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INFLUENCE OF THE PROPERTIES OF SECONDARY α-TITANIUM CASTS, OBTAINED BY CHAMBERLESS ELECTROSLAG CASTING, FOR PROCESSING BY TURNING

The object of the study is the machinability by turning of secondary α-titanium casts produced via chamberless electroslag remelting (CESR) (hereinafter referred to as secondary α-titanium), using non-consumable electrodes fabricated from 100% VT1-0 titanium scrap. One of the most challenging issues is the difficulty of machining both primary and secondary titanium. Specifically, this includes chip adhesion to the cutting tool due to the high plasticity of titanium alloys and increased contact surface temperatures, which lead to oxidation.

The study employed modern metallographic methods to examine the macrostructure, chemical composition, and mechanical properties of α-titanium; experimental methods were used to determine optimal turning conditions; and the machinability coefficient was determined using graphical interpolation. Tool wear resistance was evaluated by comparative methods.

Optimal machining parameters were established for the removal of the alpha-case layer and achieving a surface roughness of classes 5–8: cutting speed $V=25$–30 mm/min; feed rate $S=0.5$–0.9 mm/rev; cutting depth $T=1.0$–1.2 mm. The selected turning regimes enable the production of complex threaded profiles in accordance with ISO 724:1993 requirements. The study demonstrated that turning secondary α-titanium casts does not require additional technological measures or high-wear-resistant specialized tools. The machinability coefficient was determined to be 0.47–0.48. The improved machinability of the secondary α-titanium casts is attributed to the high quality of the metal, ensured by droplet-based metal transfer and consistent crystallization in a water-cooled copper mold, resulting in higher density and structural homogeneity. The application of chamberless electroslag casting technology enhanced the quality of α-titanium and expanded the potential for its use in the manufacturing of parts for mechanical engineering, chemical, and aerospace industries.

Producing secondary α-titanium using titanium scrap through this technology allows a reduction in production cost by approximately 25–30%.

Keywords: *ingot, machinability, α-titanium, roughness, strength, macrostructure, microstructure, turning, wear resistance, hardness.*

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1. Introduction

One of the ways to increase titanium consumption is to involve titanium waste as a raw material for the production of secondary titanium casts and other titanium-based products. Numerous studies have been dedicated to this direction, including the development of recycling technologies for titanium waste through modern electrometallurgical methods. It has been demonstrated that when up to 30–40% of the ingot mass consists of scrap, high-quality casts can still be produced by such methods [1–4]. A review of the literature reveals that there are limited works focusing on secondary α-titanium production via chamberless electroslag casting, and on improving the machinability of α-titanium casts by cutting tools such as turning.

Therefore, the development of new innovative technologies for producing secondary titanium casts with a high scrap input (above 40%), as well as the investigation of their technological properties, particularly machinability by turning, remains a relevant and important task.

Current research on the turning of difficult-to-machine materials, including titanium alloys, is conducted through both theoretical and experimental approaches.

The application of plasticity theory to the study of cutting processes allows for a scientific explanation of the underlying phenomena, enabling the development of computational models, identification of load distributions on tool surfaces, and evaluation of residual stresses and strains on machined surfaces. This also supports the selection of optimal cutting tool geometry and machining parameters [5].

The deformation theory of plasticity, as proposed by Hencky and Nadai [6], is most appropriate for describing the deformation processes during cutting.

A phenomenological macroscopic theory based on experimental results and continuum mechanics principles makes it possible to characterize chip formation mechanisms [5].

Experimental methods are also crucial and informative for studying the machinability of titanium alloys. A commonly used "classical method" involves tracking the relationship between cutting speed and tool wear at fixed time intervals. This enables the calculation of the machinability coefficient while considering the structural condition and mechanical properties of the material. Using this method, the machinability coefficient has been determined for many standard titanium alloys.

The machinability of titanium alloys can be evaluated based on cutting parameters such as cutting force, temperature, chip shrinkage, energy consumption, and comparison with reference materials [7, 8].

Results of prior machinability studies on standard titanium alloys have laid the scientific foundation for selecting turning parameters and have defined the requirements for tooling and equipment [9–13].

A critical analysis of the literature confirms that producing α-titanium alloys with enhanced machinability remains a challenge, justifying the aim of the present study.

The aim of this paper is to determine the machinability characteristics of secondary α-titanium casts by turning, taking into account their structural state, chemical composition, mechanical properties, and the presence of an alpha-case surface layer. These findings will support technological decisions in the mechanical processing of components manufactured from secondary α-titanium casts.

