Iranian Journal of Materials Forming 11 (1) (2024) 44-61

IJMF

Online ISSN: 2383-0042

Iranian Journal of Materials Forming

Journal Homepage: http://ijmf.shirazu.ac.ir

Research Article

# Experimental Study of the Effects of the Ultrasonic Peening Treatment on Surface Hardness and Hardness Depth of Wire EDMed Workpieces

A. Abdollahi, M. Honarpisheh* and S. Amini

Department of Manufacturing, Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran

ARTICLE INFO

*Article history:*

Received 12 April 2024
Reviewed 18 May 2024
Revised 29 May 2024
Accepted 15 June 2024

*Keywords:*

Surface hardness
Hardness depth
Wire electric discharge machining (WEDM)
Ultrasonic peening treatment (UPT)
Mo40 alloy steel (DIN 1.7225)

*Please cite this article as:*

Abdollahi, A., Honarpisheh, M., & Amini, S. (2024). Experimental study of the effects of the ultrasonic peening treatment on surface hardness and hardness depth of wire EDMed workpieces. *Iranian Journal of Materials Forming*, *11*(1) 44-61. https://doi.org/10.22099/IJMF.2024.49938.1290

ABSTRACT

Wire EDM is a modern machining process that uses electrical discharge to cut workpieces. High temperatures generated by wire EDM can cause surface cracking due to metallurgical changes. A new approach is to use the ultrasonic peening treatment to cause surface severe plastic deformation to improve the mechanical properties, especially the hardness. In this study, the focus was on exploring the impact of cutting types in wire EDM, feeding rate, and the number of peening passes as input parameters on Mo40 (1.7225) alloy steel. The experiments were designed using the multilevel factorial design method. The average hardness values were then analyzed based on the input parameters. The maximum hardness value was determined through optimization using the multilevel factorial design method. Analysis of variance was used to evaluate the impact of parameters on hardness. The highest hardness value of 952.7 (HV) was obtained with a feeding rate of 0.12 (mm/rev) and 3 peening passes in roughing mode, leading to a 48% increase in hardness. A mathematical model with 99.87% desirability was developed to study the correlation between input parameters and response variables. The hardness distribution in the peened workpieces continued up to 200 μm below the surface layers. The highest hardness was found at a feeding rate of 0.12 (mm/rev), which influences the time needed to alter dislocation density and form a new sublayer structure. Overall, increasing the feeding rate decreases hardness, while increasing peening passes increases it. According to a single-objective optimization, the cutting types, feeding rate, and number of peening passes respectively affect hardness value.



## 1. Introduction

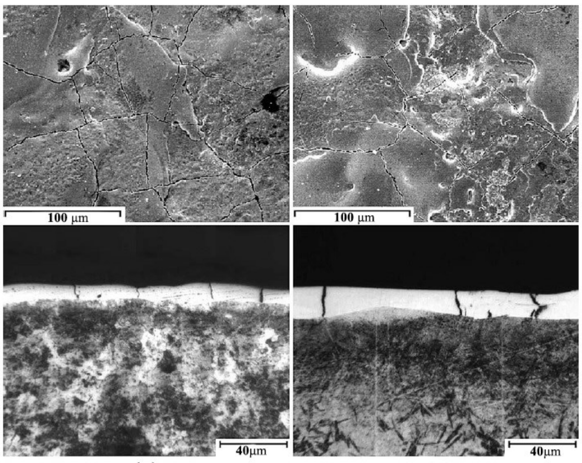
Electrical discharge machining, commonly referred to as EDM, is a thermal mass reduction technique used to form cavities in metals and other conductive materials. In this process, material removal is achieved through the phenomenon of electrolytic discharge erosion (EDE), in which electrical sparks are created between two electrodes immersed in a dielectric liquid. The tool and the workpiece are connected to non-identical poles of an electrical source. As the tool nears the workpiece, the sparks between the electrodes remove small pieces of the surface. This process takes place within a dielectric

* Corresponding author
E-mail address: honarpishe@kashan.ac.ir (M. Honarpisheh)
https://doi.org/10.22099/IJMF.2024.49938.1290

fluid that helps to facilitate the machining operation by preventing the electrode from contacting the workpiece.

Wire EDM (WEDM) is a unique form of EDM that uses a continuously moving conductive wire electrode. In this process, the material is removed by spark erosion while the wire electrode is guided through the workpiece by a fresh wire spool. Wire EDM is preferred for cutting intricate shapes and tight tolerances in hard materials that are difficult to machine using conventional methods. As there is no mechanical contact between the electrode and the workpiece, intricate machining operations are possible, enabling the production of various geometries with high precision. It is commonly used in industries such as aerospace, automotive, and medical device manufacturing. WEDM is a thermoelectric machining process that combines electricity, heat, and mechanical explosion to facilitate machining. In this process, high heat is generated by the concentrated discharge current and explosions result from the boiling of the volume-both essential factors for the cutting mechanism. It is the intense heat that quickly burns the workpiece and leads to its erosion. The high local temperatures of 8000 to 12000 °C generated during electrical discharge machining have a profound effect on the metallurgical structure and mechanical properties of the machined surfaces. After completion of the electrical discharge process, three different layers usually form on the metal cross-section of the workpiece. The first layer is the splattered layer, which is formed by the eruption of the molten metal from the workpiece and the molten effects of the wire material on the surface of the workpiece, which can be easily removed after machining. The layer underneath is called the white layer or recasting layer. This area is created by the re-solidification of the molten metal in the machined recesses. The molten material is rapidly cooled and solidified by the dielectric fluid. Microcracks can occur in this extremely hard and brittle layer. If this layer is excessively thick or is not reduced in some way, the consequences of this layer can lead to premature failure or malfunction of the part. The last layer is called the heat-affected zone (HAZ), which has been affected by heat without melting. Bülent and Ekmaki [1] have illustrated that surface cracks are analyzed based on the composition of the white layer, the heat treatment of the workpiece material, and the operating parameters used, including the average discharge current and pulse duration. As shown in Fig. 1, surface cracks that originate at the surface and propagate perpendicular to the interference zone are mainly caused by the presence of inhomogeneities in the metallurgical phases within the white layer [1].

The presence of the white layer reduces the service life of mechanical components subjected to impact loads and accelerates the occurrence of fatigue failure [2]. The surface layer of a workpiece plays a crucial role in determining its mechanical and functional properties. The integrity of the surface, whether it is inherent or modified, is a key factor in maintaining the desired quality of a machined surface [3]. Surface integrity is a critical aspect of machining processes that encompasses metallurgy and surface topography. Key factors to consider include surface roughness, cracks, residual stresses, plastic deformation, and the formation of defects and voids. The monitoring and treatment of these elements are essential to ensure the quality and durability of the machined components [2]. Surface cracks occur when the tensile stresses caused by material contraction during the cooling of the workpiece after the spark exceeds the maximum tensile stress of the workpiece material. These transformed areas significantly affect the surface integrity of the workpiece [3]. Several factors affect the surface integrity of an




(a) (b)

**Fig. 1.** EDM surfaces and cross-sectional views of normalized (a) roll steel and (b) plastic mold steel samples. Average pulse current: 6 A, pulse duration: 400 µs, and dielectric liquid: kerosene [1].

EDMed part, including spark current, spark duration (pulse-off time), open circuit voltage, electrode polarity, tool, and workpiece material properties, characteristics of dielectric fluid, and chip concentration in the fluid. The fatigue resistance, chemical resistance, corrosion resistance, and wear resistance of the workpiece materials are significantly influenced by these variables [4]. Under dynamic stress, small cracks may develop on the surface of a part, leading to an increased risk of part failure. Therefore, the smoothness and thickness of the surface layer produced by the WEDM process are critical factors in the overall quality of the surface. However, the fatigue strength of alloys is significantly reduced by the altered surface layer that forms during EDM. This altered layer consists of a post-processing layer that may or may not contain micro-cracks, some of which may penetrate the underlying metal. It is strongly recommended that post-treatment methods are used to restore the fatigue strength of critical or highly stressed surfaces. Effective methods such as stress-relieving grinding, chemical processing, metallurgical coating, reheat treatment, and shot peening can be employed to remove altered layers and enhance fatigue properties. The UPT is an innovative method for improving the mechanical and metallurgical properties of materials. By using high-frequency ultrasonic vibrations, the UPT induces residual compressive stresses, refines grain size, and improves hardness and wear resistance. This process not only changes the surface properties of the workpiece, but also increases its overall durability and performance [7]. A study by Amini et al. [8] investigated the abrasion behavior of graphite steel during ultrasonic peening treatment. The results showed that the application of this process to rolling rolls increases their durability, strength, and surface smoothness. Adil Akram Mahmoud et al. [9] conducted a study to compare the mechanical properties and fatigue strength of AA1100 aluminum alloy in its ultrasonically peened condition with its unpeened condition. The results showed that the tensile strength, yield strength, and hardness increased by 8, 7.05, and 9%, respectively. In addition, a significant improvement in the fatigue life of AA1100 alloy was obtained. Zhu et al. [5] conducted a study on the influence of ultrasonic shot peening process parameters on the surface nanocrystallization and hardness of pure titanium. The results showed that UPT led to nanocrystallization of the surface, resulting in a significant increase in the hardness of pure titanium. This suggests that the UPT has the potential to improve the mechanical properties of materials by increasing their hardness. Similarly, Xing et al. [6] explored the use of ultrasonic peening treatment to improve stress corrosion resistance of AlSi10Mg components fabricated using selective laser melting. The study demonstrated that the UPT was effective in enhancing the stress corrosion resistance of the components, further emphasizing the potential of the UPT in improving the durability and performance of additive manufactured workpieces. This suggests that the UPT not only influences the hardness of materials but also contributes to their overall resistance to stress corrosion, which is a crucial factor in determining the durability and reliability of components.

