Fabricating Micro-texture on Surface of Cutting Tool Based on NC WEDM Technology

Fengshuang Yang1, *, Chen Pan2, a and Yingyu Shi2, b
1College of Machinery and Vehicle Engineering, Changchun University, Changchun 130022, China
2FAW Car Co., Ltd, 4888 Weishan Road of High-tech Zone, Changchun, 130012, China

*Corresponding author e-mail: y13756312716@163.com, a17743125369@163.com, b491044911@qq.com

Abstract. It is a very complex and difficult technology to fabricate micro-texture on tool surface. At present, available technology such as laser marking, femtosecond laser, ion beam and WEDM can be used to fabricate micro texture. However, little research has been done on the fabrication of micro-texture by WEDM. In this experiment, micro-texture was fabricated on surface of cemented carbide tool by NC WEDM technology. The effect of WEDM parameters (pulse width, pulse stop and current) on the width of micro-texture was studied, so as to control the size of micro-texture fabricated by WEDM. At the same time, the least square method was used to establish the prediction model between the width of micro-texture and the WEDM parameters. The experimental results showed that the micro-texture size fabricated by WEDM technology was in the micron scale, which met the requirements of micro-texture tool size in the field of cutting. Pulse width, pulse stop and current affected the width of micro-texture, but pulse width was the main factor affecting the width of micro-texture. The prediction model of micro-texture width was successfully established by least square method.

1. Introduction
NC-WEDM (Numerical Control Wire Electrical Discharge Machine) technology uses mechanical drawing software to draw cutting graphics, generates cutting trajectory and forms G code, then controls WEDM wire cutting path, instantaneously generates high temperature through positive and negative discharges, so as to melt and vaporize workpiece material and remove the material from corrosion. As a special processing technology, WEDM has no cutting force and has little effect on machined surface stress of workpiece, and has high processing accuracy. In the research of WEDM, the effect of WEDM parameters on material removal rate and machined surface quality was studied. Raj. D. et al. [1] studied the effects of cutting parameters including pulse opening time, pulse closing time and wire feeding speed on surface roughness and material removal rate, and optimized the conditions of WEDM. The results showed that the optimum process conditions were pulse opening time = 1 µs, pulse closing time = 17 µs and wire feeding speed = 3.85 mm/min. Nourbakhsh et al. [2] studied the effects of seven parameters, such as pulse width, servo reference voltage, pulse current and wire tension, on the processing
performance parameters (such as cutting speed, wire breakage and surface integrity) of wire-cut titanium alloy. It was found that the cutting speed increased with the increase of peak current and pulse interval. The surface roughness increased with the increase of pulse width, but decreased with the decrease of pulse interval. Because of the poor surface finish and low size of chromium-nickel-iron alloy 706 in conventional processing. Therefore, Sharma et al. [3] have carried out WEDM on chromium-nickel-iron alloy 706. The material removal rate (MRR), surface roughness (SR), recast surface, morphology, hardness, micro-structure and metallurgical changes of the parts have been improved. They revealed that servo voltage, pulse on time, and pulse off time had greatly influence on MRR and SR.

