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IDENTIFICATION OF THE APPLICATION FEATURES OF FINISHING PROCESSING METHODS OF PARTS WITH FREE ABRASIVES AT RAILWAY ROLLING STOCK REPAIR ENTERPRISES

The object of research is the technological process of vibration finishing of the "Rotor Sheet" type flat parts, which are made of thin sheet metal at the enterprises of the railway industry of Ukraine in the process of repairing electric motors of rolling stock. Due to the peculiarities of operation, such parts often have residual defects after laser cutting – burrs, sharp edges, contamination – which negatively affect their further functioning. One of the most problematic areas is ensuring uniform, high-quality processing of a large number of thin parts simultaneously without their deformations and damages. During the study, methods of comparative analysis of technological solutions, experimental testing of vibration processing parameters and selection of the most effective operating modes of the machine were used. A selection of abrasive tools of various shapes and compositions was made and the influence of active alkaline solutions was studied, as well as the design of three structurally different special devices for placing parts in a container. The presented devices ensure positioning of the part with simultaneous access of the abrasive tool to all surfaces being processed. The research results can be used to design processing technologies for various types of flat parts made of thin sheet metal. A rational technological process has been obtained that allows for effective removal of surface defects, improving the quality of processing while maintaining high productivity. This is due to the fact that the proposed approach combines precise selection of processing modes and improved devices, in particular by controlling the movement of parts and optimal distribution of the working environment. This provides the possibility of obtaining high surface quality indicators with a significant reduction in processing time. Compared with similar known methods, this provides improved technological controllability, cost-effectiveness and adaptability to the conditions of mass production in mechanical engineering.

Keywords: *finishing, vibration method, rolling stock, abrasive tool, thin sheet part.*

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1. Introduction

The creation of new and modernization of existing production systems requires complex technological preparation of production. Obvious trends in the development of modern mechanical engineering in the future are the production of a wide range of products while simultaneously reducing production time and economic costs. Modern enterprises for the repair of railway rolling stock, as a rule, use in production high-tech multi-coordinate centers with numerical program control for machining operations and universal equipment for finishing. Analysis of modern directions of development of mechanical engineering technology shows the exceptional importance of finishing operations, since it is at this stage that the surface quality and appearance of products are formed. Finishing, which is performed after mechanical and thermal treatment, as a rule, causes a number of difficulties, the reasons for which may be due, on the one hand, to a wide range of processed parts, and on the other hand, to the choice of processing method. Parts can have different parameters of mass and dimensions, have a complex geometric shape. Processing methods also impose limitations, for example, the dimensions of the part may not allow processing or the technological capabilities of the equipment do not allow achieving the required process productivity in terms of quantitative or qualitative indicators.

Problems that arise when processing parts are typical for both enterprises that produce new products and enterprises that repair and modernize existing products.

The current state of the railway complex of Ukraine is characterized by significant wear and tear and aging of fixed assets. One of the main components of the work of Ukrainian railways is rolling stock, which accounts for the majority of operating costs. Today, more than 90% of rolling stock has exhausted its planned operational resource and requires major repairs with simultaneous modernization. This problem requires enterprises that repair and maintain rolling stock to manufacture and replace a huge number of parts and products, examples of such parts are presented in Fig. 1. Various studies are constantly being conducted on this topic, for example, in works [1, 2] an analysis of the types of damage to the windings and magnetic cores of traction electric motors of electric locomotives during their operation was carried out. It is shown that one of the factors affecting the reliability of engines is the quality of the finishing of the magnetic cores of the rotor windings. In the article [3], based on the modeling of a pulsating current traction electric motor, the importance of accurate processing of magnetic cores for magnetic losses in steel is shown. A significant part of the research is aimed at modeling critical situations that arise during operation, as well as studying the dynamics of processes of technical systems [4]. In particular, high loads and, accordingly, wear lead to the need for complete replacement or overhaul of electric motors. An example of a rotor of such an electric motor that requires replacement is shown in Fig. 2.