Mo40 alloy steel (DIN 1.7225) is a versatile material widely used in various industries due to its excellent machinability, strength, thermal conductivity, and hardenability. It is particularly suited for industrial equipment exposed to pressure, impact, and high heat. The study aimed to analyze the impact of different parameters on the hardness of workpieces cut using wire EDM and peened through ultrasonic treatment. Workpieces were wire-cut from Mo40 Alloy steel round bars in three modes: finishing (Current 7 amps), semi-finishing (Current 9 amps), and roughing (Current 15 amps). The study examined the effects of peening passes, feeding rate, and wire EDM cutting types post-ultrasonic treatment on surface hardness and hardness depth. Surface and depth microhardness tests were conducted both before and after the ultrasonic peening treatment. The Multilevel Factorial method was utilized to plan the experiments and optimize the process parameters.

## 2. Experimental Setup and Process Parameters

### *2.1. Materials*

Three cylindrical bars made of alloy steel Mo40 (DIN 1.7225) with a diameter of 25 mm were used for the study. These bars were purchased from the Yazd Alloy Steel Company in Iran. They were then pre-machined to obtain a uniform diameter of 23.5 mm ±0.1, with all surface roughness removed. The chemical and physical properties are listed in Table 1. The alloy steel Mo40 is widely used for high-performance applications such as axles, shafts, crankshafts, connecting rods, spindles, and other workpieces. It is an alloy steel with excellent mechanical properties that make it ideal for a variety of industrial applications that require strength and toughness.

**Table 1.** Chemical and physical properties of Mo40 alloy steel (DIN 1.7225) from Iran Alloy Steel Company– Yazd

| **Chemical compounds (average weight percentage)** | | | | | |
|---|---|---|---|---|---|
| **Elements** | Mn | Si | Cr | C | Mo |
| **Average percentage by weight (%)** | 0.7% | 0.28% | 1.05% | 0.41% | 0.2% |
| **Physical properties** | | | | | |
| **Yield tensile strength (MPa)** | **Elastic modulus (GPa)** | **Ultimate tensile strength (MPa)** | | | |
| 415 | 210 | 655 | | | |

The workpieces without heat treatment had a hardness of 23 Rockwell C. Due to the chromium content in its structure, this frequently used steel can be hardened, making it a cost-effective mold steel. For the purpose of hardening, the workpieces were cleaned, degreased, and placed in a salt bath furnace at 860 °C for 20 minutes. They were then quickly cooled to 400 °C in oil to be normalized. Then, they were reheated in the furnace at 860 °C for 10 minutes. They were then cooled to room temperature in oil. During the hardening process, the second step was repeated to maintain consistent surface hardness. Following this, all samples underwent a hardness test to verify the attainment of 54 Rockwell C hardness levels. The wire-cutting machine requires adjustable parameters such as current, pulse-off time, open circuit voltage, wire tension, wire feed speed, gap voltage, and dielectric material. The most important parameter is the proportional current between the workpiece and the wire. Once this is set, the other parameters are usually recommended according to the machine's guidelines. The current parameter can vary from 0 to 15 amps. However, it is important to note that a higher current intensity can lead to wire breakage. The intensity of the current is directly related to the surface roughness. In this study, the cutting parameters for wire EDM were determined based on the current, and a total of 30 workpieces were cut from the round bar with 8 mm thickness in three different modes: finishing (7 amps), semi-finishing (9 amps), and roughing (15 amps). In Fig. 2, the final workpieces have a diameter of 23.5 mm and a thickness of 8 mm, with a tolerance of ±0.1.

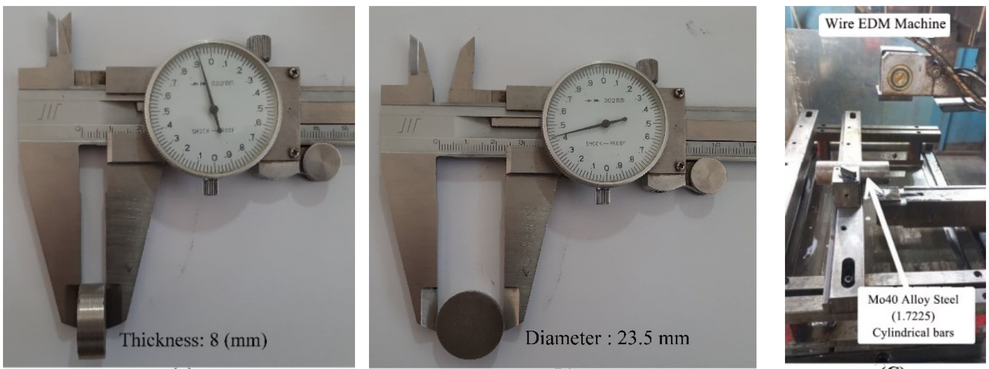



**Fig. 2.** (a, b) Thickness and diameter of the final workpieces, and (c) setting parameters in the wire EDM machine.

### 2.2. Design of experiments and process parameters

The UPT is a topic that still captivates researchers, despite the extensive research already conducted. The UPT provides a unique way to enhance the mechanical properties of a surface without the need for subsequent heat treatment or size limitations while consuming minimal energy. It is a non-destructive mechanical surface treatment method that doesn't include burrs and can convert tensile residual stresses caused by the wire-cut process into compressive residual stresses. Additionally, this technology has immense potential for various industries seeking to enhance the performance and durability of their components. During the process, the lower layers undergo plastic deformation. When the spherical tool is removed from the surface, the lower layer bounces back elastically at the impact point, causing the workpiece surface to undergo compressive stresses from the rebound. This results in the creation of a compressed layer through overlapping depressions. In order to prepare for ultrasonic peening, several equipments are required, including a generator, pneumatic system, transducer, booster, horn, tool, workpiece, lathe, and fixture. The generator plays a vital role in producing electrical energy, which is then converted into vibrations by the transducer. The horn then focuses, amplifies, and transmits these vibrations to the peening tool, which transfers them to the workpiece. It is important to note that the horn increases the transducer's vibration amplitude to 10 µm. Fig. 3 shows the arrangement for ultrasonic peening treatment on the frontal area of the workpiece. During the process, the workpiece is fixed within a fixture and rotated by a lathe. By adjusting the revolution speed of the lathe, the peening tool moves at a predetermined feeding rate and performs ultrasonic peening. This study employs a rotational speed of 45 rpm and a workpiece diameter of 23.5 mm. The frequency employed in the process is 20 kHz, while the feeding rate is maintained at three different levels: 0.08, 0.12, and 0.16 mm/rev.

During the process, the surface of the workpiece undergoes severe plastic deformation, which results in a more refined nanoscale structure. This leads to increased hardness and strength as per the Hall-Patch relationship. The Hall-Patch formula (Eq. (1)) is the dependence of hardness and grain size [7]. H represents hardness, $H_0$ is the hardness constant, d is grain size, and K is the material constant. It is an experimental approach to quantify the strength of grain boundaries in metals and alloys. Additionally, this correlation indicates that the material's hardness rises with a decrease in grain size [8].

$$H_y = H_0 + k.d^{-1} \quad (1)$$

The peening equipment is powered by an ultrasonic generator that converts low-frequency electrical energy (60 Hz) into high-frequency energy (20 kHz). When an electric field is applied to a piezoelectric element, it expands, typically increasing the transducer thickness by a few micrometers. The transducer is then

