was used. The bag was filled with lead shots and prepared to a total mass of 45±1 kg. It was suspended at a height of 2500 mm and released freely from a position close to the sample surface. This method is important for evaluating the impact resistance of glass under real эксплуатацион conditions.

In the experiments, polished glass samples were used. The chemical composition of the glass (in wt.%) was as follows: SiO_2 – 73.0; Al_2O_3 – 1.5; CaO – 8.5; MgO – 3.2; Na_2O – 13.5; SO_3– 0.3.

To calculate the tempering temperature:

$$t_{tob}=t_g+80$$

the equation was used, where *Tg* is the glass transition temperature. To determine this parameter, the Vogel–Fulcher–Tammann (VFT) equation was applied:

$$lg\eta=-3,03+5005/t-220,3$$

Here, η is the viscosity of the glass and T is the temperature.

The tempering of glass samples was carried out under laboratory conditions using muffle furnaces. Particular attention was paid to preventing the uncontrolled formation of macroscopic stresses during the process, as such conditions may lead to deformation of the product and a reduction in mechanical strength. During the cooling stage, compressed air at a pressure of 6 kPa was applied.

3.Results and Discussion

Optimal parameters of the tempering process. According to the experimental results, the optimal temperature for tempering the glass samples was determined to be 693 °C, with a holding time of 4 minutes at this temperature [7,10]. Under these conditions, uniformly distributed internal stresses were formed within the glass body, which led to a significant increase in its mechanical strength (Table 1).

Table 1

Properties of tempered and non-tempered glass samples

Glass type	Main properties				
	Density, kg/m³	Bending strength, MPa	Specific heat capacity, kJ/(kg·°C)	Thermal conductivity, W/(m·°C)	Linear thermal expansion coefficient, $\alpha\times10^{-7}$ °C^{-1}

Non-tempered	2475,0	60,0	0,72	0,93	70,0
Tempered	2500,0	340,0	0,85	1,0	90,0

During rapid cooling above the glass transition temperature, different thermal states arise in the outer and inner layers of the material. This leads to the formation of an internal stress field, which is the main functional feature of tempered glass. If this process is properly controlled, the impact and bending resistance of the glass increases; otherwise, uneven stress distribution may result in increased brittleness. Therefore, the cooling regime was considered an important technological parameter in this study.

Comparative analysis of tempered and non-tempered samples. The experimental results showed that the bending strength of non-tempered glass samples ranged from 48 to 60 MPa, whereas in tempered samples this value increased to 310–340 MPa. Thus, the tempering process significantly enhanced the mechanical strength by several times. At the same time, a slight decrease in light transmittance was observed.

The analysis of the main properties of tempered and non-tempered samples revealed that the density of tempered glass reached up to 2500 kg/m³, bending strength up to 340 MPa, specific heat capacity 0.85 kJ/(kg·°C), thermal conductivity 1.0 W/(m·°C), and linear thermal expansion coefficient up to 90×10^{-7} °C^{-1}. These values clearly reflect the structural changes in the material caused by thermal treatment [8, 11, 30, 31].

Technology for producing enameled tempered glass. At the next stage of the research, the possibility of obtaining a composite material with functional and decorative properties by enameling the surface of tempered glass was investigated. Based on the optimal composition (Sample ShEF-3), the glass enamel frit batch was prepared with the following composition: quartz–feldspar sand from the Khiva deposit – 25.0 wt.%; feldspar from the Sultan Uvays deposit – 29.0 wt.%; lead-containing waste – 10.0 wt.%; calcined soda – 20.0 wt.%; boron oxide – 16.0 wt.%.

The technological process was carried out under laboratory conditions using a batch-type model unit. Glass sheets with thicknesses of 4, 6, 8, and 10 mm were selected as samples. These thicknesses were chosen due to their ability to achieve high mechanical strength during the tempering process.

