CIRCULAR ECONOMY PRINCIPLES IN MODELING AND PRODUCTION OF THE "HYDRAULIC CYLINDER HEAD" PART

Lappeenranta–Lahti University of Technology LUT

Master's thesis

2022

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Master's thesis

for the Joint Study Programme
"International Master of Science in Engineering, Entrepreneurship and Resources"
(MSc. ENTER)

TOPIC: Circular economy principles in modeling and production of the "hydraulic cylinder head" part

edited by: Karpov Anatolii

for the purpose of obtaining one academic degree (triple degree) with three diploma certificates

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Handover of the topic: 09.07.2022

Deadline of the master's thesis: 09.12.2022

Place, date: Freiberg,08.12.2022

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Supported by

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

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ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Engineering Science

Mechanical Engineering (MSc. ENTER programme)

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Master's thesis

2022 year

68 pages, 10 figures, 12 tables and 1 appendix

Examiners: Adj. Professor Arto Laari, Associate Professor Serhii Patsera and Professor Henning Zeidler

Keywords: CIRCULAR ECONOMY, TITANIUM ALLOY, MECHANICAL

PROCESSING, CHIPS, RECYCLING.

The purpose of this work is a comprehensive analysis of the course of processes in the technological cycle of production and use of titanium alloys, by-products and production waste, taking into account the principles of the circular economy.

The result of the thesis is an algorithmic block diagram of titanium recycling, which was created during the work.

The scientific novelty of the qualification work is characterized by the fact that for the first time a block diagram of the algorithmic model of titanium recycling was proposed, covering all industries where titanium and titanium alloys are used.

The practical value of the work is that an algorithmic block diagram allows one to create a computer program for analyzing the results of monitoring of existing enterprises that use titanium and titanium alloys. In addition, such a program will allow to perform automated prognostic studies of recycling. This will further allow to expand the understanding of titanium waste recycling processes and to propose ways to reduce the cost of finished products and create new products from usable waste. The results will also allow to reduce dependence on politically unstable countries (most titanium deposits are located in them) which is risky for the industry, to reduce the need for waste disposal, as well as to reduce the need for greater extraction of this resource from the depths of the Earth. This will speed up the implementation of circular economy principles.

Content

INTRODUCTION

Titanium is an extremely important material in mechanical engineering.

It is of greatest interest as an alloy. The modern alloy has excellent properties. The main quality indicators of titanium are its high strength, resistance to extreme temperatures, and lightness, like that for aluminum. Despite the difficulties in processing, the material is very necessary in many types of production and industry. It is used in the space industry and defense industry, in production of building materials, household items, medical devices, and for the production of machine parts and mechanisms.

In connection with the global trend of metallurgy development based on secondary raw materials, titanium waste acquires special importance. Maximally complete and rational use of waste is one of the priority ways to reduce the price of titanium products.

The use of secondary titanium resources (above all shavings) is important. Titanium recycling is the main source of effective formation of the titanium metal pool, as a result of machining, most of the work pieces become waste, which is a big problem in waste disposal and negatively affects the final cost of the product.

It is also important to pay attention to the technological process, since the utilization rate of the material depends on the method of production of the part.

Properly designed technological processes for the manufacture of products, control of qualitative and quantitative indicators of manufactured products, checking the operability, timely carrying out of appropriate work to eliminate emerging defects and the creation of normal operating conditions – all these are measures to increase the durability of products and the reliability of their work.

The main directions in the design of technological processes are:

- improving the quality characteristics of materials, stabilizing and reducing their consumption through the use of progressive methods of obtaining workpieces; increasing the level of completeness of process mechanization through the use of modern equipment: CNC machines, automatic machines and semiautomatic devices, the use of high-performance types of technological equipment, in order to reduce the complexity of manufacturing parts and the product as a whole.
- improvement of control and testing works and rational organization of production.
- maximum possible ensuring the continuity, safety, flexibility and productivity of the process, which can be ensured as a result of improving the level of mechanization and automation;

These measures can significantly increase the quantity and range of products, improve its quality, at relatively low cost. Improving the technological process of processing products should lead to an increase in the quality of the product, a decrease in the cost of production, etc. The development of Ukraine's economy is possible only with the implementation of high-tech and resource-saving production, capable of ensuring the development and implementation of competitive products of a new generation in a short time, focused on meeting demands, internal and external (priority due to the fall of the economy and GDP within the country and the destruction of a large number of industrial enterprises (Azovstal as an example of a lost giant enterprise of the industry in Ukraine’s markets)). It is also important to focus on the resources that already exist (machines, control and measuring machines, etc.) because the probability of investment in the next 5-7 years is very low (especially foreign investments).

It is also necessary to try to take into account the principle of a circular economy in production. The most effective way to do this is to find a rational, efficient and cost-effective way to recycle waste and reduce the consumption of materials for the production of the part. while it is desirable to find recycling methods for waste at different stages of production.

The purpose of this work is to find and analyze the possibilities of using titanium chips and waste titanium in production and in mechanical engineering in general. The result is that an algorithmic flow chart has been created that can be used to improve titanium processing.

1 ANALYTICAL SECTION

In the analytical section, we will consider the specific part, its purpose in the design, material, its chemical and physical properties, chemical composition, as well as the manufacturability of the part.

1.1 Technical analysis of the initial data of the project

The initial data for the development of technological processes are the working drawings of a specific head of hydraulic cylinder, technical requirements for the products, release program, and other materials.

1.1.1 Service purpose of the product

The considered part of the "head" is included in the assembly of the shock absorber of the landing gear of the AIRCRAFT AN 148. The landing gear absorbs the load during landing and allows you to control taxiing and braking when the aircraft is moving on the ground. A shock absorber is a device that converts mechanical energy into thermal energy. It serves to dampen vibrations and absorb shocks and shocks acting on the frame. Its task, as well as the task of the entire chassis design, is to mitigate overload when in contact with the runway coating on landing, so that the load on the components of the aircraft does not exceed the permissible when performing a regular landing, and also so that in emergency cases it is possible to carry out a safe landing for people when exceeding the maximum landing mass up to the maximum take-off.

Because of this, strict requirements are put forward to this node. First of all, it is rigidity, high strength and lightness, because excess weight adversely affects the flight characteristics of the aircraft. Greater weight causes greater fuel consumption and lower economic efficiency which is a fundamental indicator for aircraft.

1.2 Analysis of the manufacturability of the hydraulic cylinder head design

Analysis of the manufacturability of the design of parts can be reduced to the study of the possibilities of reducing labor intensity and material consumption, reducing costs, processing it with high-performance methods without compromising service use and maintainability. The manufacturability of the design largely depends on the scale of production and the type of production.

Manufacturability is determined by the measure of compliance of the design of the part with the conditions of its manufacture. GOST 2.121-73 provides for a qualitative and quantitative assessment of the manufacturability of the structure. GOST refers to a set of international technical standards maintained by the Euro-Asian Council for Standardization, Metrology and

Certification (EASC), a regional standards organization operating under the auspices of the Commonwealth of Independent States (CIS).

All sorts of regulated standards are included, with examples ranging from charting rules for design documentation to recipes and nutritional facts of Soviet-era brand names. The latter have become generic, but may only be sold under the label if the technical standard is followed, or renamed if they are reformulated.

The specified part belongs to the parts of the class "Not round rods". The head is made of titanium alloy of high strength VT22 (GOST 19807-91) Temporary resistance $\left(\sigma_B = 1078...1274 MPa\right)$. The machinability of titanium alloys is characterized by low ductility, high chemical activity during cutting and low thermal conductivity. The chemical composition of VT-22 in Table 1.1 according to GOST 19807-91.

Table 1.1- Chemical composition of VT-22

brand	Mass fraction of chemical elements, %						
	Titanium	Aluminum	Vanadium	Molybdenum	Tin	Zirconium	Niobium
VT22	Main component	4,4-5,7	4,0-5,5	4,0-5,5	-	0,30	-

Continuation of the table 1.1

Mass fraction of chemical elements, %								
Manganese	Chromium	Silicon	Iron	Oxygen	Hydrogen	Nitrogen	carbon	sum of other impurities
-	0,5-1,5	0,15	0,5-1,5	0,18	0,015	0,05	0,1	0,30

Table 1.2 - Mechanical properties of VT-22 according to GOST 26492-85

Alloy grade	Condition of tested samples	Bar diameter,mm	Temporary resistance σ_B, MPa (kgf/mm^2)	Relative elongation δ, %	Relative narrowing ψ, %	Impact strength KCU*, J/cm^2 (kgf·m/cm^2)
			not less			
VT22	Annealed	From 10 to 12 included	1080-1230 (110-125)	10	30	-
		More than 12 to 35	1080-1230 (110-125)	10	30	30 (3)

		included				
		More than 35 to 60 included	1080-1230 (110-125)	9	25	30 (3)
		More than 60 to 100 included	1080-1280 (110-130)	8	18	25 (2,5)
		More than 100 to 150 included	1080-1280 (110-130)	7	17	25 (2,5)
	Hardened and aged	From 10 to 12 included	Not less than 1280 (130)	7	18	-
		More than 12 to 40 included.		7	18	20 (2)
		More than 12 to 40 included				
		More than 40 to 60 included		6	16	18 (1,8)

* KCU, KC – impact strength symbol, the third symbol shows the type of cut: sharp (V), with a radius of curvature (U), crack (T)

The properties of titanium are described in reference. [1]

Titanium exists in two modifications: up to a temperature of 880 ± 20 ° it is in the form of an alpha phase and has a hexagonal crystal lattice. At higher temperatures, titanium transforms into the beta phase, which has a body-centered cube lattice.

The addition of different elements affects the transition temperature of the alpha phase titanium into the beta phase in different ways. Some elements, called alpha phase stabilizers, contribute to an increase in the temperature of the transition of the alpha phase into the beta phase, other elements, called beta phase stabilizers, help reduce the temperature of the transition of the alpha phase into the beta phase. In addition, there are elements that reduce the temperature of transition of the alpha phase into the beta phase, but titanium alloys with these elements, having reached a certain, so-called eutectoid, temperature, undergo transformations during further cooling, at which the beta phase completely disintegrates, forming an alpha phase and an intermediate gamma phase enriched with an alloying element.[1]

According to the effect on titanium polymorphism, all alloying elements are divided into three groups: a-stabilizers, b-stabilizers and neutral elements. a-stabilizers (Al, O, N) increase the temperature of the polymorphic transformation, expanding the region of solid solutions based on Tia. Only aluminum is of practical importance for doping titanium, since others cause a decrease in the ductility and viscosity of titanium alloys.[2] Aluminum reduces density and susceptibility to hydrogen brittleness, increases strength, heat resistance, modulus of elasticity of titanium alloys.

b-stabilizers reduce the temperature of the polymorphic transformation of titanium, expanding the area of solid solutions based on Tig. They form two types of state diagrams with titanium. Isomorphic b-stabilizers Mo, V, Ta, Nb, having, like Ti, crystalline lattices of a volume-centered cube, dissolve unlimitedly in Ti. Sg, Mn, Fe, Ni, W, C and others form graphs of a state with eutectoid decay with titanium. In some alloys (Ti-Mn, Ti-Cr, Ti-Fe) when cooled in conditions different from equilibrium, eutectoid decay does not occur, and the transformation goes along a dash line. Most b-stabilizers, especially V, Mo, Mn, Sg, increase strength at 20-25 ° C and sub-zero temperatures, heat resistance and thermal stability of titanium alloys, slightly reducing their ductility. Neutral elements (Sn, Zr, Hf) have little effect on the temperature of the polymorphic transformation. Tin and zirconium are of the greatest practical importance. Tin strengthens titanium metals without a noticeable decrease in ductility, increases heat resistance; Zirconium increases creep limit and long-term strength.

According to the manufacturing technology, titanium alloys are divided into deformed, casting and powdered. By mechanical properties, the alloys can be divided for alloys of normal strength, high-strength, heat-resistant, increased ductility. According to the ability to strengthen by heat treatment, they are divided into those that are strengthened and not strengthened by heat treatment. Based on the structure in the annealed state, they are classified into a-, pseudo-a, a + c, pseudo-b and b-alloys.[2]

Transition class alloys contain more alloying elements and more B-phases (25–50%) in the equilibrium structure than martensitic class alloys. The structure of these alloys is sensitive to fluctuations in the chemical composition and heat treatment modes. So, after quenching in these alloys, it is possible to obtain a single-phase structure of the supercooled B-phase or a structure consisting of this phase and martensite a". The presence of a large number of B-phases provides transition-class alloys with the highest strength among (a + B)alloys. For example , the VT22 alloy (50% of the B-phase) has after annealing the same time resistance as the VT6 alloy after quenching and aging.

Two-phase alloys are satisfactorily cut and welded. After welding, annealing is required to increase the ductility of the weld. They are less susceptible to hydrogen brittleness than a-and pseudo-a-alloys, since hydrogen has a greater solubility in the B-phase. Two-phase alloys are forged, stamped and dug more easily than alloys with an a-structure. They are supplied in the form of forgings, stamps (used to produce a workpiece for that part), bars, sheets, tape.

The high chemical activity of titanium alloys during cutting contributes to the absorption of oxygen and nitrogen from the air, the activity of which increases with increasing temperature in the cutting zone. This contributes to increased oxidation and gives the material brittleness. The low thermal conductivity of titanium alloys contributes to the occurrence of temperatures in the cutting zone on average 2.2 times higher than in the processing of steel 45.(according to GOST 1050-88: steel - alloy is unalloyed carbon ordinary; 45- carbon content in steel within 0.45%) Therefore, when processing titanium alloys, the use of lubricating and cooling process fluid (cutting fluid) is recommended.

The configuration of the part provides free access to cutting and measuring tools. The design has sufficient rigidity (l/d = 156/128 = 1.22<12), which involves the use of high cutting modes. However, when processing titanium alloys, it is not recommended to prescribe a feed for a revolution of less than 0.08 mm, work with a tool with a wear of more than 0.8-1 mm and cutting speeds of more than 100 m/min.

As technological bases, it is advisable to use the outer cylindrical surface and the end of the head processed in the first operation. In the latest operations, it is advisable to use machined holes as technological bases. The dimensions in the drawing are affixed correctly, fully and conveniently for control. Surface roughness corresponds to machining accuracy.

The non-technological element of the "head" part is the process on the conical surface. In general, the detail is technological.

2 TECHNOLOGICAL SECTION

In the technological section, the technological process is defined for the production of the part.

2.1 Determination of the type of production

The type of production depends on the annual program, the characteristics of the products, and the complexity of manufacturing parts. The annual production program is 90 products.
In this case we have small-scale production. It is characterized by the manufacture of a limited range of products in batches (series), repeated at regular intervals, and a wide specialization of jobs.