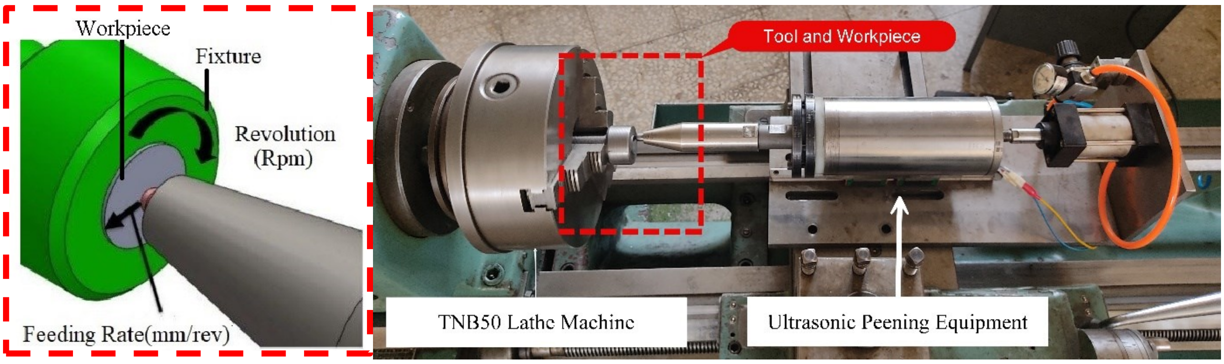



**Fig. 3.** Schematic of the ultrasonic peening equipment on the TNB50 lathe machine (peening tool and workpiece).

stimulated at the resonant frequency to enhance the range of tool vibration. Additionally, a booster and horn are included in the transducer to elevate its resonant frequency. The generator used in the study, developed by Swiss company MPI, has a power output of 3000 watts and operates within a frequency range of 20 to 100 kHz. The ultrasonic peening equipment's transducer receives a 20 kHz frequency from the generator and transforms it into mechanical vibrations. These vibrations are then amplified by the booster and horn. The spherical tool transfers the vibrations to the workpiece. It is important to note that the longitudinal natural frequency of the horn is 20466 Hz, which should align with the transducer's natural frequency of 20 kHz. The CK45 steel horn amplifies the vibration amplitude produced by the transducer and transfers it to the spherical tool. In this study, as shown in Fig. 4, a 6 mm tungsten carbide tool with a hardness of RC80 was employed for mechanical impacts on the workpiece surface. The air pressure serves to prevent tool kickback during surface peening and assists in the movement of the ultrasonic peening equipment. To accomplish this, a compressor with 8 bar pressure, a SC-50X25 S pneumatic cylinder, and a control valve equipped with a pressure gauge set at 1 bar were utilized to provide compressed air. The air pressure can be modified by using a pressure-regulating valve located at the inlet path to the pneumatic cylinder.

In the field of research and engineering, it is crucial to use a design table at the beginning of each experiment to ensure that the factors and their respective values are allocated appropriately. This is where the Design of Experiments (DoE) method can be used to assess the impacts of different factors on responses, and determine the necessary number of experiments. The use of DoE is essential for the cost and precision of tests. By planning and executing experiments carefully with DoE, it becomes possible to ensure that the gathered data is meaningful and useful in making inferences. Therefore, the use of a design table and the application of DoE techniques are critical stages in the experimental process [9]. The present study employs Minitab software to create the design table, using a multilevel factorial design with three input factors and three levels. Table 2 displays the resulting design, which reveals a total of 30 distinct states where the UPT needs to be executed. The input factors, which include cutting types in WEDM (current), feeding rate (mm/rev), and number of peening passes (No.), represent the process parameters.

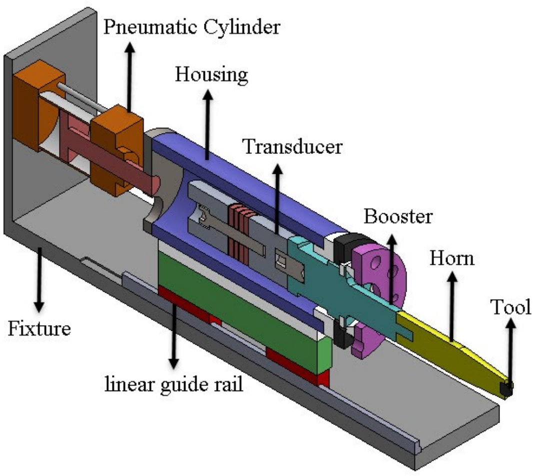



**Fig. 4.** 3D modeling of the UPT equipment.

**Table 2.** The parameters tested in the UPT

| Cutting types in WEDM | Feeding rate (mm/rev) | Number of passes |
|---|---|---|
| Finishing (7 amps) | 0.08 | 1 |
| Semi-finishing (9 amps) | 0.12 | 3 |
| Roughing (15 amps) | 0.16 | 5 |

## 3. Design of Expriments

In the field of experimental design, the utilization of multilevel factorial designs holds significant significance in exploring intricate interactions among various factors. By incorporating multiple levels within these designs, a thorough comprehension of how different variables impact the experiment's outcome can be attained. Furthermore, the optimization process enables the adjustment and enhancement of experimental conditions to effectively achieve the desired results [9]. Table 3 specifies the 27 UPT operation plans generated by Minitab software using input parameters. The table includes StdOrder for the standard order of experiments and RunOrder for the random order of experiments.

**Table 3.** Design of experiments based on multilevel factorial design

| StdOrder | RunOrder | Factor 1 A: Cutting types in WEDM (A) | Factor 2 B: Feeding rate (mm/rev) | Factor 3 C: Number of peening passes (No.) |
|---|---|---|---|---|
| 20 | 1 | 9 | 0.08 | 5 |
| 22 | 2 | 7 | 0.12 | 5 |
| 9 | 3 | 15 | 0.16 | 1 |
| 17 | 4 | 9 | 0.16 | 3 |
| 2 | 5 | 9 | 0.08 | 1 |
| 23 | 6 | 9 | 0.12 | 5 |
| 6 | 7 | 15 | 0.12 | 1 |
| 11 | 8 | 9 | 0.08 | 3 |
| 3 | 9 | 15 | 0.08 | 1 |
| 25 | 10 | 7 | 0.16 | 5 |
| 27 | 11 | 15 | 0.16 | 5 |
| 1 | 12 | 7 | 0.08 | 1 |
| 24 | 13 | 15 | 0.12 | 5 |
| 4 | 14 | 7 | 0.12 | 1 |
| 15 | 15 | 15 | 0.12 | 3 |
| 26 | 16 | 9 | 0.16 | 5 |
| 19 | 17 | 7 | 0.08 | 5 |
| 12 | 18 | 15 | 0.08 | 3 |
| 5 | 19 | 9 | 0.12 | 1 |
| 14 | 20 | 9 | 0.12 | 3 |
| 16 | 21 | 7 | 0.16 | 3 |
| 13 | 22 | 7 | 0.12 | 3 |
| 7 | 23 | 7 | 0.16 | 1 |
| 8 | 24 | 9 | 0.16 | 1 |
| 18 | 25 | 15 | 0.16 | 3 |
| 10 | 26 | 7 | 0.08 | 3 |
| 21 | 27 | 15 | 0.08 | 5 |

Workpieces 28, 29, and 30 are finishing, semi-finishing, and roughing wire EDMed workpieces that were not subjected to the ultrasonic peening treatment. The surface hardness of the workpieces was evaluated before and after the ultrasonic peening process using the KOOPA micro hardness tester model UV1 from Iran. The micro-hardness tests were conducted on the workpiece surfaces using a 1 kg force for 10 seconds with a square pyramid indenter. The average indentation depth was determined to be 6.79 µm. The microhardness data in Vickers units were obtained from Table 4 based on the RunOrder.

**Table 4.** Measured hardness values based on RunOrder in multilevel factorial design

| **RunOrder** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|
| **Average hardness (HV)** | 875.85 | 875.2 | 932.29 | 874.07 | 877.57 | 890.2 | 950.65 | 882.24 | 937.1 |
| **RunOrder** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** |
| **Average hardness (HV)** | 862.3 | 930.56 | 868.42 | 947.62 | 877.63 | 952.7 | 867.3 | 865.38 | 938.41 |
| **RunOrder** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** |
| **Average hardness (HV)** | 889.82 | 891.13 | 863.93 | 879.35 | 863.61 | 871.04 | 935.7 | 869.21 | 929.91 |

Table 5 displays hardness values for unpeened workpieces in three modes: finishing, semi-finishing, and roughing.

**Table 5.** Measured surface hardness values of unpeened workpieces

| Modes | Finishing | Semi-finishing | Roughing |
|---|---|---|---|
| **Average hardness (HV)** | 667.9 | 662.6 | 642.4 |

In Minitab, modeling sufficiency means evaluating how well a statistical model represents and predicts relationships between variables. This involves determining whether the model captures important patterns and trends in the data. To assess the modeling sufficiency for the hardness (HV) variable, residual plots were examined, including the normal probability plot and histogram graphs, as shown in Fig. 6. In data distribution, it is crucial to identify the mathematical function that closely represents the nature of the distribution for accurate analysis and calculations. One of the key statistical distributions is known as "normal distribution" or "Gaussian function". The data may exhibit a right-skewed, left-skewed, or clustered around the mean. When data shows a bell-shaped distribution with clustering around the mean, it is considered to be normally distributed. Additionally, the normal probability plot confirms the histogram's validity by showing that the remaining points are closely clustered around the specified line without exhibiting any discernible trend.

## 4. Results and Discussion

### *4.1. Hardness measurement*

#### *4.1.1. Measurement of surface hardness*

Surface severe plastic deformation (SSPD) processes have demonstrated their effectiveness in modifying and refining the structure of metals and alloys. By subjecting materials to significant plastic strain, these methods lead to improvements in mechanical properties through processes such as hardening, homogenization of structure, distribution and crushing of sediments, and increasing the density of dislocations [10].

