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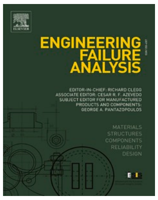

Root cause analysis of coining tool failure with proposed solution to extend its service life

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ABSTRACT

The article deals with a root cause analysis of coining tool failure after its untimely discarding and the design to extend its service life by innovating the manufacturing process. The analysis was performed on the coining die which had to be put out of service due to the insufficient quality of minted stainless coins. The purity of steel and the microstructure of the material of the semi-finished goods were evaluated. Furthermore, an analysis of the coining die failure under the surface and in the core was performed as well as the state of the chromium layer failure on the coining die relief. Based on the results of the analysis, a new experimental coining die was designed and produced according to an innovative manufacturing process. The pressing of the relief was carried out in a vacuum furnace and relief was coated with a TiAlN by the PVD method. New processes introduced in the production of coining die prevented the failure of die punches, extended the time of operation, thereby increasing quality of the coin production.

1. Introduction

Coinage is a specific forming technology that requires a very precise preparation and the manufacture of tools. Circulating coins, as a national currency, have to meet strict national and international quality standards [1–3].

Manufacturing of coining dies consists of several sub-processes. The first one is the selection of high-quality tool steel which is made by electroslag remelting or vacuum remelting, with a high degree of purity [4–6], according to the standards [7–11]. Next one is chip machining [12–14], then relief pressing in closed and/or open press cases [1,2,15] and heat treatment by hardening and subsequent tempering to the required hardness [16–18]. Final steps are grinding and polishing [1,19,20]. A special attention is paid to the final surface treatment in various ways, from galvanic chrome plating, which, in addition to achieving insufficient life of the relief, also

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represents a health and environmental hazard [2,21–23], to the coating of tools using the CVD (Chemical Vapor Deposition) method, PVD (Physical Vapor Deposition), DLC Films and so on [3,18,19,24–27].

When stamping high-strength and anti-corrosion steels, the wear associated with the increase in contact pressures increases. Fatigue and creep failures are typical consequences of operational degradation processes, which affect the material properties of machine parts and tools [5,28,29]. This is due to the impact of cyclically variable stresses (fatigue) or stresses and temperature (creep) [6,13,19,28,30,31]. Taking into the consideration the fact that the coining tools transmit great forces and the die works under dynamic shock loads with a frequency of approx. 750 – 850 S/min [1,5,14], they are designed with a great caution.

The service life of coining tools and thus the quality of coins are therefore influenced by several factors [1,19,32,33]. The most important factors are material of the die – mainly its cleanliness, technology of relief production, heat treatment of the dies – mainly the strict following the procedures and the choice of equipment, and the method of final treatment of the relief connected with a suitable method of its coating [1,2,18,34–36].

The manufacturers of the coining tools can not affect the purity of the steel. It is determined by the brand of steel and the method of production of semi-finished products. When choosing semi-finished products for the production of coining tools, more expensive steels, but of higher quality in terms of micro-purity, can be used. They are produced by electroslag remelting or vacuum remelting. However, they can also choose classic moulded semi-finished products at a lower price, which only guarantees standard micro-cleanliness [1,2,11,34,37].

Non-metallic inclusions in steel are one of the most important parameters of metallurgical quality [38,39]. The content of non-metallic inclusions in steel depends on the technology of its production. It is necessary to use high-quality steels for tools, such as punches for the production of coins, in terms of the content of undesirable elements that form compounds in steels – non-metallic inclusions (oxides, sulphides, silicates, aluminates). These worsen their mechanical and technological properties [34,40]. Globular inclusions (aluminates, silicates) are hard and brittle. They impair machinability and formability [9,15,37,41]. During finishing grinding and polishing operations, they are released from the surface and cause surface defects on functional surfaces. If non-metallic inclusions appear on the functional surface of the die, they act as a stress concentrator and become the seeds of failure (contact fatigue) of the relief surface during cyclic shock stressing of the dies during coin production. [20,36,] They also cause premature cracking even if the surface of the punches has been coated. Each coating is completely characterized by a very wide set of basic properties and parameters, among which we can include the chemical and phase composition, microstructure, and thickness of the coating (in the case of multi-layer coatings, the number and thickness of individual layers). In addition, the types of bonds at the substrate-coating interface and the bonds between individual layers are also important. [23,27,42].

The aim of the presented research was therefore to analyse and experimentally evaluate the degree of the impact of important selected factors on the service life of the dies. The research was supposed to help find the causes of the failure of the die from the viewpoint of profitability of a very low number of coins and then to propose innovations and new solutions into the production process, which would lead to the elimination of their breaking and thus the increase in the service life of the dies. Based on the best knowledge of the authors, it is possible to claim that only a few studies have dealt with coining tools damage [6,14,19,23,25,26,32,43,44] while a comprehensive analysis of the root causes of their failure together with a newly proposed solution has not yet been processed in such a way that it can be considered a novelty of the presented research.

The contribution of the study points to the fact that each step of the technological process is very important in the production process chain and significantly affects not only the quality of the tool but also the resulting quality of the minted coins. The detection of fails in each of the steps therefore plays a significant role in preventing failure and can thus contribute to the elimination of damage to the tools after they are put into operation. The innovation of the technological production process ensured a 148-fold increase in the number of minted coins in the quality demanded by customers and also under requirements of national and international standards since poorly produced coins can be considered counterfeits and must be withdrawn from circulation. In the article, the authors tried to briefly but factually present the results of the experimental investigation, which was carried out at the initiative of practice and its results demonstrably brought highly valuable improvements, namely in the area of quality, savings of expensive material (tool steel for cold forming) and, last but not least, in areas of environmental protection (substitution of chrome plating for ecological coating).

As already pointed out above, there are only a few articles dealing with this issue [14,19,23,44], but even these are mostly studies in a different sense than in this article It is, therefore, possible to consider the novelty of the presented research not only the topic of the production of coining tools but also following the scope of the journal, it is also about identifying the possibilities of failure of various aspects in individual phases of the coins production (technology, construction, material, etc.) and pointing out ways solutions to occurring problems. The inverse methodology investigation for the causes of failure can subsequently be applied in various production processes, which can be interesting for both the professional and lay public.