Fig. 1. Examples of railway rolling stock parts requiring repair

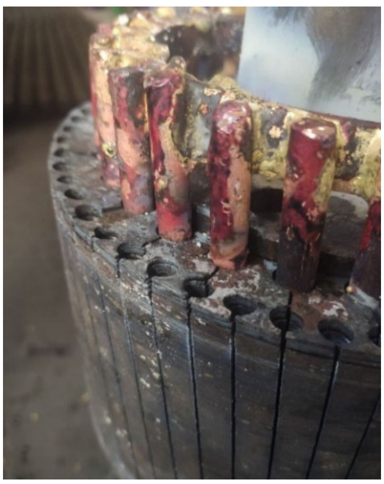


Fig. 2. Appearance of the rotor of an electric motor requiring replacement

During the repair process, it is necessary to manufacture various parts that will later become parts of products. Some of such parts are obtained by laser cutting thin-sheet rolled steel, after which the problem of cleaning, removing burrs and rounding sharp edges arises. Rotor sheets of asynchronous electric motors are such parts.

However, the authors of the above works do not give recommendations for solving the problems considered in practice in industrial conditions.

The aim of research is to identify the features of vibration finishing of thin-sheet flat parts of the "Rotor Sheet" type in conditions of simultaneous processing of a large number of parts, in particular, to determine the influence of the design parameters of special devices, the geometry of the abrasive tool and vibration modes on the uniformity and quality of processing. This will provide an opportunity to justify the choice of rational technological modes, equipment designs, and the type of abrasive tool to ensure a stable processing process without deformation of parts, which, in turn, will contribute to increasing the productivity and quality of surface treatment in multi-series production conditions.

2. Materials and Methods

The object of research is the technological process of vibration finishing of the "Rotor Sheet" type flat parts, which are made of thin sheet metal at the enterprises of the railway industry of Ukraine in the process of repairing electric motors of rolling stock.

For the research, the technology of processing the "Rotor Sheet" part, which is a component of the rotor of an asynchronous electric motor, was considered, the number of parts in one product is 250 units. The workpiece for the part is a rolled sheet. Material – thin sheet electrical steel DSTU EN 10107:2009 Sheet and sheet of electrical steel textured in a fully processed state technical conditions of delivery (EN 10107:2005, IDT), the thickness of the part is 0.5 mm. The "Rotor Sheet" part has a large number of holes. The appearance of the part is presented in Fig. 3, a sketch of the part – in Fig. 4. The main requirements for the part surfaces after laser cutting are that cleaning is required, burrs and sharp edges are unacceptable.

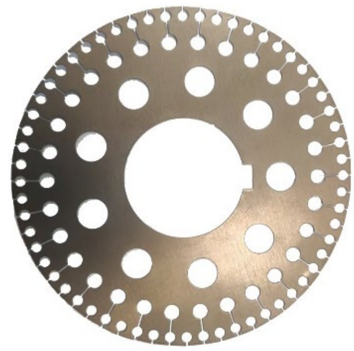


Fig. 3. Appearance of the "Rotor Sheet" part

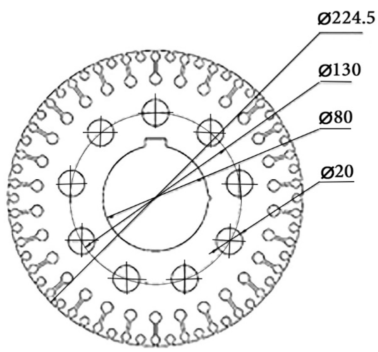


Fig. 4. Sketch of the "Rotor Sheet" part

The technical requirements for the part indicate the following methods of finishing: cleaning, removing burrs, rounding sharp edges. The initial roughness of the part surface is sufficient and does not require quality improvement, which, in turn, provides a wide choice of processing methods – grinding with abrasive wheels and cloths, tumbling in rotating drums, jet-abrasive processing, vibro-abrasive processing. It is also possible to use manual processing, but the level of productivity of this type of processing does not meet modern trends in the development of production and makes its use impractical. Let's consider each of the listed methods, analyze their advantages and disadvantages. Today, the most common processing method remains grinding or polishing with a fixed abrasive tool – grinding wheels. In this case, grinding belts, grinding heads, abrasive bars are used as tools. In this processing, the tool performs a rotational motion, which is the main cutting motion, and the workpiece – longitudinal, transverse or cyclic motion. At present, the method continues to be studied [5, 6] and improved [7], and has also been developed in the form of new types of grinding – high-performance grinding (HPG) and high-efficiency deep grinding (HEDG) [8].

The advantages of this method are its sufficient study, and therefore, ease of application, high productivity, the possibility of automating the process.