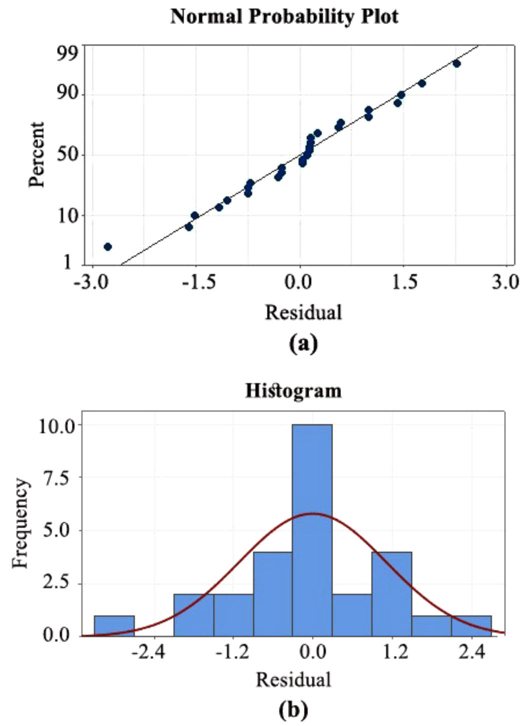



**Fig. 6.** Residual plots for hardness (HV): (a) normal probability plot and (b) histogram

The UPT, which involves applying dynamic loads to small subsurface thicknesses, can modify the hardness of a workpiece. Fig. 7 provides graphs that analyze the changes in surface hardness percentages of peened workpieces across three different modes: finishing, semi-finishing, and roughing. The analysis is based on the number of peening passes. Interestingly, the highest percentage of hardness was observed after three peening passes in all three modes. However, it is worth noting that increasing the number of peening passes from 3 to 5 resulted in a slight decrease in the percentage of hardness, although this decrease was not significant. In general, increasing the number of peening passes typically leads to a higher percentage of hardness in materials. However, it is important to note that the specific values of feeding rate also plays a crucial role in the process of altering the hardness. Therefore, finding the optimal balance between the number of passes and feeding rate is essential for achieving the desired hardness levels in the material being treated. By increasing the number of peening passes in conjunction with an appropriate feeding rate, the accumulated impact energy rises, leading to further modification of the sub-layer structure and closure of surface cracks, ultimately boosting the workpiece's hardness. Analysis of hardness percentages across all groups reveals that the highest hardness percentage is associated with the rough mode in Fig. 7(c). Within the roughing group, the hardness percentage ranges from 44.86% to 48.3%. Surface hardness in the UPT increases with the number of peening passes due to mechanisms like surface roughening, grain refining, compressive stress, and nanocrystallization [11]. The high-energy impacts during the UPT can induce surface nanocrystallization, forming a surface layer with extremely fine grains. This nanocrystalline structure contributes to the increased hardness due to the higher number of grain boundaries and the resulting resistance to deformation [12]. From another point of view, the severe plastic deformations caused by ultrasonic peening lead to a significant increase in dislocation density within the surface layer. This increased dislocation density impedes the movement of dislocations, resulting in higher hardness. Additionaly, grain refinement can be considered as one of the factors of increasing the hardness due to the number of peening passes. The high-frequency vibrations and severe plastic deformations caused during ultrasonic peening lead to grain refinement in the surface layer. This results in increased hardness due to the higher number of grain boundaries and enhanced resistance to deformation [12]. The feeding rate influences the hardness percentage, as seen in the roughing group where the highest hardness percentage of 48.3% occurs with an average feeding rate of 0.12 for 3 passes, compared to 47.9% in the case of one pass and 47.5% in the case of 5. It is possible to achieve greater hardness in a metal surface with one peening pass and a lower feeding rate, such as 0.08 mm per revolution, than with five peening passes.

It is important to understand that merely increasing the number of passes in the UPT does not always result in a harder surface. Although it is logical to assume that more passes would lead to a harder

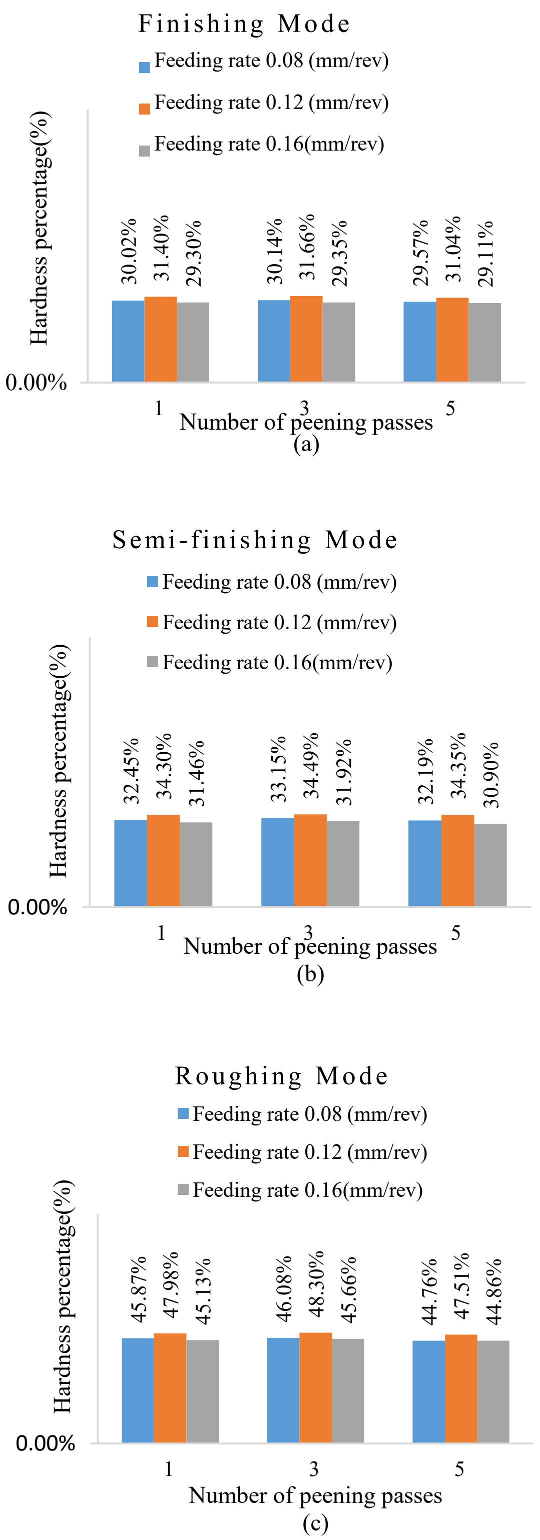



**Fig. 7.** (a) Surface hardness changes according to the number of passes in finishing mode, (b) surface hardness changes according to the number of passes in semi-finishing mode, and (c) surface hardness changes according to the number of passes in roughing mode.

surface, this study proves that there is a point where the advantages of additional peening diminishes. Ultrasonic peening works by inducing compressive stresses on the surface of the material, which can improve its hardness. However, there is a limit to how much deformation the material can handle before negative effects such as reduced ductility occur. In order to achieve the best results, it is important to carefully consider the number of peening passes applied during treatment. Applying more passes may not always lead to a harder surface and can even have a negative impact on the material's overall properties. Fig. 8 displays graphs that illustrate the percentage changes in surface hardness of peened workpieces across three modes: finishing, semi-finishing, and roughing, based on varying feeding rates. Notably, the highest percentage of hardness across all modes is consistently associated with a feeding rate of 0.12 (mm/rev). However, as the feeding rate escalates from 0.12 (mm/rev) to 0.16 (mm/rev), a decline in hardness percentage is observed. This phenomenon can be attributed to the fact that with higher feeding rates, although the surface layers are peened in a shorter timeframe, the compression time for these layers is reduced, consequently leading to a decrease in hardness. In other words, the reason for this unexpected outcome lies in the mechanics of the process. When the feeding rate is increased, the energy imparted to the material is spread out over a larger surface area, resulting in a less intense impact on individual grains. This leads to a shallower depth of hardening and ultimately a lower level of hardness. The UPT is effective in closing both surface and subsurface cracks. It achieves this by creating compressive residual stress and inducing plastic deformation in the surface enhancement layer. These two mechanisms work together to reduce the driving force for crack initiation and facilitate the storage of high-density dislocations in the material [12]. However, reducing the feeding rate will increase the peening time, which can decrease the accumulated impact energy and the density of dislocations, leading to lower hardness values. On the other hand, when the feeding rate is kept constant and the number of peening passes increases from one to three, the hardness percentage increases as well. Fig. 8 shows that excessive feeding rate can lead to microstructural changes, such as the formation of defects like microcracks and porosity.

