DOI: https://doi.org/10.37434/tpwj2023.08.09

TECHNOLOGY AND EQUIPMENT FOR ELECTRON BEAM SINTERING OF HARD ALLOY BILLETS

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ABSTRACT

The paper studies application of electron beam in a technology of high-speed sintering of hard alloy billets made of secondary raw materials as well as high-performance equipment developed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine for the implementation of this technology.

KEYWORDS: electron beam processing, hard alloy, sintering

INTRODUCTION

High-power electron beam for many years has been used for commercial purposes as a tool of thermal influence on metals and their alloys. Firstly, it was used only for welding, surfacing and remelting of metals. Later on, with development of controlling equipment it was used for other tasks, for example, for local heat treatment [1, 2] (preheating, hardening, complete and incomplete annealing) as well as in additive manufacturing processes with application of surfacing wire as well as powder materials [3, 4]. This paper considers application of electron beam in sintering technology (conditionally) of cylinder billets of hard alloy as well as corresponding equipment for realization of this process on mass batches of such products.

TECHNOLOGY OF SINTERING THE BILLETS FROM VK HARD ALLOY

Hard alloys are widely used for technical applications. At the same time, resources used for their manufacture are limited worldwide. Discovered and predicted world reserves of tungsten are estimated at 21 mln tons [5]. At that, tungsten ore reserves in Ukraine are concentrated mainly in the North-Western part of the Ukrainian Shield (the South-Western part of the foundation of the East European Platform) and are estimated at 105 thou tons of metal [6]. Whereas Ukraine's annual needs in tungsten products amount to 2.5 thou tons and are constantly growing. Therefore, today, tungsten carbide powder produced from secondary raw material (for example, from used cutting tools, stamps, molds, dies, etc.) is also used for manufacture of hard alloy products. The available technology of processing of hard alloy wastes is environmentally-friendly (i.e. it does not harm the environment) and ensures the production of high-quality, that is, highly pure, raw material.

Change of parameters of the process of carbidization allows regulating the size of particles of tungsten carbide powder in a range from 50 nm to 10 μm (Figure 1). Corresponding composition and grain-size of alloy is selected depending on area of application and conditions of specific part operation.

Manufacture of "raw" billet is carried out using traditional technology, namely mixing of components, mixing in plasticizer, formation of hard alloy billets on hydraulic presses in steel moulds, removal of plasticizer in course of previous sintering in hydrogen medium. Further these billets require final sintering.

It should be noted that a traditional furnace sintering of hard alloys provokes intensive growth of carbide grains at appearance of liquid phase. It is caused by the process of recrystallization of carbide through liquid phase as well as growth of neighbor grains due to prevailing growth of one grain at the expense of other ones. These phenomena can be prevented by application of growth inhibitors, namely carbides of vanadium, chromium and others.

In contrast to the traditional technology the electron beam technology, first of all, can provide high sintering speeds and, secondly, due to possibility of high-level regulation of the process itself, allows sufficiently "fine" regulation of alloy microstructure (Figure 2). In electron beam bombardment of "raw" billet at acceleration voltage of high-voltage power supply 60 kV, around 75 % of its power is transformed in heat in a surface layer of billet of thickness S of around 10 μm [7]. From the surface layer heat spreads deep in the billet according to heat conductivity laws. After energy supply from electron beam is stopped the surface layer quickly cools down. Cooling time τ is