The characteristic disadvantages of grinding or polishing with a fixed abrasive tool include: high uneven wear of the grinding tool. This process consists in the fact that abrasive grains, when in contact with the surface being processed, are subjected to periodic force, thermal and chemical effects. As a result, the cutting edges of the grinding grains wear out and a wear area is formed. The pores of the grinding wheel are filled with chips. The shape of the wheel is disturbed, and its grinding properties deteriorate. Errors in the selection of an abrasive tool and processing modes can lead to surface damage. There are also limitations on shaping associated with a certain (fixed) shape of the abrasive wheel, which does not allow for effective processing of parts of complex shape and causes great difficulties in processing corners and burrs. In addition, when grinding with grinding wheels, uneven metal removal is observed. This occurs for the following reasons:

1) inhomogeneity of the structure of the grinding wheels;

2) incorrect setting of the tool rotation speed, deviations in its geometry or the geometry of the workpiece;

3) change in pressure on the surface to be processed, which leads to unstable contact and variation in the intensity of the abrasive effect.

Automation of this method is not a simple task for processing one part and causes many complications when it is necessary to simultaneously process several parts. Also, like most of the methods that will be considered below, processing with grinding wheels is accompanied by the release of dust consisting of small particles of material, which creates additional difficulties and requires more complex actions aimed at production safety.

Quite often, machine-building enterprises encounter equipment for finishing parts in rotating drums – tumbling. Such equipment is simple in design and does not require complex setup, and the process itself is easily modeled and allows the use of combinations of various abrasive tools [9, 10]. Processing in tumbling drums is carried out due to the relative movement of the part and the abrasive tool when pouring the load mass (a mixture of abrasive granules, working fluid and parts to be processed). The speed of relative movements in this case does not exceed 1 m/s, and the zone of intensive processing is only part of the load volume [10]. The number of revolutions of the drum is chosen so that its acceleration does not exceed the acceleration of free fall. This is due to the fact that if the acceleration of the drum exceeds the acceleration of free fall, then processing in the drum will stop due to the fact that the centrifugal force will press the processed mass to the walls, and it will rotate with it.

The limitation of the use of tumbling is the processing of thin-walled and fragile parts, which can be deformed when pouring and falling. The inner surface of the part cannot be processed either. This is due to the fact that the relative movement of the granule that enters the cavity of the part stops. As a result, the granules begin to move at the speed of the part. Also, this method excludes the possibility of simultaneous processing of parts of different dimensions and masses, since during the movement a heavy part can damage a lighter one. In addition, such equipment is characterized by a high noise level during operation and limited ability to automate the processing cycle. Jet abrasive treatment methods are also widely used – these are surface treatment methods in which abrasive particles are directed to the surface of the product using a jet of high-speed gas or liquid [11–13]. Jet abrasive treatment combines the versatility of application, which allows working with different materials and processing parts with different shapes and contours, including internal areas, holes and channels. A high-speed jet of abrasive particles allows for rapid and accurate removal of contaminants, oxides, and other layers from the surface of products, and does not create significant thermal effects, which avoids changes in the hardness or structure of the processed material [13].

Jet-abrasive processing, depending on the method of supplying the abrasive tool, is divided into sandblasting and hydrojetting (hydroabrasive). In the sandblasting method, abrasive fine particles are directed under high pressure to the surface of the product using a gas jet. In the hydrojetting (hydroabrasive) method, the abrasive is moved using a liquid. A subtype of sandblasting is shotblasting, in which the feed is also carried out by gas, but larger elements (grains) are used as a tool.

The use of this type of processing requires detailed development of the technological process, since the incorrect selection of parameters may damage the surface of the part. At the same time, the processing of thin-walled or fragile parts is even more complicated and, in some cases, impractical, since it can lead to the destruction of the part. However, the main disadvantage of this method is its environmental friendliness and harmfulness to the operator. During the processing process, an air mixture (dust) is formed in large quantities, consisting of particles of abrasive material and part. Without the use of strict safety measures, the use of this method harms the environment. In production, the processing of parts in this way is carried out in closed chambers, which are partially automated, but this does not solve the problem of auxiliary operations for installing and moving the workpiece, which usually have to be performed by the operator. The processing of large structures, which include rolling stock, does not allow the use of closed chambers, the operator must work in protective equipment, and abrasive materials can get into the environment. The subsequent disposal of spent abrasive material and waste is also difficult and costly.

One of the rather "young" methods of processing with free abrasives is the processing of parts in a vibrating container – vibration processing, which is actively used at the stage of cleaning, grinding, polishing and other operations.