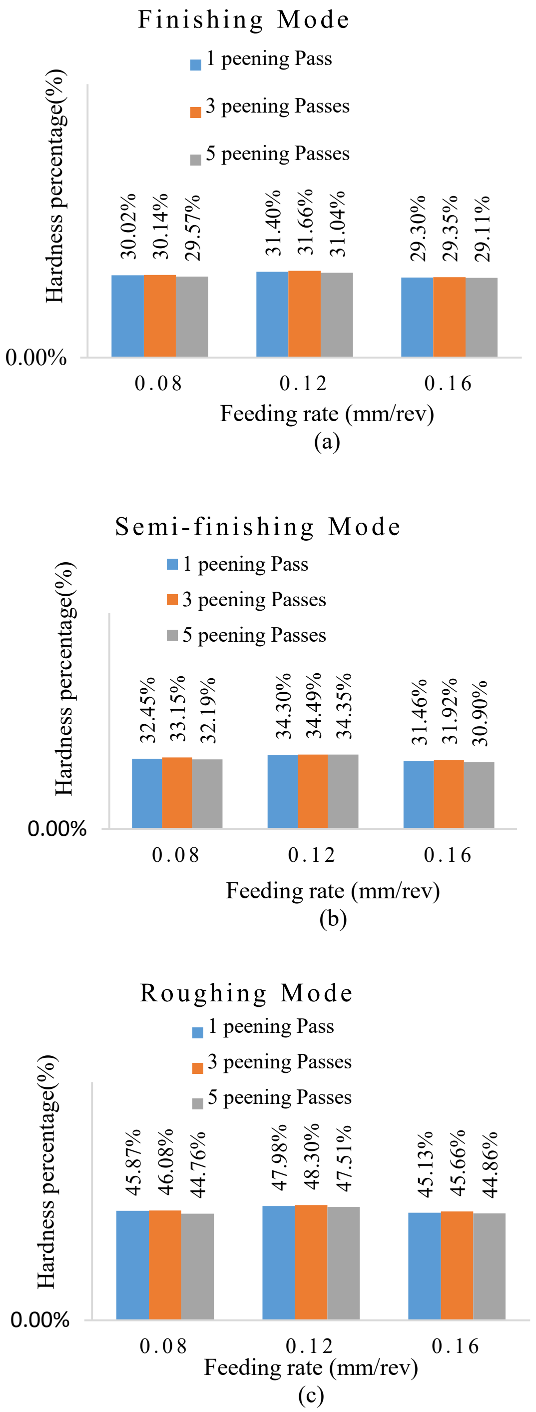



**Fig. 8.** (a) Surface hardness changes according to the feeding rate (mm/rev) in finishing mode, (b) surface hardness changes according to the feeding rate (mm/rev) in semi-finishing mode, and (c) surface hardness changes to the feeding rate (mm/rev) in roughing mode.

These microstructural changes can negatively impact the surface hardness of the material. When the feeding rate is too high, the material does not undergo sufficient plastic deformation, leading to a decrease in the induced compressive residual stresses and grain refinement [11].

#### *4.1.2. Measurement of hardness depth*

In Fig. 9, to evaluate the hardness distribution in the depth of peened workpieces after the UPT, the peened workpieces need to be sectioned first. The water-jet process, which minimally affects the surface structure, was used for this purpose. Both peened and unopened workpieces were equally sectioned in the middle. Subsequently, hardness values were measured from 10 micrometers below the surface using the UV1 micro-Koopa hardness tester. The hardness assessment continued until the point where the difference in hardness between the peened and unpeened workpieces became insignificant. The measurement intervals of the hardness values were 20 µm.

Fig. 10 shows hardness changes in depth at a constant feeding rate of 0.08 (mm/rev), 0.12 (mm/rev), and 0.16 (mm/rev) with different peening passes compared to hardness changes in the depth of workpieces before the UPT. According to this graph, it can be seen that the hardness distribution resulting from the UPT continues up to a depth of 0.2 mm (200 µm) from the surface. The hardness values of the peened workpieces at a distance of 0.2 mm (200 µm) below the surface, with the hardness value of unpeened workpieces being nearly identical. The data indicates a clear trend of increasing hardness values as we move closer to the surface. Peened workpieces consistently exhibit higher hardness values compared to unpeened workpieces, with the highest values observed in roughing workpieces. The UPT induces severe plastic deformation on the surface of the workpiece through the application of static and dynamic forces produced during the peening process. This deformation enables dislocations to migrate more readily, aided by the high frequency of the operation. The reorganization of dislocations is enhanced by the ultrasonic vibrations, leading to the development of a high strain rate. As a result, the surface undergoes stretching, as illustrated in Fig. 9. In order to conduct a more detailed analysis, the examination of workpiece microstructures, including both surfaces and cross-sections, was conducted using the Quanta FEG 450 scanning electron microscope from FEI Company. Fig. 10 shows the SEM images of the workpiece surface before and after the UPT, respectively. The clear effectiveness of performing UPT operations in modifying the features of the workpiece surface is evident. The UPT allows for controlled plastic deformation of the surface, which can be utilized to shape and modify the surface properties without altering the bulk material characteristics.

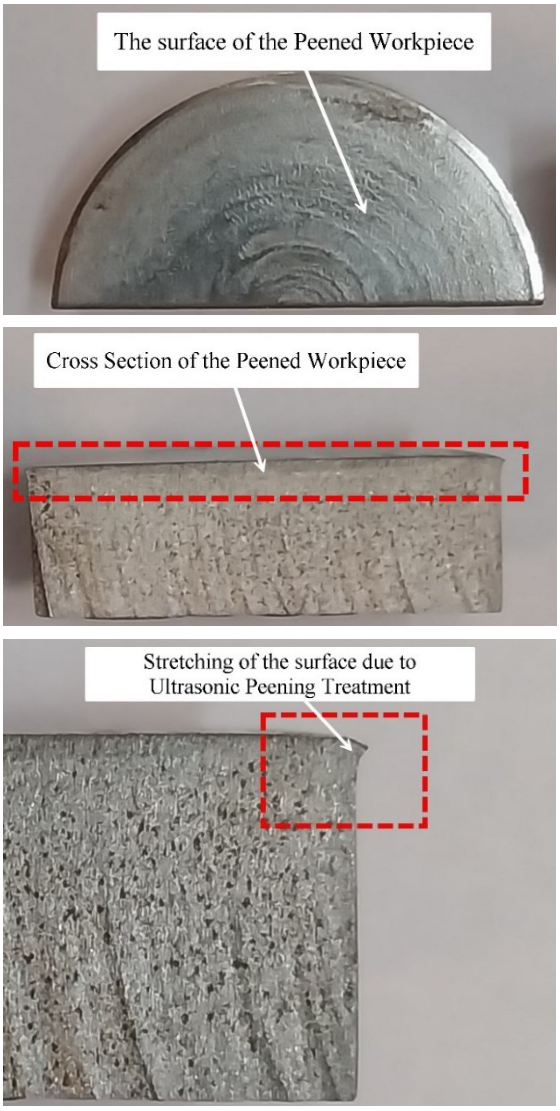



**Fig. 9.** The surface of the peened workpiece and cross-section cut with the water-jet process.

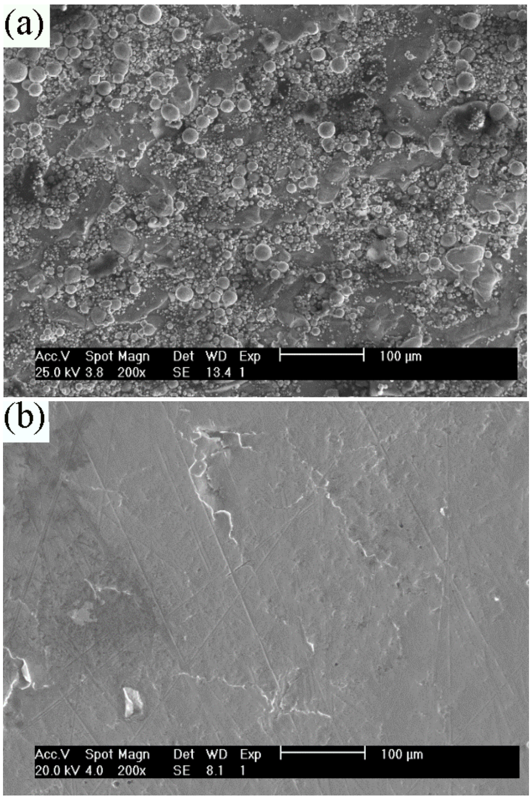



**Fig. 10.** (a) SEM of the surface structure of the workpiece before performing the UPT and (b) SEM of the surface structure of the workpiece after performing the UPT with 200x magnification.

In addition, Fig. 11 shows the SEM cross-sectional image of the workpiece after the UPT. Utilizing ultrasonic vibrations can enhance the process of dislocation rearrangement and lead to the formation of high strain rates. This, in turn, can generate a finer microstructure that shows in Fig. 11.

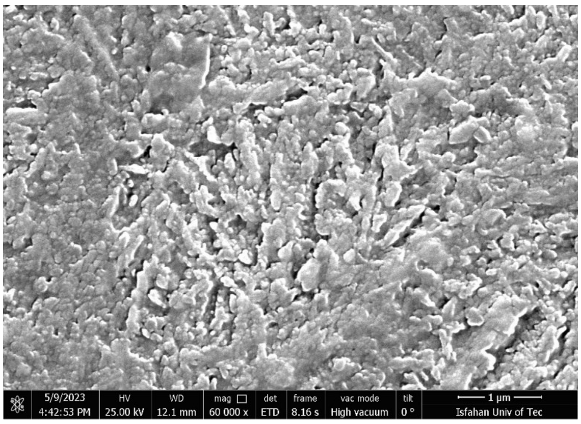



**Fig. 11.** SEM of the surface cross-section of the workpiece after performing the UPT with 60000x magnification.

In Fig. 12(b), it is clear that the surface hardness of the workpieces experienced the most significant increase at a feeding rate of 0.12 (mm/rev) in all three modes of finishing, semi-finishing, and roughing, regardless of the number of peening passes. The highest hardness value of 952.7 (HV) was achieved at a feeding rate of 0.12 (mm/rev) with 3 peening passes on the roughing workpiece, marking a substantial 48% enhancement compared to the roughing workpiece without peening. Additionally, at the same feeding rate, the hardness values for the peened finishing and semi-finishing sections were measured at 879.4 (HV) and 891.19 (HV), respectively, demonstrating increases of 32% and 34%. The maximum hardness distribution is evident at a depth of 50 micrometers at a feeding rate of 0.12 (mm/rev), shown in Fig. 12(b), signifying the optimal timing for peening application.