2. Materials and Methods

The object of this study is the machinability by turning of secondary α-titanium casts produced via chamberless electroslag remelting (CESR) (hereinafter referred to as secondary α-titanium), using titanium-based feed electrodes fabricated from 100% VT1-0 sheet scrap.

The experimental secondary α-titanium casts were obtained by an A-550 unit for chamberless electroslag casting with consumable electrodes fabricated entirely from VT1-0 titanium sheet scrap [14].

A schematic diagram of the chamberless electroslag casting process for secondary α-titanium is shown in Fig. 1. Conventionally, the end of the consumable titanium electrode *1* is melted in a slag bath *2* at a temperature of 1750–1850°C, generated by an electric current from a power supply *7*. The molten titanium droplets flow into the molten metal pool *3* and solidify into an ingot *4* inside a water-cooled copper mold *6*. The electric current is supplied from the power source *7* to the mold bottom plate *5* and to the consumable electrode *1* via a sliding current feeder *10* mounted on an insulating plate *8* located at the top flange of the mold *6*.

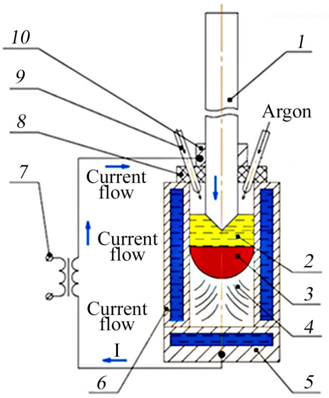

Fig. 1. Schematic diagram of the chamberless electroslag remelting process of secondary α-titanium: *1* – consumable titanium electrode; *2* – slag bath; *3* – molten metal bath; *4* – titanium ingot; *5* – bottom plate; *6* – mold; *7* – power supply; *8* – insulating plate; *9* – argon feed unit; *10* – sliding current feeder

In conventional special metallurgy and electroslag remelting processes, the current passes through the entire consumable titanium electrode, causing it to heat up significantly (to 500–600°C), leading to oxidation and degrading the quality of the remelted titanium.

To prevent this, protective vacuum chambers are typically used. In the CESR process, however, the electrical current supplied via the sliding contact heats only the section of the electrode between the current contact and the slag bath. This part is located inside the mold, which is filled with protective argon gas, ensuring shielding from oxygen and nitrogen.

This current delivery scheme fundamentally changes the thermal state of the titanium electrode, preventing its oxidation and eliminating the need for vacuum chambers typical of vacuum arc, cold hearth, plasma arc, electron beam, and chamber-type electroslag remelting technologies. Protection of the slag bath and heated electrode portion is ensured by argon fed through device *9* in Fig. 1.

This technology was developed at the National University "Zaporizhzhia Polytechnic".

The external appearance of the investigated casts (85 mm diameter) is shown in Fig. 2.

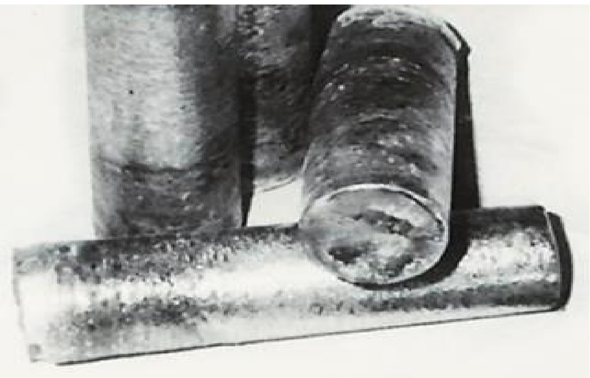

Fig. 2. Appearance of secondary α-titanium casts: diameter 85 mm, length 340 mm

The surface of the casts was smooth, free of waviness, pinches, or folds, which contributes to better machinability. However, during the melting process, a hardened alpha-case layer forms on the surface of the titanium casts [15, 16], which significantly hinders machinability during initial cutting passes.

In the produced secondary α-titanium casts, the alpha-case layer extended to a depth of 0.3–0.5 mm, with a hardness of 10–13 GPa. The depth of the alpha-case was determined using the method described in [17], as well as by sequential grinding (in 0.1 mm increments) and measuring hardness.

The chemical composition of the casts was determined via optical emission spectrometry using the SPECTROMAX instrument (SPECTRO, Germany) according to standard methods. Impurities such as nitrogen, oxygen, and hydrogen were measured with an ON900 gas analyzer (ELTRA, Germany). These tests were conducted in accredited laboratories, "Send Lab" (Dnipro, Ukraine) and the Zaporizhzhia Titanium and Magnesium Combine (Zaporizhzhia, Ukraine).