The equations to calculate production are presented by Kosilova [3]
The cycle of release is determined by the formula:

$$\tau = \frac{60 \cdot F\text{d}}{\text{N}}, \tag{1.7}$$

where F_{d} valid annual fund of equipment time, hours, $F_{\text{д}} = 4060$ h;
N annual program for the production of parts, pcs.

$$\tau = \frac{60 \cdot 4060}{90} = 2707 \text{ min for head;}$$

The coefficient of seriality Ks is determined by the formula:

$$K_c = \frac{\tau}{T_{p.av}} \tag{1.8}$$

where $T_{part\ averaqge}$. the average time for one piece for the main operations on the site, determined by the formula:

$$T_{part.average} = \frac{\sum_{i=1}^{н} T_{part.i}}{\sum n} \tag{1.9}$$

where $T_{part\ averaqge}$ artificial time of the i-th operation;
n number of main operations of the technological process.

$$T_{\text{pieces average including "heads"}} = 543{,}67/8 = 67{,}96 \text{ min;}$$

$$K_{\text{including heads"}} = 2707/67{,}96 = 39{,}83;$$

If the coefficient of seriality meets the condition of 20 < Ks < 40, then the type of production is small-scale. Since in our case Ks = 39.83, the type of production is small-scale. Small-scale production is characterized by the lack of continuity and stability in the nomenclature of homogeneous products; large range of products; lack of fixing operations on a specific machine. This type of production is characterized by a non-current production method [3], that is, the equipment is located on the principle of uniformity of processing (turning section, milling section, etc.) or in a sequence of technological operations for one or more parts. Parts are processed in batches, the time for performing operations on some machines is not agreed with the time of operation on others and the parts during operation are stored near the machines, and then transported in a whole batch. The location of the equipment is accepted by the design section of the workshop. Therefore, we determine the size of the batch of parts that are put into production. The batch size of parts is determined by the formula:

$$n = \frac{N \cdot f}{\Phi} \tag{1.10}$$

where N annual program of production of products in pieces;

f the number of days when it is necessary to have a supply of warehouse parts, $f = 24$ Days;

Φ – number of working days per year in Ukraine (until 24.02.2022), $\Phi = 253$.

$$n = \frac{90 \cdot 24}{253} = 8{,}54 \text{ piece.}$$

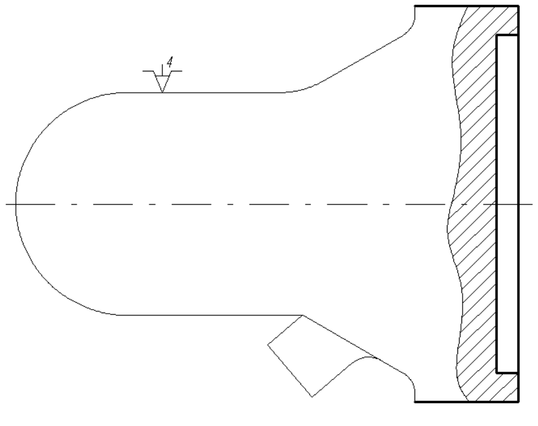
We accept the batch of launching parts into production n = 10 pcs.

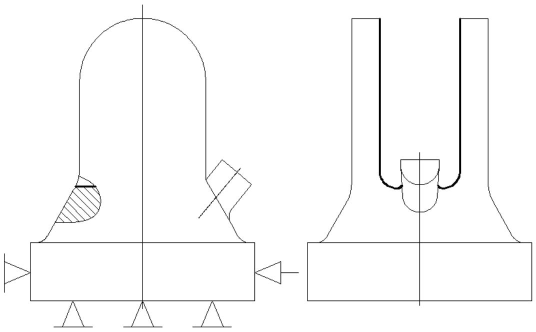
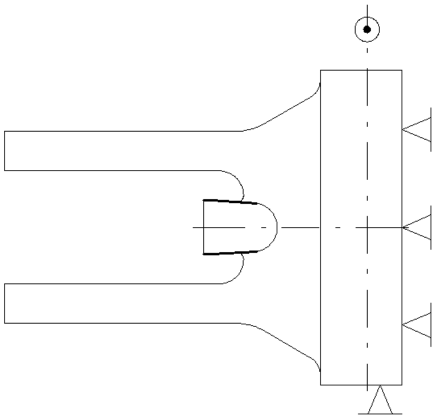
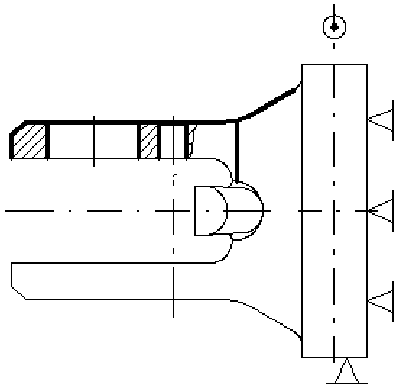
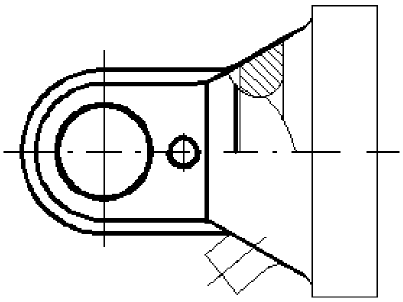
In this workshop we accept one-station maintenance of equipment. For transportation of parts in the areas we use handcarts.

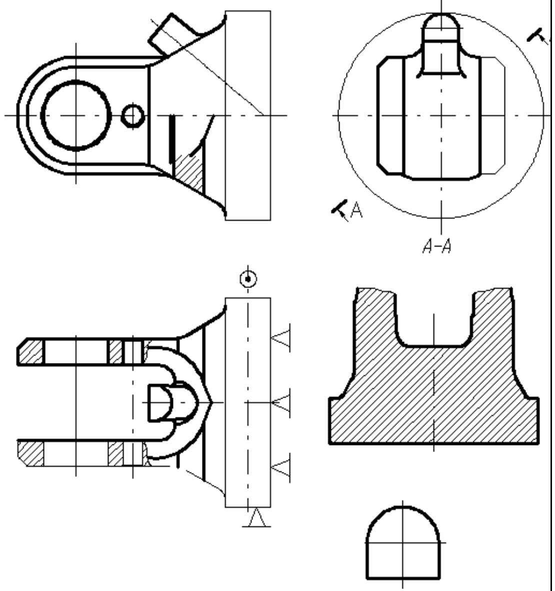
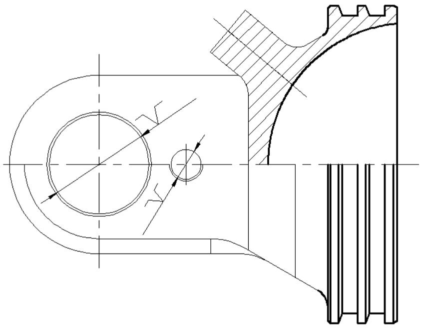
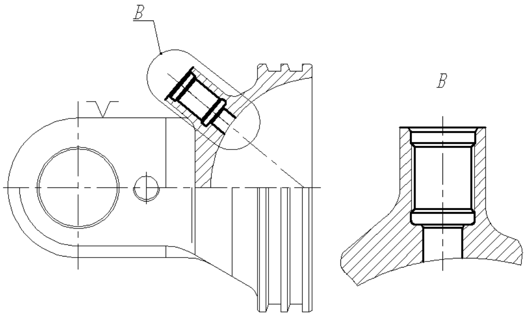
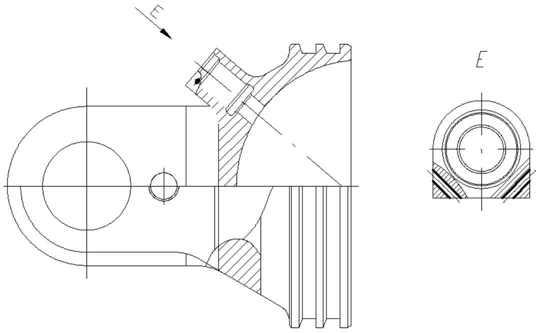
2.2 Analysis of technological processes of the base plant

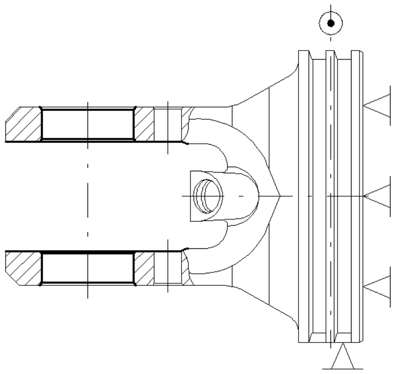
Basic technological processes for the manufacture of the head are presented in the form of Tables 2.2. The route technical process for manufacturing the head of the base plant is also shown in Table 2.2.

Table 2.2 – Route technical process of the base head processing plant

№ Operation	Name of operation	Scheme of installation of the workpiece on the machine	Name and model of equipment
010	Turning		Turning and screw-cutting machine 16К20

№ Operation	Name of operation	Scheme of installation of the workpiece on the machine	Name and model of equipment
015	Milling-drilling		CNC milling and drilling machine VMC-2060
020	Milling-drilling		CNC milling and drilling machine VMC-2060
025	Milling-drilling	 	CNC milling and drilling machine VMC-2060
030	Milling-drilling		CNC milling and drilling machine

№ Operation	Name of operation	Scheme of installation of the workpiece on the machine	Name and model of equipment
			VMC-2060
035	Turning		CNC Lathe MDW-10F
040	Turning		CNC Lathe MDW-10F
045	Drilling		Vertical drilling machine 2H125

№ Operation	Name of operation	Scheme of installation of the workpiece on the machine	Name and model of equipment
050	Milling-drilling - boring		CNC milling and drilling machine VMC-2060

2.3 Proposals for improving factory technical processes

In the basic technological process, one can make some changes regarding the workpieces. For the manufacture of the head, it is rational to use the stamping workpiece on horizontal forging machines (HFM), which will significantly increase the utilization rate of the material, as well as reduce the number of operations and reduce the complexity of manufacturing parts.

In the manufacture of the head, thanks to a more accurate workpiece, there is no need to remove a large layer of material during processing. Also, the use of special devices can be added to the basic technological process, while reducing the cost of manufacturing equipment.

To reduce the manufacture of defective parts, it is necessary to introduce into the technological process timely control of sharpening of the cutting tool or timely replacement of the cutting plate and strengthen the quality control of the blanks, since the quality of the workpiece affects the percentage of the production defect (the presence of sinks, adhesions of the material, etc.). In addition, in the basic technical process it is necessary to introduce a complete replacement of the CUTTING FLUID Brand Ukrinol-1M [45] with Blasocut 4000 Strong [44]. The cost of CUTTING FLUID Blasocut 4000 Strong, although three times higher compared to CUTTING FLUID Ukrinol-1M, but its term of use in the work is two years, in contrast to CUTTING FLUID Ukrinol-1M – two months. In addition, cutting FLUID Blasocut 4000 Strong showed the best results in the processing of titanium alloys.

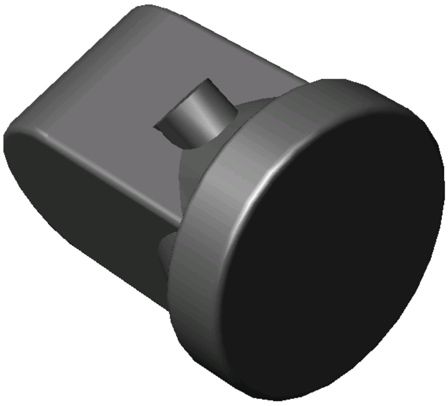
2.4 Design of technological processes

2.4.1 Selection of the method of obtaining workpiece

The choice of the method of obtaining the workpiece details "Head ”

When choosing the technological process of obtaining the workpiece and the method of its formation, it is necessary to take into account a number of factors given in the [3].

In the basic technological process, the head is made by stamping from titanium metal VT22. A 3D model of the basic version of the head workpiece, its volume and weight are shown in Fig. 2.1.



V_w-volume of workpiece; m_w -mass of workpiece

$$V_w=1,45*10^{\wedge}(-3)\ m^3;$$

$$m_w= V_w *\rho = 1,45*10^{\wedge}(-3)\ m^3 * 4500\ \text{кg}/m^3 = 6,53\ \text{кg}.$$

Figure 2.1 three-dimensional model of the basic version of the workpiece "Head".

In accordance with the requirements of the drawing and as a result of the analysis of the design of the part, we come to the conclusion that the workpiece can be obtained by stamping on horizontal forging machines (HFM).

The choice of a rational method of obtaining procurement is determined taking into account the technical and economic feasibility. However, with an increase in the volume of production, the efficiency of material use and the reduction of the complexity of machining are of particular importance.

To calculate the size of forging, it is necessary to determine the initial index according to GOST 7505-89. Its definition depends on the calculated forging mass of the MPR, steel grade M1-M3, the degree of complexity C1-C4 according to GOST 7505-89 and the accuracy class of forging.

Estimated forging mass $M_{ПР}$ determined based on the mass of the part $m_д$ (кg) taking into account the calculated coefficient K_p from the equation

$$\text{М}_{\text{ПР}} = \text{m}_\text{p} \times \text{К}_\text{p} \qquad (2.1)$$

Calculated coefficient K_p [3] for group 2,3 - parts with with branches is 1,4 -1,6.

Accept K_p = 1,6.

Then the estimated forging mass is:

$$M_{ПР} = 1,77 \times 1,6 = 2,832\ \text{кg}.$$

Determine the steel group.

With a total mass fraction of alloyed elements above 5%, the VT22 alloy belongs to the M3 group. The degree of complexity is determined by the method of calculating the mass (volume) Gв forgings to mass (volume) GФ geometric figure, in which the shape of the forging fits. For a given part, such a geometric figure is a cylinder.

Forging volume

$$G_П = M_{ПР} : \rho = 2,832 : 4500 = 0,000629\ m^3.$$

The volume of the geometric figure into which the forging shape fits is allowed to increase by 1.05 times relative to the linear overall dimensions of the part, determining the position of its treated surfaces. The overall dimensions of the part and the dimensions of the figure are recorded in Table 2.3.

Table 2.3- Overall dimensions of the part and dimensions of the figure.

Dimensions of the part		**Dimensions of the figure**	
Maximum diameter, mm	*Maximum length, mm*	Maximum diameter, mm	*Maximum length, mm*
128	156	134,4	163,8

Determine the volume of the cylinder shape

$$G_Ф = \frac{\pi d^2_{\max ф}}{4} \cdot L_{\max ф} = \frac{3{,}14 \cdot 0{,}1344^2}{4} \cdot 0{,}1638 = 0{,}00232\,\mathrm{m}^3.$$

Then $G_П / G_Ф = 0,00063 / 0,00232 = 0,272$

Since the ratio of $G_П / G_Ф$ is from 0,16 to 0,32, the degree of difficulty of forging is C3.

The results of the calculations are recorded in Table 2.4.

Table 2.4 - Calculation results

Calculated coefficient K_p	Estimated forging weight $M_{ПР}$, к’	Forging volume $G_П$, m^3	The volume of the geometric figure $G_Ф$, m^3	Ratio $G_П / G_Ф$
1,6	2,832	0,00063	0,00232	0,272

It is accepted that obtaining a forging on HFM meets such conditions with the accuracy class T5. The initial index for the further assignment of the main assumptions is determined using [3]: initial index – 16.

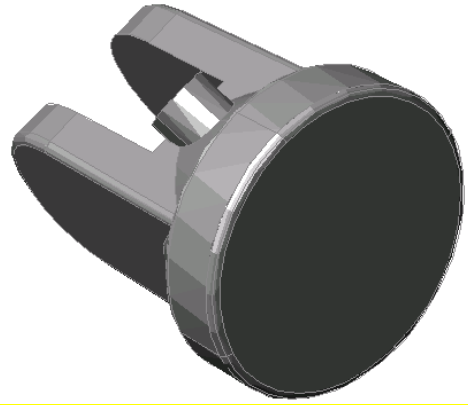
The allowances are deterimend for machining (on the side) of forgings according to GOST 7505-89, depending on the initial index, linear dimensions and roughness of the surface of the part using [3]. Selected allowances and calculated dimensions of the forging are recorded in Table 2.5.

Table 2.5 - Allowances and estimated dimensions of the forging.