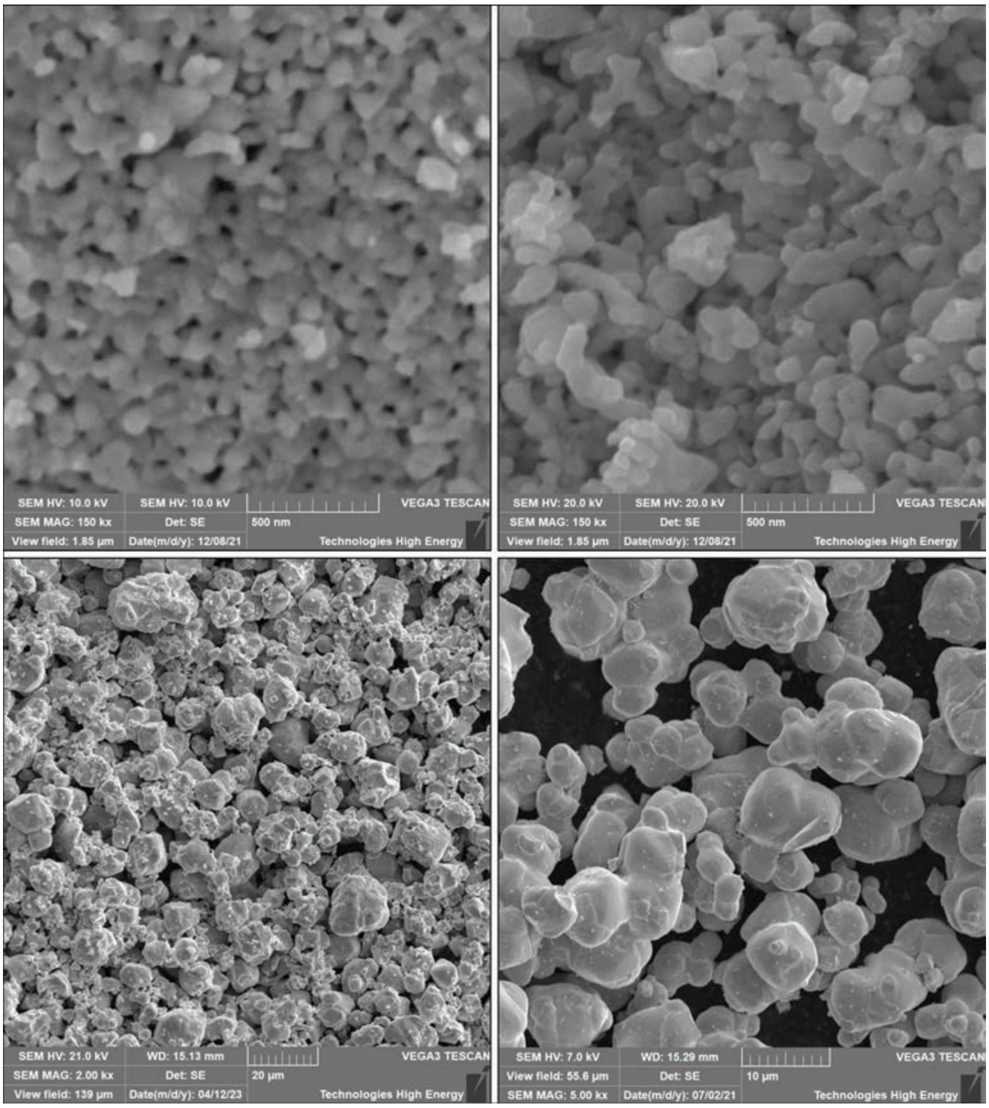

Figure 1. Morphology of particles of VK alloy powder

proportional to thickness S of the surface layer being irradiated and inversely proportional to temperature conductivity of material a, namely this time $\tau \sim S^2/a$. If, for example, for steels the temperature conductivity $a = 0.05$ cm^2/s than cooling time makes $\tau = 2\cdot10^{-5}$ s. Such significant cooling rates allow eliminating intensive growth of carbide grains without growth inhibitors application.

Product mix produced using given technology includes metallurgical, rolling and guide rollers, rollers for straightening of wire in draw bench, various drawing tools, chipping knifes, burrs, special products of military designation etc. (Figure 3).

UNIT FOR ELECTRON BEAM SINTERING OF HARD ALLOY BILLETS

The specialists of PWI together with the specialists of State enterprise “Engineering Center of Electron Beam Welding” developed and produced installation SV-229 for electron beam processing (EBP) of hard alloy preliminary sintered billets for the purpose of their (final) sintering. General appearance of this installation is shown on Figure 4.

Except for innerchamber mechanisms this installation has a design mostly typical for electron beam welding equipment developed at the PWI with similar volume of vacuum chamber [8, 9]. A vacuum chamber (Figure 4, pos. 2) has a rectangular shape and inner volume approximately 0.5 m^3. Its door (Figure 4, pos. 3) moves left along the plane of front edge (flange) of chamber. Using movable screens the door is hanged on a longitudinal guide. The door is moved using a pneumatic cylinder. The chamber is fixed above rigid frame. A body of vertical pneumatic vacuum lock (Figure 4, pos. 4) is fixed using an arm to a hole on a back wall of the chamber. A running water trap and a diffusion pump are connected to it in series from the bottom. At some distance from them on the flour there is a mechanical forevacuum station which consists of the rotor and double-rotor pumps working in series. An electron beam gun (Figure 4, pos. 1) is dead fixed on a chamber roof and has strictly vertical orientation.