In addition, some optimization methods such as Taguchi method, neural network algorithm and genetic algorithm were applied to WEDM technology. Dabade et al. [4] used Taguchi methodology and L8 Orthogonal Array methods to study the effects of WEDM parameters on the removal rate, surface roughness, cutting width and size deviation of chromium-nickel-iron alloy 718. It was found that at 95% confidence level, the effect of pulse opening time on material removal rate, surface roughness, cutting width and dimensional deviation was significant, with the impact rates of 54.32%, 58.42%, 83.21% and 36.11%, respectively. In addition, peak current was considered to be the second important parameter of cutting depth and dimensional deviation, while servo voltage were considered to be the second important parameter affecting material removal rate and surface roughness. Priyadarshini et al. [5] used Taguchi method to design experiments using L25 orthogonal arrays, and investigated the effects of various parameters of WEDM on the processing response of Ti-6Al-4V alloy. They considered that the optimum EDM parameters were $T_{on} = 30 \mu s$, $\tau = 9$, $I_p = 10 \ A$ and $V_g = 8 \ V$. Ishfaq et al. [6] comprehensively studied the interaction between stainless steel 304 and WEDM. Taguchi grey correlation method was used to optimize all conflict responses. Analysis of variance (ANOVA) showed that the most significant parameters for cutting speed and kerf, whereas roughness was the current. Sanchez et al. [7] predicted the thickness change of workpiece which was difficult to control in WEDM by deep neural network method. By combining convolution layer with gate-controlled cycle unit, the thickness change of the cutting workpiece could be predicted in 97.4% cases, at least 2 mm ahead of time. Mukhopadhyay et al. [8] used artificial neural network (ANN) combined with genetic algorithm (GA) to correlate and optimize the WEDM process parameters, so as to enhance the surface characteristics of WEDM. Scanning electron microscopy analysis showed that the combination of artificial neural network and genetic algorithm could significantly improve the surface texture of WEDM and reduce the formation of recrystallized spheres. Chaudhary et al. [9] solved the processing problem of Ni-Ti-Al alloy with shape memory function by wire cutting technology. Combining response surface methodology (RSM) and heat transfer search (HTS) algorithm, they took pulse opening time, pulse closing time and current as input parameters, and took material removal rate (MRR), surface roughness and hardness as output responses to generate residual graphs and mathematical models. The two-dimensional and three-dimensional Pareto optimum points were generated by multi-objective HTS algorithm. The optimized process parameters could make the alloy processed reasonably. Wang et al. [10] proposed a new method for geometric defect detection in WEDM process of disc turbine fir tree groove. They collected useful data about WEDM process every 5 milliseconds using depth neural network, and each discharge was classified as a function of ignition delay time. The predicted results and transmission results were obtained. The results of the coordinate measuring machine (CMM) were matched. So and Bae [11], based on WEDM technology, proposed a method to fabricate multi-scale super hydrophobic metal seamless roll dies directly in one step. Using the stripping characteristics of metal surface, nano-scale surface roughness could be formed spontaneously while preparing micro-scale structure. That was to say, in the simple one-step preparation process, it was easy to produce large scale and two-scale hierarchical structure. Verm et al. [12] used L9 orthogonal array method to optimize the forming process parameters of Ti6Al4V and observed the micro-mechanism in the process of WEDM. They pointed out that the removal rate of titanium alloy material (MRR) was the best when the WEDM pulse opening time was 130 $\mu$s, the pulse closing time was 50 $\mu$s, the fluid pressure was 3 kg/cm2, and the voltage was 50 V. The surface micro cracks of titanium alloy increased with the increase of pulse opening time and the shortening of pulse closing time. Saha et al. [13] introduced the application of nano-hard surface
materials in WEDM lathe insert welding. In order to optimize the performance characteristics (MRR, processing time and surface roughness) of WEDM, a hybrid method combining grey correlation analysis with principal component analysis was proposed to identify the optimal combination of process parameters in WEDM. Grey correlation analysis showed that discharge pulse time was the most important parameter for copper wire and galvanized copper wire. A mathematical model of the influence of WEDM parameters on grey correlation degree was established by response surface methodology. It was found that galvanized copper wire was especially suitable for processing nanostructured cemented carbide. Nayak et al. [14] studied and optimized various technological parameters of chromium-nickel-iron alloy 718 treated at deep and low temperature in WEDM process. By considering six input parameters, such as part thickness, taper angle, pulse duration, discharge current, line speed and line tension, an artificial neural network (ANN) model was proposed to determine the relationship between input parameters and performance characteristics. Finally, the process model was optimized by BAT algorithm to obtain the best combination of parameters. Klink et al. [15] carried out the experiment cutting tool steel ASP2023 with WEDM, and surface integrity such as surface finish, microstructure, micro hardness, residual stress and element distribution were compared comprehensively. They achieved the average surface finish Ra 0.1 µm and Ra 0.2 µm for CH- and water-based dielectrics.

At present, micro-texture on cutting tool surface is a hot research topic in the field of cutting. A lot of experiments show that reasonable micro-texture on tool surface can effectively reduce cutting force and cutting temperature, improve machined surface quality and reduce tool wear [16-19]. Due to the size of micro/nano scale, the fabrication of micro-texture on surface of cutting tool is quite complex. Generally, special processing methods are used to fabricate micro-texture, such as laser technology [20] [21], femtosecond laser technology [22-24], and ion beam method [25]. Besides, Zhang et al. [26] fabricated micro-texture on surface of cutting tool by WEDM technology, the experimental results showed that the micro-texture size of WEDM was in micron scale, which confirmed the feasibility of WEDM technology to fabricate micro-texture on surface of tools.