Vibration processing is the process of removing metal from the processed surfaces of parts with grains of abrasive granules of the working medium, to which vibrations are transmitted. Processing occurs as a result of the sequential application of a plurality of micro-impacts to the surface of parts with abrasive granules. In this case, the granules of the working medium continuously contact both with each other and with parts during their mutual sliding. This occurs under the influence of force pulses transmitted to the working medium from the vibration exciter of the vibrating machine.

The main advantages of this processing method include, first of all, the ability to simultaneously process a large number of parts. The process occurs using various chemical solutions, with the possibility of their gradual application and subsequent cleaning from them. This processing method, with the appropriate choice of tool, allows to process hard-to-reach surfaces without damaging thin-walled and fragile parts. It is used for cleaning, removing scale, removing burrs and rounding sharp edges, grinding, polishing, preparing the surfaces of parts for galvanic and paint coatings, creating optimal residual stresses in the surface layers of parts.

Separately, it is worth noting vibro-impact processing, which allows to improve the quality and strength of the surface layer of the processed surfaces.

At the same time, this method is limited by the design features of the equipment. Classic machines have containers of U-shaped or toroidal shape, which in turn imposes restrictions on the maximum size of the processed parts and requires the use of through-feed (conveyor) machines. Also, as a rule, to ensure uniform processing of complex parts, the development of special devices is required. The process of simultaneous movement of the abrasive tool and parts is multifactorial, and despite a number of studies [14], does not require further research.

Let's make a comparative analysis of the above processing methods from the point of view of the efficiency of processing the part presented in this work. The results of the analysis are summarized in Table 1.

From the table presented, it follows that processing with a fixed abrasive tool and jet-abrasive processing have safety and environmental restrictions, and also do not allow processing a large number of parts simultaneously.

Tumbling and vibration processing are devoid of the disadvantages of the two above-mentioned methods, however, tumbling has limitations in terms of processing thin-walled parts, since the parts may be damaged during rotation in the drum. Therefore, for simultaneous processing of a large number of presented parts, it is advisable to choose vibration processing.

Table 1

Comparative analysis of finishing methods from the point of view of the possibility of processing a thin-walled "Rotor Sheet" part

Processing method	Fixed tool machining	Rotating drum machining	Abrasive blasting	Vibration machining
Surface cleaning	+	+	+	+
Burr removal	+	+	+	+
Rounding sharp edges	+	+	+	+
Possibility of simultaneous processing of several parts	–	+	–	+
Existence of environmental restrictions	+	–	+	–
Limitations on processing of thin-walled parts	–	+	+	–

3. Results and Discussion

The choice of equipment for processing the presented part by the vibration method is quite wide. The parameters of the machine must ensure the efficiency of processing, which depends on the characteristics of the equipment and the part being processed. The main parameters of the required equipment were as follows: the internal dimensions of the working container and operating modes. Requirements for the design of the container – its linear dimensions must ensure the free passage of granules of the working medium from all sides of the part when it is freely loaded, without fixation. In the case under consideration, the maximum linear size of the part is 224.5 mm, therefore the width of the container (*Y* axis) must be at least 250 mm. Considering that the technological features of the method provide for filling the container with parts and an abrasive tool by 75%, the height of the container (*Z* axis) must be at least 300 mm. The length of the container (*X* axis) depends on the number of parts being processed simultaneously, the minimum size that will ensure processing from all sides is similar to the width – 250 mm.

Since the technological process of processing the "Rotor Sheet" part does not require improving the surface quality, the processing modes, namely the amplitude and frequency of oscillations, can be selected from the standard parameters of known equipment. For cleaning, removing burrs and rounding sharp edges, the initial values should be at least 0.2 mm for the amplitude and at least 50 Hz for the frequency of oscillations. The general parameters required for the equipment are presented in Table 2.

Table 2

Required parameters of vibration equipment

Parameter	Value
Minimum internal linear dimensions of the container, mm	250 × 250 × 300
Amplitude of oscillations, mm	0.2
Frequency of oscillations, Hz	50

As a result, the engineering solution will be reduced to the choice of known equipment presented on the finished product market, or the design of a new one. The synthesis of new equipment is complex, and modern production requires maximum versatility from the equipment, which must be taken into account when developing it [15]. The model of the equipment with the necessary parameters is presented in Fig. 5. The dimensions of the inner part of the container are as follows: length 400 mm, width 250 mm, height 350 mm. The working volume of the container is 25 liters, the power of the vibration exciter is 4.5 kW.

