Possibilities of the Electron-Beam Machine «LUCH» for Dimensional Microprocessing of Glass and Ceramic Materials

Y Zhuo 1, M Liang 1, K M Moiseev 1, L. L. Kolesnik 1 and Yu V Panfilov 1
1 Bauman Moscow State Technical University, 105005, Moscow, Russia
E-mail: k.moiseev@bmstu.ru, kolesnik@bmstu.ru, panfilov@bmstu.ru

Abstract. The article presents the modern applications and advantages of electron beam technology in the processing of glass and ceramic materials. The design and technological capabilities of the vacuum machine «LUCH» for electron beam melting, welding and dimensional microprocessing of vacuum glass and ceramic materials, including LTCC ceramics, are considered.

1. Introduction

The technology of electron beam processing has been known and has been used for more than 60 years, but interest from science and industry continues to grow [1]. One of the most interesting, but still little used applications, is micro- and nanoscale processing [2-4].

In the electronic industry and instrumentation, vacuum and optical glass and ceramic materials are used in the manufacture of parts and components of electronic devices. But the technology of melting, welding and dimensional processing of electric vacuum glass does not always meet modern requirements. For example: when drilling ceramic materials, including low-temperature co-fired ceramics (LTCC) used for the manufacture of microwave device substrates, by traditional methods (mechanical and laser methods), the hole diameter is up to 50 microns [5], however, for further miniaturization of electronic devices sizes should decrease to 30 microns and less [6].

LTCC has been used in various industries for many years. This ceramic is used as a substrate for microwave devices used to create microwave emitting devices, for example, Bluetooth and Wi-Fi modules. Improvements in LTCC materials, processes and manufacturing methods have led to lower costs and improved technical characteristics of electronic products. This has significantly increased interest in LTCC technology from manufacturers of high-frequency technology, optoelectronics and micro-electromechanical systems. New opportunities are opening up for the production of electronic products in such areas as telecommunications, medicine, and automotive technology [7].

Compared to mechanical processing, electron beam processing is devoid of such disadvantages as changing the size of the holes when the tool is worn and the need to change the tool when changing the profile of the hole, and compared to the laser processing, the lack of tapering of the holes and changing the composition of the material in the area near the processing [8-11].

The main difficulties encountered in the electron beam treatment of dielectrics are associated with the low electrical conductivity of these materials [12, 13]. A low dielectric conductivity leads to charge accumulation, which reduces the electron energy of the beam, causing defocusing and distortion of the shape, as well as an increase in the diameter of the beam. Generation of an electron beam in the pressure range from 5 to 20 Pa leads to the formation of a plasma in the processing zone, which ensures the discharge of charge from the treated dielectric object [14, 15].
In addition to dimensional micro- and nano-processing, high-energy electron beams can be successfully used for other types of processing of glass and ceramic materials. The use of electron-beam heating during cutting and welding of parts from electrovacuum glass and ceramic materials ensures a constant chemical composition of the material in the zone of the welding joint. When melting, electron-beam heating eliminates the influence of the environment on the composition and structure of the material, and makes it possible to more precisely control its properties. Electron beam polishing creates additional opportunities for surface modification with a significant reduction in the surface roughness of the part [16].

For the implementation of processing technologies for products from vacuum glass and ceramic materials, as well as for further research on micro- and nanoscale processing of LTTC ceramics, the basic requirements for the basic processing technology and installation for their implementation are presented (Tables 1 and 2).

Table 1 Basic technology requirements.

| Parameter                        | Value                          |
|----------------------------------|--------------------------------|
| Types of glass processing        | Welding, smelting, dimensional processing |
| Product form                     | Tubular, flat                  |
| Welding speed, cm/min.           | 1.0                            |
| Penetration depth, mm            | Up to 5.0                      |

Table 2 Machine requirements.

| Parameter                        | Value                          |
|----------------------------------|--------------------------------|
| Overall dimensions of installation, m | $2.0 \times 2.0 \times 3.0$ |
| Vacuum chamber volume, m$^3$      | 0.3                            |
| Power consumption, kW            | 10.0                           |
| Control                          | Automated                      |

2. Electron-beam machine

The «LUCH» technological machine (Figure. 1) includes a vacuum chamber with pumping and control system mounted on a single frame; in-chamber equipment for securing, rotating and moving processed products; an electronic source (gun) and an electronic source control unit.

Figure 1. Electron beam installation «LUCH»
The vacuum system of the installation is equipped with oil-free pumping means and provides a maximum pressure in the chamber of $5.0 \times 10^{-4}$ Pa. The vacuum system consists of the following elements: Edwards XDS35i pump; Edwards EH250 pump; Edwards STPX3A503C ISO320F pump; shutter VAT Series 14 DN320 (14050-PE44); four valves VAT Series 26 DN63 (26436-QE41); three valves VAT Series 26 DN25 (26428-KE41); wide-range pressure transmitter Edwards WRG-S; pressure sensor thermocouple Edwards APG-100; control cabinet. Technical characteristics of the installation are given in Table 3.

| Parameter                                      | Value          |
|------------------------------------------------|----------------|
| The volume of the vacuum chamber, m³          | 0.3            |
| Maximum residual pressure, Pa:                |                |
| - when using fore-vacuum pumps;               | $5.0 \times 10^{-1}$ |
| - when using a high vacuum pump                | $5.0 \times 10^{-4}$ |
| The total flow of leakage and gas separation, Pa × m³ / s | $5.0 \times 10^{-3}$ |
| Number of process gas supply channels         | 2              |
| Process gas flow rate for each channel, sccm   | 10.0 – 200.0   |
| Range of working pressures, Pa                | 1.0 – 25.0     |
| Pumping time to a pressure of $5.0 \times 10^{-1}$ Pa, min | 5              |
| Pumping time to a pressure of $5.0 \times 10^{-4}$ Pa, min | 15             |

The vacuum chamber has a water-cooling system for the walls, upper and lower plates. On the top plate of the working chamber there is a flange for installing an electron beam gun and a device for its vertical movement. The camera door has a water-cooling system. A window with a diameter of 200 mm is located on the door of the chamber, made of materials that provide protection against ionizing radiation.