Nominal dimensions of the part mm	Tolerance and deviation of forging allowed, mm		Allowance for machining (to the side), mm	Full allowance value, mm	Nominal forging size, mm
∅128	4,0	+2,7 -1,3	3,0	6,0	∅134,0
∅111	4,0	+2,7 -1,3	2,7	5,4	∅116,4
33	3,2	+2,2 -1,2	2,3	4,6	37,6
78	3,6	+2,4 -1,2	2,5	5,0	83,0
48	3,6	+2,4 -1,2	2,5	5,0	43,0
60	3,6	+2,4 -1,2	2,5	2,5	57,5
125	4,0	+2,7 -1,3	2,7	2,7	127,7
R36	3,2	+2,1 -1,1	2,3	2,3	R38,3
22	3,2	+2,2 -1,2	2,3	4,6	26,6
R11	3,2	+2,2 -1,2	2,3	2,3	R13,3
73	3,6	+2,4 -1,2	2,3	2,3	75,3

On A2 paper, a technical sketch is carried out of the design version of the forging.

A 3D forging model is performed in a graphic editor and determine the volume:



V_w *-volume of workpiece;* m_w *-mass of workpiece*

$V_w = 1,09 * 10\text{^}(-3)\ m^3$;

$m_w = V_w * \rho = 4,905\ kg$

Figure 2.2. 3D model of the design version of the forging part "Head"

Let's compare the coefficients of material use for both methods:

- for workpiece forging the design version

$$К_{B.T.1} = 1,77 / 4,905 = 0,361;$$

- for workpiece forging the basic version

$$К_{B.T.2} = 1,77 / 6,21 = 0,285.$$

From the comparison of the values of KV.T.1 and KV.T.2, we come to the conclusion that the first method is more rational, we accept it.

2.4.2 Determination of the sequence of execution of technological operations

The totality of technological operations is the processing route. To draw up a processing route, we establish a plan for processing the main surfaces of the part (see Table 2.1; 2.2). The number of steps and methods of processing the main surfaces of parts are given taking into account the reference book [3].

Table 2.6 - Plan for processing the main surfaces of the head

Part surface	Drawing requirements for the surface		Post-treatment surface settings		
	Accuracy	Rough-ness Ra	Technological transitions (operations)	Accuracy	Rough-ness Ra
∅128f7	$\varnothing 128^{-0,043}_{-0,083}$	$R_a0,8$	workpiece Turning rough Turning finishing Sharpening (diamond)	h14 h13 h10 f7	R_a25 $R_a12,5$ $R_a3,2$ $R_a0,8$
∅40H7 (2Holes)	$\varnothing 40^{+0,025}$	$R_a0,8$	workpiece Centering Drilling Defrausering	H14 H12 H10	R_a25 $R_a12,5$ $R_a3,2$

Part surface	Drawing requirements for the surface		Post-treatment surface settings		
	Accuracy	Rough-ness Ra	Technological transitions (operations)	Accuracy	Rough-ness Ra
			Rolling	H7	$R_a0,8$
$\varnothing120h8$	$\varnothing120_{-0,054}$	$R_a0,8$	workpiece Turning rough Turning finishing Sharpening (diamond)	h14 h13 h10 h8	R_a25 $R_a12,5$ $R_a3,2$ $R_a0,8$
$\varnothing12H9$ (2 Holes)	$\varnothing12^{+0,043}$	$R_a1,6$	workpiece Drilling Zenkering reaming	H14 H12 H10 H8	R_a25 $R_a12,5$ $R_a3,2$ $R_a1,6$
$\varnothing10H9$	$\varnothing10^{+0,036}$	$R_a1,6$	workpiece Drilling Zenkering reaming	H14 H12 H10 H8	R_a25 $R_a12,5$ $R_a3,2$ $R_a1,6$
48H9	$48^{+0,062}$	$R_a1,6$	workpiece Rough milling Finishing milling	H14 H13 H9	R_a25 $R_a12,5$ $R_a1,6$
$\varnothing16,5H11$	$\varnothing16,5^{+0,11}$	$R_a0,8$	workpiece Drilling Finishing boring	H14 H12 H9	R_a25 $R_a12,5$ $R_a0,8$
6,2H12	$6,2^{+0,15}$	$R_a0,8$	workpiece Turning rough Turning finishing	H14 H13 H10	R_a25 $R_a6,3$ $R_a0,8$
$\varnothing17,8^{+0,3}$	$\varnothing17,8^{+0,3}$	$R_a0,8$	workpiece Drilling Finishing boring	H14 H12 H9	R_a25 $R_a12,5$ $R_a0,8$
$\varnothing16,3^{+0,5}$	$\varnothing16,3^{+0,5}$	$R_a3,2$	workpiece Drilling Finishing boring	H14 H12 H9	R_a25 $R_a12,5$ $R_a3,2$
$\varnothing11^{+0,5}$	$\varnothing11^{+0,5}$	$R_a1,6$	workpiece Drilling Finishing boring	H14 H12 H9	R_a25 $R_a12,5$ $R_a1,6$
MR16×1,5-5H6H	MR16×1,5-5H6H	$R_a3,2$	Workpiece Drilling Thread cutting	H14 H12 H6	R_a25 $R_a12,5$ $R_a3,2$
78h14	$78_{-0,74}$	$R_a3,2$	Workpiece Rough milling Finishing milling	h14 h13 h10	R_a25 $R_a12,5$ $R_a3,2$
6×45°h14	6±0,3×45°±1°	$R_a3,2$	Workpiece Rough milling Finishing milling	h14 h13 h10	R_a25 $R_a12,5$ $R_a3,2$
22±0,5	22±0,5	$R_a3,2$	Workpiece Rough milling Finishing milling	h14 h13 h10	R_a25 $R_a12,5$ $R_a3,2$
R11h14	R11±0,5	$R_a3,2$	Workpiece Rough milling Finishing milling	h14 h13 h10	R_a25 $R_a12,5$ $R_a3,2$

Part surface	Drawing requirements for the surface		Post-treatment surface settings		
	Accuracy	Rough-ness Ra	Technological transitions (operations)	Accuracy	Rough-ness Ra
$R36^{+1}_{-0,3}$	$R36^{+1}_{-0,3}$	$R_a3,2$	Workpiece Rough milling Finishing milling	h14 h13 h10	R_a25 $R_a12,5$ $R_a3,2$
Field $R57^{+0,3}_{-0,6}$	Field $R57^{+0,3}_{-0,6}$	$R_a3,2$	workpiece Turning rough Turning finishing	H14 H13 H10	R_a25 $R_a12,5$ $R_a3,2$
∅111h14	$\varnothing 111_{-0,84}$	$R_a3,2$	workpiece Milling disposable	h14 h12	R_a25 $R_a3,2$
∅98±1	∅98±1	$R_a3,2$	workpiece Turning rough Turning finishing	h14 h13 h10	R_a25 $R_a12,5$ $R_a3,2$
∅1,8H14	$\varnothing 1,8^{+0,25}$	$R_a3,2$	workpiece Drilling	H14 H12	R_a25 $R_a3,2$

In accordance with the accepted processing plan, a route technological process and route maps are drawn, in accordance with GOST 3.1105-74 (See. Appendix A, B). The accepted equipment is entered in the corresponding graphs of the route map.

2.4.3 Justification of the adopted equipment

Taking into account the type of production (small-scale) and the complexity of the manufactured parts, we accept CNC machines and machinable centers that allow us to perform complex processing of the shaped surfaces of parts, obtain high productivity and are easily reconfigured.

The head is a part of the class "Not round rods" weighing 1.77 kg. The workpiece is obtained by stamping on horizontal forging machines. The surfaces of the workpiece are pretreated and then used as base surfaces.

The decisive factors in the choice of equipment are to ensure the specified accuracy and quality of the surfaces processed with maximum labor productivity, the overall dimensions of the workpieces and the possibility of automating the processing. Machines are selected by catalogs indicating the type and model in the route technological process. The use of special machines is advisable, since the head is a rather complex part in configuration, is made of high strength material (the machinability of titanium alloys is characterized by their low ductility, high chemical activity during cutting, low thermal conductivity) and are parts of the critical part of the aircraft. The accepted equipment is entered in the appropriate graphs of the route map of the route technological process.

2.4.4 Selection and justification of technological and measurement bases

Based on the analysis of the technical requirements for the part and the conditions of its operation, we identify the technological bases for all the proposed operations of its processing.

The choice of bases for further processing is based on the fact that the greatest accuracy of processing is achieved when using the same basic surfaces on all machining operations, that is, compliance with the principle of constancy of bases.

In accordance with the recommendations, we accept the following technological bases for processing the head: at the first operation, we carry out processing of the end and the outer cylindrical surface of the head, which will later be used as installation bases in a special device when processing holes on milling and drilling operations (processing of flat, radius, shaped surfaces, hole treatment); in subsequent turning operations, holes obtained in previous operations are used as installation bases (installation is carried out in a special device).

2.4.5 Determination of operating allowances for processing

General allowances for the treatment of each surface are taken according to GOST 26645-85, which are indicated in the drawing of the workpiece..

For the most accurate working surface of the head ∅128f7 $\left(^{-0,043}_{-0,083}\right)$we perform the calculation of operational allowances and tolerances by the calculation and analytical method.

To obtain the surface on a CNC lathe with the specified tolerance T = 0.04mm and roughness Ra = 0.8 microns, we adopt the following surface treatment plan [3]:

1st junction – rough turning with tolerance T_1=1.0 mm and surface roughness Rz=80 (Ra=12,5);

2nd transition – finishing turning with tolerance T_2= 0.16 mm and surface roughness Rz=20 (Ra=3,2);

3rd transition – thin turning (diamond) with tolerance T_3=0.04 mm and surface roughness R_a=0,8.

The calculation of the minimum allowances is carried out according to the formula:

$$2Z_{i\,\min}=2[(R_z+h)_{i-1}+\sqrt{\Delta^2_{\Sigma(i-1)}+\varepsilon_i^2}\,], \qquad (2.2)$$

The method of obtaining the workpiece is forging obtained by stamping, then for the first transition (with a forging mass of 6.21 kg [3] $R_{z\,\text{заг.}}$ =200 microns, $h_{\text{заг}}$=250 microns).

To determine $\Delta_{z\text{заг}}$ we find on the table of the directory [3] $\Delta_{\text{к}}$=1,6 microns per 1 mm forging length. With the length of the forging L=162mm $\Delta_{\text{к}}=1,6\cdot 162=260$ microns.

Deviations from coaxiality (Δ_c) elements of the workpiece of normal accuracy [3] accept Δ_c =1,1 mm=1100 microns.

Total deviations of surface location and shape

$$\Delta_{\Sigma total}=\sqrt{260^2+1000^2}=1033 \text{ microns.}$$

Installation of a single stamped workpiece is assumed in a special device. Therefore, the installation error for radial direction is taken o

$$\varepsilon_{rough\ processing.}= 200 \text{ microns.}$$

Minimum allowance for rough turning

$$2Z_{1min}=2[(80+250)+\sqrt{1033^2+200^2}]=3004 \text{ microns.}$$

We accept the minimum allowance for rough turning

$$2Z_{1min}=3000 \text{ microns.}$$

For the second transition, we take the roughness adopted in the first transition Rz_1=80 microns. From the directory table given in Kosilova [3] take the depth of the defective ball after the first transition (operation)h_1=100 microns.

We calculate the error of the location and shape of the surface after the first transition.

We take the K_y coefficient(0,06) from the reference table in [3]

$$\Delta_{\Sigma 1}=1033\cdot 0{,}06=62 \text{ microns.}$$

The installation of the workpiece at the second transition during finishing turning assumes the same as the previous transition. From the directory table [3] installation error for radial direction

$$\varepsilon_2= 200 \text{ microns.}$$

Minimum allowance for finishing turning:

$$2Z_{2min}=2[(20+100)+\sqrt{62^2+200^2}]=779 \text{ microns.}$$

We accept the minimum allowance for finishing turning $2Z_{2min}$=800 microns.

For the third transition, we take the roughness adopted in the second transition Rz_2=20 microns. From the directory table [3] take the depth of the defective ball after the second transition h_2=25 microns.

The error of the location and shape of the surface after the second transition is calculated similarly to the previous transitions with a coefficient K_y = 0,04

$$\Delta_{\Sigma 2}=1033\cdot 0{,}04=41{,}32 \text{ microns.}$$

The installation of the workpiece of the third transition with thin (diamond) turning is assumed similarly to the previous transitions. From the directory table [3] installation error for radial direction

$$\varepsilon_2=200 \text{ microns.}$$

Minimum allowance for thin (diamond) turning:

$$2Z_{3min}=2[(20+25)+\sqrt{41^2+200^2}\,]=498 \text{ microns.}$$

We accept the minimum allowance for thin (diamond) turning $2Z_{1min}=500$ microns.

The calculation of maximum allowances is performed according to the following formula:

$$2Z_{i\ max}=2Z_{i\ min}+T_{d(i-1)}-T_{di}, \qquad (2.3)$$

where $T_{d(i-1)}$, T_{di}, - dimensional tolerances at the preliminary and executive transitions.

$$2Z_{1max}=3000+4000-1000=6000 \text{ microns,}$$

$$2Z_{2max}=800+1000-160=1640 \text{ microns,}$$

$$2Z_{3max}=500+160–40=620 \text{ microns.}$$

Table 2.7 – Operational allowances and tolerances when processing the head to the surface ∅ $128f7\left(\begin{smallmatrix}-0,043\\-0,083\end{smallmatrix}\right)$.

Technological operations (transitions) of processing	tolerance T, microns	Allowance elements microns				The value of allowances, microns		Limit dimensions, mm	
		Rz	h	Δ_Σ	E_y	2Zi min	2Zi max	max	min
Workpiece	4000	200	250	1030	-	-	-	136,217	132,21
Rough turning	1000	80	100	62	200	3000	6000	130,217	129,21
Finishing turning	160	20	25	42	200	800	1640	128,577	128,41
Thin (diamond) turning	40	0,8	-	-	-	500	620	127,957	127,91
General allowances						4300	8260		

The layout of the operating allowances and tolerances on the most accurate surface of the head is shown in Figure 2.4.

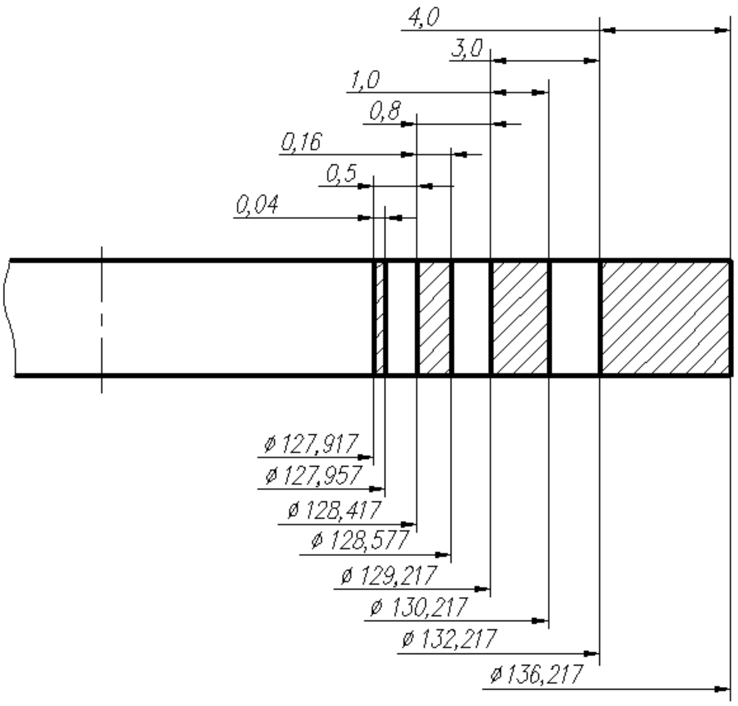


Figure 2.4. Layout of allowances and tolerances when processing the surface of the head $\varnothing\ 128f7\left(^{-0,043}_{-0,083}\right)$.