Because NC-WEDM technology uses the pulse discharge between the wire and the workpiece to produce instantaneous high temperature, which makes the workpiece material vaporize instantaneously, removes the surface material and has no effect on the workpiece. Therefore, on the basis of many literature about WEDM, micro-texture is fabricated on the surface of cemented carbide tools by NC-WEDM technology.

2. Experiment

2.1. The Purpose of Experiment
Because of the micro-texture by fabricated WEDM, there still exists the problem of "cutting tool setting" that is similar to that of traditional cutting. When the wire cutting path is formed on the drawing software and the NC G code is generated, if the "cutting tool setting" operation is not carried out in advance, the contact position between the electrode wire and the workpiece surface is not consistent with the wire walking position produced by G code, which will cause the inaccurate dimension of micro-texture. In addition, the parameters of WEDM will affect the discharge range of the wire, which results in the difficulty of controlling the micro-texture size, inaccurate processing, and it will have a great impact on the internal surface quality of micro-texture.

Therefore, in this experiment, the micro-texture was fabricated on surface of cutting tool by numerical control WEDM at the middle cutting speed. The main research contents are as follows:

1) To solve the problem of "cutting tool setting" between electrode wire and tool surface when WEDM was used to fabricate micro-texture on surface of cutting tool, so as to ensure the dimension accuracy of micro-texture.

2) By designing WEDM cutting parameters, the effects of pulse width (TON), pulse stop (TOFF) and current (IP) on the size of micro-texture were analyzed.

3) A mathematical model for predicting the relationship between the parameters of WEDM and the size of micro-texture was established by using the least square method. By comparing the correlation
indices of pulse width (TON), pulse stop (TOFF) and current (IP), the proportion of the three factors affecting the size of micro-texture was analyzed.

2.2. The Scheme of Experiment
The experiment adopted the numerical control WEDM machine tool CTW G320TB produced by DMcut Company. Table 1 was the main parameters of WE DM machine tool. Molybdenum wire was used as electrode wire, whose diameter was 0.075 µm. Working fluid was a WEDM emulsifier developed by DMcut Company, it has the advantages of environmental protection, cooling and high efficiency.

| Work Table dimensions (mm) | X/Y travel (mm) | Maximum Cutting Thickness(mm) | Maximum cutting Speed h≈ 60mm | Surface Roughness (µm) | Host machine Size (mm) |
|---------------------------|-----------------|------------------------------|-----------------------------|----------------------|------------------------|
| 630*440                   | 400*320         | 300                          | ≥180 mm2/min                 | Ra≤0.8~1.0 µm         | 1250*1810*2100         |

Firstly, the above research content (1) that the “cutting tool setting” problem of WEDM was solved. As shown in Figure 1, the workpiece was fixed on the work table with a fixture, and the WEDM was started for "finding edge" to achieve “cutting tool setting”. Taking the side of the workpiece pointed by the red arrow in Figure 1 as the "finding edge" benchmark, the "perceptual return quantity" in the control system of WEDM was set. When the molybdenum wire contacted the surface of workpiece pointed by the red arrow, the sensor sensed the contact signal and transmitted it back to the WEDM system. The molybdenum wire returned according to the set "perceived return" at this time. The distance between molybdenum wire and workpiece was the set "perceptual return quantity". The "finding edge" in WEDM system was similar to the “cutting tool setting” operation in traditional cutting process. In WEDM experiment of fabricating the micro-texture on the tool surface, the "cutting tool setting" was carried out according to the above-mentioned "finding edge" method.

![Figure 1. Finding edge operation of WEDM](image)

The experimental workpiece was cemented carbide cutter, as shown in Figure 2 (a), and its model was CNMG 120412. The cutter model was drawn with drawing software, and the size of the cutter was marked, as shown in Figure 2 (b).
Figure 2. Finding edge operation of WEDM: (a) CNMG 120412 cemented carbide cutter; (b) the size of cutter

In the experiment, the medium speed of molybdenum wire traveling is 40 Hz, and the feed speed of electrode wire is 1 Hz. Twelve sets of orthogonal experimental parameters, such as Table 2, were designed to analyze the effects of pulse width (TON), pulse stop (TOFF) and current (IP) on the dimensional accuracy of fabricated micro-textures.

