

Surface Layer Formation of a 12KH18N10T Stainless Steel Toothed Base During Wire Electrical Discharge Machining

Kombayev K.K., Azamatov B.N., Kaliyev D.I., Mukhametbek Zh.M., Gabdyssalyk R.*

D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan

* corresponding author

Abstract. Wire Electrical Discharge Machining (WEDM) is an effective manufacturing process for producing complex-shaped components from difficult-to-machine materials. However, the thermal effect of electrical discharges alters the structure and condition of the surface layer. The aim of this study was to investigate the surface layer formation of a 12KH18N10T stainless steel toothed base during WEDM. Machining was performed on a DK7745 wire EDM machine using a 0.18 mm brass wire electrode and deionized water as the dielectric medium. Two machining regimes with different pulse energies were investigated. Surface morphology, recast layer microstructure, and elemental composition were characterized using optical metallography, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS), while the mechanical state of the surface layer was evaluated by Vickers microhardness measurements. The results showed that increasing the pulse energy promoted the formation of a more developed recast layer and a more heterogeneous surface morphology without significantly changing the concentrations of the principal alloying elements (Fe, Cr, and Ni). In addition, an increased oxygen content and a slight transfer of Cu and Zn from the brass wire electrode were observed in the near-surface region. Higher microhardness was obtained after finish machining. The practical significance of this study lies in the substantiation of WEDM regimes that ensure the required dimensional accuracy and surface integrity for manufacturing toothed components of high-precision medical positioning mechanisms.

Keywords: wire electrical discharge machining, WEDM, 12KH18N10T stainless steel, surface layer, recast layer, toothed base, surgical holder, microstructure, surface morphology.

Introduction

Modern high-precision mechanical positioning systems are widely used in instrument engineering, robotics, optical measurement systems, and medical equipment, where the accuracy of the relative positioning of components, the rigidity of the clamping, and the stability of geometric parameters directly determine the functional reliability and operational characteristics of the products [1–3]. These requirements are of particular importance for components of hinged clamping mechanisms, in which even minor deviations in shape, dimensions, or surface condition can significantly affect the precision of clamping, the smoothness of adjustment, and the durability of the assembly [4]. One such component is the toothed base of a mechanical holding system, which ensures the transmission and reliable locking of the angular position of the mating links. The design of the component under study is shown in Figure 1.

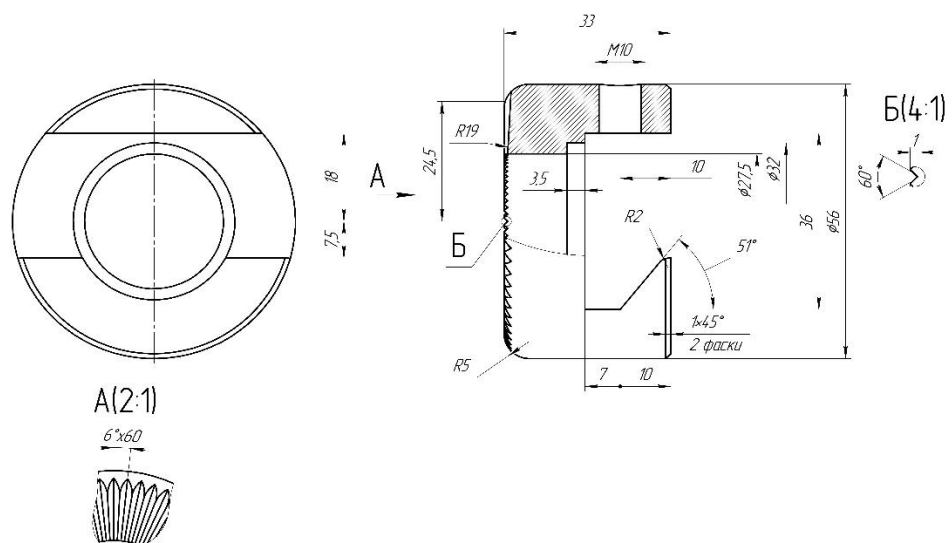


Fig. 1 - Drawing of a toothed base made of 12KH18N10T steel, manufactured using wire-cut electrical discharge machining

The geometry of the toothed base is characterized by radially arranged teeth with a profile angle of 60°, operating under conditions of repeated contact interaction. The precision with which the working surfaces of the teeth are formed directly determines the rigidity of the mechanism's locking, the level of contact stresses, and the uniformity of load distribution across the working faces, which ultimately affects the reliability and durability of the assembly [5]. Consequently, the manufacturing process for these components must meet stringent requirements to ensure geometric accuracy, minimal surface roughness, and the absence of surface-layer defects.

Corrosion-resistant austenitic steels are widely used for manufacturing such components, with 12X18H10T steel being particularly prevalent. This material is characterized by high corrosion resistance, a good balance of strength and ductility, and high operational reliability [6]. At the same time, its high ductility, intense work hardening (work hardening), increased toughness, and relatively low thermal conductivity result in poor machinability of 12X18H10T steel using traditional cutting methods, which is accompanied by increased cutting forces, accelerated tool wear, and reduced machining process stability [7, 8]. For the manufacture of details with complex geometries from difficult-to-machine materials, electrical discharge machining methods are finding increasingly widespread application; among these, wire electrical discharge machining (Wire Electrical Discharge Machining, WEDM) occupies a leading position due to its high shaping accuracy, the absence of mechanical contact with the workpiece, and the ability to machine electrically conductive materials regardless of their hardness [9–11]. Wire electrical discharge machining is based on the localized removal of material resulting from a sequence of electrical discharges between a wire electrode and the workpiece, both of which are immersed in a dielectric medium [12]. The absence of mechanical contact between the tool and the workpiece surface makes it possible to produce details with complex contours and high precision, regardless of the material's hardness and strength characteristics [13]. Thanks to these advantages, WEDM technology is widely used in the manufacture of critical components for mechanical engineering, aviation, power generation equipment, instrumentation, and various high-precision mechanical systems [14, 15].