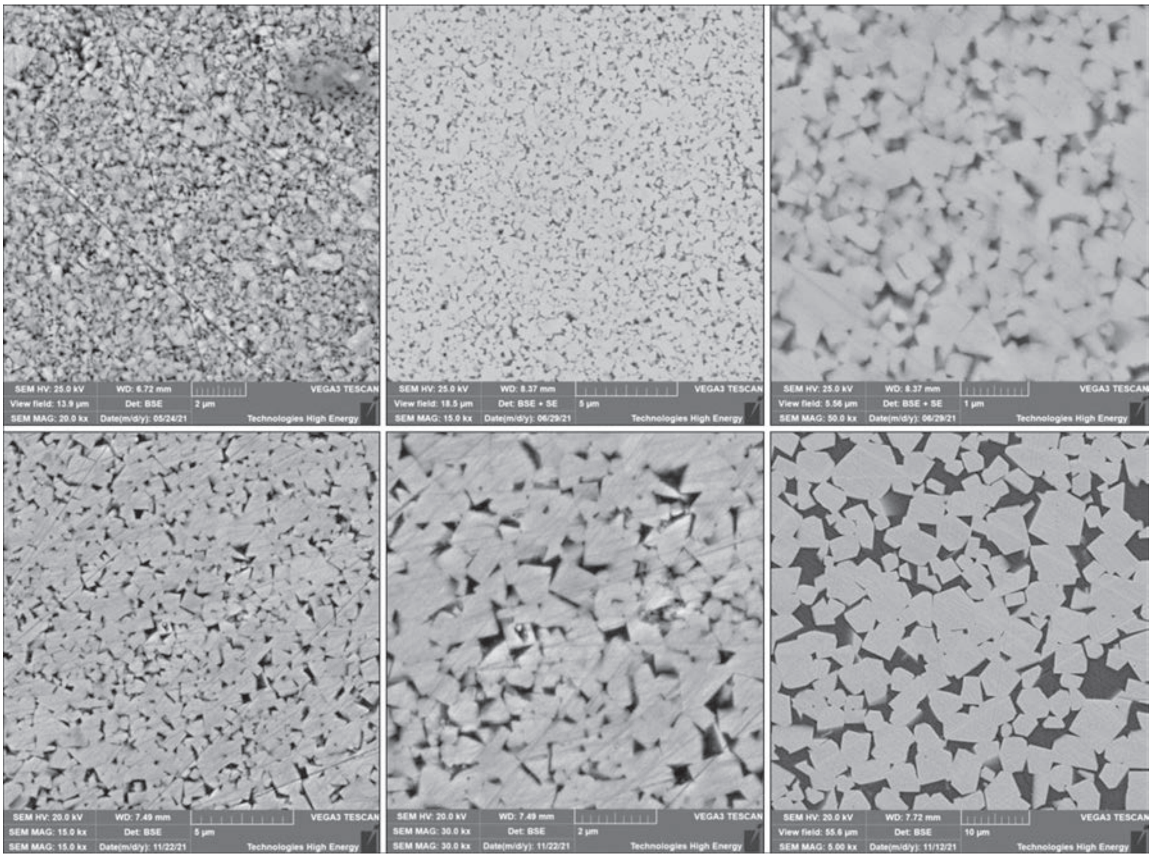

Figure 2. Microstructure of VK alloys produced by electron beam sintering

Usually it is a pneumatic gate valve isolating a source of gun electrons from the inner volume of vacuum chamber. Exhaust of a turbomolecular pump of the gun through a valve is connected with the volume of vacuum chamber, i.e. role of a step of prepumping of the gun is fulfilled by the volume of chamber itself. Productivity of the vacuum system of installation is sufficient for development of pressure of $2\cdot10^{-4}$ mbar in the vacuum chamber and, respectively, $5\cdot10^{-5}$ mbar in the gun for approximately 15 min.

Working place of installation operator is located on the right from the vacuum chamber before a control cabinet (Figure 4, pos. 5). Respectively, in the right wall of the chamber it is an inclined tube of the main window for visual observation of processes in the chamber (Figure 5).

A main display of the control cabinet is located at eye level of a person of average height standing on the floor. It displays the graphical interface of the installation control program (upper level for Windows OS), including the secondary emission monitoring system RASTR-6.

An additional display is fixed above the main display, which is designed for displaying the image from a camera (and also, if necessary, to display the operational information of the lower level control program for QNX OS). The video camera is installed on the roof of the vacuum chamber — opposite a small window.