The control module contains control elements: a vacuum pump start-up system, a control and regulation system for valves. The main part of the control module is a specialized industrial controller that provides Ethernet data transfer between the server and the control units of the executing mechanisms.

The electrical equipment of the installation consists of pumping control systems, measuring pressures at characteristic points of the installation, supplying and controlling an electron-beam source, admitting process gases into the volume of the vacuum chamber, positioning the workpieces / products inside the vacuum chamber relative to the electron-beam source, video surveillance of the technological process, and also centralized control and visualization of the parameters of the installation.

One of the advantages of plasma sources of electron beams is the possibility of their operation in medium vacuum, however, the developed technology does not imply a change in the chemical composition of the material in the processing zone. Based on this, it becomes necessary not only to pump the working volume to the required pressure, but also to ensure that the composition of the residual atmosphere in the working chamber is replaced with an inert gas. For this purpose, a gas supply system with flow controllers is provided in the product design.

The gas inlet system in the volume of the vacuum chamber consists of two identical channels. The gas inlet channel includes a shut-off valve and a gas mass flow controller from Brooks. The following operating modes are provided:

- two independent gas supply channels, each of which supports a gas flow set for it;
- one channel operates in a fixed gas flow rate mode, the other - in the chamber pressure stabilization mode;
- both channels operate in the pressure stabilization mode in the chamber, maintaining a predetermined ratio between the mass flow rates through the channels.
3. Electron-beam gun

The «ELTA-60» electron-beam gun manufactured by the Tecarte company is shown in Figure 2. The electron source 1 is intended to create and form an electron beam. In the intermediate housing 2, which is the connecting link between the electron source and the focusing-deflecting system, a locking mechanism 4 is installed, which serves to cut off the volume of the electron source from the rest of the gun volume. Focusing-deflecting system 3 is designed to focus and deflect the electron beam during processing. The vacuum system is designed for differential pumping of the gun, and consists of an angular vacuum conduit with a flange for connecting a turbomolecular pump (TMP) 5. The gun cooling system is connected in series with the TMP cooling system. The vacuum system provides a pressure of no higher than 10^{-2} Pa in the electron source.

![Figure 2. External design of the electron beam gun «ELTA-60»: 1 – electron source; 2 – intermediate housing; 3 – focusing-deflecting system with double refraction of the beam; 4 and 5 – vacuum system](image)

The electrons emitted by the heater are accelerated by a voltage of the order of 1 kV and bombard the cathode, heating it. A lanthanum hexaboride tablet is used as an electron source.

Adjustment and stabilization of the electron beam current is carried out by changing the bias voltage at the control electrode. To focus and deflect the electron beam, a focusing lens and a deflecting birefringent system are used. The electron source is located vertically on the top plate of the chamber, the electron beam is directed down. The characteristics of the electron gun are given in Table 4.

| Parameter                                              | Value       |
|--------------------------------------------------------|-------------|
| The value of the accelerating voltage, kV              | 60±1        |
| Range of change of welding current, mA, not less than the “welding” mode | 1-250        |
| Frequency modulation current, Hz                       | 0 – 50      |
| Maximum deviation angle, deg., not less than           | ±10         |
| Maximum parallel electron beam transfer, mm, not less than | ±12         |
| Supply voltage, V                                      | 380         |
| Supply voltage frequency, Hz                           | 50          |
| Maximum power consumed by the equipment, kW            | 50          |
| The minimum range of variation of the bombardment current, mA | 10-50      |
| Water flow for cooling, m³ / s                         | 3.58·10⁻⁴   |

4. Workbench

The processed product is placed on a water-cooled workbench (Figure 3), mounted inside the chamber on its lower plate. The table is equipped with stepper motors 1, 2, and provides movement of the processed sample by 200 mm in a horizontal plane in two mutually perpendicular directions, if the
sample is fixed in rotating faceplates 3, then its rotation around an axis parallel to one of the axes of horizontal movement is ensured. To focus the electron beam on the treated surface, a vertical movement of the electron beam gun by 100 mm is provided. The selected solution allows electron beam processing of both flat and cylindrical surfaces of the products.

![Figure 3. Workbench for placing samples (security elements are not shown)](image)

The positioning system serves to change the position of the workpieces / products inside the vacuum chamber relative to the electron beam source, and includes a two-coordinate workbench, a spindle for rotating the part and a drive for moving the electron beam source relative to the part in the vertical axis in order to focus the electron beam.

The positioning system consists of four FL57STH stepper motors, four SMD-4.2 stepper motor drivers, driver power supplies and four EM253 expansion modules in the control controller. The controller sets the necessary speed, acceleration and braking times, searches for reference marks, monitors the status of the sensors of extreme positions. Communication between the controller and the stepper motor drivers is carried out via the "Step / Direction" interface.

5. Conclusions

The developed electron-beam machine «LUCH» implements various technologies for processing glass and ceramic materials: melting, welding, cutting, polishing and dimensional microprocessing. The most promising areas for research are dimensional microprocessing of LTCC ceramics. In addition, due to its characteristics, the installation has great potential for use in additive technologies.

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