Despite the high precision of the shaping process, WEDM is accompanied by intense localized heat exposure. The temperature in the electrical discharge zone can reach 8,000–12,000 °C, which leads to the melting and partial vaporization of the workpiece material [16]. The subsequent ultra-rapid cooling of the molten metal causes the formation of a characteristic remelted (“white”) layer, whose structure differs significantly from that of the base metal [17]. This layer may contain products of recrystallization, micropores, microcracks, residual stresses, and inclusions of material from the electrode tool [18, 19]. The thickness and microstructural state of the remelted layer have a significant impact on the fatigue strength, wear resistance, and service life of parts, therefore, in the current literature, the condition of the surface layer is considered one of the most important criteria for the quality of electrical discharge machining, along with process productivity, surface roughness, and shaping accuracy [20–22].

Numerous studies on the electrical discharge machining of stainless steels, titanium, and nickel alloys have shown that electrical discharge parameters have a decisive influence on the thickness of the remelted layer, surface roughness, the magnitude of residual stresses, and the microhardness of the surface layers [23–25]. For austenitic steels, additional processes involving the diffusion of elements from the brass wire (Cu and Zn) into the workpiece's surface layer have been observed, leading to local changes in chemical composition and the formation of secondary structural components [26, 27].

Of particular interest are studies of the microstructure of the surface layer after WEDM using optical metallography, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and EBSD analysis [28–30]. The results indicate that the thickness of the white layer can vary from a few to several tens of micrometers depending on the energy parameters of the process, and the resulting structure is characterized by high dispersion and significant differences from the material's original austenitic structure due to extremely high heating and cooling rates [31,35].

However, most published studies focus on heat-resistant nickel alloys such as Inconel 718, titanium alloys, and stainless steels such as AISI 304 and AISI 316 [32–34]. At the same time, the formation of the surface layer following wire-cut electrical discharge machining (EDM) of parts made of 12X18H10T steel—used in the manufacture of high-precision components for clamping and positioning mechanisms—has not been studied in sufficient detail. The analysis of the surface layer condition of gear elements is of particular scientific and practical interest, since it is the working surfaces of the teeth that bear the main contact loads and largely determine the operational characteristics of the mechanism.

In this regard, the objective of this study is to investigate the characteristics of the formation of the surface layer of a 12X18H10T steel gear base following wire-cut electrical discharge machining. To achieve this objective, an analysis of the geometric characteristics of the cut was performed; the surface morphology and microstructure of the remelted layer were investigated using optical and scanning electron microscopy; the thickness of the heat-affected zone was determined and changes in microhardness in the near-surface region were evaluated.

Materials and methods

The research was conducted at the “Smart Engineering” Competence Center of the D. Serikbayev East Kazakhstan Technical University. The subject of the study was the toothed base of a high-precision mechanical

positioning system, manufactured from a 24.5-mm-thick sheet blank of corrosion-resistant austenitic steel 12KH18H10T (Table 1). The toothed profile of the part was formed using wire-cut electrical discharge machining.

The chemical composition of the steel under study complied with the requirements of GOST 5632–2014 and is presented in Table 1.

Table 1 - Chemical composition of 12Kh18N10T stainless steel according to GOST 5632–2014

Element	C	Cr	Ni	Ti	Mn	Si	P	S	Fe
Content, %	≤0,12	17,0–19,0	9,0–11,0	0,4–1,0	≤2,0	≤0,8	≤0,035	≤0,020	Base

Wire-cut electrical discharge machining was performed on a DK7745 machine (Suzhou Sanguang Science & Technology Co., Ltd., China) equipped with numerical control. A brass wire with a diameter of 0.18 mm was used as the electrode. The wire was fed continuously at a speed of 6–9 m/min. Deionized water with a specific electrical resistance of at least 50 kΩ·cm was used as the dielectric medium. The dielectric was fed into the interelectrode gap through upper and lower nozzles at a pressure of 0.5–0.8 MPa. The temperature of the working fluid was maintained at no higher than 25 °C.

To evaluate the influence of the process's energy parameters on the formation of the surface layer of 12X18H10T steel, two modes of wire-cut electrical discharge machining were used: finishing and intensive. The main parameters of these modes are presented in Table 2.

Table 2 - Wire Electrical Discharge Machining conditions

Parameter	Finish-cutting regime	High-energy regime
Wire diameter, mm	0,18	0,18
Wire feed speed, m/min	6	9
Dielectric medium	Deionized water	Deionized water
Dielectric electrical resistivity, kΩ·cm	≥50	≥50
Dielectric flushing pressure, MPa	0,5–0,8	0,5–0,8
Discharge energy per pulse, μJ	780	3600

The difference in single-pulse energy between the modes under study (780 and 3,600 μJ) resulted in different levels of thermal effects on the material in the electrical discharge machining zone, which made it possible to investigate the effect of energy input on the formation of the surface layer of 12X18H10T steel.

For metallographic studies following wire-cut electrical discharge machining, metallographic sections measuring 5 × 10 × 20 mm were prepared from representative areas of the machined specimens. The specimens were prepared according to a standard metallographic procedure, which included sequential grinding with abrasive materials of varying grit sizes, followed by mechanical polishing to a mirror finish on a LaboPol-5 automatic grinding and polishing machine (Struers, Denmark). To reveal the microstructure, the specimens were chemically etched with a 5% aqueous solution of nitric acid (HNO₃).