Macrostructure was examined visually and using a Stemi 200-c stereomicroscope (Carl Zeiss, Germany) on etched macrosections. Ultrasonic inspection of the casts was performed using a UD4-1 flaw detector with a 5K6 transducer in the laboratory of the Zaporizhzhia Titanium and Magnesium Combine.

Microstructural analysis was carried out using an Axio Observer. DLM optical metallographic microscope (Carl Zeiss, Germany) and a NEOFOT-32 metallographic microscope. Samples for microstructure analysis were prepared by sequential grinding with papers from grit No. 40 to micron-grade M20, followed by polishing on cloth with DialDuo suspension (STRUERS).

Etching was done using two reagents: one composed of HF – 10 mL, HNO_3 – 25 mL, and glycerin 65 mL; the other, known as Kroll's reagent, containing H_2O – 100 mL, HNO_3 – 6 mL, and HF – 3 mL.

Mechanical properties (σ_u, $\sigma_{0.2}$, ψ, δ) were determined using standard methods on calibrated equipment at the "Send Lab" facility.

The results were as follows:

– *chemical composition* of the experimental secondary α-titanium casts, wt. %: Fe – 0.31%; C – 0.12%; Si – 0.11%; O – 0.28%; N – 0.056%; H – 0.016%; Ti – balance;

– *mechanical properties*: ultimate tensile strength $\sigma_u = 560$ MPa; yield strength $\sigma_{0.2} = 505$ MPa; elongation $\delta = 7.6\%$; reduction in area $\psi = 13.5\%$;
– *macrostructure*: solid, dense, coarse-grained, homogeneous, with no metallurgical or process-related defects (Fig. 3, *a*);
– *microstructure*: typical of cast titanium, with transformed α-grains consisting of β-lamellae (Fig. 3, *b*).

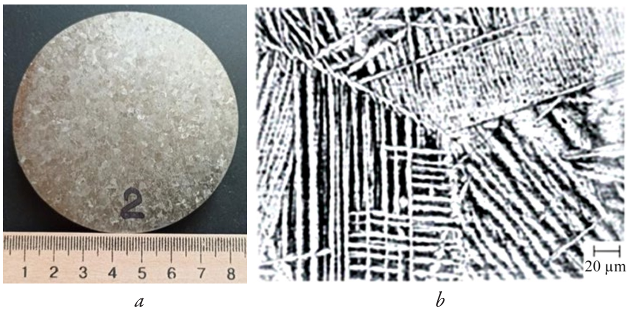

Fig. 3. Secondary α-titanium ingot: *a* – macrostructure; *b* – microstructure

To remove the alpha-case layer by turning, the cutting parameters shown in Table 1 were used. The carbide inserts (VK-8 grade) had the following geometry: major cutting edge angle $\varphi_1 = 45°$; minor cutting edge angle $\varphi = 14°$; rake angle $\gamma = 0°$; clearance angle $\alpha = 12°$.

The machinability coefficient was determined by graphical interpolation. Based on data from [11] correlating machinability coefficients (K) with tensile strength (σ_u) for standard titanium alloys, a $K=f(\sigma_u)$ graph was constructed and used to determine the machinability coefficient of secondary α-titanium.

To achieve the required surface roughness class and produce threaded profiles by turning, the recommended machining parameters from [11, 13] were used. A technological test piece was fabricated with rough, semi-finish, and finish surfaces, along with an M36 × 4 metric thread.

Surface roughness was measured using a VIT TR200 profilometer ($R_a = 0.005$–16 μm, $R_z = 0.02$–160 μm, indexing resolution 0.001 mm). The geometric parameters of the M36 × 4 thread were assessed using a UIM-21 universal tool microscope.

The machinability of the central part of the ingot was also assessed by turning a section to 14 mm diameter and drilling a 10 mm hole, comparing the performance with that of the outer sections. All machining was carried out on a 1K62 lathe.

3. Results and Discussion

In removing the alpha-case layer by turning, it is critical to ensure that the cutting edge of the tool operates below the hardened surface layer. This was achieved by chamfering the ingot end (3 × 45°) and selecting an appropriate cutting depth.

Turning of the secondary α-titanium ingot surfaces was performed using three cutting regimes (Table 1), recommended for difficult-to-machine materials [18].