Achieving optimal hardness in materials is a critical factor in enhancing wear resistance and fatigue strength, thereby extending the service life and performance of components. The feeding rate of 0.12 (mm/rev) presents a key opportunity for maximizing the density of dislocations and accumulated impact energy, resulting in the desired increase in hardness. By employing the appropriate feeding rate, one can ensure the ideal timing for attaining higher hardness levels, leading to a broader distribution of hardness. This depth of hardness plays a vital role in fortifying workpieces against wear and fatigue, ultimately contributing to improved durability and functionality.

### *4.2. Multilevel factorial design*

Fig. 13 displays the half-normal graph and Pareto chart of standardized effects. In the half-normal graph, the proximity of input-independent parameters or interactions to the baseline indicates a lesser impact on the UPT, whereas a greater distance signifies a stronger effect on the treatment. Based on the half-normal graph, the initial parameter affecting the UPT is the quantity of electric current applied during the wire EDM process, followed by the feeding rate

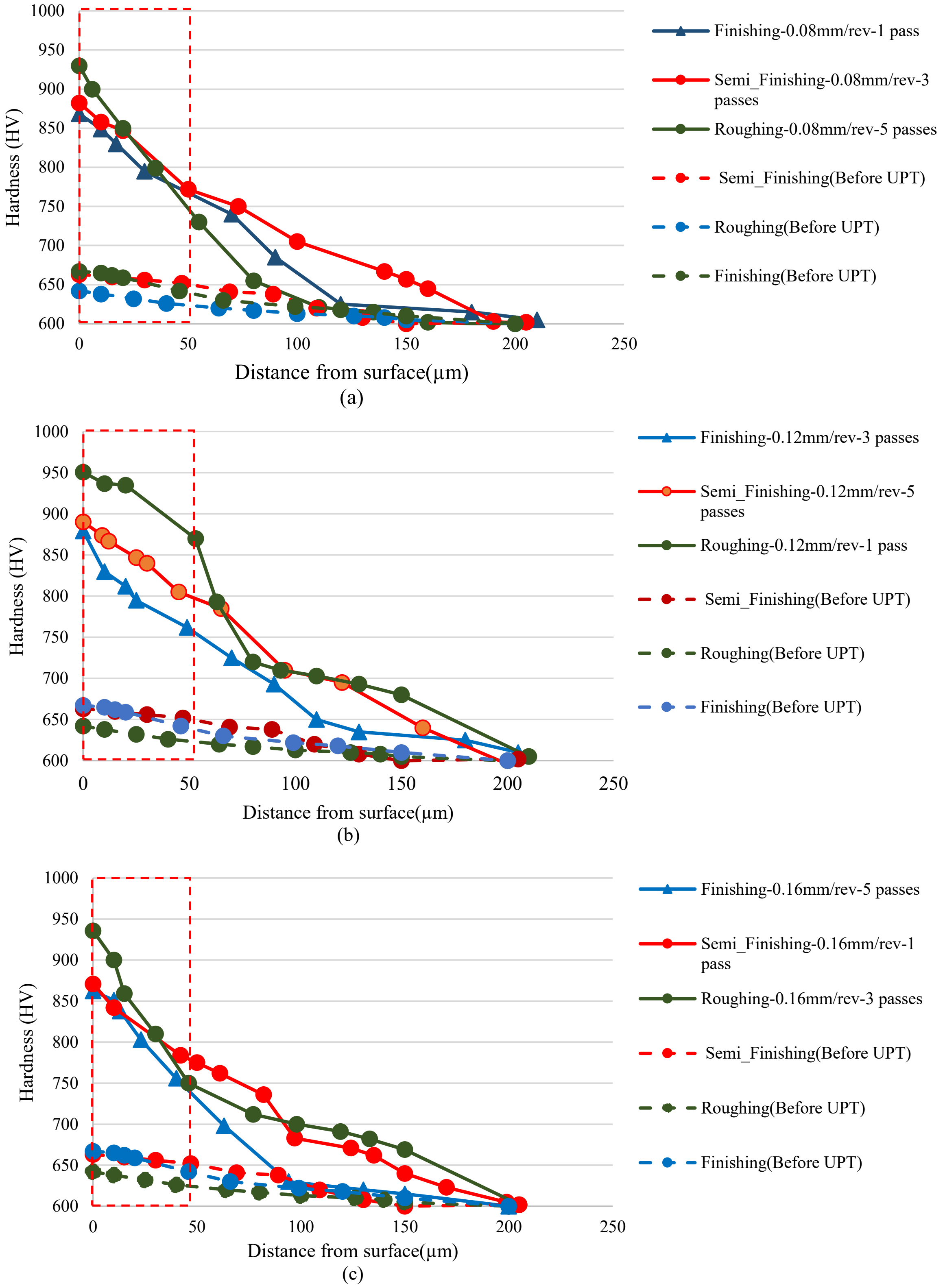



**Fig. 12.** Hardness changes in depth of workpieces after the UPT at varying feeding rates; (a) 0.08 (mm/rev), (b) 0.12 (mm/rev), and (c) 0.16 (mm/rev) with different peening passes compared to hardness changes in the depth of workpieces before the UPT.

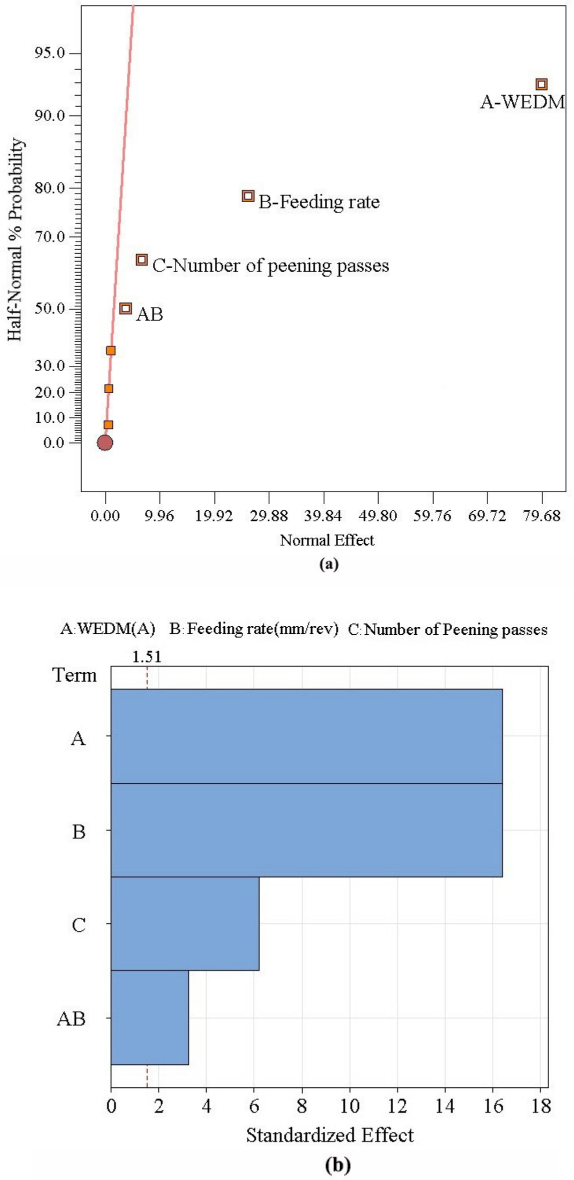



**Fig. 13.** (a) Half-normal % probability and (b) Pareto chart of standardized effects.

parameter, after that is the number of peening passes, and lastly, the interaction between the electric current amount and feeding rate. The Pareto chart of standardized effects also shows the effect of the input parameters and their interaction on the UPT. Parameters exceeding the specified threshold are classified as significant parameters. This graph also validates the results of the half-normal chart.

ANOVA, also known as analysis of variance, is a statistical method utilized to identify potential variations among the means of variables. It achieves this by examining the population distribution within each sample, thereby allowing us to assess the impact of input variables on output variables. In this section, the analysis is conducted utilizing the ANOVA method, focusing on the interaction and main effects plots. The main effect of factors on hardness is illustrated in Fig. 14(a). This graph illustrates the significant impact of cutting modes in wirecut, feeding rate, and the number of peening passes on hardness. When the electric current parameter in wire cut is maximized, resulting in roughing mode workpieces, they exhibit the highest hardness post-ultrasonic peening treatment compared to finishing and semi-finishing modes. In wire EDM process, increasing amperage results in a rougher surface in addition to a thicker recast layer. A thicker recast layer is more prone to the formation of voids and cracks due to the rapid solidification and thermal stresses involved in the process. A thicker recast layer is more likely to have a higher density of voids and cracks. Therefore, due to the presence of more voids and cracks in the rough mode, the possibility of increasing dislocations due to the UPT increases and severe plastic deformation occurs, which leads to an increase in hardness. Additionally, hardness decreases with higher feeding rates. Increasing peening passes from one to three raises the average hardness, but further increasing to five passes results in a decline in hardness values.