The microstructure was examined using optical metallography on an Olympus BX51 microscope (Olympus Corporation, Japan). The morphology of the cut surface, the structure of the recast layer, the nature of the interface between the recast layer and the base metal, and the presence of surface defects were examined using scanning electron microscopy on a JSM-6390LV microscope (JEOL Ltd., Japan), equipped with an INCA Energy Penta FET X3 energy-dispersive X-ray microanalysis system (Oxford Instruments Analytical Ltd., United Kingdom).

The elemental composition was determined using energy-dispersive X-ray spectroscopy at three representative points on each sample: two points in the remelted surface layer and one control point in the base metal, which allowed for an assessment of the possible redistribution of chemical elements following electrical discharge machining.

The microhardness of the surface layer was determined using the Vickers method on a DuraScan-20 microhardness tester (EMCO-TEST Prüfmaschinen GmbH, Austria). Measurements were taken perpendicular to the treated surface, from the remelted layer into the base metal. For each processing mode, a series of measurements was conducted; based on the results, microhardness distribution profiles were plotted, and the influence of WEDM energy parameters on the mechanical state of the surface layer was evaluated.

Results and discussion

Following wire-cut electrical discharge machining of the teeth of a gear blank with a 60° profile angle, the microstructure of the surface layer was examined using optical metallography. The microstructure of the working surfaces formed under various machining modes is shown in Figure 2. The studies were conducted for two WEDM modes, the parameters of which are given in Table 2. Figure 2a shows the surface after the finishing mode, and Figure 2b shows the surface after the intensive mode.

Analysis of the metallographic images shows that in both cases, the base metal retains the austenitic polycrystalline structure characteristic of 12X18H10T steel, with clearly defined grain boundaries. In the near-surface zone, a layer is observed that was formed as a result of local melting and subsequent crystallization of the material

under the action of electrical discharges. This layer differs from the base metal in its increased contrast and thickness, which varies along the length of the surface.

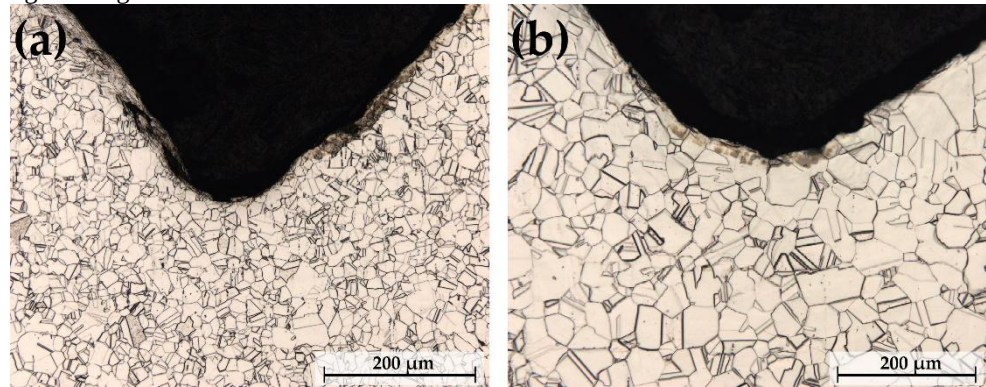


Fig. 2 - Microstructure of the surface layer of 12KH18N10T steel after wire-cut electrical discharge machining: a — fine machining mode; b — intensive machining mode.

In the finishing mode (Figure 2a), the remelted layer has a relatively small thickness and a more uniform morphology. The boundary between the surface layer and the base metal is quite clearly defined, and no pronounced structural changes detectable by optical metallography were observed in the adjacent zone. This pattern corresponds to a lower energy input into the material when using a mode with a reduced single-pulse energy.

Under intensive processing conditions (Figure 2b), an increase in the energy of a single pulse to 3,600 μJ (Table 2) is accompanied by an intensification of the local thermal effect, which leads to the formation of a more developed remelted layer with greater thickness nonuniformity. In certain areas, a more pronounced heat-affected zone is observed, which is consistent with the known characteristics of the WEDM process as discharge energy increases. The results obtained indicate that an increase in energy input promotes the development of local melting and subsequent crystallization of the material, significantly influencing the morphology of the surface layer.

To investigate in greater detail the characteristics of surface layer formation following wire-cut electrical discharge machining, a scanning electron microscopy analysis of the cut surface was performed. The resulting micrographs are shown in Figure 3. Figure 3a shows the surface morphology of a tooth formed during the finishing mode, while Figure 3b shows that formed during the intensive mode.

The SEM analysis showed that, regardless of the machining mode, the tooth profile with a 60° angle was formed without any visible distortions in the geometry of the working faces. Material continuity is maintained across the entire examined surface, with no macrocracks, large pores, or signs of delamination detected. The results indicate that the selected WEDM modes ensure the formation of a surface free of pronounced macroscopic defects arising from the localized thermal effects of electrical discharges.

In the finishing mode (Figure 3a), the surface is characterized by a relatively uniform morphology. The micro-relief is formed uniformly along the entire length of the tooth's working edge, and the dimensions and distribution of surface irregularities do not exhibit significant local variability. These characteristics are consistent with the lower energy of a single pulse (780 μJ), which reduces the amount of thermal energy introduced into the material during each electrical discharge, thereby limiting the intensity of local melting and promoting the formation of a more uniform surface.