2. The root case analysis of the coining die failure put out of the operation

The service life of coining tools is expressed by the number of coins minted by one punch, while maintaining the required quality of the coins [14,16,19,36]. The values of 600,000 to 800,000 pieces of minted coins are considered to be the average lifetime of coining tools. Coining dies are taken out of service mostly due to wear – violation of their relief which manifests itself on the sharp edges of the relief as a damaged, chipped relief. The quality of the produced coins is checked continuously in certain batches. In case of reduced quality of minted coins, it is necessary to put out the tool and replace it with a new one [1,2,5,14,25].

Coinage is technology of cold volume forming. The production of coinage tools – coining dies, consists of several sub-processes from chip machining, through relief pressing, heat treatment up to surface treatment. As the coining tools transmit large forces, they are designed with high stiffness. The coining tools are subject to high demands in terms of surface quality and shape and dimension accuracy ranging from ± 0.01 to ± 0.05 mm. The functional surfaces of these tools are ground and polished, while a special attention is paid to the surface treatment of the punch and die, so that the relief embossed on the coin is clear, distinct and unambiguous [1,2,5].

The coining die, which became the motivation for the presented research, was taken out of service, as only 5,000 coins of the required quality were minted. It was made of a soft-annealed Böhler K455 (DIN/EN 1.2550, 60WCrV7) steel rod semi-finished goods with a maximum hardness of 225 HB [18,45]. In general, it is an impact-resistant steel with high toughness and resistance to compressive stress and is characterized by high resistance to wear and tear. It is used for the production of shearing tools (matrices and punches) for the processing of thicker sheets, for punches for cold punching, for massive coining tools, for scissors blades for cold cutting, etc. The chemical composition of steel according to [18] is shown in Table 1.

The coining die was intended for producing coins made of anti-corrosion steel X6Cr17, W. Nr. 1.4016, AISI 430. It is a magnetizable ferritic stainless steel. It is characterized by a good corrosion resistance, very good polishability, deep extensibility and bendability. When forming at temperatures below 20 °C, it tends to become brittle. The machinability is comparable to alloy case-hardened steels. The use is very diverse, due to its resistance to water, water vapor and humidity, weak acids, and alcohols. It is suitable for furniture production, in architecture, in medical technology, in the chemical industry, etc. [43,44,46]. The chemical composition of the steel used for the production of coins is shown in Table 2. The technological process of making a coining die is illustrated in Fig. 1.

Fig. 2a shows the semi-finished goods of the coining die before pressing the relief with a mother punch. Fig. 2b shows the parts of the punch, the functional cylindrical part, the transition radius and the clamping conical part of the punch. In Fig. 2c there is a finished coining die with a pressed relief.

According to the manufacturer's available information, the put out coining die was hardened in a hardening furnace with a protective nitrogen atmosphere (H-75 %, N-25 %). The heat treatment mode is shown in Fig. 3.

The coining dies were hardened to a higher hardness than the required value of 58 HRC and it was to a value of 62 HRC. This is because the hardness will drop by several Rockwell units during chromium-plating. Tempering of the is done by heating in the furnace immediately after martensitic hardening and subsequent cooling in oil.

A destructive method was used for punch analysis. The reason was to achieve the uniformity of comparing the condition of the discarded punch with the new, experimental punch. In this case, the destructive method is more accurate and complex than the non-destructive method. For reasons of the analysis, the coining die were cut in the longitudinal direction by electro-erosive wire cutting (WEDM) technology (Fig. 4). The coining tool was cut in the only step by WEDM technology under supervision of the experts from the given company.

In order to reveal the reasons for early putting out the coning die, the following investigations were done:

a) macroscopic evaluation;
b) evaluation of micropurity;
c) evaluation of the microstructure and evaluation of the chrome layer thickness.

a) Macroscopic evaluation of the coining die

The macroscopic evaluation of the material has found that when the semi-finished goods was placed in an undivided – monolithic casing of the press, the material did not have a necessary degree of freedom during shaping. By coining in a closed die (monolithic press case), large internal stresses are introduced into the material and they are added to the stresses arising during chip machining (turning of the semi-finished goods of the punch – the second step of the manufacturing process when manufacturing the punch) and mainly also during heat treatment – hardening. As it can see in Fig. 5, a barrel-like shape was created on the cylindrical part of the tool. At the same time, the deformation of the fibres in the punch body was observed. A crack spread from the surface to the inside of the tool – an unacceptable state of the tool failure. Macroscopic evaluation was performed on the Stereomicroscope STEMI 2000C, Zeiss Co.

b) Evaluation of the micro-purity in the coining die material

The coining die are exposed to a high impact cyclic stress (they mint 750 coins per minute). Therefore, high demands are placed on the material and its heat treatment. The micro-purity of steel which the coining die are made from must be very high, as the present non-metallic inclusions can be the source of fatigue cracks. [47–49].

The primary evaluation of the micropurity of steel was performed on a longitudinal section of a put out coining die. Several fields of vision with the prescribed size are evaluated on the samples according to the standard and the relevant table – standard. The result is the average value of the existence of insets. The micro-purity of K544 tool steel was evaluated on polished, non-etched samples according to ISO 4967:2013 [7]. According to the Jernkontoret table [10], the degree of purity is evaluated as 3D – globular oxides of a medium size and occurrence (Fig. 6a). Using a scanning electron microscope, non-metallic inclusions with a size of up to 10 μm were identified (Fig. 6b and 6c). Similar findings were made by Zerbst [50], who claims that sizes as small as ten or tens of microns can induce fatigue cracks. According to his study, the fatigue limit of high-strength steels tends to be affected by inclusions, while the fatigue limit of low-strength steels is not. Thus, inclusions would be expected to take over the role of initial defect size when the material strength is high enough. On the other hand, larger inclusions would be required to achieve the same effect in lower-strength

Table 1
Chemical composition of the Böhler K455 steel used for the production of the tool [18].

Element	C	Si	Mn	Cr	V	W	Fe
(% wt.)	0.63	0.60	0.30	1.10	0.18	2.00	balance

Table 2
Chemical composition of X6Cr17 steel [46].