The abrasive tool (granules of the working medium), which is used in vibration processing, should be considered as a single solid abrasive element of a certain shape, as well as a set of these single elements. The shape and dimensions of the granules should allow processing the entire surface of the part, for this their dimensions should correspond to the minimum dimensions of the part, and ideally be smaller to ensure the free passage of the abrasive during the processing process.

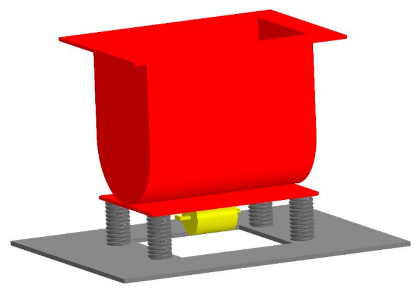


Fig. 5. Model of vibration equipment

The choice of abrasive granule shapes is very large and diverse, and the influence of their geometric parameters on the efficiency of processing plays a key role [16]. According to the authors, the most suitable granules in terms of shape for the developed technology are granules with a large number of faces. Ceramic granules in the shape of a triangular star in cross section, with a height and length of 2 mm, meet these requirements.

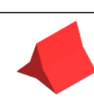
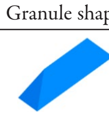
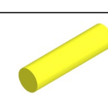
Given that granules in the form of a triangular star are quite difficult to manufacture, and accordingly expensive, it is possible to use more common analogues. High process productivity will be provided by corundum granules in the form of a trihedral beveled prism. The length and height of the granules are 8 mm and 2 mm, respectively. Another option is corundum granules in the form of cylinders, cylinder diameter 2 mm, length 5–8 mm. Cylinder-shaped granules have fewer sharp faces, but will also provide the required result, but for a longer processing period, which is compensated by their low cost.

The characteristics of abrasive granules are presented in Table 3.

Processing in a vibrating container is carried out with the obligatory presence of liquid solutions. When using this method, the supply of various solutions can be carried out in portions. For example, this process can take place in three stages: at the first stage, the processing is carried out with the addition of water for primary cleaning, then a chemical solution is added, and at the final stage, rinsing with water takes place. The use of alkaline solutions based on sodium bicarbonate is recommended as technological solutions.

Table 3

Characteristics of abrasive tools

Characteristics	Granule shape		
			
Material	ceramics	corundum	corundum
Height/diameter, mm	2	2	2
Length, mm	2	8	5–8

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The selected method of processing with free abrasives allows processing flat parts made of thin sheet metal "in bulk", that is, the parts are loaded into the container without fixing, like an abrasive tool. However, with this method of simultaneous loading of a large number of parts, there is a possibility of sticking parts, they can gather in packages, which naturally excludes the processing of the entire surface. It is rational to develop special devices for fixing and positioning parts, which at the same time will ensure the possibility of processing the entire surface of the part, that is, they must maintain the ability to move the part within the specified ranges.

The design of all modern containers, as a rule, provides for the possibility of their division into separate compartments. The number and volume of these compartments can be adjusted depending on the parameters of the processed parts. Deflectors can be located on the separators or they can be covered with abrasive material to increase the intensification of the process. The design of the separator can provide for complete isolation of the separated sections of the container, which allows simultaneous processing of different parts with individual selection of abrasive tools and solutions. Another design option, on the contrary, should ensure the passage of abrasive tools and chemical solutions. In the case of processing of "Rotor Sheet" parts, the need for the passage of abrasive through the partitions is not mandatory, since it is the same for all sections, however, for better washing, it is desirable to ensure the circulation of chemical solutions. To solve this problem, the developed separator, presented in Fig. 6, provides technological openings on both sides and from below.

Fig. 6. Separator with technological holes

The length of the proposed container is 400 mm, for processing the presented part, as already noted earlier, it is necessary to ensure the passage of abrasive tool granules from all sides. In this case, the part must move in limited ranges. Given the thickness of the separators of 3 mm, it is rational to place them at a distance of 25 mm. Thus, using 13 separators, it is possible to obtain 14 sections and, accordingly, it is possible to process 14 parts simultaneously. The placement of the separators and the processed parts is presented in Fig. 7. The use of separators installed at a sufficiently large distance will allow the use of a larger and cheaper abrasive tool, when using a smaller abrasive tool recommended in this article, the distance between the separators can be reduced, thereby increasing the number of processed parts.