Under an intensive processing regime (Figure 3b), a significant change in surface morphology is observed. The microtopography becomes more developed and heterogeneous, the variability in the dimensions of surface irregularities increases, and individual surface areas are characterized by a more complex configuration. This morphology is consistent with an increase in the energy of a single pulse to 3,600 μJ , at which the thermal energy released in the discharge zone increases. This leads to an increase in the volume of material subjected to localized melting and its subsequent high-speed solidification, which is a characteristic feature of the surface formation mechanism in wire-cut electrical discharge machining.

It should be noted that, despite a 4.6-fold difference in the energy of a single pulse, in both cases the surface retains a continuous structure without signs of macroscopic damage. Thus, the main effect of the parameter under study manifests not in the formation of critical defects, but in changes in surface morphology, the degree of micro-relief development, and the spatial heterogeneity of the surface layer.

To assess possible changes in the chemical composition of the surface layer, energy-dispersive X-ray microanalysis was performed at three representative points. Points Spectrum 1 and Spectrum 2 were located immediately near the cut surface on the working edges of the teeth, where the material was subjected to the most intense electrical discharges. Spectrum 3 was located within the base metal, outside the zone of direct thermal exposure, and served as a control area. This arrangement of measurement points allowed us to compare the elemental

composition of the surface layer with that of the base metal and to assess possible changes in the concentration of alloying elements resulting from the WEDM process.

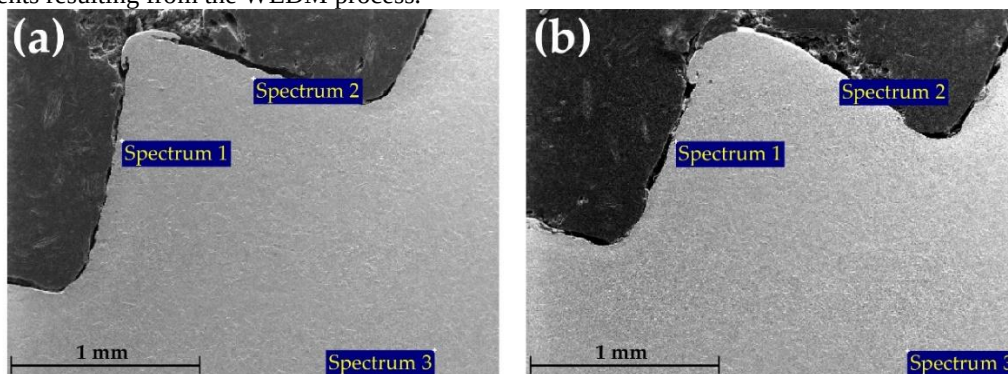


Fig. 3 - SEM images of the surface of teeth made of 12X18H10T steel after wire-cut electrical discharge machining (EDM), showing the energy-dispersive X-ray microanalysis (EDS) points: a — finishing mode; b — intensive mode

The results of energy-dispersive X-ray microanalysis of the surface layer of 12X18H10T steel after fine-finish electrical discharge machining are presented in Table 3. Analysis of the data shows that at all points examined, the main elements remain Fe, Cr, and Ni, with a total content of approximately 93–94 wt.%, indicating that the chemical composition of the austenitic stainless steel is preserved after WEDM. The Fe content varies between 66.70–67.22 wt.%, Cr between 17.15–17.63 wt.%, and Ni between 9.34–9.71 wt.%. When comparing the surface areas (Spectrum 1 and Spectrum 2) with the control area (Spectrum 3), no significant redistribution of the main alloying elements is observed. At the same time, the oxygen content at the surface points is 0.74–0.95 wt.%, whereas at the control point it decreases to 0.69 wt.%. This distribution indicates that oxygen is predominantly localized in the near-surface zone of the remelted layer. Furthermore, Spectrum 1 and Spectrum 2 contain small amounts of copper (0.52–0.56 wt.%) and zinc (0.48–0.51 wt.%), whereas in Spectrum 3, their contents decrease to 0.03 and 0.07 wt.%, respectively, indicating the localized nature of mass transfer from the brass wire electrode material.

Table 3 - Results of EDS analysis of localized areas of the surface layer of 12X18H10T steel after wire electrical discharge machining (WEDM) in the finishing mode

Spectrum (a)	Ti	O	Si	Cr	Mn	Fe	Ni	Mo	Cu	Zn	Total
Spectrum 1	0.91	0.95	0.59	17.15	1.56	66.95	9.53	1.32	0.56	0.48	100.00
Spectrum 2	0.98	0.74	0.58	17.43	1.39	67.22	9.34	1.29	0.52	0.51	100.00
Spectrum 3	1.1	0.69	0.58	17.63	1.44	66.70	9.71	2.05	0.03	0.07	100.00

The results of the EDS analysis following intensive treatment are presented in Table 4. As in the previous case, the chemical composition of the surface layer is dominated by iron, chromium, and nickel. The concentration of Fe ranges from 66.27 to 66.97 wt.%, Cr from 17.21 to 17.34 wt.%, and Ni from 9.42 to 9.69 wt.%, which practically corresponds to the values obtained during the finishing treatment. At the same time, the oxygen content in the surface regions increases to 1.04–1.08 wt.%, whereas at the control point it is only 0.55 wt.%. At the same time, copper (0.61–0.64 wt.%) and zinc (0.52–0.54 wt.%) remain present in the surface regions, whereas in Spectrum 3 their concentrations decrease to 0.08 and 0.06 wt.%, respectively. This distribution of elements indicates that the processes of oxidation and mass transfer of the electrode material are predominantly confined to the surface region of the remelted layer.