* graphic representation of tolerances and allowances specified in Table 2.7

2.5 Design of operational technological process

Based on the accepted route technological processes of head processing, we develop operational technological processes [4],for each transition operation.

Operating cards are filled in according to all columns of forms established by the system of technical documentation.

Operational sketches are made on an arbitrary scale. The number of projections is due to the need to show all surfaces and operational dimensions to be processed, that is. to have a complete picture of the workpiece being processed. The part on the operational sketch is crossed out in the working position that it occupies on the machine, and in the form that it has after processing a particular operation. Basing and fixing the part in the device are symbols in accordance with GOST 3.1107-81.

The treated surfaces are indicated by thickened lines. The operational sketch indicates the dimensions with tolerances and surface roughness.

Taking into account possible deformations as a result of the redistribution of internal stress, we first process surfaces that are not subject to strict accuracy requirements, and then more accurate surfaces.

2.6 Selection of devices, cutting tools and means of technical control

2.6.1 Selection of devices and auxiliary tools

The choice of devices and auxiliary tools is carried out for each operation separately. The device must provide the necessary machining accuracy, high performance, safety and economy. Since the plant has an extensive compressed air system, we use pneumatic devices during processing.

When processing parts on CNC lathes, we use standard and special three-cam cartridges [5;6].

They provide reliable fastening of the part, sufficient accuracy of fixing the part, sufficient accuracy of position, speed when fixing and removing the part. With the use of these devices, the cost of manufacturing parts is reduced.

In the milling and drilling operations of the head, special single-seater devices are used, which allows to achieve the greatest productivity and efficiency, occupational safety, as well as convenience in work.

At locksmith operations, we use universal vices with a mechanical clamp, because their use in these operations does not require high accuracy of processing.

After selecting the necessary devices in the appropriate columns of the operating cards, we indicate their name.

2.6.2 Selection of cutting tools

The choice of cutting tools was carried out taking into account the nature of production, processing method, type of machine, configuration, size, material of the workpiece to be processed, the required surface quality and machining accuracy.

Depending on the type of processing in the designed technological process, a standard cutting tool is used:

- for roughing and finishing of cylindrical surfaces of the head and cylinder, cutters with plates made of hard alloy VK8 are used;
- for drilling, zenkering and reamer holes – tools made of high-speed steel R9M4K8, designed for processing high-strength alloys in conditions of increased heating;
- for milling coots and grooves in the cylinder, cutters made of hard alloy VK8 and high speed steel R9M4K8 are used;

For cutting threads in the hole of the horn of the head, rough and finishing marks made of steel R6M5K5 are used;

- for cutting the outer thread of the cylinder - threaded cutter with a plate made of hard alloy VK8;
- specially designed and ground cutters with plates made of hard alloy VK8 are used for turning chamfers and radii;

- for blunting sharp edges and removing burrs, a file and a scraper are used.

Since the operating conditions of the tool on CNC machines differ from the operating conditions of the tool on conventional machines, the proportion of cutting time from the total operating time increases. This reduces stability and increases the cost of cutting tools, therefore, given the operating conditions when choosing cutting tools, you must be guided by the following:

- for milling the ledge, flat and shaped surfaces of the head, use cutters with fast-changing plates (created by MITSUBISHI company) made of hard alloy not being ground..
- for turning, use cutters with mechanical fastening of multifaceted non-sharpened fast-changing plates made of hard alloy. The designs of the passing incisors use tetrahedral plates with a main angle in plan 45°.

2.6.3 Selection of means of technical control

When designing this technological process in relation to the means of technological control, the following rules are taken into account. Since the main part of operations is performed on machine tools with program control, the accuracy of dimensions is ensured technologically, without controls, especially for sizes that cannot be measured. If it is impossible to do without technological control tools, active controls are used in order to eliminate or minimize the time for technical measurements. To measure the diameters of external surfaces, holes and lengths, universal tools and devices are used, which include: rod tools, measuring heads, micrometric tools, measuring brackets and plugs.

2.7 Selection and calculation of processing modes

For one hydraulic cylinder head processing operation described below the cutting modes are analytically defined, and for other operations we determine the cutting modes using reference tables [7;8].

Analytical calculation of cutting modes will be performed on the surface treatment of the head $\varnothing 128f7\binom{-0{,}043}{-0{,}083}$ mm. f7 is a symbol in Table of limit deviations according to ISO 286-2:2010.

The technological process of surface treatment includes: rough turning, finishing turning and thin turning (diamond).

Equipment used - CNC lathe brand “MDW-10F”, cutting tool - pass-through cutter bent with a plate of hard alloy VK8 with a main angle in plan 45° and mechanical fastening.

The cutting speed (m/min) is obtained by the formula [3]

$$V_P = \frac{C_V}{T^m \cdot t^x \cdot S^y} \cdot K_V, \text{ m/min} \tag{2.4}$$

where T = 30 min incisor stability;

t cutting depth, mm;

S representation, mm/rev.

When roughly turning the outer surface of the workpiece, the cutting depth is t= 3.0 mm; feed value S=0.3 mm/rev (Vol. 2 table 24 p. 375 [3]).

The value of empirical coefficients is taken from the reference book [3]

$C_v = 243$; $x = 0{,}15$; $y = 0{,}4$; $m = 0{,}2$.

Coeffcient Kv can be calculated from:

$$K_v = K_{mv} \cdot K_{nv} \cdot K_{иv}, \tag{2.5}$$

where K_{mv} coefficient taking into account the quality of the material being processed;

K_{nv} coefficient reflecting the condition of the workpiece surface, $K_{nv} = 0{,}8$;

$K_{иv}$ coefficient taking into account the quality of the tool material, $K_{иv} = 0{,}83$.

$$K_{mv} = K_r \left(\frac{750}{\sigma_в} \right)^{n_V}, \tag{2.6}$$

where K_r coefficient characterizing the group of alloy for machinability, $K_r = 1$;

n_v Degree indicator, $n_v = 1{,}0$;

$$K_{mv} = 1 \cdot \left(\frac{750}{1274} \right)^1 = 0{,}59;.$$

$$K_V = 0{,}59 \cdot 0{,}8 \cdot 0{,}83 = 0{,}39$$

Then

$$V_P = \frac{243}{30^{0,2} \cdot 2^{0,15} \cdot 0{,}3^{0,4}} \cdot 0{,}39 = 70{,}8 \text{ m/min.}$$

Machine spindle speed, rpm [3]

$$n_p = \frac{1000 \cdot V}{\pi \cdot D}, \text{ rpm} \tag{2.7}$$

where D is the diameter of the treated surface, mm.

$$n_p = \frac{1000 \cdot 70{,}8}{3{,}14 \cdot 128} = 176 \text{ rpm.}$$

Accept $n_{пр} = 180$ rpm.

According to the accepted rotation frequency, we make a correction of the rotation speed

$$V_{кор}=\frac{\pi \cdot D \cdot n}{1000}=\frac{3.14 \cdot 128 \cdot 180}{1000}=72 \text{ m/min.}$$

The cutting force is determined by the formula [3]

$$P = 10 \cdot C_P \cdot t^x \cdot S^y \cdot V^n \cdot K_P \qquad (2.8)$$

where C_P; x; в; n – coefficient and degree indicators taken by the directory [3].

$$P = 10 \cdot 300 \cdot 2^1 \cdot 0{,}3^{0{,}75} \cdot 72^{-0{,}15} \cdot 1{,}7 = 2175N .$$

Cutting power is determined by the formula [3]

$$N = \frac{P \cdot V}{1020 \cdot 60} kW . \qquad (2.9)$$

where P is the cutting force, N.

$$N = \frac{2175 \cdot 72}{1020 \cdot 60} = 2{,}56 \text{ kW}$$

The power of the machine drive is sufficient to work with the selected cutting modes.

Determine the cutting conditions for finishing turning.

Cutting depth t=0,7 mm; supply S=0,18 mm/rev $V_P = \frac{243}{30^{0{,}2} \cdot 0{,}7^{0{,}15} \cdot 0{,}18^{0{,}4}} \cdot 0{,}39 = 100{,}5 \text{ m/min.}$

The rotation frequency of the spindle of the machine

$$n = \frac{1000 \cdot V}{\pi D} = \frac{1000 \cdot 100{,}5}{3{,}14 \cdot 128} = 250{,}05 \text{ rpm.}$$

Accept $n_{пр} = 250$ rpm.

According to the accepted rotational speed, we make a correction of the rotational speed

$$V_{кор}=\frac{3.14 \cdot 128 \cdot 250}{1000}=100 \text{ m/min.}$$

Cutting strength and the rest are calculated by the equations above

$$P = 10 \cdot 300 \cdot 0{,}7^1 \cdot 0{,}18^{0{,}75} \cdot 100^{-0{,}15} \cdot 1{,}7 = 493{,}6N .$$

Cutting power

$$N = \frac{493{,}6 \cdot 100}{1020 \cdot 60} = 0{,}8 \text{ kW}$$

The power of the machine drive is quite sufficient to work with the selected cutting modes.

Determine the cutting modes for thin (diamond) turning.

The cutting depth t=0,25 mm; supply S=0,03 mm/rev

$$V_P = \frac{243}{30^{0{,}2} \cdot 0{,}25^{0{,}15} \cdot 0{,}03^{0{,}4}} \cdot 0{,}39 = 241{,}1 \text{ m/min.}$$

The rotation frequency of the spindle of the machine

$$n = \frac{1000 \cdot V}{\pi D} = \frac{1000 \cdot 241{,}1}{3{,}14 \cdot 128} = 599{,}87 \text{ rpm.}$$

Accept $n_{пр} = 600$ rpm.

According to the accepted rotational speed, a correction is made on the rotational speed

$$V_{кор} = \frac{3.14 \cdot 128 \cdot 600}{1000} = 241{,}15 \text{ m/min.}$$

The cutting strength:

$$P = 10 \cdot 300 \cdot 0{,}25^{1} \cdot 0{,}03^{0{,}75} \cdot 241{,}15^{-0{,}15} \cdot 1{,}7 = 40{,}3 \text{ N}.$$

The cutting power

$$N = \frac{40{,}3 \cdot 241{,}15}{1020 \cdot 60} = 0{,}16 \text{ kW}$$

The power of the machine drive is sufficient to work with the selected cutting modes.

For the rest of the operations, we select the processing modes according to the directory [7; 8] and enter them into the operating cards.

The results of selecting cutting modes for other operations are summarized in the table 2.8.

Table 2.8 Summary of head processing modes

Number		Name of operation and transition	Processing modes						
Ope-ration	Transition		D (B), mm	L, mm	t, mm	i	S, mm/rev	V, m/min	n, rpm
010	**Turning**								
	1	Rough trimming of the end	135,8	70	3,0	1	0,25	78,9	185
	2	Rough turning of the outer surface (∅128)	135,8	28	2,65	1	0,12	59,96	140,62
035	**Milling drilling**								
	1	Rough milling of flat, conical, radius surfaces	–	–	2,0	1	1,5	40	318,47
		Finishing milling of flat, conical, radius surfaces	–	–	0,9	1	0,14	55	437,9
	2	Rough milling of a ledge (p-p 47)	96	36	2,0	1	0,35	52	414
		Finishing milling of the ledge (p-p 47)	96	36	0,9	1	0,14	70	557,3
	3	Centering 2 holes	-	-	-	1	0,09	20,4	500
	4	Drilling 2 holes	11	16	5,5	1	0,09	13,7	370
	5	1 hole zenkering	11,8	16	0,4	1	0,11	8,4	225
	6	1st hole reamer	12	16	0,1	1	0,11	8,6	225
	7	Decontamination of one hole	37	16	13	1	0,12	50	497,6
040	Milling drilling								
	1	Radius milling	R8	–	–	1	0,12	40	636,9
	2	Milling ergot (p-p 22)	22	22	2,8	1	0,14	50	398,1
045	Milling drilling								

Number		Name of operation and transition	Processing modes						
Ope-ration	Transition		D (B), mm	L, mm	t, mm	i	S, mm/rev	V, m/min	n, rpm
	1	Rough milling of flat, radius surfaces	40	–	2,0	1	1,5	40	318,47
		Finishing milling of flat, conical, radius surfaces and ledge	40	–	0,9	1	0,14	55	437,9
	2	Top slope milling	20	–	2,0	1	0,15	45	716,6
	3	Centering 2 holes	-	-	-	1	0,09	20,4	500
	4	Drilling 2 holes	11	16	5,5	1	0,15	16,8	485,5
	5	1 hole zenkering	11,8	16	0,4	1	0,2	6,7	180,8
	6	1st hole reamer	12	16	0,1	1	0,1	4,0	106,2
	7	Decontamination of one hole	37	16	13	1	0,12	50	497,6
055	**Turning**								
	1	Rough trimming of the right end	130,5	70	4,0	1	0,25	78,9	192,55
		Finishing trimming of the right end	130,5	70	1,0	1	0,12	86,8	211,83
		Finishing turning of the outer cylindrical surface	128,4	28	0,8	1	0,12	87,4	216,78
		Thin (diamond) turning of the outer cylindrical surface	128	28	0,2	1	0,09	98,76	245,7
	2	Rough turning of a spherical surface	R57	–	–	1	0,25	67,2	164
		Finishing turning of a spherical surface	R57	–	–	1	0,12	92,4	258,13
	3	Rough trimming of the left end	128	–	4,0	1	0,25	78,9	192,55
		Finishing trimming of the left end	128	–	1,0	1	0,12	86,8	211,83
	4	Turning grooves	120	6,2	4,0	1	0,12	83,25	220,94
060	**Turning**								
	1	Trimming the end of the horn	22	22	0,5	1	0,18	78,5	1136,4
	2	Drilling a hole in the horn	9,0	34	4,5	1	0,09	12	375
	3	Zenkering the hole in the horn	9,8	34	0,4	1	0,35	9,22	300
	4	reamer a hole in the horn	10	34	0,1	1	0,56	6,8	216,6
	4	Rough boring hole in the horn	16,5	4	3,0	1	0,15	92	1776
		Finishing boring hole in the horn	16,5	4	0,25	1	0,1	100	1930
	5	Cutting the carving into a horn	M16×1,5	18	–	1	0,18	12	238,9
	6	Rough boring hole in the horn	16,3	3	2,9	1	0,15	92	1776
		Finishing boring hole in the horn	16,3	3	0,25	1	0,1	100	1930
	7	Boring a hole in the horn	11	9	0,5	1	0,12	85	2460,9
065	**Drilling**								

Number		Name of operation and transition	Processing modes						
Ope- ration	Transit ion		D (B), mm	L, mm	t, mm	i	S, mm/ rev	V, m/min	n, rpm
	1	Drilling 2 backpacks	1,8	5	0,9	1	0,015	18	2857
095		**Milling-drilling-boring**							
	1	Milling understatements in the ledge	–	78	0,5	1	0,32	30,75	195
	2	Boring the rolling hole	39,99	16	0,995	1	0,25	84	743
	3	Rolling the hole	40	16	0,02	1	0,1	25	180

2.8 Technical standardization of the technological process

The calculation equations that are used throughout this tehese have been presented by Kosilova et al. [3].