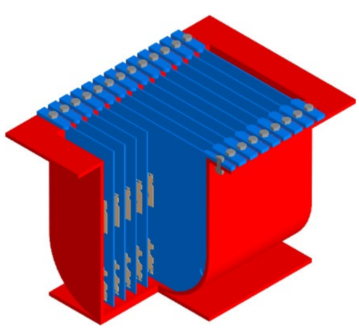
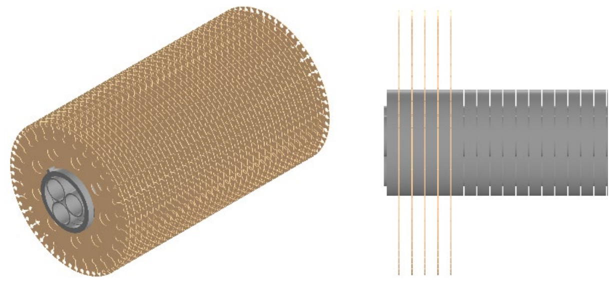


Fig. 7. Placing simultaneously processed parts in separate sections

The device shown in Fig. 8 provides for rigid fixation of the processed parts. The outer diameter of the fixture corresponds to the diameter of the central hole of the processed part, and the dividing rings located between the parts provide a fixed distance between them. The first and last rings are fixed on the fixture, respectively, the parts and the fixture form a rigid structure. Thus, it is possible to obtain "one" large-sized part. It is large-sized relative to the given volume of the machine container. The nature and behavior of large-sized parts during vibration processing are quite well studied, such parts occupy a position in the center of the container and rotate around their axis, as shown in Fig. 9. The developed device allows to simultaneously process 34 parts, as shown in Fig. 10, however, it does not allow processing of part, namely the central hole adjacent to the fixture and part of the surface overlapped by the spacer rings.



a *b*

Fig. 8. Device for simultaneous processing of parts with their rigid fixation: *a* – isometric view; *b* – front view

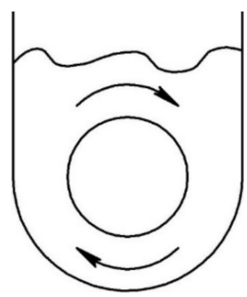


Fig. 9. Character of movement of a large-sized part in the machine tool container

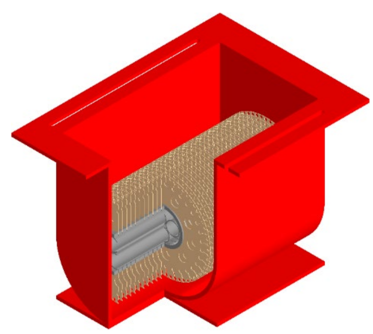


Fig. 10. Model of a device for simultaneous processing of parts with their rigid fixation

To ensure the processing of the entire surface of the part, a device with special separators has been developed, shown in Fig. 11. Due to the design of the special separator, shown in Fig. 12, the part can move in all directions with limited movement while maintaining the general positioning, which ensures access of the abrasive to the entire surface of the part. The separators are rigidly fixed on the pin, and the parts are located between them. The number of simultaneously processed parts in a 25-liter container is 34 units. The holes in the separators also contribute to the free passage of the abrasive, ensuring stable circulation of the working medium and the part being processed, and special protrusions along the outer circumference of the separator additionally position the part. The device and the part can also be considered as "one" large-sized part, and the nature of its movement is shown in Fig. 9.

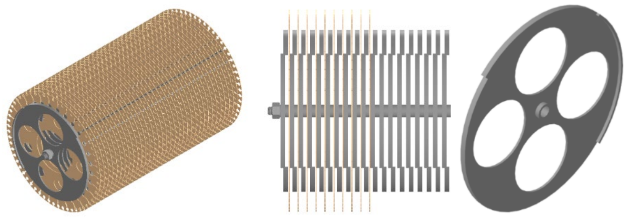


Fig. 11. Model of a device for simultaneous processing of parts with positioning without rigid fixation of parts: *a* – on the fixture (isometric view); *b* – on the fixture (front view); *c* – design of the guide separator of the fixture

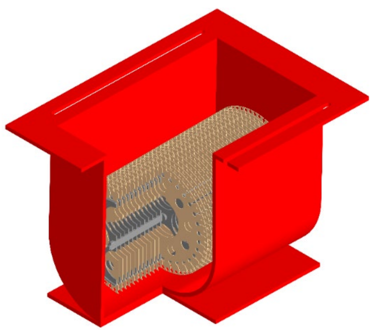


Fig. 12. Model of a device for simultaneous processing of parts with positioning without rigid fixation, placed in a machine tool container

Let's analyze the operational processing time spent on the operation of cleaning parts from dirt, removing burrs and rounding sharp edges using classic manual equipment and using the proposed vibration method of processing with a free abrasive tool.