A comparison of the results presented in Tables 3 and 4 shows that an increase in single-pulse energy has virtually no effect on the content of the main components of 12X18H10T steel. The maximum differences between the treatment modes do not exceed 0.95 wt.% for iron, 0.48 wt.% for chromium, and 0.37 wt.% for nickel, which falls within the range of local heterogeneity of the remelted layer and does not indicate a selective redistribution of alloying elements. The most noticeable changes are observed for oxygen: while its content in the surface regions is 0.74–0.95 wt.% under the finishing treatment (Table 3), it increases to 1.04–1.08 wt.% under the intensive treatment (Table 4). At the same time, at the control points (Spectrum 3), the oxygen content remains significantly lower—0.69 and 0.55 wt.%, respectively.

Table 4. Results of EDS analysis of localized areas of the surface layer of 12X18H10T steel after wire electrical discharge machining (WEDM) in high-intensity mode

Spectrum (b)	Ti	O	Si	Cr	Mn	Fe	Ni	Mo	Cu	Zn	Total
Spectrum 1	1.04	1.04	0.58	17.30	1.41	66.97	9.47	1.05	0.61	0.54	100.00
Spectrum 2	1.1	1.08	0.65	17.34	1.67	66.27	9.42	1.32	0.64	0.52	100.00
Spectrum 3	1.12	0.55	0.62	17.21	1.73	66.67	9.69	2.27	0.08	0.06	100.00

The results suggest that oxygen is concentrated primarily in the near-surface region of the remelted layer, while its concentration decreases with increasing depth. This pattern is consistent with the WEDM mechanism, in which molten metal interacts with the aqueous dielectric medium and its decomposition products during crystallization. Consequently, the elevated oxygen content at the surface points Spectrum 1 and Spectrum 2 can be regarded as indirect evidence of local surface oxidation, whereas the significantly lower oxygen concentration in Spectrum 3 indicates a substantially lower degree of oxidation of the material beneath the remelted layer. At the same time, the virtually unchanged content of Fe, Cr, and Ni indicates the absence of any noticeable redistribution of the main alloying elements.

A comprehensive analysis of the microstructure, surface morphology, and EDS results showed that the investigated WEDM modes enable the formation of a serrated profile from 12X18H10T steel without a significant change in the chemical composition of the surface layer. An increase in single-pulse energy primarily affects the morphology and structural state of the remelted layer and is accompanied by increased surface oxidation, whereas the content of the main alloying elements remains virtually unchanged.

The practical feasibility of the developed manufacturing process has been confirmed by the production of a gear base for a surgical holder (Figure 4).

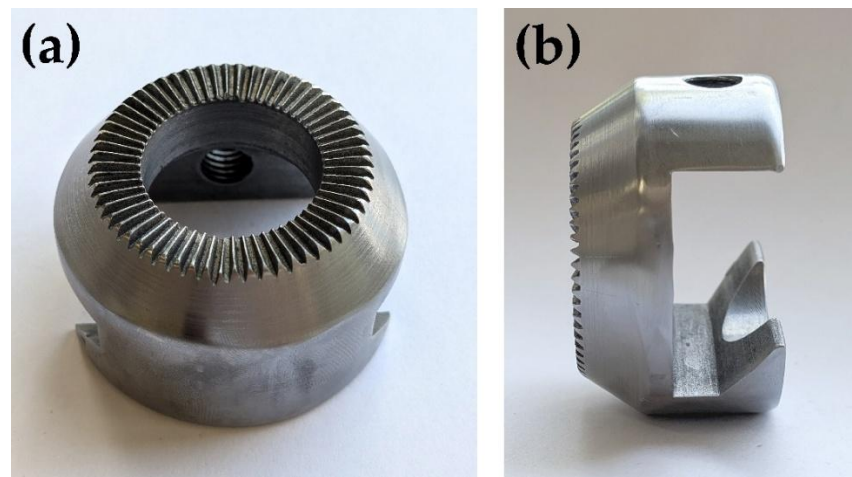


Fig. 4 – Practical application of WEDM technology in the manufacture of the toothed base of a surgical holder: (a) general view of the product; (b) profile of the toothed ring

Figure 4a shows a general view of the gear blank after WEDM machining, and Figure 4b shows the profile of the gear ring. Visual inspection confirms the formation of a complete tooth profile with a 60° angle, as well as the absence of uncut sections, chips, and other macroscopic defects, which indicates high precision in shaping and confirms the feasibility of using the developed WEDM mode in the manufacture of gear elements for medical mechanisms.

To assess the effect of WEDM modes on the mechanical properties of the surface layer, Vickers microhardness measurements were performed. The results are presented in Figure 5 as the distribution of microhardness along the examined surface section for the finishing and intensive processing modes. As shown in Figure 5, after the finishing treatment mode, the microhardness of the surface layer ranges from 195 to 200 HV, whereas after the intensive treatment mode, it ranges from 182 to 189 HV. The results indicate a higher and more stable surface microhardness achieved with the finishing treatment mode. This pattern is consistent with the results of metallographic studies and scanning electron microscopy, according to which an increase in single-pulse energy is accompanied by the formation of a more developed remelted zone with coarser structural morphology (Figures 2 and 3). It is likely that the increase in the volume of molten metal and the change in its crystallization conditions during the intensive mode contribute to the formation of larger structural components in the remelted layer, which may lead to a slight decrease in microhardness.

At the same time, the results of EDS analysis showed that the content of the main alloying elements (Fe, Cr, and Ni) remains virtually unchanged during the transition from the finishing to the intensive mode. This suggests that the differences in microhardness are primarily due to changes in the structural state of the remelted layer, rather than changes in the chemical composition of the material.