On the front side of the control cabinet, there are also two industrial computers of the installation control system (upper and lower levels), a no-break power supply unit for these computers, an industrial keyboard and touchpad unit (for the upper level

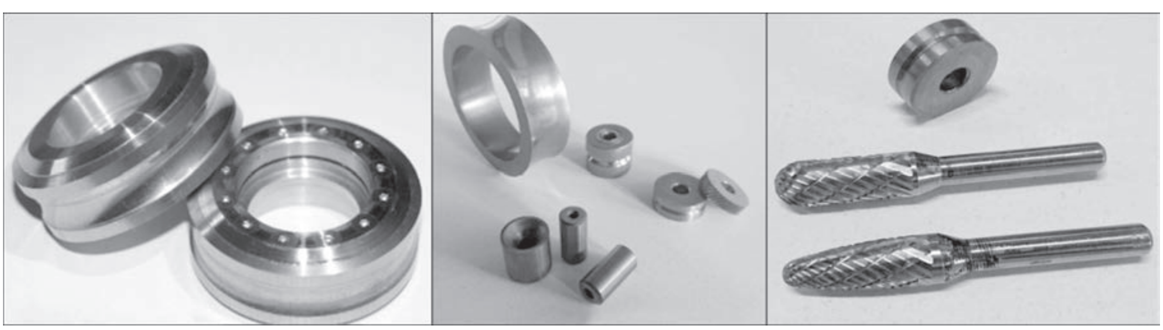

Figure 3. Products manufactured by electron beam sintering method

Figure 4. Installation for EBP of hard alloy billets, where: 1 — electron beam gun; 2 — vacuum chamber; 3 — sliding doors; 4 — vacuum system; 5 — control cabinet; 6 — power cabinet; 7 — welding high-voltage power source cabinet; 8 — loading device for two feed drums of parts

computer), a converter of a turbomolecular gun of the pump, a control unit for the RASTR-6 secondary emission monitoring system, and a push-button control panel for welding high-voltage power source.

On the right of the control cabinet, close to it, there is a power cabinet (Figure 4, pos. 6) with a start-up control equipment of the vacuum system and control elements of the SIEMENS Sinamics S120 system. A cabinet of welding high-voltage power source 15 kW/60 kV, inverter type (Figure 4, pos. 7) is located a bit further to the right.

The installation is equipped with an autonomous water cooling system with an industrial chiller located to the left of the vacuum system.

In contrast to the above-described features, in fact, usual for electron beam equipment, the features of the installation related to the specifics of EBP are discussed below.

Both the vacuum chamber and the door of this installation have a hollow structure for cooling water circulation. This allows long-term EBP, including by ensuring the stability of the overall geometry of the chamber, first of all spatial orientation of longitudinal axis of the electron beam gun.

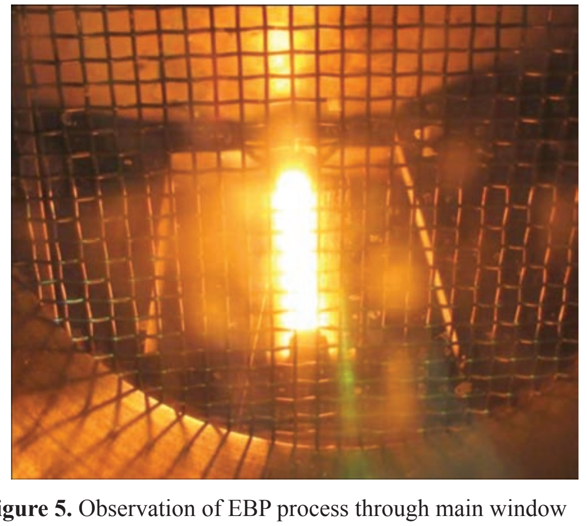

Figure 5. Observation of EBP process through main window

To protect the main window from long-term thermal radiation and spraying in EBP process, there is a device on the inner wall of the chamber in the form of a pair of vertical metal flaps, the simultaneous opposite directed movement of which is provided by an external manual drive (its handle is located on the side of the window).

In addition to the above-mentioned window for the video camera, there is another small window on the roof of the vacuum chamber for the high-temperature pyrometer OPTRIS CTratio 2M (which in two-color mode is designed for the temperature range from 550 to 3000 °C). Note that the proprietary pyrometer program is installed in the upper level computer and used in parallel with the installation main control program.

Both of the above-mentioned windows, for video camera and pyrometer, have a common manual shielding shutter, also for protection against heating and spraying during EBD. Thus, the installation provides only a relatively short-term visual observation (with a video camera or directly by eyes) of the EBP process as well as measurement of temperature of billets during processing. On the contrary, the secondary emission monitoring of the EBP process is constantly available.

These were auxiliary structural elements nevertheless related to the EBP process. Further the specific elements that directly participate in this process are considered.