The operational processing time of one part is calculated as the sum of the main and auxiliary time. The main time is spent on achieving the goal of the technological operation. Auxiliary time includes the time for installing the part, adjusting the equipment and control measurements.

When processing one part using the classic method, the auxiliary time is 2 minutes, and the processing time is from 2.5 to 3 minutes, thus, the operational processing time of one part using manual machines is from 4.5 to 5 minutes. Processing of parts using the vibration method allows to simultaneously process a large number of parts. The equipment presented in this article allows to simultaneously process up to 34 parts. All 34 parts must first be installed on the fixture, so the time for auxiliary operations increases, and for a package of parts it will be 7 minutes. The main processing time is from 25 to 30 minutes, depending on the abrasive tool used and the operating modes of the equipment.

Thus, the processing of 34 parts by the classical method takes from 153 to 170 minutes, and processing with free abrasives takes from 32 to 37 minutes. As a result, the saving of operational time is 78%.

It should be noted separately that after processing by manual machines, an additional final cleaning operation must be performed. Compared to the manual method, vibration processing is carried out with the supply of chemical solutions and allows cleaning of parts at the final stage, thereby eliminating an additional operation and reducing the total processing time.

In the process of the study, the authors did not calculate the metal removal, since the considered technological process does not involve changing the surface roughness class, however, the presented developments allow using a longer processing time to easily achieve such a result.

From the analysis of the part design, as well as the requirements for surface quality, it was established:

– processing of the presented parts requires the development of special technological processes;
– when choosing equipment and a processing method, the key factor is the reduction of the processing time of a batch of parts, which in turn requires ensuring the possibility of simultaneous processing of a large number of parts.

The comparative analysis of processing methods showed:

– the use of classical processing methods with grinding wheels and cloths compared to other considered methods is not rational, since achieving the necessary results takes more time, and simultaneous processing of a large number of parts is complicated and requires the use of complex devices. Processing of the surface of the part occurs at low pressures, which reduces productivity, and the microrelief of the processed surface has an uneven – directional nature;
– processing using tumbling equipment is also not rational, since the considered thin-sheet parts during simultaneous processing can be damaged or deformed due to uncontrolled movement and mutual collisions, both among themselves and when falling and subsequent collision with the walls of the drum;
– jet-abrasive processing methods provide high productivity and allow processing parts of almost any shape and size. However, this processing method imposes increased requirements for ensuring the safety of both the operator and the protection of the environment from the ingress of processing elements and requires a complex and costly waste disposal procedure, which also limits its application;
– the most rational processing method that eliminates the disadvantages of the above, according to the authors, is vibration processing in a vibrating container. However, for effective processing of a group of parts by this method, additional design solutions are required, which are presented in this work.

As a result of the practical application of the developed technological solutions for processing "Rotor Sheet" parts by the proposed method, the following results were obtained:

– equipment was proposed with the selection of the required overall dimensions of the main structural element – the container, which are 400 × 250 × 350 mm; the selection of amplitude-frequency parameters necessary to achieve the desired processing goals on this equipment was made, namely – amplitude 0.2 mm, oscillation frequency 50 Hz;
– as a result of the analysis of the existing abrasive tool, its geometric parameters were selected, options for the abrasive tool necessary for processing parts were proposed – a relatively expensive ceramic one, complex in shape, with a large number of faces and a more common and, accordingly, cheaper tool in the form of corundum cylinders. An average "compromise" option is also presented – corundum granules in the form of a trihedral beveled prism;
– it was established that the processing process requires the phased application of cleaning and active solutions. As active, alkaline solutions based on sodium bicarbonate were selected, which are widespread, have a low cost and do not harm the environment;
– three options for special devices were developed. The first option is special separating partitions with additional holes for the passage of solutions and granules of the working medium. Such a device is simple in design, it is rigidly fixed in the container and does not provide for fixing parts during the processing process, while this option has maximum versatility. The second special device allows to process a larger number of parts and does not require fixing in the container; however, the parts are rigidly fixed on it, which causes the presence of small unprocessed areas. The third device eliminates the disadvantages of the first two. It is structurally the most complex, does not require fixing in the container, allows to simultaneously process the maximum number of parts, and ensures uniform

processing of the entire surface of the part. These advantages are achieved due to the fact that during the processing the developed design allows the part to move limitedly relative to the device in all directions. This device, according to the authors, is the most rational for use and allows to achieve maximum process productivity.