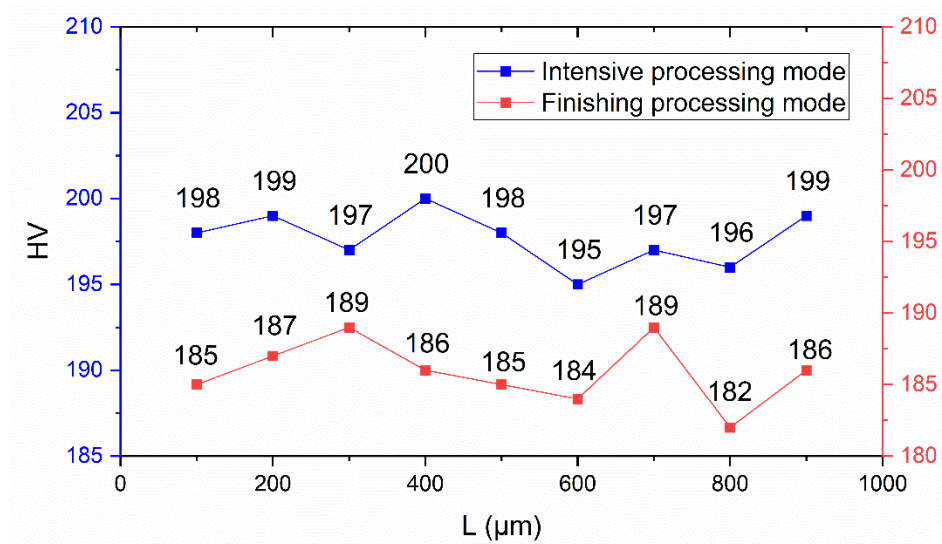


Fig. 5 - Distribution of the microhardness of the surface layer of 12X18H10T steel along the tested section after wire-cut electrical discharge machining in the finishing and intensive modes

Figure 6 illustrates the practical implementation of the developed manufacturing process, showing an assembled surgical holder with a toothed base manufactured using wire-cut electrical discharge machining. The resulting toothed joint ensures the complete formation of the working profile of the teeth and the correct meshing of the mechanism's components, confirming the feasibility of manufacturing functional parts for medical instruments with complex geometries using the developed WEDM parameters.



Fig. 6 - Practical implementation of the developed manufacturing process: an assembled surgical holder with a toothed base manufactured using the WEDM method

The combined results of metallographic examinations, scanning electron microscopy, energy-dispersive analysis, and microhardness measurements indicate that the selected processing parameters ensure the required forming accuracy while preserving the chemical composition of the surface layer and allowing for a controlled change in its microstructure. The results obtained confirm the potential of WEDM technology for the manufacture of high-precision gear elements for medical mechanisms, which have stringent requirements for surface quality and geometric accuracy.

Conclusion

The study shows that increasing the energy of a single pulse during wire-cut electrical discharge machining of 12X18H10T steel from 780 to 3,600 μJ intensifies the thermal effect on the material, leading to the formation of a

more developed and heterogeneous remelted layer, an increase in the heat-affected zone, and a more complex surface morphology.

It has been shown that increasing the machining energy has virtually no effect on the content of the main alloying elements in the surface layer: the Fe concentration is 66.27–67.22 wt.%, Cr—17.15–17.63 wt.%, and Ni—9.34–9.71 wt.%. At the same time, the remelted layer exhibits localized mass transfer of material from the brass wire, with a Cu content of up to 0.64 wt.%, Zn up to 0.54 wt.%, and the oxygen content increases to 1.08 wt.%, indicating the development of surface oxidation processes in the EDM-affected zone.

It has been established that the most favorable mechanical properties of the surface layer are achieved during the finishing machining mode. The surface microhardness is 195–200 HV, which is 7–9 HV higher than that achieved in the intensive mode (182–189 HV). The decrease in microhardness with increasing pulse energy is associated with the formation of a more developed remelted layer and changes in its crystallization conditions.

The developed WEDM mode enables the fabrication of a toothed base for a surgical holder made of 12X18H10T steel while preserving the geometry of the toothed profile, ensuring the absence of macroscopic surface defects, and maintaining stable characteristics of the surface layer, which confirms its suitability for use in the manufacture of high-precision components for medical mechanisms.

Acknowledgments

The authors would like to thank the National Scientific Center for Traumatology and Orthopedics named after Academician N.Zh. Batpenov for providing comments on medical equipment, as well as for expert advice and practical recommendations.

Conflict of interest

The authors declare no conflict of interest.

Statement of institutional ethics committee (IRB) approval

The work was purely technical in nature and did not involve humans or animals, so this section was marked "Not Applicable".

Informed consent statement

Written informed consent was obtained from all participants prior to participation in the study; if human participation is not intended, this section is marked "Not Applicable".

Data availability statement

Data supporting the results of this technical study may be provided by the corresponding author upon reasonable request; or, since the work is based on numerical modeling and theoretical analysis, no new experimental data have been generated.

Funding

This research is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR24992786, "Development of technology for manufacturing samples of domestic medical instruments and medical products").

Notice regarding the use of artificial intelligence technologies

During the preparation of this manuscript, the author(s) used artificial intelligence tools to perform academic translation and terminological editing of the text into English. All translations and technical terms were checked and approved by the authors for accuracy.