Element	C	Si	Mn	Cr	Ni	N	P	S	Fe
(% wt.)	≤0.08	≤1.0	≤1.0	16 – 18.0	–	–	≤0.04	≤0.035	balance

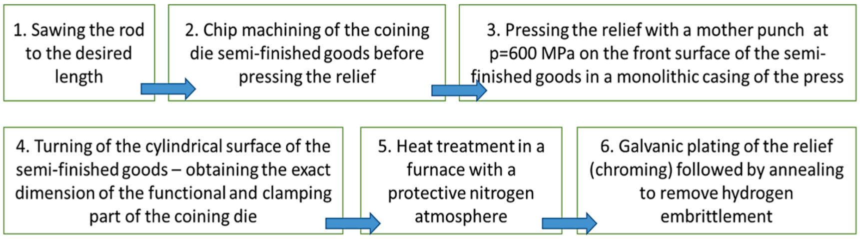

Fig. 1. The process of the production of the original coining die.

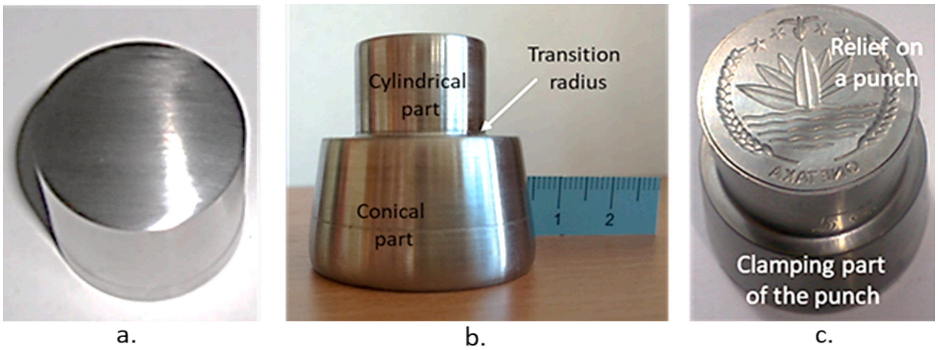

Fig. 2. Semi-finished goods of a coining die (**a**), coining die before (**b**), after pressing the relief – final appearance (**c**).

materials.

The achieved results of the pollution analysis were also consulted with the steel supplier, the company Böhler – Uddeholm Slovakia, s.r.o. Their statement was that it met the pollution criteria of steel produced by the conventional method, even though the level of pollution was at the lower allowed tolerance.

Using EDX analysis, the chemical composition of the non-metallic inclusions present was determined. It was found that there were inclusions based on Al and Mg oxides in the metal matrix (Fig. 6d). Sulphidic inclusions MnS (Fig. 6e) are also represented here.

The samples taken for the evaluation of the microstructure and thickness of the chromium layer were prepared by the standard metallographic processes. NITAL 2 % etchant was used to develop the microstructure. To evaluate the microstructure, there was used the OLYMPUS GX 71 light microscope.

Parts of the relief of the polished, unetched sample from the discarded coining die are shown in the sequence – Fig. 7, where the relief with a crack can be seen.

The microstructure of the material is shown in Fig. 8. It is made up of fine-grained tempered martensite. Linearity originating from forming the semi-finished product, which was not removed by annealing, was observed, as shown in Fig. 8a. It is caused by uneven distribution of carbides in formed tool steels. As a result of the plastic deformation during the pressing of the relief with a mother punch and the subsequent operational degradation, the continuity of the lines was disturbed, as it is presented in Fig. 8b.

There are cracks in the sample also outside the relief. It is observed in the transition radius from the cylindrical to the conical part (Fig. 9a) and also in the core of the working part of the coining die (Fig. 9b, c). It can be supposed that the cracks originated in hardening and they were spread during impact stress within operation.

A NEOPHOT 2 light optical microscope was used to evaluate the chrome layer and evaluated using image analysis – the NIS-ELEMENTS program.

Parts of the coining die relief with a chromium layer are shown in the sequence (Fig. 10).

The layer on the coining die relief in the longitudinal section is not continuous, there are places where it is completely lost. On the edges of the (Fig. 10a, f), which are more exposed, chromium layer at all hasńt been observed.

The presence of chromium in the crack (Fig. 10c) proves that it was formed before chromium-plating, probably during quenching. In the manufacturing process, the coining die are not annealed after the relief is pressed to remove internal stresses. Additional internal stresses are created by hardening during the martensitic transformation. These can cause cracks to be formed.

The described state of the chromium layer could also have been caused by incorrect chromium-plating process, e. g. insufficient