Table 2. Orthogonal experimental parameters for WEDM

| Experiment Group | Pulse Width (TON)/µs | Pulse Stop (TOFF)/µs | Current (IP)/A |
|------------------|----------------------|----------------------|----------------|
| 1                | 35                   | 200                  | 5              |
| 2                | 35                   | 175                  | 4              |
| 3                | 35                   | 150                  | 3              |
| 4                | 35                   | 125                  | 2              |
| 5                | 30                   | 200                  | 4              |
| 6                | 30                   | 175                  | 3              |
| 7                | 30                   | 150                  | 2              |
| 8                | 30                   | 125                  | 5              |
| 9                | 25                   | 200                  | 3              |
| 10               | 25                   | 175                  | 2              |
| 11               | 25                   | 150                  | 5              |
| 12               | 25                   | 125                  | 4              |

In the experiment, the micro-texture of the tool surface was fabricated in the order of Table 2. At the end of former experiment group, the next experiment group carried out "finding edge" to ensure that the micro-texture experimental conditions were the same. In this experiment, the "perceptual return quantity" of molybdenum wire was set to 1 mm. After molybdenum wire contacted the tool surface, the sensor transmitted the contact induction to the system, and the system controlled the return of molybdenum wire to 1 mm. At this time, the distance between molybdenum wire and the tool surface was 1 mm. In the NC system, the coordinate was set to the origin of the processing coordinate, and the micro-texture was returned to the coordinate position every time when micro-texture was fabricated. In theory, the 1.1 mm straight line of molybdenum wire trajectory was drawn in CAXA software to generate molybdenum wire processing trajectory and NC G code. When the micro-texture was fabricated by molybdenum wire according to the processing path, the actual processing distance of molybdenum wire on the tool surface was 0.1 mm, that is 100 µm, which ensured that the depth of
micro-texture was within the micron scale. However, in the actual operation process, the actual distance between molybdenum wire and tool surface might fluctuate in the range of 100 µm due to clamping error of cutting tool fixed on the work table. In addition, there were observation errors and reading errors when measuring the micro-texture size. Therefore, the errors of no more than 1.5 µm in the actual measurement of micro-texture size was reasonable. After the molybdenum wire returned to the origin of the processing coordinates, the molybdenum wire was moved 500 µm in the direction perpendicular to the direction of return of the sensing quantity, and the micro-texture was fabricated again. The process flow was shown in Figure 3. The fabrication of micro-texture was shown in Figure 4.

Figure 3. The process flow

Figure 4. The fabrication of micro-texture
3. Discussion and analysis of experimental results

All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper. As show in Fig. 1 and Table 1, three scheme comparing.

All According to the experimental scheme, the micro-texture was fabricated on surface of cutting tool by NC WEDM. By analyzing experimental results, the effects of pulse width (TON), pulse stop (TOFF) and current (IP) on the micro-texture width and depth were discussed. For convenience of analysis, the measurement results of micro-texture size fabricated by WEDM were listed in Table 3.

Table 3. Measurement results of micro-texture size.

| Experiment group | Width of Micro-texture W (µm) | Depth of Micro-texture D (µm) |
|------------------|------------------------------|------------------------------|
| 1                | 125                          | 196                          |
| 2                | 115                          | 145                          |
| 3                | 113                          | 127                          |
| 4                | 110                          | 134                          |
| 5                | 112                          | 138                          |
| 6                | 105                          | 125                          |
| 7                | 100                          | 115                          |
| 8                | 85                           | 103                          |
| 9                | 90                           | 108                          |
| 10               | 95                           | 114                          |
| 11               | 116                          | 184                          |
| 12               | 109                          | 130                          |

3.1. Effect of WEDM Parameters on the Width of Micro-texture

As shown in Figure 5, the measurement results of micro-texture width in the experimental group 1 to 4 were obtained under microscopic observation. From the observation of Figure 5, it could be seen that under the cutting conditions of experiment group 1 (pulse width TON=35 µs, pulse stop TOFF=200 µs, current I=5 A), the width of micro-texture fabricated by WEDM was W=125 µm, which was the largest size in the four groups. With the decrease of pulse stop (TON) and current (IP) in the experiment, the width of micro-texture decreased correspondingly. The experimental results showed that the width of micro-texture were almost proportional to the pulse stop (TOFF) and current (IP) under the combined action of pulse stop and current.