References

- [1] Xin C., Xu Y., Zhang Z., Li M. Micro-Opto-Electro-Mechanical Systems for High-Precision Displacement Sensing: A Review. *Micromachines*. 2024;15(8):1011. <https://doi.org/10.3390/mi15081011>.
- [2] Xu K., Xu S., Qi Q. Research on High-Precision Positioning Method of Robot Based on Laser Tracker. *Intelligent Service Robotics*. 2023;16:361–371. <https://doi.org/10.1007/s11370-023-00467-5>.
- [3] Tian H., Yin Y., Zhang X., et al. Development and Precision Evaluation of a Robotic System for Oral Implant Surgery Using Personalized Digital Guides and Optical Spatial Positioning Technology. *PLOS ONE*. 2025;20(4):e0319054. <https://doi.org/10.1371/journal.pone.0319054>.
- [4] Fan Z., Yang K., Yuan B., Mu X., Yin K., Sun Q., Sun W. Analysis and optimization of repetitive positioning precision for kinematic couplings of opto-mechanical components considering uncertainty. *Precision Engineering*. 2024;89:275–291. <https://doi.org/10.1016/j.precisioneng.2024.06.003>.
- [5] Cazan S., Dănilă C., Crețu S. Tooth contact analysis of helical gears using semi-analytical methods in real gearing situations. *Tribology International*. 2023;185:108482. <https://doi.org/10.1016/j.triboint.2023.108482>.

- [6] Ryaboshuk S.V., Kovalev P.V. Analysis of the causes of defect formation in 12Kh18N10T steel billets and development of recommendations for their elimination // *Metal Working (Technology, Equipment, Tools)*. 2023. T. 25. № 1. C. 6–15. DOI: 10.17212/1994-6309-2023-25.1-6-15.
- [7] Das S.R., Dhupal D., Kumar A. A review on machining performance of AISI 304 steel. *Materials Today: Proceedings*. 2022;50:629–642. <https://doi.org/10.1016/j.matpr.2021.04.495>.
- [8] Khan S.A., Gupta M.K., Mia M., et al. Comparative machinability aspects of austenitic and duplex stainless steels. *JOM*. 2024. <https://doi.org/10.1007/s11837-024-06675-3>.
- [9] Ukey K., Sahu A.R., Gajghate S.S., et al. Wire electrical discharge machining (WEDM) review on current optimization research trends. *Materials Today: Proceedings*. 2023. <https://doi.org/10.1016/j.matpr.2023.06.113>.
- [10] Rubi C.S., Prakash J.U., Juliyana S.J.S., et al. Comprehensive review on wire electrical discharge machining: a non-traditional material removal process. *Frontiers in Mechanical Engineering*. 2024;10. <https://doi.org/10.3389/fmech.2024.1322605>.
- [11] Seidi M., Yaghoubi S., Rabiei F. Multi-objective optimization of wire electrical discharge machining process using multi-attribute decision making techniques and regression analysis. *Scientific Reports*. 2024;14:10234. <https://doi.org/10.1038/s41598-024-60825-w>.
- [12] Ho K.H., Newman S.T. State of the art electrical discharge machining (EDM). *International Journal of Machine Tools and Manufacture*. 2003. Vol. 43. No. 13. P. 1287–1300. DOI: 10.1016/S0890-6955(03)00162-7.
- [13] Pisarciuc C., Dodun O., Slătineanu L., et al. Wire Electrical Discharge Machining—A Review // *Machines*. 2020. Vol. 8, No. 4. Art. 69. DOI: 10.3390/machines8040069.
- [14] Kumar P., Singh N.K., Sharma A., et al. Recent advances in wire electrical discharge machining of difficult-to-machine materials: A review. *Journal of Manufacturing Processes*. 2024.
- [15] Zhang Y., et al. Research Progress on Process Optimization of Metal Materials in Wire Electrical Discharge Machining // *Metals*. 2025. Vol. 15, No. 7. Art. 706. DOI: 10.3390/met15070706.
- [16] Zhang X., Li Y., Wang H., et al. Thermal-fluid coupling model of crater formation in electrical discharge machining // *The International Journal of Advanced Manufacturing Technology*. 2024. DOI: 10.1007/s00170-024-13999-6.
- [17] Klocke F., Hensgen L., Klink A., Ehle L., Schwedt A. Structure and Composition of the White Layer in the Wire-EDM Process // *Procedia CIRP*. 2016. Vol. 42. P. 673–678. DOI: 10.1016/j.procir.2016.02.300.
- [18] Klocke F., Hensgen L., Klink A., Ehle L., Schwedt A. Structure and Composition of the White Layer in the Wire-EDM Process // *Procedia CIRP*. 2016. Vol. 42. P. 673–678. DOI: 10.1016/j.procir.2016.02.300.
- [19] Ekmekci B. Residual Stresses and White Layer in Electrical Discharge Machining (EDM) // *Applied Surface Science*. 2007. Vol. 253. No. 23. P. 9234–9240. DOI: 10.1016/j.apsusc.2007.05.078.
- [20] Alkahlan B., Tabbakh T., Kurdi A., Pramanik A., Basak A.K. Formation and Characterization of the Recast Layer Formed on Inconel 718 during Wire Electro-Discharge Machining. *Materials*. 2023. Vol. 16. No. 3. Art. 930. DOI: 10.3390/ma16030930.
- [21] Demirtaş H., Ay M., Yıldırım C.V., Giasin K., Sharma S., Pimenov D.Y. Investigation of the Layer Effects Formed by W-EDM on Electrochemical Grooving Performance of Co-Based Superalloy. *Machines*. 2023. Vol. 11. No. 8. Art. 823. DOI: 10.3390/machines11080823.
- [22] Mishra S., Sharma A., Kumar A., Singh R., Pruncu C.I. An Experimental Investigation on Surface Integrity and Wire Wear in Rough and Trim Cut Modes of WEDM for Hybrid Composite. *Aircraft Engineering and Aerospace Technology*. 2024. DOI: 10.1108/AEAT-03-2024-0069.
- [23] Naeim N., AbouEleaz M.A., Elkaseer A. Experimental Investigation of Surface Roughness and Material Removal Rate in Wire EDM of Stainless Steel 304. *Materials*. 2023. Vol. 16. No. 3. Art. 1022. DOI: 10.3390/ma16031022.
- [24] Suresh T., Jayakumar K., Selvakumar G., Ramprakash S. Experimental Investigation on Improvement of Machinability of SS 304 Through Multipass Cutting in WEDM. *Arabian Journal for Science and Engineering*. 2023. DOI: 10.1007/s13369-022-07508-8.
- [25] Oniszczyk-Świercz D., Świercz R. Effects of Wire Electrical Discharge Finishing Cuts on the Surface Integrity of Additively Manufactured Ti6Al4V Alloy. *Materials*. 2023. Vol. 16. No. 15. Art. 5476. DOI: 10.3390/ma16155476.
- [26] Muttamara A., Nakwong P. Enhancing Wire-EDM Performance with Zinc-Coated Brass Wire Electrode and Ultrasonic Vibration. *Micromachines*. 2023. Vol. 14. No. 4. Art. 862. DOI: 10.3390/mi14040862.
- [27] Sharma A., Kumar R., Pimenov D.Y., et al. Optimization of Wire EDM Process Parameters on Cutting Inconel 718 Using Zinc-Diffused Brass Wire Electrode. *Coatings*. 2022. Vol. 12. No. 11. Art. 1612. DOI: 10.3390/coatings12111612.
- [28] Kitayama S., Yonehara M., Okamoto Y., Narita H. Wire-EDM Performance and Surface Integrity of Inconel 718 Fabricated by Laser Powder Bed Fusion. *The International Journal of Advanced Manufacturing Technology*. 2024. Vol. 130. P. 4513–4528. DOI: 10.1007/s00170-023-12924-7.
- [29] Kombayev, K., Kozhakhmetov, Y., Yerbolat, D., Dauletkanov, Y., Kim, V., Kaidar, A., Ishangaliyev, A., & Khoshnaw, F. (2026). Influence of cutting parameters and assist gases on the laser cutting quality of 09G2S (S355J2, EN 10025-2) structural steel. *Results in Surfaces and Interfaces*, 22, 100716. <https://doi.org/10.1016/j.rsi.2025.100716>
- [30] Wittenburg J., Küpper U., Herrig T., Klink A., Bergs T. Surface Integrity Analysis of Single Discharge Characteristics Derived from the Continuous Wire EDM Process. *Procedia CIRP*. 2024. Vol. 123. P. 203–208. DOI: 10.1016/j.procir.2024.05.037.
- [31] Li Z., M'Saoubi R., Axinte D., et al. Surface Integrity in Metal Machining – Part I: Fundamentals of Surface Characteristics and Formation Mechanisms. *International Journal of Machine Tools and Manufacture*. 2021. Vol. 162. Art. 103686. DOI: 10.1016/j.ijmachtools.2020.103686.
- [32] Kitayama S., Yonehara M., Okamoto Y., Narita H. Wire-EDM Performance and Surface Integrity of Inconel 718 Fabricated by Laser Powder Bed Fusion. *The International Journal of Advanced Manufacturing Technology*. 2024. Vol. 130. P. 4513–4528. DOI: 10.1007/s00170-023-12924-7.
- [33] Kombayev, K., Khoshnaw, F., Kozhakhmetov, Y., Tleuzhanova, G., Azamatov, B., & Tabiyeva, Y. (2025). Microplasma sprayed tantalum coatings on Ti Grade 5 extra-low interstitials: Investigation of thickness and porosity control. *Coatings*, 15, 464. <https://doi.org/10.3390/coatings15040464>.