The experimental procedure was conducted in the following sequence [13, 14]:

1. Glass samples with dimensions of 150×350 mm were prepared and their edges were polished.
2. The samples were washed and dried.
3. A thin layer of glass enamel frit was applied to the surface of the samples.
4. The samples were tempered according to the determined optimal режим.
5. The tempered and enameled samples were cooled to room temperature.

Based on numerous experimental studies, the processes of glass enamel application and tempered glass production were thoroughly investigated. In this section, a technological scheme for producing enameled tempered glass sheets based on the adhesion of glass enamel to the surface of tempered glass is proposed (Figure 3).

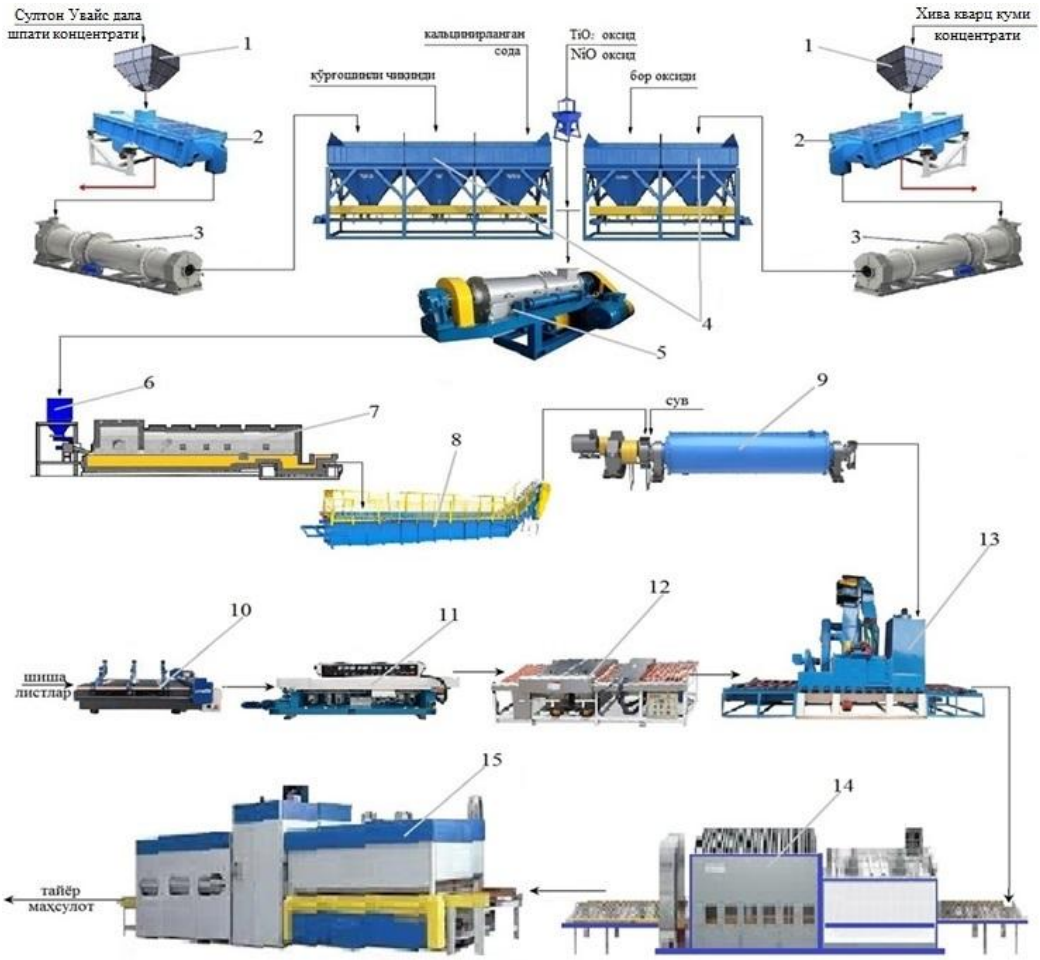


Figure 3. Technology for the production of tempered and enameled glass.