First of all, it should be noted that this installation is intended for EBP of billets of only cylindrical outer surface, with *initial* diameter of 15–30 mm and length of up to 30 mm. Although in reality the design of installation allows for processing of a wider range billets, including those with a *final* diameter of only 6 mm, the basic configuration of installation provides equipment for only three dimension types of billets (initial diameter and length, respectively): 30×30 mm, 25×25 mm and 15×15 mm.

The following mechanisms are involved in the EBP technological cycle, namely a feed drum for parts to be processed; a mechanism of working rotation of parts (rotator), on which EBP is performed; a mechanism of line feed of parts at their loading on the rotator and unloading from it; a pallet for processed parts; as well as a loading device for two feed drums (Figure 4, pos. 8).

All billets that should be processed for one session of chamber pumping are located in the cells of the *feed drum* (Figure 6, pos. 4). In the chamber, the feed drum is hung on its left inner wall. For this two horizontal cylindrical guides (Figure 6, pos. 5) are attached to the wall, on which four support wheels (rollers) of the feed drum base plate is tightly based on, so it can move freely along these guides to a limit stop. This stop, together with a clamp on the base plate, determines a working position of the feed drum in the chamber.

The installation has two identical feed drums. Each of them has a set of three replaceable inserts (Figure 6, pos. 7) with open cells along the outer perimeter, where the billets of three mentioned above dimension types are contained. The inserts are pushed on the outer diameter of the drum (Figure 6, pos. 8), and a guide key provides fixation against scrolling. The lateral dimensions of the cells in these inserts are different, therefore the number of cells in them is also different: 60 cells for "15 mm" dimension type, 40 — for "25 mm" and 36 for "30 mm". The angular pitch between the cells is integer and equal to 6, 9 and 10°, respectively. The length of cells is the same and equal to 212 mm. The billets are kept from falling out of the open cells by an external immovable ring (Figure 6, pos. 9), that has a longitudinal gap from below (Figure 7, pos. 1). Close to this gap there is a pair of flaps (Figure 7, pos. 2), a longitudinal gap between which is set depending on billet dimension type. Thus, when the drum is rotated to a corresponding angular pitch, the billets fall down from a current lower cell into this gap (one of the successive loading operations of the rotator). The open ends of the cells are closed with a common cover (Figure 7, pos. 3), which is put on the drum edge and is quickly connected to it.

A base of drum rests through a pair of bearings on an immovable tubular shaft, which is attached normal to a base plate of the feed drum. To turn the drum, such a technical method as "carrier" is used. A bar connecting the edge flange on the drum base with a drive fork of this carrier passes through a hole of the tubular shaft. An outside slot of the fork is coupled (coupling/uncoupling is possible only at horizontal orientation of the fork) with a drive pin of electromechanical drive of drum rotation (Figure 6, pos. 6). Most of the elements of this drive are brought out through the vacuum chamber sealing. It is assumed that when the feed drum is uncoupled from the drive, in particular, when the feed drum is outside the vacuum chamber, to prevent spontaneous rotation of the drum, the operator must fix it manually with the help of a locking clamp. In the future, when the feed drum is next time coupled with the drive, this clamp is automatically removed.

Thus, an axis of feed drum rotation and, respectively, all the cells are oriented along the chamber longitudinal axis. Moreover, both axes, the axis of drum rotation and the axis of the drive of this rotation, coincide and approximately intersect with longitudinal axis of the electron beam gun.

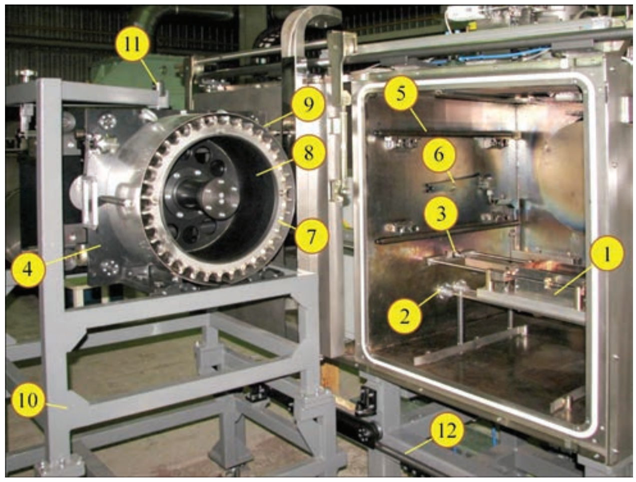

Figure 6. General appearance of most mechanisms related with EBP, where: 1 — mechanisms for rotation of parts; 2 — its drive; 3 — mechanism of line feed of parts; 4 — feed drum of parts; 5 — guides for its suspension in chamber; 6 — its drive; 7 — replaceable insert with cells for parts; 8 — rotating feed drum; 9 — outer ring of feed drum; 10 — frame of loading device; 11 — its swivel block of suspension for both feed drums; 12 — horizontal bearing guide of this device