Fig. 14(b) illustrates the interaction effects of cutting types in WEDM (A) and feeding rate (mm/rev), cutting types with the number of peening passes, and feeding rate (mm/rev) with the number of peening passes on the hardness value. These interactions provide valuable insights into the relationship between different variables and their impact on hardness values in the context of the study. There is a negative correlation between feeding rate and hardness. As the feeding rate increases, hardness tends to decrease across all cutting types in WEDM (A). Additionally, the effect of the number of peening passes on hardness

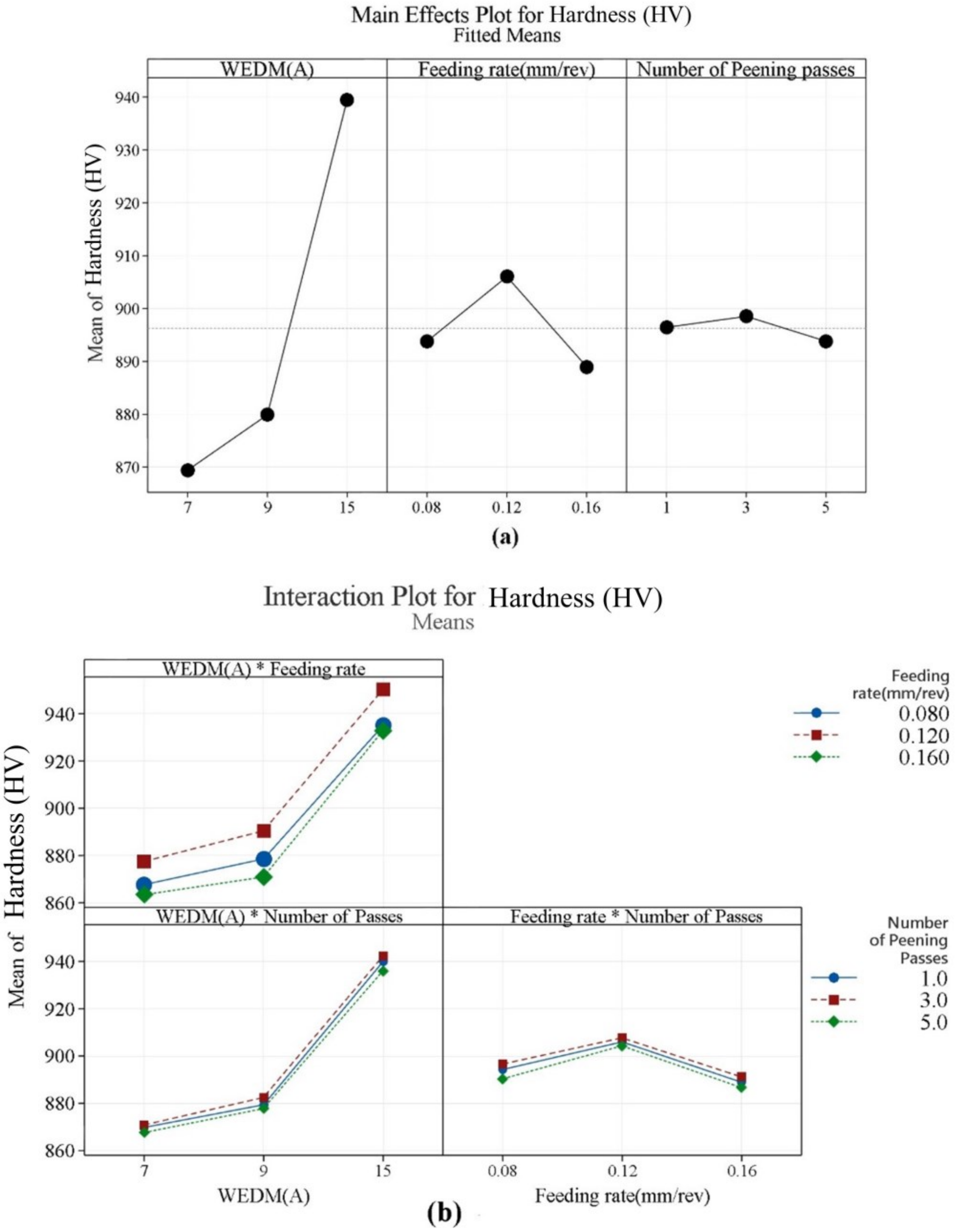



**Fig. 14.** ANOVA method for evaluating (a) main effect on hardness (HV) and (b) interaction effect.

is more significant at higher feeding rates (0.12 mm/rev). In analyzing the factors affecting hardness values, in order of priority, it is clear that cutting types in WEDM (A), feeding rate, and the number of peening passes play significant roles. Among these factors, the roughing mode demonstrates the highest level of hardness. To predict the hardness value based on the cutting types in the WEDM parameter (A), feeding rate (B), and the number of peening passes (C), a mathematical model (Eq. (2)) using multilevel factorial design can be utilized. This model takes into consideration the interactions between these factors to accurately determine the hardness value. By assigning values to A, B, and C, the model can provide a reliable prediction of the hardness value based on the specific parameters chosen.

$$\begin{aligned}\text{Hardness} = {} & 896.27 - 26.82 \times A[1] - 16.35 \times \\ & A[2] - 2.48 \times B[1] + 9.77 \times B[2] + \\ & 0.1916 \times C[1] + 2.26 \times C[2] + \\ & 0.7014 \times A[1]B[1] + 1.12 \times \\ & A[2]B[1]1.82 \times A[1]B[2] + \\ & 0.7016 \times A[2]B[2]\end{aligned} \quad (2)$$

As shown in Fig. 13, the residual plots for the hardness (HV), which included versus fits and versus order graphs were examined to assess the modeling sufficiency. In graphs versus fits and order, the consistancy of variances and the independence of data to time are shown, respectively. The precision of Eq. (2) is assessed by plotting the residual graph against the predicted values in Fig. 15. This graph illustrates the proximity of the data points to the center line, indicating the reliability of the formula in question. Residual, or error, typically represents the variance between the actual and predicted values.

In the mathematical model, the parameters of cutting types in WEDM and feeding rate play a significant role in determining the hardness value. By examining the combined impact of these two parameters across various peening passes, it was observed that the highest hardness value consistently occurred at a feeding rate of 0.12 (mm/rev) in the roughing mode. This finding is visually represented in Fig. 14 through a three-dimensional graph analysis.