The rate of artificial time is:

$$T_{\text{ШТ.}} = \left(T_{\text{Ц.А}} + T_{\text{В}} \cdot k_{t\text{Д}}\right) \cdot \left(1 + \frac{T_{\text{ТЕХ}} + T_{\text{ОРГ}} + T_{\text{Н.П}}}{100}\right), \tag{2.10}$$

where $T_{\text{ц.а}}$ – cycle time of automatic work on the program, min.

$$T_{\text{Ц.А}} = T_{\text{О}} + T_{\text{МВ}} \tag{2.11}$$

$T_{\text{О}}$ is the main technological time for processing one part, min.

$$T_{\text{О}} = \frac{L_p}{S_{\text{М}}} \cdot i, \tag{2.12}$$

where L_p – path length traveled by the tool or part in the direction of feeding when processing the i-th technological section (taking into account the insertion and flow), mm;

$S_{\text{М}}$ – minute feed for this operation, mm/min.;

$T_{\text{МВ}}$ –machine-auxiliary time during the operation of the machine according to the control program (for bringing the part or tool from the starting points to the processing and output zones, installing the tool for size, changing the tool, changing the value of the feed direction, the time of technological pauses (stops), etc., min;

$T_{\text{В}}$ – auxiliary time, min.

$$T_{\text{В}} = T_{\text{В.У}} + T_{\text{В.ОП}} + T_{\text{В.ИЗМ}}, \tag{2.13}$$

where $T_{\text{В.У}}$ – time to install and remove parts manually or lift, min;

$T_{\text{В.ОП}}$ – auxiliary time associated with the operation (which is not included in the control program), Min;

$T_{\text{В.ИЗМ}}$ – auxiliary time, not overlapping, for measurements, min.

T_{TEX} – workplace maintenance time, min;

$T_{ОРГ}$ – time of organizational maintenance of the workplace, min;

$T_{Н.П.}$ – Break time.

Calculate the time rate for lathe operation performed on a CNC lathe (operation 070).

For the first transition:

$$\text{Т}_{\text{о}\ черн.} = \frac{68}{0{,}25 \cdot 200} = 1{,}36 \text{ Min.}$$

Auxiliary time to install the part $\text{Т}_{\text{уст}}$ = 1,5 Min.

T_{MB}=0,1 min.

$$\text{Т}_{\text{о чист.}} = \frac{68}{0{,}07 \cdot 220} = 4{,}42 \text{ min.}$$

T_{MB}=0,06 min.

$$T_{Ц.А}=1{,}36+0{,}1+4{,}42+0{,}06=5{,}94 \text{ min}$$

For the second transition:

$$\text{Т}_{\text{о чист.}} = \frac{8{,}5}{0{,}07 \cdot 220} = 0{,}55 \text{ min.}$$

T_{MB}=0,06 min.

$T_{В.ИЗМ}$=0,14 min.

$$T_{Ц.А}=0{,}55+0{,}06=0{,}61 \text{ min.}$$

For the third transition:

$$\text{Т}_{\text{о}} = \frac{\frac{3{,}14 \cdot 57}{2}}{0{,}06 \cdot 180} = 8{,}29 \text{ min.}$$

T_{MB}=0,08 min.

$$T_{Ц.А}=8{,}29+0{,}08=8{,}37 \text{ min}$$

For the fourth transition:

$$\text{Т}_{\text{о чист.}} = \frac{28}{0{,}07 \cdot 220} = 1{,}82 \text{ min;}$$

$$\text{Т}_{\text{о тонк. точ.}} = \frac{28}{0{,}06 \cdot 250} = 1{,}87 \text{ min;}$$

T_{MB}=0,1×3=0,3min;

$T_{В.ИЗМ}$=0,14×2=0,28 min.

$$T_{Ц.А}=1{,}82+1{,}87+0{,}3=3{,}99 \text{ min.}$$

For the fifth transition:

$$\mathrm{T_o} = \frac{4}{0{,}144 \cdot 280} \cdot 2 = 0{,}02 \text{ min};$$

T_{MB}=0,01+0,04+0,01=0,06 min;

$T_{B.ИЗМ}$=0,14×2=0,28 min;

$T_{B.ИЗМ}$=0,1×3=0,3 min.

$$T_{Ц.А}=0{,}02+0{,}06=0{,}08 \text{ min}.$$

$$\sum T_{Ц.А} = 5{,}94+0{,}61+8{,}37+3{,}99+0{,}08 = 18{,}99 \text{ min}.$$

$$Тв.оп = 0{,}32+0{,}15 = 0{,}47 \text{ min}.$$

$$T_B = 1{,}5+0{,}14+0{,}28+0{,}28+0{,}3+0{,}47 = 2{,}97 \text{ min}.$$

$$T_{оп} = 18{,}99+2{,}97 = 21{,}96 \text{ min}.$$

$$T_{ТЕХ} = 0{,}06 \cdot T_{ОП} = 0{,}06 \cdot 21{,}96 = 1{,}32 \text{ min};$$

$$T_{ОРГ} = 0{,}08 \cdot T_{ОП} = 0{,}08 \cdot 21{,}96 = 1{,}76 \text{ min};$$

$$T_{Н.П} = 0{,}025 \cdot T_{ОП} = 0{,}025 \cdot 21{,}96 = 0{,}55 \text{ min}.$$

$$K_Д = 1{,}32.$$

$$T_{ШТ.} = (18{,}99+2{,}97 \cdot 1{,}32) \cdot \left(1+\frac{1{,}32+1{,}76+0{,}55}{100}\right) = 23{,}74 \text{ min}.$$

The norms of the time for performing other operations are presented in the summary of the time norms for operations (Table 2.9)

Table 2.9 – Summary statement of time norms for operations for the "head" part, min.

№ oper	Name of operation	$T_о$	$T_в$	$T_{оп}$	$T_{тех}$	$T_{орг}$	$T_{н.п}$	$T_{шт}$
010	Turning	4,57	6,35	10,92	0,66	0,87	0,27	12,72
035	CNC milling and drilling	142,78	11,34	154,12	9,25	12,33	3,85	197,87
040	CNC milling and drilling	3,82	6,76	10,58	0,63	0,85	0,26	12,96
045	CNC milling and drilling	127,36	10,48	137,84	8,27	11,03	3,45	173,31
055	CNC turning	18,99	2,97	21,96	1,32	1,76	0,55	23,74
060	CNC turning	28,47	12,18	40,65	2,44	3,25	1,02	47,54
065	Drilling	1,92	4,86	6,78	0,41	0,54	0,17	7,9
095	CNC milling and drilling and boring	42,63	14,52	57,15	3,43	4,57	1,43	67,63
	Total:	370,54	69,46	440,0	26,41	35,2	11,0	543,67

3 SCIENTIFIC AND RESEARCH SECTION

The scientific part deals with the recycling of titanium chips from the workpiece and the recycling of titanium and titanium alloys in general for this area.

3.1 Statement of the problem of theoretical research

In connection with the global trend of metallurgy development based on secondary raw materials, titanium waste acquires special importance. Maximally complete and rational use of waste is one of the priority ways to reduce the price of titanium products, which will undoubtedly strengthen the economic position of the titanium industry.[9]

As a result, the cost of waste has recently begun to approach the cost of spongy titanium.

The use of secondary titanium resources (and primarily shavings), that is, titanium recycling, is the main source of effective formation of the titanium metal pool. Based on the structure of the titanium cycle, the sources of secondary raw materials are: at the stage of titanium production - recyclable scrap and waste, at the stage of titanium consumption - depreciation scrap.[10]

The analysis of the scientific and technical literature, in which the problems of the production of titanium alloys and by-products and recyclable scrap and waste are considered, showed the following.

3.1.1 Technological and technical features of titanium alloys

Titanium (Ti) is a chemical element with atomic number 22 and the corresponding simple substance is a solid silvery metal, melting point 1675 °C, boiling point 3262 °C, density 4540 kg/m^3. It was discovered at the end of the 18th century almost simultaneously by two scientists, independently of each other - U. Gregor, the German chemist M. G. Klaprot and later received its name in honor of the strong, powerful characters of ancient Greek mythology.

In terms of density and specific heat capacity, Ti occupies an intermediate place between iron and aluminum.

It is of greatest interest as an alloy. The modern alloy obtained at metallurgical plants and factories has excellent properties. The main quality indicators of titanium are its high strength, resistance to extreme temperatures and lightness, like aluminum.

Titanium, like steel, copper, aluminum, is a fairly common metal in nature, but it has a higher cost. The material is quite expensive due to the difficulties in the process of its manufacture and processing. The material has a high refractoriness, so it requires more energy during processing in furnaces. In addition, during mechanical processing, a special tool is needed (machine cutters of increased strength, crown drills with a special cutter), due to the high strength of the material.

Despite the difficulties in processing, the material is very necessary in many types of production and industry. It is used in the space industry and the defense industry, the production of building materials, household items, medical devices, and for the production of machine parts and mechanisms.

Dissemination

The average content of titanium in the Earth's crust (Clark) is 0.45% (according to other data, it is 0.61% to a depth of 16 km). Only three other important metals—aluminum, iron, and magnesium—are more abundant in nature than titanium. The most titanium-rich pegmatites of granites and alkaline rocks.

At the beginning of the XXI century. about 100 titanium minerals are known. Titanium is included as an impurity in the composition of a number of minerals.

The main minerals of titanium ores:

- ilmenite (43,7—52,8 % TiO2)
- rutile, anatase and brookite (94,2—99,5 %)
- leucoxene (61,9—97,6 %)
- loparitis (38,3—41 %)
- sphene (33,7—40,8 %)
- perovskite (38,7—57,8 %).

The amount of titanium in the earth's crust is several times greater than the reserves of copper, zinc, lead, gold, silver, platinum, chromium, tungsten, mercury, molybdenum, bismuth, antimony, nickel and tin combined. The content of titanium in the main igneous rocks is 20.46 atomic %.

Rutile

Rutile is a mineral of the oxide class, the most common polymorphic modification of titanium dioxide TiO_2 (along with brookite and anatase). Isomorphic impurities: Cr, Nb, Ta, V, Sn. Types of rutile: struverite - contains up to 47% Ta_2O_5 admixture; ilmenorutil - Nb_2O_5 up to 42%; nigrin - iron rutile.[11] Rutile is an important component of titanium ores, used in the electrode and paint industry. It also serves as a source of Nb and Ta extraction. From titanium-zirconium ores of placers, rutile is extracted by gravity methods on separators of various modifications, pneumatic tables into a rough concentrate of heavy metals, which is directed to proofing by magnetic and electric separation; enrichment on hydraulic and pneumatic concentration tables; flotation (for fine-grained concentrates).

It is floated with oleic acid, sodium oleate, tall oil, naphthenate at pH 5.5-6, oxidized petrolatum at pH 3-7.5, alkyl sulfate in an acidic medium, cation collector at pH-2. Depressed in an environment with a pH above 9 by soda in combination with liquid glass or starch, deep treatment with gaseous nitrogen; activated by sulfuric acid treatment.

Rutile concentrates are subjected to reduction-chlorination firing at 970-1270 K (700-1000 °C) in the presence of a solid reducing agent to obtain titanium tetrachloride.[12]

Rutile is used in the production of sponge titanium, pigmented titanium dioxide, titanium steels and carbides, as well as in the ceramic industry[13].

Titanium dioxide

TiO_2 - amphoteric oxide of tetravalent titanium. It is the main product of the titanium industry (only about 5% of titanium ore is used for the production of pure titanium)[14].

Titanium dioxide practically does not absorb light in the visible region of the spectrum, it only refracts or transmits it. It is used in the production of paints, cosmetics and in the food industry. For this, titanium dioxide with a rutile structure is more suitable, which is more stable and scatters light better. TiO_2 in the form of brookite is widely used in electrochemical electrodes, capacitors and solar cells[15].Crystal modification of anatase is most actively used as a photocatalyst, in particular for water and air purification, in medicine - to fight tumor diseases. Titanium dioxide in the anatase phase shows high sensor activity for oxygen, which makes it in demand in the production of lambda probes in the automotive industry.

In the food industry, it is known by the number E171. Prohibition in the EU. On February 7, 2022, a ban on the use of titanium dioxide (E171) in the food industry came into effect in the EU. The transition period will last 6 months. The use of titanium dioxide in the pharmaceutical industry will continue due to the lack of alternative substances.[16]

Rutile is also used to make titanium dioxide.

3.1.2 Technological cycle of production of titanium alloys and by-products

Industrial extraction of titanium is mainly carried out from ilmenite ($FeTiO_3$ 31,6 %) and rutile (TiO_2 60 %). Vanadium, scandium, tantalum and niobium are present in ilmenites and rutiles. Extraction of ilmenite from titanomagnetite is possible if the grain size of ilmenite exceeds 0.3 mm. Titanium is partially extracted from leucoxene (96% of ilmenite in leucoxene, 67% of sphene TiO_2), anatase (polymorphic modification TiO_2) and loparite (Na, Ce) TiO_3 (26,6 % Ti). Important minerals are also perovskite, titanite, ilmenorutile.

The basis of titanium production technology is the Krol process - obtaining titanium by magneithermal reduction of titanium tetrachloride followed by vacuum distillation. Part of sponge titanium is used as a raw material for the production of ingots and slabs from titanium and titanium alloys, the rest of sponge titanium is sold to consumers as commercial products.

One of the technological scheme of titanium production includes the following main sections:

- production of titanium slag by melting ilmenite concentrate in ore-thermal furnaces;
- obtaining a titanium-containing charge;
- production of technical titanium tetrachloride;
- rectification purification of technical titanium tetrachloride;
- production of magnesium-reductant by the electrolysis of magnesium chloride;
- reduction of titanium from titanium tetrachloride with magnesium to obtain a reaction mass;
- vacuum separation of the reaction mass;
- processing of spongy titanium blocks;
- smelting of titanium ingots and slabs.

Obtaining titanium slag by melting ilmenite concentrate in ore-thermal furnaces. The production of titanium slag consists of renewable ore-thermal electrosmelting of ilmenite concentrate with a TiO_2 content of at least 63% together with a carbon reducing agent - coal, coke or anthracite. The process of melting ilmenite concentrate and carbon reducing agent, previously crushed to the size of pieces no larger than 10 mm, is carried out in ore-thermal furnaces at a temperature of 1650°C - 1800°C. The resulting slag is drained and, after cooling, sent to the preparation of a titanium-containing charge. The metal formed as a result of melting (cast iron with an increased content of titanium) is taken to the warehouse for sale to the consumer. Gas vapors from ore-thermal furnaces are sent to gas treatment.

Obtaining a titanium-containing charge

The titanium-containing charge is obtained by mixing ground titanium slag, carbon reducing agent and sodium chloride. Before mixing, titanium slag and carbon reducing agent are crushed and ground. The prepared titanium-containing charge is transferred to the chlorination section for the production of titanium tetrachloride.

Obtaining technical titanium tetrachloride

Technical titanium tetrachloride is formed during the chlorination of a titanium-containing charge in molten salts in a salt chlorinator and condensation that comes from the chlorinator of the steam-gas mixture in the system of condensation devices. The process of chlorination of the titanium-containing charge is carried out in a salt chlorinator. Gaseous vapors from the salt chlorinator are sent to gas treatment.

A salt chlorinator is a device of continuous action. A titanium-containing charge is continuously loaded onto the surface of the salt melt by an auger from a waste hopper. Through the side nozzles of the chlorinator, located in its lower part, chlorine gas is fed into the melt. Two materials are removed from the chlorinator - a vapor-gas mixture of chlorination products and spent melt. The spent melt is removed from the chlorinator periodically and partially, and after cooling it is taken to the enterprise's waste management. The steam-gas mixture is discharged from the chlorinator continuously and enters the system of purification and condensation devices for technical titanium tetrachloride. Steam-gas mixture cleaning devices: dust chamber, irrigation scrubber. Apparatus for condensation of technical titanium tetrachloride: two serially installed irrigation condensers, where condensation of technical titanium tetrachloride takes place during the cooling process. The obtained technical titanium tetrachloride, after settling, is sent to the rectification area for cleaning.