The feed drum is filled with billets outside the vacuum chamber and only then moved into it. A *loading device* is used for such operations. This is a frame structure (Figure 6, pos. 10), in the upper part of which there is a swivel block of rack suspension (Figure 6, pos. 11), which is designed for two feed drums. These are two pairs of racks that are similar to those installed in the chamber and located in two parallel

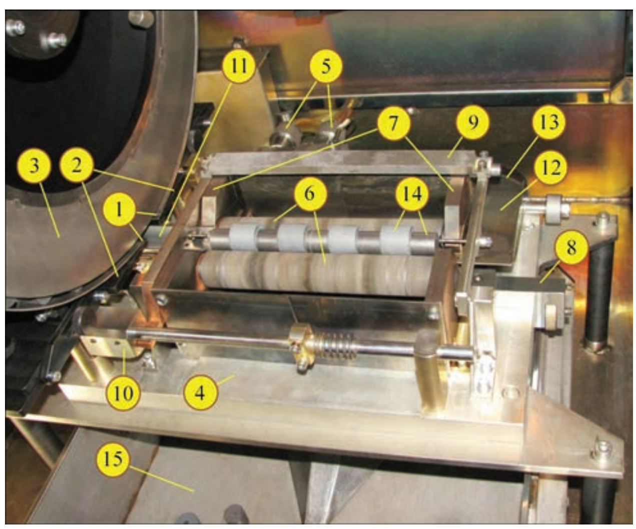

Figure 7. Inner elements of chamber for EBP (close-up), where: *a* — elements of feed drum: 1 — gap in outer ring; 2— pair of low longitudinal flaps; 3 — edge cover of drum; *b* — rotator elements: 4 — base plate; 5 — its water cooling; 6 — working rolls; 7 — pair of bearing webs of one of rolls; 8 — template for rolls positioning; 9 — lift frame of part stoppers; 10 — block cam of its clamp; 11 — delivery tray; 12 — sloping uploading tray; 13 — screw tray; *c* — other: 14 — billets and graphite inserts; 15 — pallet for processed parts

planes equidistant from a vertical axis of rotation. The drums of suspended feed drums are turned outside in opposite directions and can switch positions when the suspension assembly is rotated by 180°.

The corresponding structural measures were used to move the feed drum in and out of the vacuum chamber. The loading device is placed in front of the chamber door (without interfering with its movement). From the end far from the door, the device rests on workshop floor by two swivel wheels. From the near end, it rests by two rollers on a horizontal guide (Figure 6, pos. 12) attached to the chamber frame parallel to plane of its door frame. Thus, the device can be manually moved along the guide from stop to stop. In the extreme left position, the device does not interfere with free access to the chamber door opening. Respectively, the rightmost position is a position of joining with the chamber guides, when the current right pair of device guides should be in the same plane with the pair of chamber guides. The spring-loaded clamp prevents willful longitudinal displacement of the device from this position. In addition, the parallelism of the guides of the device to the plane of the chamber guides provides a clamp of rotation angle of rack suspension assembly of this device. Finally, for the direct (manual) movement of the feed drum between the guides of the loading device and the chamber there is an easy to mount changeable guide bridge installed in a gap between them.

It is assumed that in the arranged production cycle, during each chamber pumping session (to perform EBP), the previously filled feed drum is located in the chamber, and the current right pair of guides of the loading device remains empty waiting for the return movement of this, already empty, feed drum from the chamber. Respectively the second feed drum is located on the left pair of guides of this device during pumping. It is usually empty, therefore, before the end of pumping, an operator should manually fill each feed drum cell with the appropriate number of billets (depending on dimension type). The cylindrical graphite inserts are located the extreme position from both ends of each cell. An intermediate chain of hard alloy billets and graphite inserts is placed between them. There should be 3 billets for dimension type “30”, 4 — for “25” and 6 — for “15”, respectively. In general, only billets can be placed between the last inserts, and this will increase the total number of billets treated at a time, however it is more reliable to use intermediate inserts. The first, lowest, cell is always left empty, because it is located above the longitudinal gap in the outer ring of the feed drum.