Table 1

Cutting parameters for the initial turning pass
of secondary α-titanium casts

Cutting Regime No.	Cutting parameters		
	Cutting speed V (mm/min)	Cutting depth T (mm)	Feed rate S (mm/rev)
1	40	0.2	1.5
2	50	0.5	1.0
3	30	1.0	0.6

In the first regime, cutting was practically ineffective. The cutting edge became blunt almost immediately, which is explained by the cutting depth being less than the alpha-case thickness.

In the second regime, the increased cutting depth brought the tool edge to the boundary of the alpha-case and titanium substrate. The tool began to wear after 96 mm of cutting.

In the third regime, the cutting depth was 1.0 mm, greater than the alpha-case depth (0.3–0.5 mm). Thus, cutting was performed entirely through the titanium substrate. The chip had a fractured appearance, indicating the presence of the brittle alpha-case layer, which lacks plastic deformability. The cutting edge did not wear out. The total machined length of the ingot was 220 mm (Fig. 4).

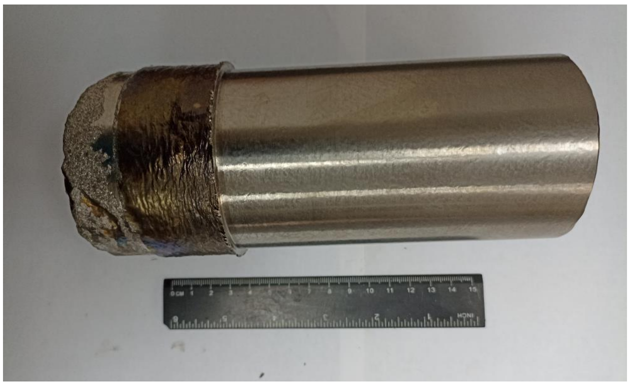

Fig. 4. General view of the secondary α-titanium ingot after removal of the alpha-case layer by turning

At the initial stage of the study, it was also established that cutting speed significantly affects the turning process. Higher cutting speeds lead to increased temperatures at the tool – workpiece interface, which is typical for titanium machining due to poor thermal conductivity.

Therefore, to effectively remove the alpha-case layer from the ingot surface, turning under regime No. 3 (Table 1) is recommended.

In the next stage, the machinability coefficient of the secondary α-titanium was determined. A graph was plotted showing the machinability coefficient (K) of standard titanium alloys versus their tensile strength (σ_B) (Fig. 5). Based on the tensile strength of 560 MPa for the studied material, the machinability coefficient was determined as $K = 0.47$–0.48.

As shown by the constructed graph, the highest machinability coefficient ($K = 0.5$) was observed for VT1-0 and VT1-1 titanium alloys. VT1-2 alloy ($K = 0.45$) exhibited slightly lower machinability than the studied secondary α-titanium, likely due to its higher impurity content.

The machinability of OT4 alloy ($K = 0.4$) is lower due to a higher tensile strength ($\sigma_B = 620$ MPa), achieved through aluminum alloying. Highly alloyed grades such as VT14 and VT22 are even more difficult to machine, with machinability coefficients of $K = 0.32$ and $K = 0.3$, respectively. Despite this, these alloys are widely used in the aerospace industry.

Thus, the machinability of secondary α-titanium casts is comparable to that of VT1-1 and VT1-2 alloys, making them suitable for precision-machined components.

It is worth noting that the machinability coefficient is typically compared with that of Steel 45, which has $K = 1.0$ and is used as a reference. All titanium alloys, including the studied one, show significantly lower machinability ($K = 0.3$–0.5) relative to Steel 45.

Another important indicator of titanium machinability is the achievable surface roughness.

At the next stage of the study, a technological test piece (Fig. 6) was produced using the cutting parameters shown in Table 2, encompassing rough, semi-finish, and finish surface treatments. The surface roughness results were measured and are shown in Fig. 6.

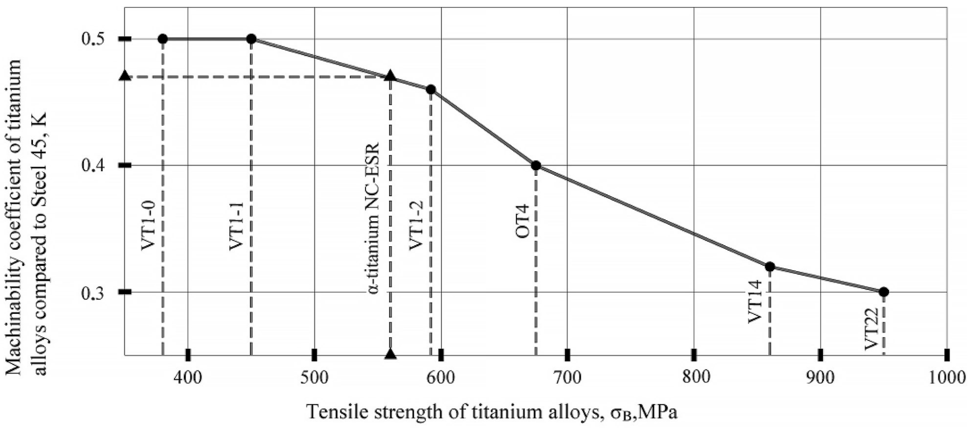

Fig. 5. Dependence of machinability coefficient (K) of titanium alloys on tensile strength (σ_u)