Rectification purification of technical titanium tetrachloride

Technical titanium tetrachloride is subject to purification from vanadium, as well as from low- and high-boiling impurities. Purification of vanadium is carried out with lower titanium chlorides in the cube of the column of the first distillation. The rectification process includes the purification of titanium tetrachloride from low-boiling impurities - the first rectification, and from high-boiling impurities - the second rectification. The process is carried out in rectification columns at a temperature of 120°C – 142°C. In the process of rectification purification of titanium tetrachloride, cubic residues are collected in evaporator cubes, which are periodically removed from the cubes, evaporated in an electric pulp evaporation furnace and treated with quicklime. As a result, a cake containing vanadium is formed, which is sold to the consumer. The gaseous vapors of the rectification purification are directed to the gas purification.

Production of magnesium by electrolysis of magnesium chloride

Magnesium is obtained by electrolytic decomposition of molten magnesium chloride (dichloride) in diaphragmless electrolyzers. In electrolyzers, the working melt is magnesium chloride, fluorspar concentrate and table salt. As a result of the electrolysis process, metallic magnesium is formed, which after additional purification is sent to restore titanium, chlorine gas is sent to a salt chlorinator, and waste: sludge and sludge-electrolyte mixture is taken to the enterprise's waste management or sold to the consumer. Gas vapors from diaphragmless electrolyzers are sent to gas treatment.

Reduction of titanium from titanium tetrachloride with magnesium to obtain a reaction mass

The recovery of titanium from titanium tetrachloride with magnesium is carried out in recovery devices. Liquid magnesium is poured into the prepared recovery apparatus. The apparatus with magnesium is installed in the recovery furnace, and titanium tetrachloride is fed into the apparatus. In the process of interaction of titanium tetrachloride with magnesium, magnesium dichloride is formed, which is periodically poured into a ladle and sent to electrolysis to obtain magnesium and a reaction mass consisting of spongy titanium and residual magnesium and magnesium dichloride. After the end of the recovery process, the apparatus with the reaction mass is sent to the redistribution of separation.

Vacuum separation of the reaction mass

The process of vacuum separation of the reaction mass is carried out as follows. The separation apparatus with the reaction mass is installed in the separation furnace. During the heating period of the separation apparatus, exposure is carried out at a temperature of 850°C. As the apparatus with the reaction mass warms up in a vacuum environment, the sublimation of magnesium vapors and magnesium dichloride begins. High-temperature aging at temperatures of 980°C – 1020°C begins after the end of the apparatus warm-up period. The magnesium and magnesium dichloride vapors are condensed in the reverse retort and used, subsequently, in the next reduction process. The time of the process is determined by the type of reaction mass and the residual pressure in the apparatus. After the end of the separation process, the furnace heaters are turned off, and argon is supplied to the apparatus. The apparatus is cooled first in the oven, and then in the refrigerator. After cooling, the separation apparatus is dismantled, and the retort with the sponge titanium block is sent for processing.

Processing of spongy titanium blocks

The processing of spongy titanium blocks consists in performing the following basic operations:

– trimming the slag lining and knocking out the block from the retort, with determination of its quality;

– division of the block into component parts - the bloom and the slag lining;

– cleaning the retort from the remains of spongy titanium;

– cleaning of the bloom from surface contamination with the selection of low-quality components: bottom trim, side trim;

– determination of the quality category of the bloom and slag lining and division by categories for their further separate processing;

– crushing of bloom and slag lining on the press and in crushers;

– scattering of crushed spongy titanium with the selection of commercial fractions;

– sorting of commercial fractions of spongy titanium with removal of pieces with defects;

– sampling, packing in prepared containers (containers, barrels), weighing, labeling, sealing.

Packed spongy titanium is assembled into product batches in accordance with contracts and sent to the consumer.

Smelting of titanium ingots and slabs

Part of the produced spongy titanium is used as a raw material for the production of ingots and slabs of technically pure titanium and titanium alloys. Sponge titanium is pre-briquetted, after which the briquettes are sent to the melting area, where they are remelted into ingots or slabs on an electron beam remelting unit. then the ingots and slabs are sent for mechanical processing (sawing, turning, chamfering), undergo quality control for chemical composition, internal and external defects. Ready ingots and slabs are marked, packed and sent to the consumer.

As an example, the block diagram of obtaining titanium at ZTMK (Zaporizhia Titanium-Magnesium Plant)

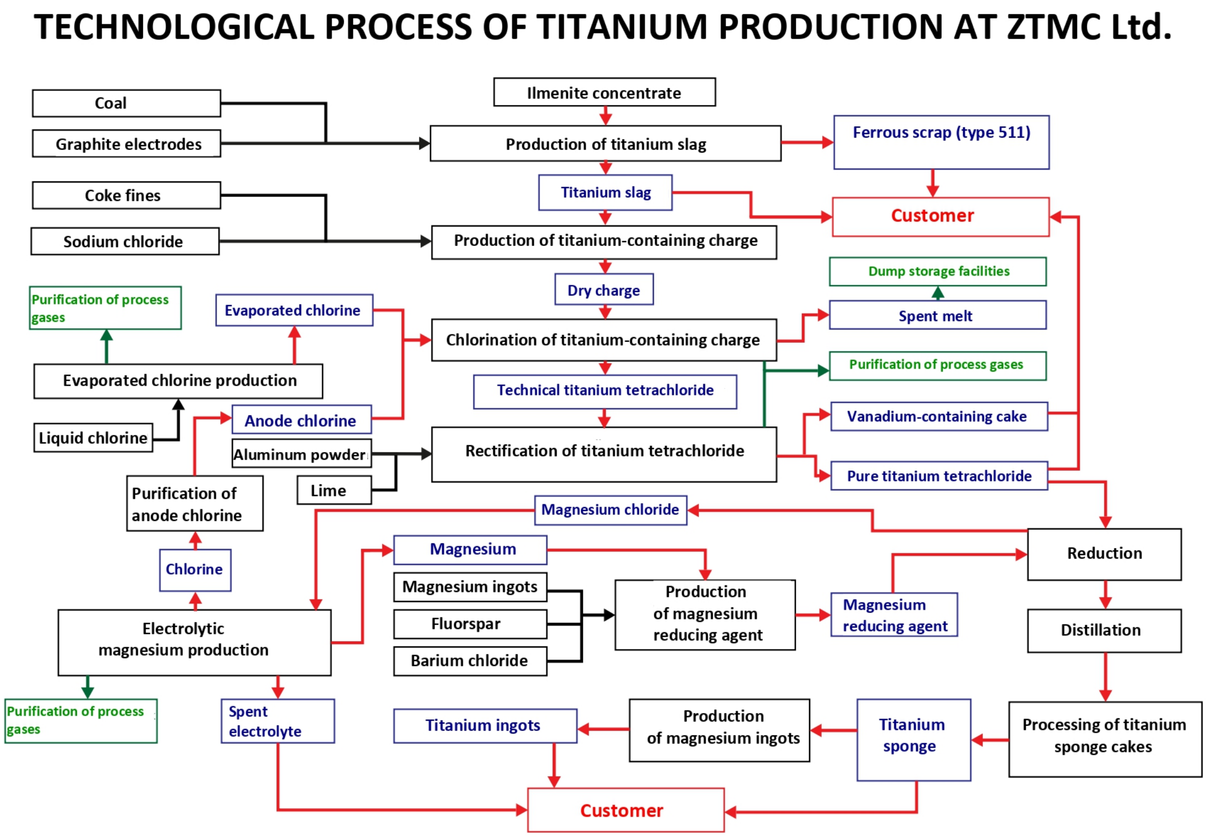


Figure 3.1- Block diagram of obtaining titanium at «ZTMK» [17]
* It represents the titanium production processes described above. is the inspiration for the block diagram created later

3.1.3 Classification of wastes of machine-building production of titanium alloys

Obtaining new raw materials from secondary resources greatly simplifies the production process, therefore, many manufacturers submit production waste in the form of scrap, shavings, or dust for repeated recycling.

To obtain the maximum benefit, it is necessary to hand over secondary raw materials to a company that has the appropriate documentation for the purchase of scrap and waste. In addition, the company must have special equipment for checking the scrap for alloy composition, radioactivity, obtaining accurate weight parameters.

Basically, there are the following types of scrap:

- Lumpy waste - Waste of non-ferrous metals and alloys obtained during casting, rolling, forging, stamping and cutting. Note - Lumpy waste does not include sludge, slag, dust, etc.[18]
- Depreciation scrap is part of automobiles, airplanes and end-of-life parts, offset mold plates, and some slags from primary magnesium smelting.[19]

Sorting and storage. Titanium scrap and shavings, at the place of processing of the material, must be sorted into separate containers according to the grade of the alloy, which is in accordance with the current regulation on waste of non-ferrous metals. The conditions of storage and transportation of dust and shavings of a small fraction must comply with the rules of fire and explosion safety.

It is not advisable to design a chip collection department, since the chips are collected in a special container at each site, near the passageways, for the convenience of its removal by the plant-wide chip processing department.

Control of the explosion safety of titanium waste should be observed during the following operations:

- loading and unloading operations, transportation;
- visual inspection of waste;
- sorting on the line and special sites;
- when tearing off containers, railway wagons;
- during packaging.

Waste delivery procedure in Ukraine:

In a specialized collection point, the delivery process takes place in the following sequence:

First, you need to get a pass by showing your passport and car documents. Go to the weighing scale, where a specialist will determine the type and weight of the loaded vehicle. Then it is necessary to unload the car at the sorting area. Put the machine again on the scale, where the operator will determine the exact weight of the waste and issue a receipt, with which you need to go to the accounting department and receive the amount of money for the scrap, according to the current prices for titanium shavings. Funds can be transferred to a bank account or collected in cash.

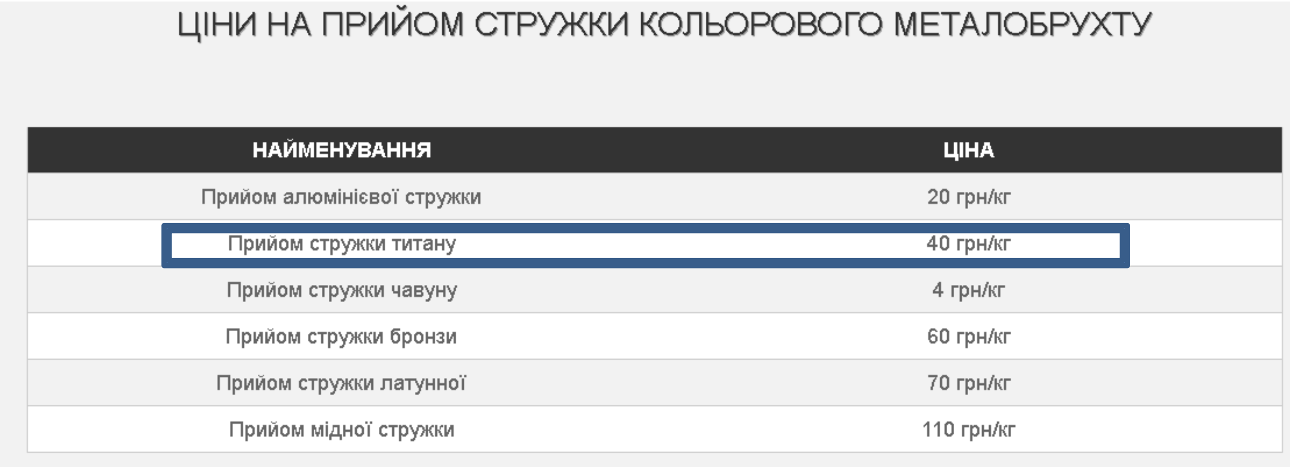
It should be noted that it is not possible to determine the brand of alloy, the correct weight and establish the corresponding cost at all points of reception of secondary raw materials. This requires a qualified staff and necessary equipment. Only in the presence of these conditions can the real value of scrap and waste be established.[20]

Reception of titanium shavings

During the manufacture of titanium products, production waste remains, and the reception of titanium shavings for further processing is one of the stages of economic use.

The price of titanium shavings due to its unique properties is much higher than the cost of waste from other metals, because the list of main qualities includes low thermal conductivity, mechanical strength, resistance to the formation of corrosion processes.

It is used in metallurgy as an alloying element for stainless, heat-resistant steels. In order to increase strength, Ti is added to other steels - aluminum, nickel, copper. Titanium dioxide is included in the production of welding electrodes. It is often used in the process of manufacturing parts, the work of which is connected with the influence of aggressive environments. The price of titanium shavings is high because it is the strongest known metal on earth and is used in the production of various products.



ЦІНИ НА ПРИЙОМ СТРУЖКИ КОЛЬОРОВОГО МЕТАЛОБРУХТУ

НАЙМЕНУВАННЯ	ЦІНА
Прийом алюмінієвої стружки	20 грн/кг
Прийом стружки титану	40 грн/кг
Прийом стружки чавуну	4 грн/кг
Прийом стружки бронзи	60 грн/кг
Прийом стружки латунної	70 грн/кг
Прийом мідної стружки	110 грн/кг

Figure 3.2 - Prices for receiving chips of non-ferrous metal scrap [21]

The price of titanium shavings is UAH 40/kg (EUR 1.21/kg – at the exchange rate until February 24, 2022 (note: the calculation at this rate is used below))

The price of metal is ten times higher per kg. The price of titanium VT22 circle is from UAH 800/kg (EUR 24.24/kg) [22], price for Titanium rod (titanium) VT22 from UAH 600/kg (EUR 18.18/kg) [23]. Price TITANIUM SHEET VT1-0 0.5X600X1500 MM from UAH 820/kg (EUR 24.84/kg) [24]

Some companies provide an opportunity to quickly calculate the mass based on the type of rolling stock, overall dimensions and brand of material, which greatly simplifies the estimation of the purchase price. [25]

The specialist assesses the quality of secondary raw materials and renders a final verdict based on the approved regulations. There is a list of provisions that specify the technical conditions for accepting recycled materials. A summary of the main categories:

- Sheets, squares, pieces, trifles.
- Large parts weighing at least 15 kg.
- Heavy pieces from 30 kilograms.
- Large pieces of at least 50 kilograms.
- Circles of a certain diameter, squares.
- The length of circles, squares, starting from 800 mm.
- Sheet thickness should be at least 5 mm and size 300x500.

Technical requirements

Table 3.1 - Scrap titanium and titanium alloys [26]

Group	Characteristics of the group	Indicator	Norm
T1	Scrap and piece waste of unalloyed titanium: housings of filters, vacuum filters and thickeners, pumping and shut-off fittings, tank, column and heat exchange equipment, air ducts, gas ducts, pipelines, sheet trim, cutting and trimming. Brands: VT1-00, VT1-0	The scrap is disassembled. Free of ferrous metals, oil, emulsions and moisture. The surface should not be oxidized, without cracks, undermining, delamination.	
		metal content, %, not less	99
		Clogging, %, not more	1
		The mass of a separate piece:	
		g, not less	100
		kg, not more	250
T2	Tin-free scrap and piece waste of titanium alloys: turbine blades, wire, connecting rods, exhaust and intake valves, rocker arms of valves and	The scrap is disassembled. Free of ferrous metals, oil, emulsions and moisture. The surface should not be	

Group	Characteristics of the group	Indicator	Norm
	silencers in diesel and automobile engines, supporting structures of automobiles, chassis of automobiles, heating coils, automobile engines, medical equipment. Brands of alloys: OT4-0, OT4-1, OT4, VT5, VT5-1, VT6, VT6S, VT3-1, VT9, VT14, VT16, VT20, VT22, PT-7M, PT3, PT-1M	oxidized, without cracks, undermining, delamination.	
		metal content, %, not less	99
		Clogging, %, not more	1
		The mass of a separate piece:	
		g, not less	100
		kg, not more	250
T3	Scrap and lump waste of titanium alloys alloyed with tin: mining equipment (manual perforators). Brands: VT5-1, VT18U, TS5	The scrap is disassembled. Free of ferrous metals, oil, emulsions and moisture. The surface should not be oxidized, without cracks, undermining, delamination.	
		metal content, %, not less	99
		Clogging, %, not more	1
		The mass of a separate piece, kg, not more	250
T4	Sheet cutting of titanium and titanium alloys.	Free of ferrous metals, oil, emulsions and moisture.	