The main element of the *parts rotation mechanism* (rotator) is a pair of graphite rolls with a cylindrical working surface of 208 mm long (Figure 7, pos. 6). Synchronous rotation of the rolls ensures uniform rotation of the billets (Figure 7, pos. 14) during EBP. The thinner ends of the rolls rest on bearing sleeves that are fixed in the holes of vertically located copper webs (Figure 7, pos. 7). The latter are attached by their lower edges to a massive horizontal base plate (Figure 7, pos. 4), which has internal channels for water cooling (Figure 7, pos. 5).The distance between the rolls is regulated depending on billets dimension type, so that the contact angle of the rolls with the raw billet and with it after sintering changes approximately from 110 to 125°. At that, the rolls should be symmetrical relative to the vertical longitudinal plane along which technological longitudinal oscillation of electron beam is performed (the maximum length of the electron beam scanning at this working distance is not less than 190 mm). A special movable template (Figure 7, pos. 8) facilitates setting a necessary distance in compliance with the above condition.

The drive end of each of the rolls (from the left side of the chamber wall) is connected with a joint electromechanical drive (Figure 6, pos. 2) through a double cardan joint. The drive is also brought outside through the vacuum chamber sealing.

The stoppers at both ends of rolls working surfaces (the distance between them is 210 mm) prevent axial displacement of billets from processing area. The rods of the stoppers are fixed in the side walls of U-shaped frame (Figure 7, pos. 9). The open side of this frame has a pivot connection with two vertical brackets attached to the base plate. In a free state, from the closed side, the frame rests on the stop on the far left web. When the frame is raised, the movable spring-loaded clamp with its cam (Figure 7, pos. 10) can block such a state of the frame and this allows passage of billets under it during loading of the rotator.

A V-shaped delivery tray (Figure 7, pos. 11) is located near the left edge of the working surface of the rolls — along the above-mentioned vertical longitudinal plane. The billets from the feed drum fall into it when turning the drum “per one cell”. The height of the tray location is adjusted depending on billet dimension type so that the points of contact of billets with sloping walls of the tray are slightly higher than the points of contact with the rolls. This allows easy movement of billets from the tray to the working rolls.

On the right end of the rotator there is a sloping unloading tray (Figure 7, pos. 12) for receiving already treated parts from the rolls. The level of this transfer is regulated by the tray slop — depending on the size of the compacted billets. The opposite end of this tray passes into a screw tray (Figure 7, pos. 13), which ensures rolling of treated billets and inserts into a *pallet*

(Figure 7, pos. 15), which lies on the floor of vacuum chamber (which, as already mentioned, is cooled by water). Two identical pallets are provided — for quick replacement of a filled pallet with an empty one. To remove the filled pallet from the chamber (of course, after opening its door), there is a manual forklift hoist, which is made based on standard product. You can install an empty pallet into the chamber both with the help of this hoist and manually.

A longitudinal feed mechanism is, in fact, an industrial linear actuator (electric cylinder) with a rod working stroke of up to 600 mm. The actuator itself is located outside the vacuum chamber, and its elongated rod enters the chamber through a seal. A tip of a special shape is fixed at the end of the rod. It is of such shape because this mechanism performs several other related operations in addition to feeding raw billets to the rotator and unloading compacted billets from it. Firstly, at the stage of unloading the treated billets from the rotator rolls (after their EBP), the rod begins to move from a zero position in the direction to the billets; before reaching them, the tip of the rod, due to slope shape of its front part, lifts the frame of the rotator stoppers, and then the open side of the frame (the extended end of its left side wall) is blocked by the cam of the spring-loaded clamp — this condition is necessary for the next stage of billets loading on the rotator. Secondly, at the stage of this loading, after the rod feeds (shifts) a portion of untreated billets from the delivery tray of the rotator to its working rolls, the rod is returned to the zero position; at that, the tip of the rod with its rear edge catches and shifts the spring-loaded clamp to the left, pulling its spring; immediately near the zero position of the rod, the cam of the clamp releases the frame of the stoppers of rotator and it under its weight goes down to the state required for the next EBP.

The *algorithm of interaction* of all these mechanisms for EBP is described below. For example, let's take a condition of regulated production process, when the full EBP cycle is completed for all the billets placed in the feed drum at current chamber pumping session, atmospheric air is blown into the chamber and its door is opened. At that, in the (empty) feed drum, an initial cell is again located from the bottom and, respectively, the drive "carrier" stands horizontally and faces doorway with its fork. At this moment, second (already filled) feed drum is located on the left guides of the loading device, and the right guides are, respectively, empty. Then the operator performs the following actions.