1 – hoppers; 2 – sieves; 3 – drum dryers; 4 – weighing дозаторы (dosing units); 5 – mixer; 6 – cubical hopper; 7 – furnace for melting glass enamel frit; 8 – tray-type glass granulator; 9 – ball mill; 10 – glass sheet cutting machine (to required dimensions); 11 – glass sheet grinding and polishing machine; 12 – glass sheet washing and drying machine; 13 – slurry spraying device; 14 – furnace; 15 – tempering unit.

Physical and Mechanical Properties of Enameled Tempered Glass. The obtained samples TESh-1, TESh-2, TESh-3, and TESh-4 were evaluated in accordance with the requirements of GOST 33891-2016. The analysis showed that the density of the enameled tempered glass samples ranged from 2660 to 2710 kg/m³, hardness from 5.3 to 6.1 GPa, compressive strength from 768 to 800 MPa, and bending strength from 114 to 118 MPa. The coefficient of linear thermal expansion was determined to be in the range of 8.2×10^{-6} to 9.0×10^{-6} K^{-1}, while thermal conductivity ranged from 1.07 to 1.25 W/(m·K).

In addition, the softening temperature of the samples was found to be within the range of 605–615 °C, which corresponds well with the enamel frit softening temperature of 552 °C. This indicates that under the selected technological regime, complete diffusion bonding occurred between the enamel layer and the glass substrate. This result confirms the formation of a homogeneous molten mass within the samples and demonstrates the high quality of the coating (Table 2).

Table 2

Physical and mechanical properties of enameled tempered smooth sheet glass samples

Physical and mechanical properties	GOST 33891-2016 requirement	Glass types (thickness), mm			
		TESh-1	TESh-2	TESh-3	TESh-4
Density, kg/m³	2500	2660	2688	2700	2710
Hardness, GPa	6	5.3	5.8	5.9	6.1
Compressive strength, MPa	700–900	768	769	780	800
Bending strength, MPa	120	114	114	116	118
Linear thermal expansion coefficient (40–300 °C), K⁻¹	7–9 ×10⁻⁶	8.2×10⁻⁶	8.2×10⁻⁶	8.5×10⁻⁶	9.0×10⁻⁶
Thermal conductivity, W/(m·K)	1	1.07	1.07	1.10	1.25
Heat capacity, J/(kg·K)	720	708	708	720	725
Softening temperature, °C	600	605	605	615	615

Discussion. The obtained results demonstrated the importance of integrating the tempering and enameling processes within a single technological chain. The selection of a tempering temperature higher than the softening temperature of the glass enamel, but within a range that does not distort the geometry of the glass sheet, ensures both coating quality and mechanical strength. From this perspective, treatment at 693 °C for 4 minutes can be considered an optimal regime.

The preservation of standard physical and mechanical properties in tempered glass samples coated with enamel indicates the practical potential of this technology. In particular, the use of locally available mineral raw materials and industrial waste can contribute to reducing production costs, creating import-substituting products, and promoting resource-efficient technologies.

3. Conclusion

Based on the conducted research, the following conclusions were drawn:

- The optimal technological regime for producing tempered glass was determined to be a temperature of 693 °C with a holding time of 4 minutes. The use of compressed air at a pressure of 6 kPa during cooling was proven to be effective in forming the required internal stresses.
- As a result of tempering, the bending strength of glass samples increased significantly compared to the non-tempered state, reaching values of 310–340 MPa.
- Enamel coatings prepared based on the ShEF-3 composition formed a high-quality and stable layer on the surface of tempered glass. The physical and mechanical properties of the enameled samples complied with the requirements of GOST 33891-2016.
- The feasibility of producing enameled tempered glass based on local raw materials was experimentally confirmed, and the proposed technology was shown to be promising for industrial-scale implementation.

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