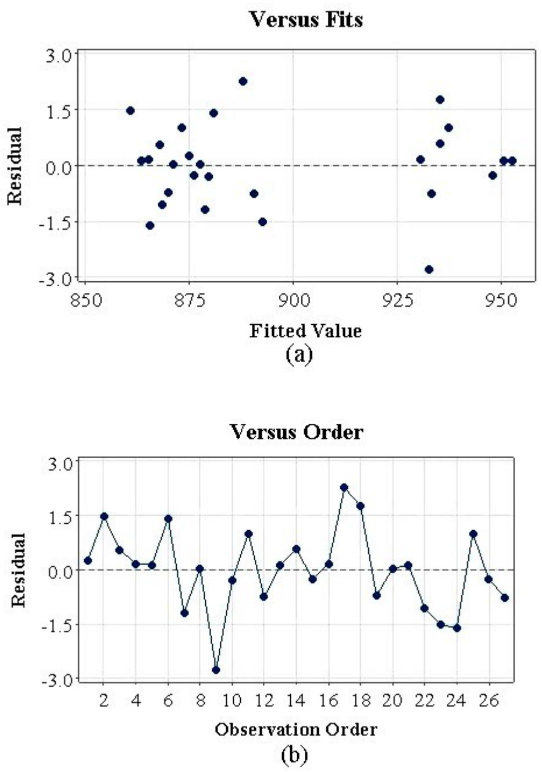



**Fig. 15.** Residual plots for hardness (HV); (a) residual versus fitted value and (b) versus order.

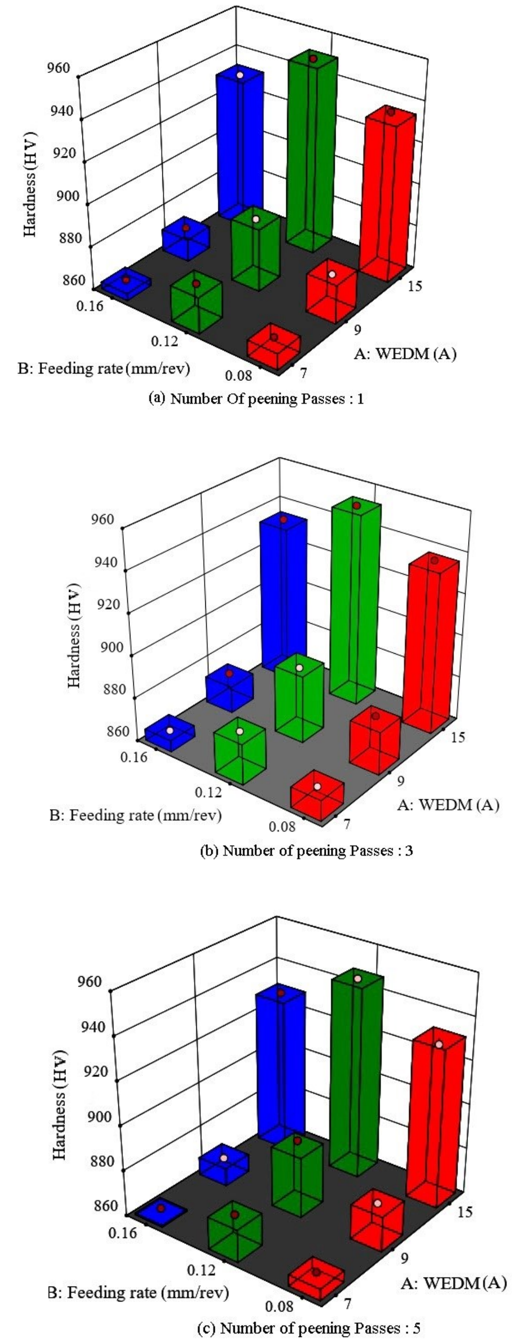



**Fig. 16.** 3D surfaces of hardness based on feeding rate (mm/rev) and cutting types in WEDM (A); (a) number of peening passes: 1, (b) number of peening passes: 3, and (c) number of peening passes: 5.

Additionally, utilizing $R^2$ in our analysis allows us to assess the accuracy of the model. The $R^2$ value indicates how well the experimental data aligns with the model, with a perfect fit being represented by a value of one. In this study, our $R^2$ value is 99.88, and the adjusted $R^2$ value ($AdjR^2$), which accounts for degrees of freedom, is 99.81. These high values demonstrate the precision and reliability of the equation under investigation. Fig. 16 shows that the feeding rate determines the speed at which the impact pin moves along the surface, influencing the energy input and the severity of plastic deformations. A higher feeding rate can lead to a lower energy input and less severe plastic deformations, potentially resulting in lower surface hardness. Conversely, a lower feeding rate can lead to a higher energy input and more severe plastic deformations, potentially resulting in higher surface hardness.

### 4.3. Optimization

Single-objective optimization is a method used to find the best solution for a specific goal. This approach focuses on maximizing or minimizing a single objective function, rather than considering multiple conflicting objectives. By concentrating on the merit of the goal, single-objective optimization aims to identify the optimal point that satisfies the desired criteria. This optimization was done in such a way that the hardness can find the highest possible value in the process of ultrasonic peening treatment. Utilizing Minitab software, the optimal points of the experimental processes can be identified. Finally, the optimal point to achieve the highest hardness value is obtained by including the values mentioned in Table 6.

To confirm the effectiveness of the optimization process, a new workpiece was treated under the UPT using the optimal input parameters. The hardness value of this workpiece, obtained after three peening passes on the rough workpiece with a feeding rate of 0.12 (mm/rev), was measured at 949.7 (HV). The error value, less than one percent, between this hardness value and the one listed in Table 6, demonstrates the accuracy of the optimization.

**Table 6.** Optimized factors using desirability

| Solution | Input parameters | | | Response | Composite desirability |
|---|---|---|---|---|---|
| | Cutting types in WEDM (A) | Feeding rate (mm/rev) | Number of peening passes | Hardness (HV) | |
| 1 | 15 (Roughing) | 0.12 | 3 | 952.3 | 0.9987 |

## 5. Conclusion

Wire EDM machining is a widely used process in manufacturing industries, known for its thermo-electromechanical nature. The heat generated during operation quickly melts the workpiece, shaping it to precise specifications. This heat causes a significant rise in local temperatures, impacting the structure and properties of the machined surfaces. Metallurgical changes occur in the surface layers, with the formation of three subsurface layers in wire EDMed workpieces. The white layer, resulting from the resolidification of molten metal, is particularly critical due to its susceptibility to developing cracks that can lead to premature or complete failure of the workpiece. To address this issue, the study utilized the UPT method, which is a process of surface severe plastic deformation, to modify the subsurface structures. The study investigated the cutting types in WEDM, feeding rate, and the number of peening passes as parameters. The experiments were designed using the multilevel factorial design method, and a total of 27 experiments were conducted with varying input parameter values. Subsequently, the micro-hardness test was performed on both the peened and unopened workpiece surfaces using the Vickers method. The average hardness values were then analyzed based on the input parameters. Optimization was carried out using the multilevel factorial design method to determine the maximum hardness value. Additionally, the ANOVA method was employed to assess the effect of the parameters on the hardness value. Based on the findings and results, the following conclusions can be drawn: A mathematical model titled "multilevel factorial design fit" was developed to establish the relationship between the input parameters and the response (hardness). The composite desirability of this model was determined to be 99.87%. In a single-objective optimization study, the optimal hardness value of 952.3 (HV) was achieved for roughing mode with 3 peening passes and a feeding rate of 0.12 (mm/rev). A graphical representation illustrated the two-by-two effect of input parameters on hardness value and percentage, highlighting factors that enhance hardness. The impact of each parameter on hardness amount and percentage was analyzed, revealing a hardness depth of up to 200 µm. Notably, workpieces peened at a feeding rate of 0.12 (mm/rev) exhibited a broader hardness distribution within the first 50 µm. The results showed that the type of wire EDM cutting, feeding rate, and then the number of peening passes, as well as the combined effect of cutting type and feeding rate, respectively, affect the surface hardness values. Increasing the amperage in the wire EDM process can lead to a thicker layer that is more susceptible to voids and cracks due to rapid solidification and thermal stresses. As a result, potentially, higher amprage leads to severe plastic deformation and an increase in hardness. In addition, increasing the number of peening passes at the same time as reducing the feeding rate leads to an increase in plastic deformation and ultimately an increase in surface hardness.

## Conflict of Interests

The authors declare no conflict of interest in this research.

## Funding

This research received no funding.

## 6. References

[1] Ekmekci, B. (2009). White layer composition, heat treatment, and crack formation in electric discharge machining process. *Metallurgical and Materials Transactions B*, *40*, 70-81. https://doi.org/10.1007/s11663-008-9220-0

[2] Modgil, A. (2003). *Effects of high speed machining on surface topography of titanium alloy (Ti6Al4V)* [Doctoral dissertation, University of Florida].

[3] Das, S., Klotz, M., & Klocke, F. (2003). EDM simulation: finite element-based calculation of deformation, microstructure and residual stresses. *Journal of Materials Processing Technology*, *142*(2), 434-451. https://doi.org/10.1016/S0924-0136(03)00624-1

[4] Ekmekci, B. (2007). Residual stresses and white layer in electric discharge machining (EDM). *Applied Surface Science*, *253*(23), 9234-9240. https://doi.org/10.1016/j.apsusc.2007.05.078

[5] Zhu, L., Guan, Y., Wang, Y., Xie, Z., Lin, J., & Zhai, J. (2017). Influence of process parameters of ultrasonic shot peening on surface roughness and hydrophilicity of pure titanium. *Surface and Coatings Technology*, *317*, 38-53. https://doi.org/10.1016/j.surfcoat.2017.03.044

[6] Xing, X., Duan, X., Jiang, T., Wang, J., & Jiang, F. (2019). Ultrasonic peening treatment used to improve stress corrosion resistance of AlSi10Mg components fabricated using selective laser melting. *Metals*, *9*(1), 103. https://doi.org/10.3390/met9010103

[7] Hansen, N. (2004). Hall–Petch relation and boundary strengthening. *Scripta Materialia*, *51*(8), 801-806. https://doi.org/10.1016/j.scriptamat.2004.06.002

[8] Amanov, A., Penkov, O. V., Pyun, Y. S., & Kim, D. E. (2012). Effects of ultrasonic nanocrystalline surface modification on the tribological properties of AZ91D magnesium alloy. *Tribology International*, *54*, 106-113. https://doi.org/10.1016/j.triboint.2012.04.024

[9] Montgomery, D. C. (2017). *Design and analysis of experiments*. John wiley & sons.

[10] Abbasi, A., Amini, S., & Sheikhzadeh, G. A. (2018). Effect of ultrasonic peening technology on the thermal fatigue of rolling mill rolls. *The International Journal of Advanced Manufacturing Technology*, *94*, 2499-2513. https://doi.org/10.1007/s00170-017-0840-x

[11] Malaki, M., & Ding, H. (2015). A review of ultrasonic peening treatment. *Materials & Design*, *87*, 1072-1086. https://doi.org/10.1016/j.matdes.2015.08.102

[12] Chen, Y., Liu, F., He, C., Li, L., Wang, C., Liu, Y., & Wang, Q. (2022). Effect of ultrasonic peening treatment on the fatigue behaviors of a magnesium alloy up to very high cycle regime. *Journal of Magnesium and Alloys*, *10*(3), 614-626. https://doi.org/10.1016/j.jma.2021.07.028