Table 2

Cutting parameters for surface finishing of secondary α-titanium casts

Surface Treatment	Cutting parameters		
	Cutting speed V (mm/min)	Cutting depth T (mm)	Feed rate S (mm/rev)
Roughing	20	3.5	1.5
Semi-finishing	60	2.5	0.4
Finishing	80	1.2	0.1

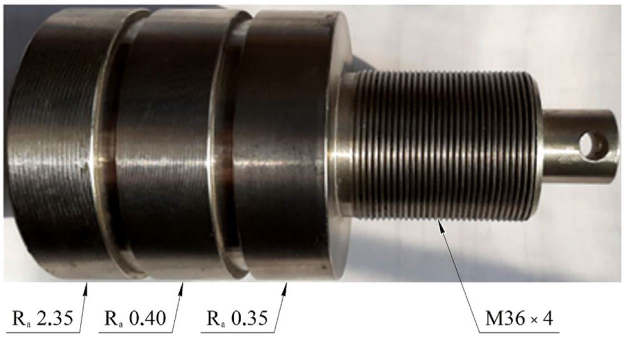

Fig. 6. Surface roughness measurement on a technological test piece made of secondary α-titanium after mechanical processing

As a result, the machined surface roughness ranged from class 5 to class 8.

Thread cutting performance was also evaluated as an indicator of machinability. On the same test piece, an M36×4 metric thread was produced. No surface defects such as chipping, burrs, or crest breakage were observed.

The resulting thread dimensions (M36×4): pitch – 4 mm; pitch diameter – 36.4 mm; minor diameter – 33.67 mm; thread height – 2.16 mm met ISO 724:1993 standards, verified using a UIM-21 universal tool microscope.

There is a possibility that a columnar structure forms in the ingot center due to solidification conditions, which may negatively affect machinability. Therefore, a 14 mm diameter section corresponding to the central axis was machined. It was found that machinability remained uniform throughout the cross-section. This is supported by the homogeneous macrostructure shown in Fig. 3, *a*.

Additionally, the wear resistance of VK-8 carbide inserts was assessed during the turning of the secondary α-titanium. Tool wear did not exceed acceptable limits, confirming that machining of the casts does not accelerate tool degradation and does not require special tool grades with enhanced wear resistance.

The practical significance of these results lies in extending the capabilities of chamberless electroslag casting technologies for titanium alloys, developing new grades for specialized applications, and confirming that secondary α-titanium can be used for precision-machined critical components.

Reproducibility and industrial implementation are supported by the properties of secondary α-titanium and the specialized equipment used in the remelting process.

However, the study does not fully explore the potential of secondary α-titanium in other machining operations such as drilling, milling, and grinding. Therefore, further research is warranted to explore the performance of secondary α-titanium casts in other machining processes, including drilling, milling, and grinding.

4. Conclusions

The influence of the properties of secondary α-titanium casts produced by chamberless electroslag casting on machinability by turning was investigated. It was demonstrated that turning of these casts does not require additional technological procedures, specialized equipment, or cutting tools with enhanced wear resistance.

It was established that to effectively remove the alpha-case layer from the surface of the casts, the following cutting parameters should be applied: cutting speed V=25–30 mm/min; feed rate S=0.5–0.9 mm/rev; and cutting depth t=1.0–1.2 mm which must exceed the thickness of the alpha-case layer.

The density and monolithic macrostructure of the casts ensure good machinability by turning, enabling the achievement of surface roughness classes ranging from 5 to 8, as well as high-quality thread profiles.

The machinability coefficient for turning secondary α-titanium casts was found to be 0.47–0.48, indicating favorable conditions for machining with cutting tools.

Conflict of interest

The authors declare that they have no conflicts of interest related to this study, including financial, personal, authorship, or any other interests that could have influenced the research and its results as presented in this article.

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Data availability

The manuscript is associated with data available in a data repository.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the preparation of this work.

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