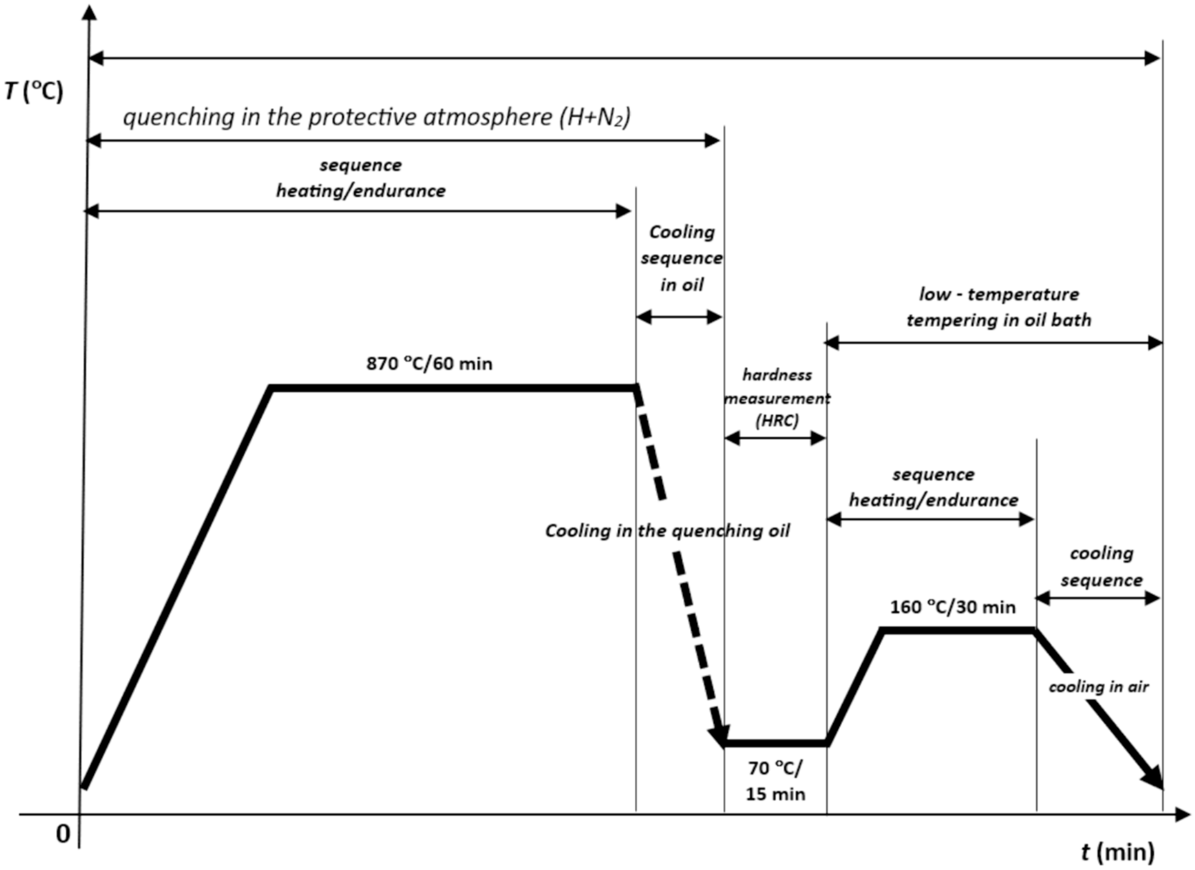

Fig. 3. Heat treatment mode – hardening and tempering of the original K455 steel coining die.

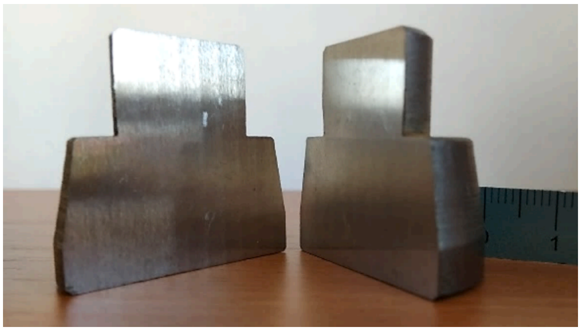

Fig. 4. The cut-up coining die for performing the analysis.

cleaning of the surface or incorrect position of the coining die in the electrolyte.

Table 3 shows the values of the chromium layer thickness measured in the chosen places of the coining die relief illustrated in Fig. 10 b, c, e.

In Fig. 10, the layer is not continuous all over the relief, it is failed in some places and the layer thickness does not reach the required values. The average value of the layer thickness within all measurements is of only 2.87 μm. It can concluded that this was another reason for reducing the service life of coining die and minting only 5,000 coins.

3. Suggestions for improvement

Based on the above mentioned facts found out by the analysis of the discarded failed coining die, several innovations and changes in the manufacturing process were developed. Thus, a precondition for increasing the service life of the coining die was created and

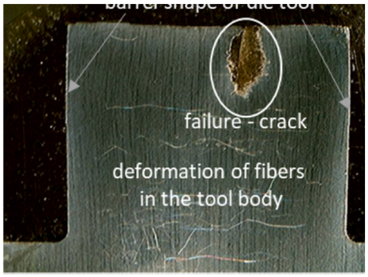

Fig. 5. Longitudinal section with a visible deformation and failure (a crack) coming out of the relief (magnification 10x).

thereby also improving the quality and increasing the number of minted coins. Therefore, an experimental coining die was produced according to the developed innovated manufacturing process (Fig. 11).

Since the micropurity of the K455 tool steel of the coining die was evaluated with the 3D degree considered as acceptable even for dynamically stressed tools, the material of the experimental coining die was not changed.

The introduction of a new type of the press for forming the relief in the semi-finished goods was the first modification in the manufacturing process of the coining die (step 3 of the innovated manufacturing process). The reason was to ensure the reduction of internal stresses during the forming of the relief. The press with a three-part case was used (Fig. 12 a, b). Such a design of the case eliminates the occurrence of high internal stresses in the semi-finished goods compared to the situation when pressing the relief on the presses that had monolithic – undivided cases.

In step 5 of the technological procedure, heat treatment in a furnace with a protective nitrogen atmosphere was replaced by heat treatment in a vacuum tempering furnace from the manufacturer BMI Fours. It is suitable for laboratory use, or for smaller operations in the spheres of watchmaking, medical, and minting. The furnace is suitable for vacuum quenching with N2 cooling. The casing and lid of the furnace are cooled by water. The cooling circuit is closed, cooling is ensured by the TAEevo 031 cooling unit. As a cooling medium is used N_2, whose max. overpressure is 6,000 mbar. The circulation of the cooling medium in the furnace is ensured by a turbine ensuring rapid cooling of the batch in the working space of the furnace. The working space of the furnace is heated by the graphite heating bodies. For programming there is used the Pro-face Siemens unit with process archiving using the Eurotherm 6000E recorder. Subsequent tempering was carried out in the semi-gas-tight tempering furnace PP45/85 with a maximum temperature of $T = 850\ ^{\circ}C$. The furnace is equipped with the INDUSTRY controller for simple programming (starting-up, persistence) of heat treatment processes. The new heat treatment mode – vacuum quenching in furniture BMI micro 20–30 with low-temperature tempering in device LAC PP 85/45 is shown in Fig. 13.

An advantage of the heat treatment mode in the vacuum furnace compared to the furnace with a protective atmosphere is that heating to the tempering temperature is gradual, cooling is faster (up to 600 °C in 8 min), with subsequent tempering in the furnace. Since the casing is cooled by water, it also helps prevent from injuries caused by burns when operating the equipment. The vacuum furnace is program controlled and displays the curves of heating and cooling. In a vacuum, the components are ensured with the protection against surface oxidation.

In order to determine the hardness values after heat treatment, hardness tests using the HRC method according [51]. were performed at each stage of heat treatment on a Rockwell 150 ANALOG workshop hardness tester, directly in the premises of the hardening shop (Table 4). The average value was calculated from measurements in five places. The hardness measurement of tool hardening in the core was carried out on the samples sawn by the wire electrical discharge machining technology (WEDM).

Based on the measurement results it can be stated that the HRC values correspond to the required hardness.

Fig. 14 shows the microstructure of the coining die after heat treatment in a vacuum furnace.