Group	Characteristics of the group	Indicator	Norm
	Brands: VT1-00, VT1-0, OT4-0, OT4-1, OT4, VT5, VT 5-1, VT 6, VT 6C, VT 3-1, VT 9, VT 14, VT 16, VT 20, VT22, PT-7M, PT3, PT-1M, VT5-1, VT18U, TS5	The surface should not be oxidized, without cracks, undermining, delamination.	
		metal content, %, not less	99
		Clogging, %, not more	1
		The dimensions of the piece, mm, not more	60x60x60
		Briquette dimensions, mm, not more	600x600x600
T5	Shavings of titanium and titanium alloys. Brands: VT1-00, VT1-0, OT4-0, OT4-1, OT4, VT5, VT5-1, VT6, VT6S, VT3-1, VT9, VT14, VT16, VT20, VT22, PT-7M, PT3, PT- 1M, VT5-1, VT18U, TS5	Free of ferrous metals, debris, non-magnetic cutters, lubricants, emulsions and moisture.	
		Without visible color variability (Shiller effect)	
		metal content, %, not less	99
		Clogging, %, not more	1
		The length of the coil of metal shavings, mm	20-100
T6	Metallurgical production wastes with a high content of gases or not having a certain chemical composition: slag, spent electrodes,	Supply by agreement of the parties	-

Group	Characteristics of the group	Indicator	Norm
	bottoms (for uncut ingots), "crowns" of foundry production, splashes, tires, etc.		
T7	Piece waste and sheet trimmings, press residues; ingots and semi-finished products from titanium alloys rejected by chemical composition or mechanical properties	Supply by agreement of the parties	-

3.1.4 Recycling of titanium waste and titanium alloys

The functioning of an enterprise that produces products from titanium with a high degree of readiness should be characterized not only by the profit indicator, but also by the added value. An important factor in increasing added value is the reduction of material intensity. One of the main directions of reducing the material intensity of titanium products with a high degree of readiness is saving on primary raw materials due to the involvement in processing of recyclable waste. More complete use of production waste provides savings on ligature and other materials, which leads to a decrease in the cost of the intermediate product, an increase in labor productivity and added value.

The method of reducing the cost of titanium during operation of production based on the use of electron-beam furnaces with intermediate capacity (ELPPE). The use of such furnaces allows, firstly, to obtain flat slabs by one-time remelting and, secondly, to use any amount (up to 100%) of titanium scrap as a charge, which becomes an especially important factor in the conditions of increasing scrap generation. the need to minimize losses during the processing of scrap to the sizes required when involving them in the charge, as well as the fact that the equipment and technology of the finishing operation - the mechanical processing of ingots/slabs depends on how much of the waste can be reversible, that is, suitable for the return of the charge when subsequent smelting.[27]

Thus, the above-mentioned paragraphs once again draw attention to the important role of titanium waste in solving the problem of reducing the price of titanium products.

3.1.4.1 Recycling of waste from metallurgical titanium production

Spongy titanium: Titanium waste refers to low-quality spongy titanium (TG-Tv brand), of which up to 10% is formed in the process of sponge production. Up to 60% of TG-TV sponge can be used for melting ingots intended for the manufacture of non-aerospace products and parts from them.

An example of spongy titanium and its characteristics

Brands | Ti %, not less| other component %, not more| HB, not more

Марка	Хімічний склад титану губчастого								Твердість за Брінеллем, HB, 10/1500/30, не більше
	Ti, %, не менше	Масова частка домішок, %, не більше							
		Fe	Si	Ni	C	Cl	N	O	
ТГ-90	99,74	0,05	0,01	0,04	0,02	0,08	0,02	0,04	90
ТГ-100	99,72	0,06	0,01	0,04	0,03	0,08	0,02	0,04	100
ТГ-110	99,67	0,09	0,02	0,04	0,03	0,08	0,02	0,05	110
ТГ-120	99,64	0,11	0,02	0,04	0,03	0,08	0,02	0,06	120
ТГ-130	99,56	0,13	0,03	0,04	0,03	0,10	0,03	0,08	130
ТГ-150	99,45	0,2	0,03	0,04	0,03	0,12	0,03	0,10	150
ТГ-Тв	97,75	1,9	–	–	0,10	0,15	0,10	–	–

TG-TV

Figure 3.4 - Characteristics of spongy titanium [28]

The mass fraction of titanium is determined by the difference: 100% minus the sum of the mass fractions of regulated impurities.

The dimensions of the irregularly shaped pieces: (-30+12) mm, (-25+12) mm, (-12+2) mm, (-12+5) mm, (-5+2) mm, (-2+0) mm, (-2+1) mm.

Sponge titanium of the TG-Tv brand is produced in the form of pressed briquettes with a diameter of (115 – 170) mm and a height of (20 – 180) mm or in the form of pieces of the specified fractions.

One of the packaging methods: Sponge titanium is packed in steel barrels with a capacity of 0.25 m^3.

Figure 3.5 - Sponge titanium 12+2 mm [29]

Manufacturers of sponge titanium strive to increase the output of sponge of the highest grades (TG-90 - TG-120 brands) with a simultaneous decrease in the so-called "waste" of spongy titanium (TG-TV brand and non-standard). This can be achieved both by improving the technology at the limits of recovery and vacuum separation, and by increasing the cyclic productivity of recovery devices due to an increase in their geometric dimensions [30].The use of the largest in the CIS (7 tons per cycle) devices with an upper condenser at the new sponge production at the Solikamsk Magnesium Plant (SMZ) made it possible to raise the share of high-grade sponge to 80%.[31]. In addition, in order to reduce the output of TG-Tv spongy titanium, a new scheme for removing the bottom part of the block was implemented at the SMZ, which made it possible to reduce the output of TG-Tv sponge by almost 4%. At the Zaporizhzhya Titanium-Magnesium Plant State Enterprise, the lowest quality sponge titanium (cleaning from the retort and block), containing less base metal (< 97.75%) and more iron (> 1.9%) than sponge TG-TV, used for the production of high-percentage ferrotitanium (FTi70). Ferrotitanium is smelted using steel scrap and briquetted low-grade titanium sponge in furnaces of the VACUUM ARC SKULL FURNACE type, the transition to smelting in induction furnaces is being prepared.

Sponge titanium of small fractions (-2 mm), which is used to obtain powders, is obtained in industrial production as screening during the screening of crushed sponge in the process of assembling product batches. At the Zaporizhzhya Metallurgical Research and Industrial Plant (ZMOZ) of the Institute of Titanium, spongy titanium of small fractions is produced by the method of mechanical crushing and grinding of sponge fractions -30+10 and -12+2 mm according to GOST 17746-96. For this purpose, rotary toothed crushers of the DHT type with replaceable linings made of 5KHNM steel are used. For crushing larger pieces of spongy titanium, the ShDS-4 jaw crusher is used. Spongy titanium, which has passed the crushing stage, is screened on a vibrating screen with magnetic separation and packed in metal barrels with a capacity of 0.2 m3 with a polyethylene liner. Commercial products of ZMOZ are also titanium powders with a grain size of less than 1 mm according to TU U 14-10-026-98 "Titanium powders" and according to TU 48-10-78-83 "Chemical titanium powder", which are made from TG-Tv brand sponge. At the request of the customer, sponge titanium or powders can be saturated with hydrogen by hydrogenation.

3.1.5 Recycling of recyclable titanium waste

Smelting of ingots: Titanium alloy waste is represented by piece waste, shavings and sheet trimmings, as well as depreciation scrap. Most of these scraps are recyclable metal and can be used as a charge component in the production of ingots.

Involvement of waste titanium alloys in melting is the most rational and effective way of their utilization. The best unit for this purpose is the slag lining of furnaces using the SSE technology (slag lining - spent electrode). An important economic advantage of furnaces and SSE technology is the reduction of the volume of work on preparation for melting of returnable material (waste), the shape and dimensions of which in this technology are limited only by the size of the melting crucible of the furnace.[32]

The furnace crucible, otherwise known as a coreless induction furnace, is a melting crucible, usually cylindrical in shape, made of refractory material and placed in the cavity of an inductor connected to an alternating current source. The metal charge is loaded into the crucible and, absorbing electromagnetic energy, melts.

A crucible is a container for heating, drying, burning, firing or melting various materials. Crucibles are an integral part of metallurgical and laboratory equipment for casting various metals, alloys, etc. A distinctive feature of crucibles is the use of fire-resistant materials and highly resistant metals and alloys for their construction. The crucible usually has a conical (truncated cone) or cylindrical shape. Melting cups and melting boats are also a type of crucible.

In addition, SSE technology provides high quality smelted ingots, which are homogeneous and defect-free in chemical composition.

VSMPO-AVISMA Corporation expands the use of slag lining furnaces and introduces SSE + VDP technology instead of triple VDP when smelting ingot alloys Ti-10-2-3 and Ti-6Al-4V for use in the aerospace industry. VSMPO-AVISMA Corporation has declared a secondary titanium alloy and a method of its manufacture. The alloy contains, % mass: Al 0.01-6.5, V 0.01-5.5, Mo 0.05-2.0, Cr 0.01-1.5, Fe 0.1-2.5, Ni 0.01-0.5, Zr 0.01-0.5, Si 0.01-0.25, O d" 0.3, C d" 0.1.N d" 0.07 and Ti – everything else.[33]

The charge is arranged depending on the required value of the temporary resistance of the alloy, and the content of alloying elements in the alloy is determined based on the calculated values of aluminum and molybdenum strength equivalents. The technical result of the invention is to obtain regulated stable strength and technological properties of the alloy using a wide range of titanium waste. The alloy is intended mainly for the manufacture of sheet semi-finished products, structural products and can be used in defense and civilian industries.

At work [34] the paper presents the results of the study on the smelting of ingots of titanium alloys in a cathode ray slag lining furnace made of charge materials of various types (lump and sheet waste, chips and sponge). The need to take into account the type of raw materials when choosing the smelting mode, in particular the degree of concentration of the electron beam and the rate of increase in power at the initial stage of smelting, is shown. The development of a rational technology of electron beam slag lining smelting (EBSS) should provide for an optimal set of basic process parameters, of which the electron beam power and exposure time at a given temperature are decisive.

Titanium foundry waste can be processed into ingots at ELUTO-1 and ELUTO-2 installations equipped with electronic guns with a cold cathode [35].These installations worked at the Zaporozhye Motor Plant, and also found application in other industries.

3.1.6 Ways of using waste

The technology of etching titanium waste, in addition to the target task of removing the surface oxidized layer, involves obtaining titanium phosphate powder TiP_2O7 as a passing product, which can be used as a filler for varnishes, paints, plastics and polymeric materials.[36]

Titanium waste after etching, washing and drying can be processed into metal titanium powders by hydrogenation and electrolytic refining with increased technical effect due to the preliminary preparation of their surface.[37]

To obtain titanium of high purity, the method of iodide refining is used. Titanium iodide can be used in nuclear energy, the production of superconductors and single crystals. For this technology, promising raw materials are titanium metal chips VT1-0.

Waste titanium alloys can also be used in self-propagating high-temperature synthesis processes. The influence of the main characteristics of the original titanium material (chips, scales) on the properties of the final SHS of the titanium-based product has been proven. [38]

Spent lithium chemical current sources (LCCS) of the MRL type can be considered as one of the types of secondary raw materials of titanium [39].For 1 ton of lithium in spent LCCS contains 1.3 tons of titanium brand VT1-0. OJSC "VNIYKHT" has developed a technology for processing spent LCCS, which allows to extract and return to production lithium in the form of carbonate and manganese in the form of dioxide, as well as to dispose of other valuable components of LCCS, including titanium and nickel. The utilization efficiency of titanium can be significantly increased if it is used for the manufacture of such a functional material as an alloy based on titanium nickelide (nitinol) grade TN1 with a shape memory effect.

Properties of titanium carbide and its areas of application

Earlier it was mentioned about the reaction of high-temperature synthesis, self-propagating. This is the use of heat released from chemical reactions instead of heating a substance from an external source, so SHS processes successfully compete with traditional energy-intensive technologies. The powder mixture (charge) is placed in the reactor and the gas medium produces a local initiation of the process (ignition). Then there is a spontaneous propagation of the combustion wave, covering the entire mixture, the completion of the reaction and the cooling of the synthesized product.

Another advantage of SHS is the self-cleaning effect - the thermodesorption of volatile impurities at the synthesis temperature. Therefore, the resulting products may be cleaner than the initial reagents.

In SHS practice, the following types of reactions are known:

- reactions of elements (the most common), in particular gaseous: Al+Ni; Ti+C; Zn+S; Al+I_2; Nb+C+N_2 Etc;
- reactions of elements with more complex compounds, for example, oxidation in complex oxide media (Al+CrO_3; KNO_3+S), reactions of metals with organic compounds (Ti+ urotropin);
- reactions of complex molecules, for example, metal oxides, organic compounds.

Titanium carbide will be considered in more detail. Titanium carbide due to its high hardness and wear resistance is used in metallurgy as the basis of tungsten-free hard alloys, in carbide steels, is of practical importance in obtaining thin films and coatings based on it, in the production of cutting tools. Titanium carbide is resistant to aggressive media of most acids. Reacts with HF and HNO_3. Interacts with halogens. It is possible to heat in a hydrogen medium to a melting point without decomposition. It has a high melting point (>3000 °C). These properties make it possible to use it in mechanical engineering, aviation and rocket industries, in the oil sector, as a structural material in the creation of combustion chambers, turbine blades, ionizers in ion engines.

Due to its properties, titanium carbide is also in demand as a component of ceramic composites and functional ceramics.

3.1.7 Chlorination-evaporation of metal titanium scrap during processing using molten salt, which mediates the reaction

Titanium scrap

A significant amount of titanium scrap is also formed during the processing and machining of ingots for the final product. The aerospace industry is the largest consumer of crushed titanium product and provides 40-50% of global demand [40] demand in the aerospace industry is expected to grow steadily in the near future. It has been reported that 80–90% of the titanium material used in aircraft frames is an alloy of Ti-6Al-4V (Ti, doped with 4 % vanadium and 6 % Aluminium) and as shown in Fig. 3.6 (b), the material yield in the manufacture of aerospace parts is often only 10–20%.