He moves the loading device to the position of joining with the chamber guides and installs the guide bridge. After that, the operator unlocks the movement of the feed drum (in the chamber), rolls it onto the rods of loading device (firmly) and fixes this position, as well as the feed drum. Then, the operator swaps the feed drums. For this he temporarily removes the guide bridge, unlocks a swivel block of rack suspension of the loading device, turns it by 180° and locks it again. Thus, the filled feed drum is already on the right rods. Then the operator again installs the guide bridge, unlocks the movement of this feed drum, rolls it into the chamber (firmly) and fixes this (working) position. At that, the "carrier" fork will already be coupled with the drive pin of rotation drive of feed drum, and the bolt clamp of the drum will be taken out. Next, the operator finally removes the rod bridge and moves the loading device away from the doorway (firmly).

In addition, with the help of a forklift hoist, the operator pulls out a pallet filled with treated billets (and graphite inserts) from the chamber and installs a second, empty pallet in its place.

The correct position of the internal chamber mechanisms at this time is as follows: the rod of line feed mechanism (actuator) is in a zero position, accordingly, the frame of the rotator stoppers is lowered. In addition, the rotator rolls are empty. Therefore, the operator should manually load the last batch of billets and graphite inserts on the rolls (because the bottom cell of the drum is empty).

After pumping the chamber and gun and turning on a high-voltage power source, the operator immediately starts the EBP program cycle. It repeats the same sequence of operations cyclically. The number of such repetitions is equal to the number of loaded portions of billets of a specific dimension type, i.e. portions in (n–1) cells of the feed drum plus one portion on the rolls. In other words, this is the total number of cells of the feed drum (n).

The abovementioned repeated sequence of operations includes: firstly, direct EBP of a portion of the billets, secondly, operations of unloading a portion of treated billets from the rotator rolls, and, thirdly, operations of loading a portion of still untreated billets onto the rotator rolls.

EBP of a portion of billets starts with a programmed launch of working rotation of the rolls and longitudinal oscillation of the electron beam. The "length" of this technological scanning of the beam covers the entire chain of billets as well as about half of the length of the extreme graphite inserts contacting with the rotor stoppers (that is, it is not less than 190 mm). Only in the presence of these two factors, it is possible to turn on electron beam current. A defocused electron beam which performs scanning along a linear trajectory develops a heat source necessary to perform a thermal cycle of processing of all hard alloy billets rotating on the rolls at the same time. It is necessary to note that the program that generates beam oscillation, including distribution of power density along its trajectory, can be adjusted by the user with the help of a special software interface. A time-programmed change of power of the electron beam determines a heating rate, holding time and cooling rate of the billets.

Unloading is performed in the following sequence: the actuator rod begins to move from a zero position in the direction of the rotor rolls; on this way, it firstly raises a frame of the rotator stoppers and then it is blocked with a cam of the spring-loaded clamp; then the actuator rod one by one pushes the treated billets (and graphite inserts) from the rolls onto a sloping tray, from which they roll onto the screw tray and down it into a pallet; after this, the rod is moved in the reverse direction, and stops at some distance from a zero position — when the tip of the rod no longer interferes with fall of a portion of billets from the feed drum into the delivery tray of the rotator, but the raised frame of its stoppers is still blocked.

Loading is performed in the following sequence: a drive of the feed drum turns the drum to the corresponding angular pitch and a portion of raw billets (and graphite inserts) from a feed drum cell through its lower gap falls into the delivery tray of the rotator; then the actuator rod shifts (feeds) this chain onto the rotator rolls (to the EBP position); finally, the rod moves back to the zero position, in which the raised frame of the rotator stoppers is unlocked and then lowered in a position necessary for next EBP.

Let's note the peculiarity of completion of EBP program cycle. After unloading the last (*n*-th) portion of treated (sintered) billets from the rolls of the rotator, in fact, there is nothing to load because the feed drum is already empty. But such an "empty" loading is necessary for the uniformity of the entire cyclic process. Then the feed drum will finally make a full revolution, i.e. it will be in the initial position, in which the drive "carrier" is oriented horizontally and faces the doorway. In addition, the actuator rod will be in a zero position and, respectively, the frame of the rotator stoppers will lower to a position necessary for EBP already in the next session of chamber pumping.

CONCLUSIONS

1. An industrial technology has been developed for manufacture of WC–Co alloy powders from production wastes, their precision pressing into various shapes and electron beam high-speed sintering of semi-finished products.

2. There was developed and produced a high-performance installation for electron beam processing of hard alloy previously formed billets used for sintering and obtaining the necessary service characteristics.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

V.M. Nesterenkov, K.S. Khripko, V.V. Lukyanov, M.O. Sysoev, V.V. Chernyavskyi (2023) Technology and equipment for electron beam sintering of hard alloy billets. *The Paton Welding J*., **8**, 65–72.

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Received: 21.07.2023
Accepted: 07.08.2023