The structure is formed by fine-grained tempered martensite. The linearity originates in the formed semi-finished goods from which the coining die are made. In the vacuum hardening furnace, the quality of the structure and mechanical properties is guaranteed even with repeated production batches, which could not be achieved in classic furnaces with a protective nitrogen atmosphere.

The last change in the innovated manufacturing process is the replacement of PVD (Physical Vapor Deposition) chromium-plating with coating (step 6 of the innovated manufacturing process). On the experimental coining die, the relief was coated with a TiAlN coating. The PVD method was chosen because the coating temperatures are already from $T = 200\ ^{\circ}C$. This ensures that during the process of applying the coating, the coining die will not be loosened and thus an unwanted decrease in hardness will not occur. TiAlN is a nanostructured multilayer coating. The coating hardness reaches 3,300 HV0.05. When using the PVD method, the coating thickness achieved 3–5 μm.

The experimental coining die was put into operation. The number of produced coins of a sufficient quality reached 740,000 pieces. It is 148 times more than the original coining die, which produced only 5,000 coins of the required quality.

After the coining die was discarded out of service, it was again subjected to the analysis, namely:

a) macroscopic evaluation of the surface wear.
b) evaluation of the thickness of the TiAlN coated layer.

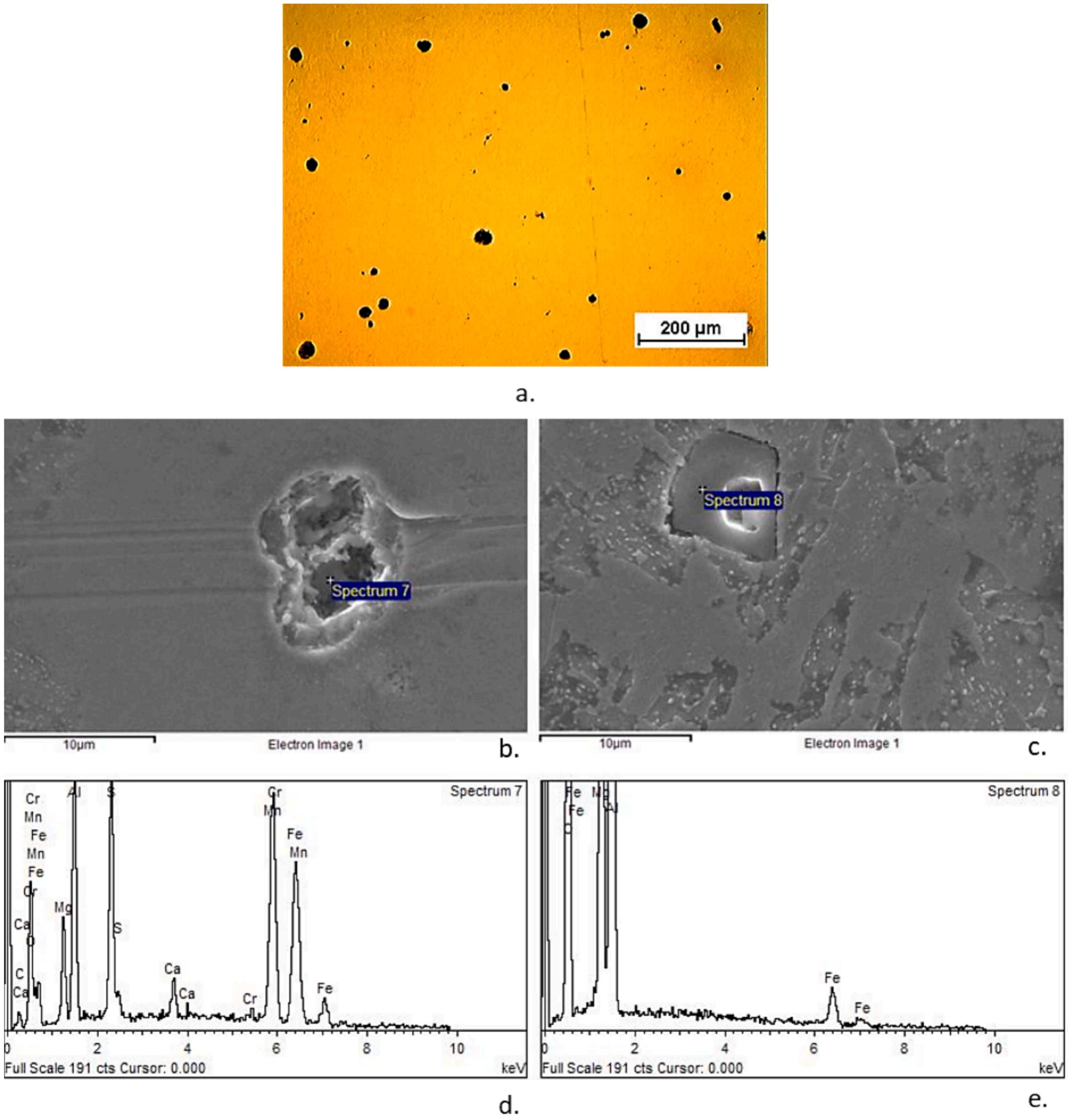

Fig. 6. Globular oxides observed in the coining die material **(a)**; identification of non-metallic inclusions in steel **(b, c)** and their chemical composition **(d, e)**.

a) Macroscopic evaluation of the coated surface of the experimental coining die

Macroscopic evaluation was performed on the Stereomicroscope STEMI 2000C, Zeiss. Failure (a crack) appeared on the experimental coining die which minted an adequate number of coins – 740,000 pieces. It spread towards the centre of the relief (Fig. 15).

Furthermore, the state of failure to the relief, coated with TiAlN coating, was examined. Fig. 16 shows a part of the relief of the experimental coining die after it was discarded out of service.