[34] Kar S., C. A. Niranjana, Prabhuswamy N. R., Majumder T., Baroi B. K., Kebede A. W. Experimental Investigation and Parametric Optimization of Machinability and Surface Characteristics in Wire EDM of Inconel 718. Scientific Reports. 2025. DOI: 10.1038/s41598-025-11188-3.

[35] Sherov K.T., Mardonov B.T., Buzauova T.M., Tussupova S.O., Smakova N.S., Izotova A.S., Gabdyssalik R., Kurmangaliyev T.B., Elemen D.E. The research of micro-hardness of side surfaces of teeth cylindrical wheels processed by "shaver-rolling device". Journal of Theoretical and Applied Mechanics. 2020; 50(1): 50–56.
<https://doi.org/10.7546/JTAM.50.20.01.05>

Information of the authors

Kombayev Kuat Kurganovich, PhD, associate professor, senior researcher, D. Serikbayev East Kazakhstan Technical University

e-mail: kkombaev@edu.ektu.kz

Azamatov Bagdat Nurlanovich, PhD, associate professor, General Director, SciMed LLP

e-mail: bazamatov@edu.ektu.kz

Kaliyev Daniyar Issatayuly, PhD, Head of "Smart Engineering" Competence center, D. Serikbayev East Kazakhstan Technical University

e-mail: dkaliyev@edu.ektu.kz

Mukhametbek Zhaksylyk Mukhametbekuly, doctoral student, researcher, D. Serikbayev East Kazakhstan Technical University

e-mail: zmukhametbek@edu.ektu.kz

Gabdyssalyk Riza, PhD, associate professor, senior researcher, D. Serikbayev East Kazakhstan Technical University

e-mail: rgabdysalyk@edu.ektu.kz