Thus, the results obtained during the research differ from the existing ones in that:

1. The vibration method of processing in the environment of free abrasives is quite productive and economically feasible in conditions of multi-series and mass production [14, 16]. But it is oriented more towards the processing of rigid or thick-walled parts, while the study presents an effective solution specifically for thin-sheet parts that are easily deformed. The proposed design solutions allow simultaneous processing of up to 34 parts, which is not typical for classical approaches, where individual or small-batch processing prevails when processing parts made of thin-sheet material.

2. When solving the problem of choosing equipment, instead of using standard containers or fixation systems, three types of special structures were proposed, one of which provides partial freedom of movement of parts in the process, which allows achieving full contact with the abrasive over the entire surface. This eliminated the main problem – sticking and shading of parts of the surface during vibration processing "in bulk".

3. The proposed method provides savings of up to 78% of operational time compared to classical manual processing, which is a significant step forward in increasing the productivity of technological processes for processing parts made of thin-sheet material.

4. Reasoned recommendations are given regarding the choice of granule geometry (triangular star, trihedral prism, cylinder) depending on the budget, type of processing and number of parts, which is usually not detailed in most sources.

These engineering solutions comprehensively take into account economic feasibility, versatility and technological efficiency, which favorably distinguishes the work from known analogues.

The practical significance of the research results, which is not presented in the article, lies in the development of an effective method for vibration processing of thin-sheet parts in an oscillating container using special devices. Recommendations are provided for the selection of operating modes of vibrating machines, abrasive tools and active solutions that can be used at mechanical engineering and instrument-making enterprises to increase the productivity and quality of processing of thin sheet metal products in conditions of mass production.

The limitations of research are the need to refine the designs of devices for specific standard sizes of parts and derive optimal processing modes for different materials, which requires additional experimental studies.

The prospects for further research include improving the designs of equipment for process automation, as well as expanding the application of the method to processing parts from other materials and complex geometric shapes.

4. Conclusions

As a research result, the features of vibration finishing of thin-sheet flat parts of the "Rotor Sheet" type were determined, in particular, the influence of the designs of the devices, the type and shape of the abrasive tool, as well as the operating modes of the machine tool (the amplitude of the container oscillations is 0.2 mm and the frequency is 50 Hz) on the uniformity of surface treatment without deformation of the parts was established.

Three design options for special devices for placing parts in a vibration container were proposed, of which the most effective was the device with partial freedom of movement of the part. This solution provides uniform access of the abrasive medium to the entire surface of the part and allows to avoid the sticking effect, which is a characteristic drawback of classical methods of vibration processing "in bulk".

The patterns of the influence of design and technological parameters on the quality of processing of a group of thin-sheet parts processed in large quantities (34 units) simultaneously were determined. In particular, it was established that the use of an abrasive tool in the form of a trihedral prism provides the optimal ratio between the intensity of processing and protection of parts from damage.

The practical significance of the results lies in substantiating the choice of effective operating modes of vibration equipment, active alkaline solutions (based on sodium bicarbonate) and device designs that can be used for automated processing of up to 34 parts simultaneously. This allows reducing processing time by 78% compared to manual processing, while maintaining high surface quality.

The results obtained have the potential for implementation at mechanical engineering enterprises, in particular in the railway industry, where it is necessary to process a large number of thin-sheet parts in conditions of multi-series and mass production. The use of the proposed solutions ensures increased technological controllability of the process, reduced labor intensity of operations and resource savings.

The experiments conducted confirm the stability of the achieved quality indicators – the absence of burrs, rounding of sharp edges and uniform cleaning, which is critically important for the further operation of parts in electric motors of rolling stock.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Use of artificial intelligence

The authors confirm that they did not use artificial technologies intelligence when creating the presented work.

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