On the relief detail (Fig. 17b.), it can be seen that the coating has been worn. The wear is almost exclusively concentrated in the places of cavities or protrusions of the relief, where the greatest plastic deformation of the material – coinage metal (AISI 430) takes place.

b) Evaluation of the thickness of the coated TiAlN layer

The thickness of the t_c layer was measured in several places of the longitudinal section by a coining die. In this way, the state of

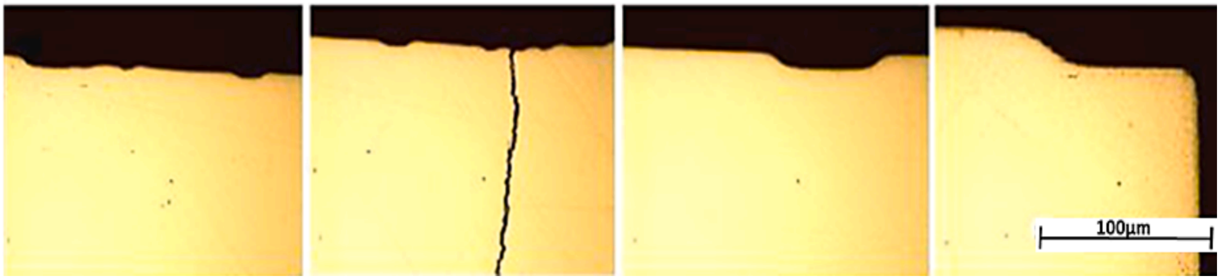

Fig. 7. Parts of the relief in the polished sample.

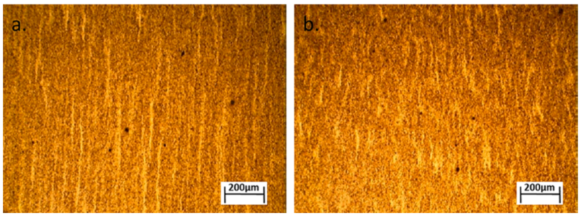

Fig. 8. Microstructure of the core (**a**); under the surface (**b**).

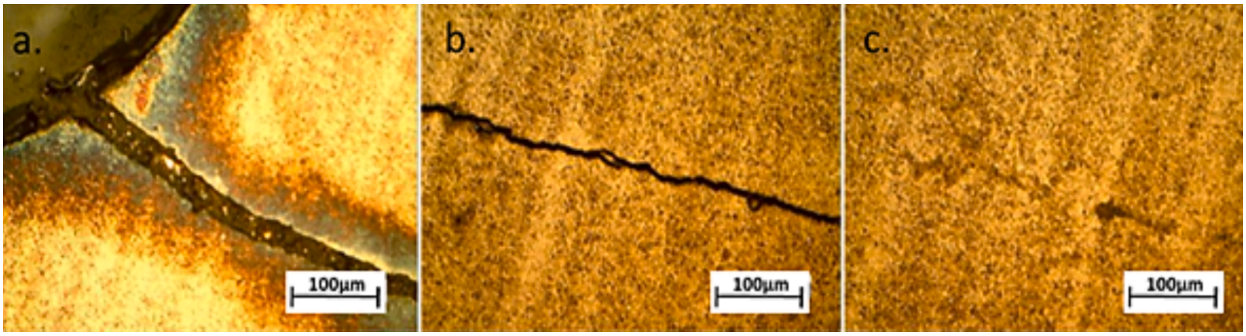

Fig. 9. Locations of failure – cracks (**a**) crack in the transition radius, (**b**) crack in the core, (**c**) microcracks in the core.

wear was evaluated along the entire observed profile of the coining die relief. A NEOPHOT 2 light optical microscope was used to evaluate the coated layer and evaluated using image analysis – the NIS-ELEMENTS program. Fig. 17 shows greater differences in the coating thicknesses on the plane and on the inclined surface of the relief. The layer thickness in the horizontal part is 4.11 µm, on the inclined surface only 2.6 µm.

The arrows point to a coating failure due to wear and tear during the minting of coins. Even if it could be stated that the coating is not uniform in all places, even if its failure has occurred, the results can be considered satisfactory compared to the wear of the original chrome coining die.

4. Conclusions

The aim of the presented research was to find out the causes of the failure of the coining tool material and to design and test an experimental tool that would achieve satisfactory results in the number and quality of minted coins.

To determine the root causes of the failure and insufficient quality of the coins, the following analyses were performed and conclusions made:

- analysis of the macroscopic evaluation of the stamp, in which an inappropriate stamping method was identified – stamping in a closed stamp. It was about storing the blank in a monolithic case, which caused internal stresses to be introduced into the blank of the tool;
- evaluation of the micropurity of the material according to ISO 4967, according to which the purity of the punch was evaluated with the 3D degree, which is considered permissible even for dynamically stressed tools, for that reason the material was not changed during further research of the experimental punch;

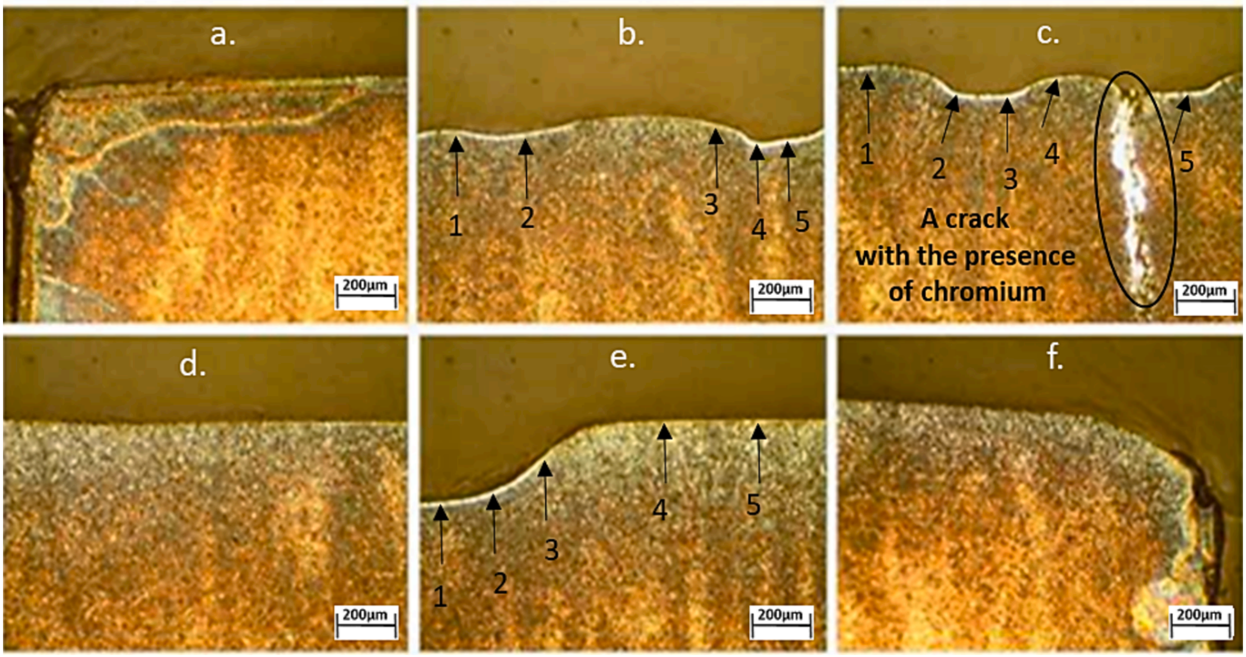

Fig. 10. Relief with a chromium layer and places to measure the layer thickness.