To reduce the cost of production of titanium products, titanium waste must be processed into ingots of titanium or its alloys. Remelting is the easiest and most common way to obtain ingots from scrap metal. However, the use of common melting methods of Ti and its alloys offer very limited refining capabilities with respect to basic impurities such as O and Fe compounds, as well as typical alloying elements such as Al and V. As a result, only scrap metal relative to relatively low levels of contamination and/or well-sorted compositions of alloys can be melted into ingots. The ratio of mixing titanium scrap with raw materials for smelting depends on the use of the ingot and the quality of the scrap. the blending ratio of the Ti scraps used for the production of aerospace-grade ingots has been increased, owing to the generation and recycling of high-grade scraps during manufacturing of aerospace parts. [43]

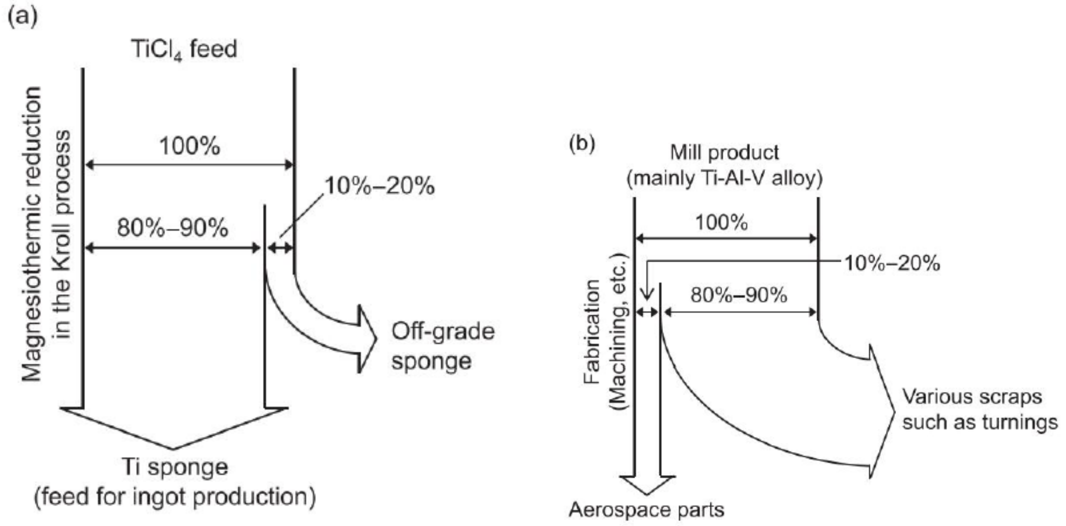


Figure 3.6- Flow of materials in (a) production of sponge titanium and (b) in aerospace manufacturing parts [41],[42],[43]

Low grade titanium scrap

Low-grade scrap that can't be remelted (including substandard sponge formed during the Kroll process) is reused as additives in the manufacture of steel or other metals (such as Al and Cu) or simply recycled as non-recyclable waste. The consumption of titanium scrap in steel and other industries is inherently a cascading and dissipative use of titanium. Since the growing demand for titanium products will undoubtedly lead to an increase in the amount of scrap generated in the future, it is necessary to develop an effective method for recycling this waste.

The extraction of $TiCl_4$ by combining Ti scrap metal with iron chloride waste ($FeCl_x$, x = 2.3) was proposed as an environmentally friendly recycling method. The extraction of Ti in the form of $TiCl_4$ is beneficial in terms of providing better control over the level of impurities and, therefore, is well suited for the processing of scrap of low-grade titanium. In addition, this process helps to minimize the problems associated with chloride waste, which is usually generated and ejected both in the Coll process and in the chloride process used to produce the TiO_2 pigment. In these processes, raw materials such as synthetic rutile (about 90–95% TiO_2) and ilmenite ($FeTiO_3$, approximately 43–65% TiO_2) carbochlorinate Cl_2 gas, with significant amounts of $FeCl_x$ and other chlorides generated as waste. The disposal of chlorine waste is not only a loss of chlorine in these processes, but is also a serious problem in terms of ecology and the high cost of disposal. The formation of chloride waste will increase markedly in the future due to a decrease in the quality of the TiO_2 raw materials used. Moreover, if pyrometallurgical selective chlorination is widely available for enrichment of low-grade titanium ores, the formation of $FeCl_x$ waste will increase even more.

From a thermodynamic point of view, the gaseous $TiCl_4$ can be extracted by direct interaction of Ti with $FeCl_x$ at a temperature of about 1100 K. However, the chlorination reaction is based on direct physical contact between Ti and $FeCl_x$ creates a number of technical problems, one of which is the initially slow kinetics of chlorination of Ti at a temperature of about 1100 K. For example, when thin Ti rods (φ = 1.5 or 3.0 mm, diameter) were heated to the temperature of molten $FeCl_2$ (i.e. pl. = 950 K) at 1100 K chlorination of Ti stopped in a few hours and most of the Ti remained unreacted. This is due to the fact that the Fe besieged during the process rigidly covers the surface of Ti, where it acts as a strong kinetic barrier. High volatility is also a problem when Ti scrap reacts directly with $FeCl_x$ waste. [43]

As written by Taninouchi [43] The chlorination behavior of metal Ti scrap when heated in molten $MgCl_2$ containing $SmCl_3$ was investigated to demonstrate the viability of chlorination based on the mediator reaction for the processing of both Ti scrap and $FeCl_x$ waste. Through a combination of thermodynamic analysis and fundamental experiments, it was demonstrated that the titanium component of substandard titanium sponge and Ti-6Al-4V alloy can be effectively chlorinated and evaporated by reacting with $SmCl_3$ in molten salt at 1100 K. It has also been confirmed that Fe and Ni in a substandard sponge are not chlorinated, but remain as a metal in molten salt. On the contrary, Al and V in Ti 6Al-4V alloy are chlorinated by $SmCl_3$ and evaporated.

In work [43] it was found that oxygen introduced into the reaction system forms a non-volatile TiOCl and does not consume SmCl3 when chlorinating Ti with molten mgCl2-SmCl3 salt at 1100 K. Oxygen was deliberately injected into the reaction system by adding MgO. Although the titanium rod in the crucible disappeared after heat treatment at 1100 K within 1 hour, only 14% of titanium evaporated. On the contrary, 44% of Ti evaporated when molten salt containing No MgO was used under the same conditions. [43]

These data indicate that chlorination using molten salt, which slows down the reaction, is a viable way to recycle not only substandard titanium sponge formed in titanium smelting plants, but also waste Ti-6Al-4V alloy, such as shavings formed in metalworking plants.

As a result of the analysis, it was established:

- The Zaporizhzhia Titanium-Magnesium Plant(«ZTMK») has developed a block diagram of the technological process of obtaining titanium [16], which is shown in Figure 3.1. But the block diagram covers only the technology of titanium production, and the issue of recycling concerns only this enterprise and not the industry in general.
- In the scientific and technical literature [1-2;10-42] there is no algorithmic block diagram of titanium recycling.
- • The scientific task of **creating an algorithmic block diagram of titanium recycling** that would cover the entire industry is urgent. The lack of such an algorithmic block diagram hinders the monitoring of the current industry and the predictive capabilities of analysis using automated computer tools.

The method of solving a scientific problem
Methods of system analysis (analysis and synthesis) were used to solve the above scientific problem.

3.2 The result of the solution of the scientific problem and the analysis of the results

The analysis was carried out - the flow of processes in the technological cycle of the production of titanium alloys and by-products, and a large amount of production waste was shown. Most of them are suitable waste for recycling, which can be effectively used if they are properly sorted and follow the quality standards of scrap and waste.
An algorithmic block diagram of titanium recycling by the synthesis method was created, summarizing the options and possibilities of using titanium shavings and titanium production and engineering waste in general for reuse. and develops an understanding of the variability of the use of waste at different stages of production for recycling. The algorithmic block diagram of titanium recycling is graphically presented in Appendix D.

The scientific novelty is characterized by the fact that for the first time a block diagram of the algorithmic model of titanium recycling has been proposed, covering all industries where titanium and titanium alloys are used.
Practical significance - the algorithmic block diagram allows to create a computer program for analyzing the results of monitoring of operating enterprises that use titanium and titanium alloys. In addition, such a program will allow to perform automated prognostic research, that is, researchers of recycling processes will receive a tool for conducting computer experiments.

This will make it possible to expand the understanding of titanium waste recycling and, on this basis, reduce the cost of finished products, create new products from suitable waste, reduce the need for waste disposal, and also reduce the need for greater extraction of this resource from the depths of the Earth. This will speed up the implementation of circular economy principles.

CONCLUSIONS

As a result of analysis of the current technical processes, we can make the following conclusions:

During the production of heads, thanks to more accurate workpiece, there is no necessity to remove a large layer of material during processing. Rationally, one should use the stamping workpiece on horizontal forging machines (HKM) to even more increase efficient use of material and reduce number operations.

Use the maximum principle concentration of operation and one worker place and use pneumatic devices (lathes cartridges), reducing at the same time manufacturing costs on special equipment.

In the Scientific Research section, properties of titanium were considered and its production cycle. An analysis was carried out about opportunities of using titanium shavings and waste titanium production and mechanical engineering generally for reuse. Options of processing titanium sponge, shavings, pieces and cushioning scraps were considerd.

An analysis was carried out about the basic processes in the technological cycle and production titanium alloys and by-products products, and a large amount of production waste is shown. Most of the waste can be recycled, which is possible when effectively using proper sorting and adherence to scrap and waste quality standards.

An algorithmic block diagram of titanium recycling by the synthesis method was created, which summarizes the options and possibilities of use titanium shavings and wastes of titanium production and engineering generally reusable. and develops understanding the variability of the use of waste at different stages of production for recycling . The algorithmic block diagram of titanium recycling is graphically presented in Appendix D.

Let's look at the block diagram in more detail (for visual perception, use Appendix D). The reason for choosing this direction was the high percentage of waste titanium chips in the process of manufacturing a part. Later, this direction was expanded to the extent of the possibility of recycling waste at earlier stages.

It is important to mention that recycling opportunities are considered from the stage of preparation of the components for the production of titanium sponge and ends with the finished product and the method of its recycling after the end of its useful life.

Will be analyze the stages of production and methods of recycling waste that are formed at each stage.

It is important to mention that sometimes the raw materials for recycling can be taken from different stages of production (the arrows show this in the diagram), but this only improves the situation, as it simplifies the creation of a recycling production line (will need fewer devices and machines to process all recyclable waste).

The first process, is the production of titanium sponge from components for the production of titanium sponge. At the same time formed up to 10% low-quality spongy titanium (TG-TV alloy brand). From this process, there are at least 4 uses for low-quality sponge titanium:

- Up to 60% low-quality spongy titanium can be remelted to produce non-aerospace(it is important) titanium ingots;
- Production titanium powders less than 1 mm in size
- Titanium sponge scraped off the retort and block is component of recyclable waste low-quality spongy titanium and thanks to smelting with steel scrap possible to get a high percentage of ferrotitanium (FTi70)
- Also low-quality spongy titanium can be used in the chlorination-evaporation of titanium scrap using molten salt for TiCl4 extraction but this process will be described later.

Second step is remelting titanium sponge in titanium ingots. In this step, piece waste, shavings, sheet trim, depreciation scrap are a component of the charge in the production of ingots for remelting non-aerospace titanium ingots.

In turn, titanium ingots are divided into aerospace workpiece (due to high requirements) and non-aerospace workpiece.

Analyze the situation with the aerospace workpiece - by machining, get aerospace parts. It is important to mention that less than 20% of a workpiece becomes a part. The rest becomes waste.

Next, divide into the general case and the situation with the possibility of recycling alloy Ti-6Al-4V.

First, let's analyze the case of alloy Ti-6Al-4V, since it has fewer branches and includes a full recycling cycle, allowing to get $TiCl_4$. And also because 80–90% of titanium material in the aerospace industry is alloy Ti-6Al-4V. For this process, will have to use additional sources of components, namely waste iron chloride ($FeCl_x$, $x = 2, 3$) which also reduces the amount of waste and is very rational.

A rational option for recycling titanium chips and other titanium waste of this alloy is chlorination-evaporation of titanium scrap using molten salt because as a result we get the possibility of extraction of $TiCl_4$ which is used in components for the production of titanium sponge

At the same time, Al and V evaporate. while Fe and Ni remain in the molten salt.

Back to the general case with titanium chips and other titanium waste in the machining aerospace workpiece. It can be combined with titanium chips and other titanium waste from non-aerospace workpiece into one column.

Next is ways to use these wastes. From them it is possible to produce:

- titanium powders less than 1 mm in size
- titanium phosphate $\underline{TiP_2O_7}$
- self-propagating products of high-temperature synthesis based on titanium

Also titanium chips and other titanium waste participates in chlorination-evaporation of titanium scrap using molten salt.

If add additional sources of components as lithium chemical current sources (LCCS) then titanium nickelide (nitinol) can be produced. this material has a memory effect.

And also together with shavings of a titanium alloy of VT1-0 it is possible to produce titanium iodide

The scientific novelty is characterized by the fact that for the first time a block diagram of the algorithmic model of titanium recycling has been proposed , covering all industries where titanium and titanium alloys are used .

Practical significance - the algorithmic block diagram allows you data to create a computer program for analyzing the results of monitoring of operating enterprises that use titanium and titanium alloys. In addition, such a program will enable automated predictive research, that is, process researchers recycling to get a means for conducting computer experiments.

This will allow to expand your understanding recycling titanium waste and, on this basis, reduce the cost of finished products, create new products from suitable waste, reduce the need for waste disposal, and also reduce the need for greater extraction of this resource from the depths of the Earth. and the fact that most titanium deposits are located in politically unstable countries, which is risky for the industry (as taught in the Sustainable Engineering courses at TUBAF), so processing will help reduce dependence on these countries .

This will speed up the implementation of circular economy principles.

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Appendix. An algorithmic block diagram of titanium recycling in the industry

Components for the production of titanium sponge (sec. 3.1.2)

Production of titanium sponge (sec. 3.1.2)

titanium sponge (sec. 3.1.2)

Remelting (sec. 3.1.2)

Titanium ingots (sec. 3.1.2)

Aerospace workpiece

Machining

Aerospace parts (<20% of the workpiece) (sec. 3.1.7)

piece waste, shavings sheet trim, depreciation scrap (sec. 3.1.5)

component of the charge in the production of ingots (sec. 3.1.5)

formed up to 10% (sec. 3.1.4.1)

Machining

non-aerospace parts

Non-aerospace titanium ingots (sec. 3.1.4.1)

Remelting (sec. 3.1.4.1, . 3.1.5)

(80 +% of the workpiece) Titanium chips and other titanium waste (sec. 3.1.7)

<60% TG-TV (sec. 3.1.4.1)

Titanium chips and other titanium waste

lithium chemical current sources (LCCS) type MRL (sec. 3.1.6)

low-quality spongy titanium (TG-TV alloy brand) (sec. 3.1.4.1)

80–90 % of titanium material – Alloy Ti-6Al-4V (sec. 3.1.7)

titanium powders less than 1 mm in size (sec. 3.1.4.1 , 3.1.6)

titanium phosphate TiP_2O_7 (sec. 3.1.6)

shavings of a titanium alloy of VT1-0 (sec. 3.1.6)

titanium nickelide (nitinol) – has a memory effect (sec. 3.1.6)

titanium sponge scraped off the retort and block (sec. 3.1.4.1)

self-propagating products of high-temperature synthesis based on titanium (sec. 3.1.6)

Titanium iodide (sec. 3.1.6)

smelting with steel scrap (sec. 3.1.4.1)

high percentage of ferrotitanium (FTI70) (sec. 3.1.4.1)

Chlorination-evaporation of titanium scrap using molten salt (sec. 3.1.7)

Waste iron chloride (FeClx, x = 2, 3) (sec. 3.1.7)

Extraction of $TiCl_4$ (sec. 3.1.7)

Al and V evaporate (sec. 3.1.7)

Fe and **Ni** in the molten salt (sec. 3.1.7)

The beginning of the block diagram

Process

Recyclable waste

The main product

Additional sources of components

Component of recyclable waste

Intermediate product

Completed product after recycling