Table 3
The values of layer thickness (μm).

Measurement (μm)	1	2	3	4	5	Average value *x*	Decisive deviation *s*	Min. value	Max. value
Thickness b.	2.65	2.30	2.33	2.63	3.63	2.71	0.48	2.30	3.63
Thickness c.	2.53	3.84	3.84	2.48	3.02	3.14	0.6	2.48	3.85
Thickness e.	3.18	3.18	2.85	2.68	2.37	2.79	0.26	2.37	3.18
Average values						2.87	0.45	2.38	3.55

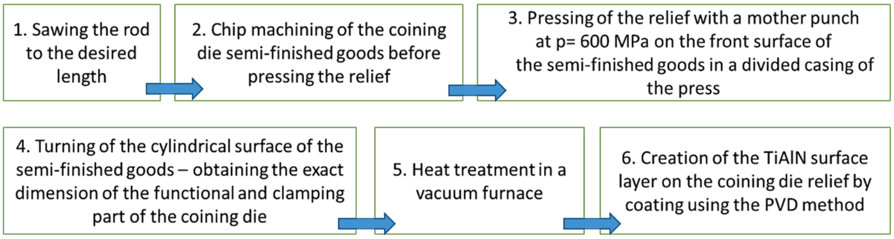

Fig. 11. Innovated manufacturing process for the production of experimental coining die.

- evaluation of the microstructure, where the linearity of the fine-grained martensitic structure was observed and revealed cracks on the surface and in the core of the punch, which probably arose during hardening and propagated during impact stress in operation;
- unacceptable state of the chrome layer – the evaluation of the thickness of the chrome layer pointed out that the layer is not continuous over the entire relief and the thickness of the layer did not reach the required values.

Based on the results of the failed coining die, the changes were designed in selected steps of the manufacturing process. A new, experimental coining die was made and put into operation. The number of produced coins that were of sufficient quality reached 740,000 pieces. It is 148 times more than it was minted by the original coining die. After the coining die was discarded out of service, it was again subjected to the macroscopic analyses of the relief and coating thickness which confirmed the appropriateness of the introduced changes with a subsequent increase in the service life of the coining tool. The results of the analyses and measurements can be summarized in three steps, the content of which is included in the three innovated steps of the manufacturing process of the experimental coining die. It is:

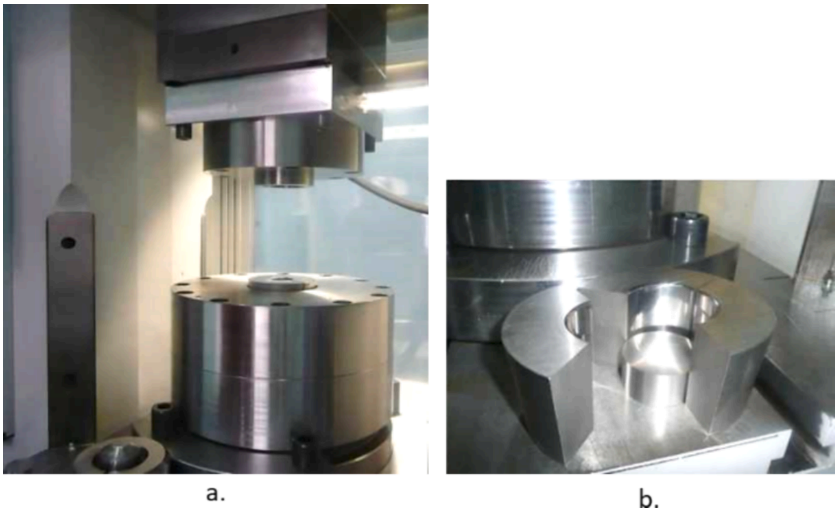

Fig. 12. (**a**) Detail of the press device and (**b**) the divided case with the roller before pressing the relief.

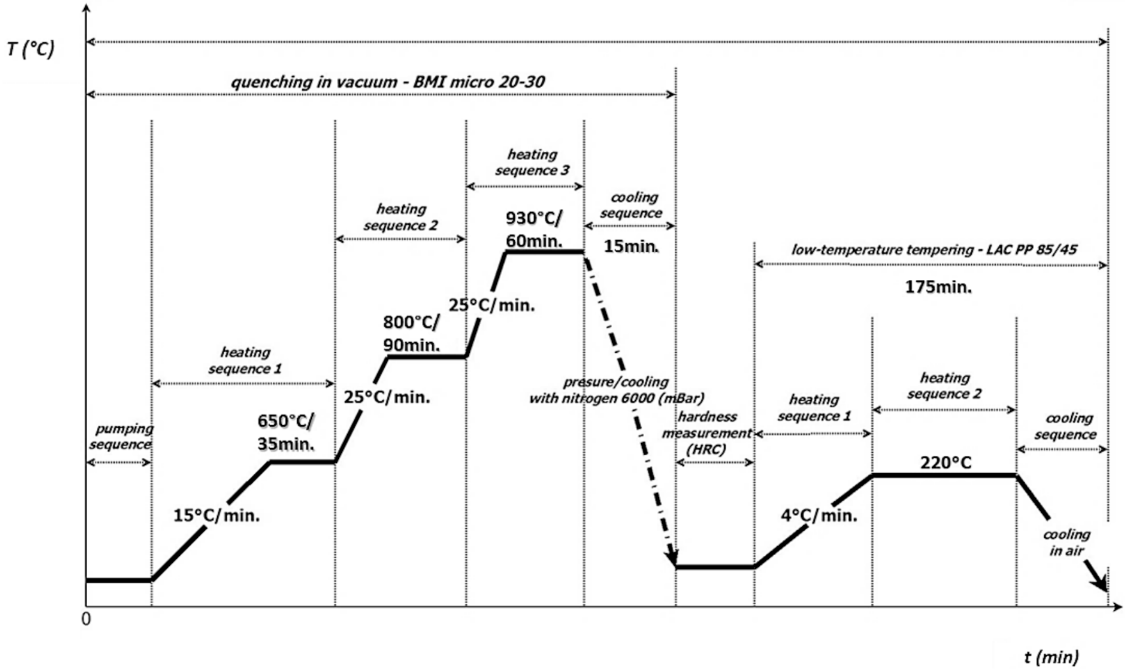

Fig. 13. Innovated mode of heat treatment.

Table 4
Measurement of hardness of the HRC samples after heat treatment in a vacuum furnace.

	Heat treatment stage		
	Vacuum hardening	Low temperature tempering	Hardening in the core
Average	61 ± 0.5 HRC	58 HRC	58 HRC

1. Use of the divided case – a press with a three-part case for forming the relief – elimination of internal stresses during cold forming.
2. Use of a vacuum hardening furnace for heat treatment – enabling the achievement of a more suitable microstructure formed by fine-grained, tempered martensite when the required hardness is reached. Compilation of a new heat treatment mode in a vacuum

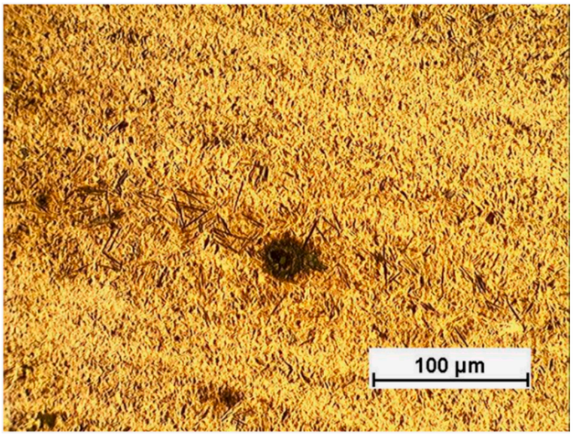

Fig. 14. Microstructure of the coining die after heat treatment in a vacuum furnace in the presence of an acceptable globular inclusion.

Fig. 15. Failure (a crack) on the discarded experimental coining die (**a**); crack detail (**b**, **c**) (magnification 6.5x).

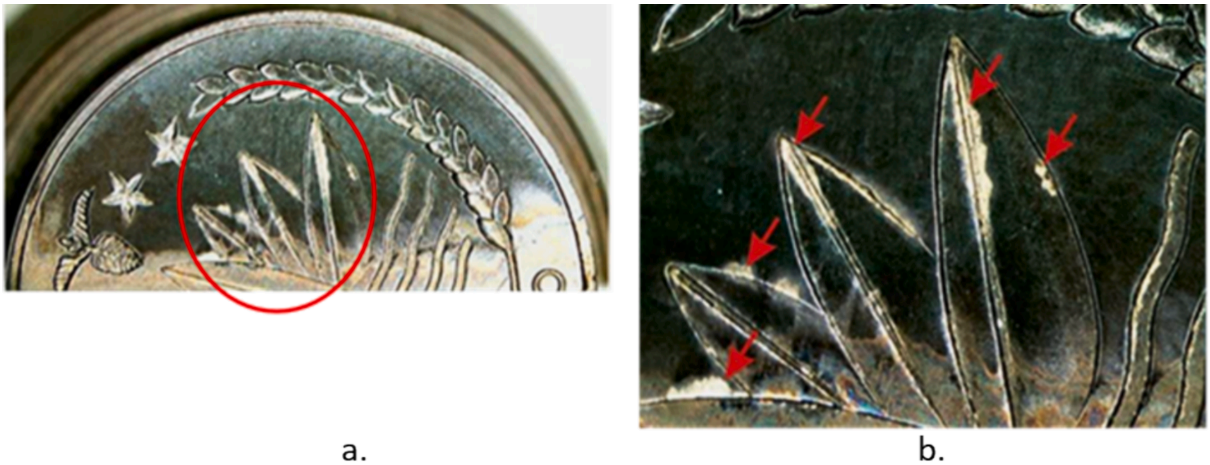

Fig. 16. Part of the coining die relief (**a**), detail of relief with the failure (a crack) (**b**) (magnification 6,5x).

furnace – heating to the hardening temperature is gradual, cooling is faster with a subsequent tempering in the furnace. This eliminates the formation of hardening cracks on the surface of the coining die which significantly reduce their service life.

3. Application of a TiAlN coating by the PVD (Physical Vapor Deposition) method as a replacement for the chromium-plating of the coining die relief – increasing in the service life of the tool in the form of minting a satisfactory number of coins.

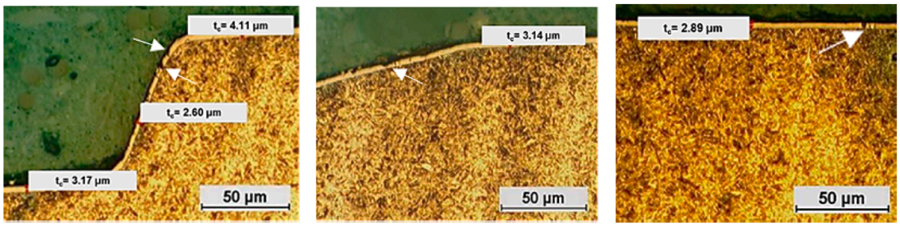

Fig. 17. Measurement of the t_c coating thickness on the used experimental coining die and the places of the coating failure.

In addition to the scientific contribution, the given results of the experiment have also a practical contribution. Apart from an increase in the number of minted coins of an acceptable quality, this also consists in saving expensive materials and eliminating harmful effects on the environment.

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CRediT authorship contribution statement

Miroslava Ťavodová: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Pavel Beňo:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Jana Luptáková:** Writing – review & editing, Validation, Project administration, Formal analysis. **Dana Stančeková:** Visualization, Data curation. **Nataša Náprstková:** Validation, Resources. **Katarina Monkova:** Writing – original draft, Validation, Software, Resources, Project administration, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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