Figure 5. The width of micro-texture in experiment group 1 to 4: (a) experiment group 1; (b) experiment group 2; (c) experiment group 3; (d) experiment group 4
Figure 6 was the width of micro-texture fabricated by WEDM according to parameters in experiment group 5 to 8. When the pulse width (TON) was 30 µs, the width of micro-texture decreased with decrease of the pulse stop (TOFF) by analyzing only from the point of pulse stop (TOFF). However, from the point of current, the current I = 5 A in experiment group 8 was largest among experiment group 5 to 7, but the pulse stop (TOFF) in experiment group 8 was 125 µs, which was less than that in experiment group 5 to 7. Under the interaction of pulse stop and current, the width of micro-texture in experiment group 8 was the smallest. It could be seen that the effect of pulse stop on the width of micro-texture was greater than that of current.

![Figure 6](image)

**Figure 6.** The width of micro-texture in experiment group 5 to 8: (a) experiment group 5; (b) experiment group 6; (c) experiment group 7; (d) experiment group 8

Look at Figure 7, the width of micro-texture fabricated under the condition of WEDM parameters in experiment group 9 to 12. The results showed that when the pulse width (TON) was 25 µs, the size of micro-texture width tended to be smaller with the decrease of the pulse stop (TOFF). On the contrary, when only considering the current (IP), it was found that the current IP = 5 A in experiment group 11 was the largest, followed by experiment group 12, whose current was IP = 4 A, and the width of the micro-texture was only smaller than that of experiment group 11. The results showed that the width of micro-texture increased with the increase of current.

![Figure 7](image)

**Figure 7.** The width of micro-texture in experiment group 9~12: (a) experiment group 9; (b) experiment group 10; (c) experiment group 11; (d) experiment group 12

The effect of pulse width (TON) on the width of micro-texture was analyzed in this part. The average size of micro-texture width in experiment group 1 to 4 was taken as the micro-texture width fabricated at pulse width 35 µs, $W_{TON=35\mu s} = 113.25$ µm. Similarly, when the pulse width (TON) was 30 µs, the size of micro-texture width $W_{TON=30\mu s} = 100.50$ µm, and when the pulse width was 25 µs, the micro-texture width size $W_{TON=25\mu s} = 102.50$ µm. According to the data, the relationship between pulse width (TON) and micro-texture width was drawn, as shown in Figure 8. From the curve trend in Figure 8, it could be seen that the micro-texture width tended to increase with the increase of pulse width.
3.2. Establishing Prediction Model for Micro-texture Size by Least Square Method

Combining WEDM parameters of pulse width (TON), pulse stop (TOFF) and current (IP), the prediction model about the size of micro-texture width was established by least square method. The relevant formula was as follows:

\[ W = C \cdot T_{\text{Ton}}^\alpha \cdot T_{\text{TOFF}}^\phi \cdot I_{\text{IP}}^\sigma \]

(1)

In the formula (1), \( W \) represented the width of micro-texture; \( C \) represented the function coefficients between WEDM parameters and the width of micro-texture; \( \alpha \) represented the exponent of pulse width; \( \phi \) represented the exponent of pulse stop; \( \sigma \) represented the current exponent of current.

Because the formula (1) was a non-linear function and its calculation was complex, it was necessary to transform the non-linear function into a linear function. What’s more, due to some human errors in the process of experiment operation, such as observation errors and reading errors, the formula (1) was logarithmic and then incorporated the error \( \varepsilon \), as follows:

\[ \log W = \log C + \alpha \log T_{\text{Ton}} + \phi \log T_{\text{TOFF}} + \sigma \log I_{\text{IP}} + \varepsilon \]

(2)

Make \( y = \log W \), \( b_0 = \log C \), \( x_1 = \log T_{\text{Ton}} \), \( x_2 = \log T_{\text{TOFF}} \), \( x_3 = \log I_{\text{IP}} \), \( b_1 = \alpha \), \( b_2 = \phi \), \( b_3 = \sigma \), which substituted the formula (2), and it got the linear function formula (3):

\[ y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \]

(3)

The formula (3) had independent variables \( x_1, x_2, x_3 \). Since there were 12 experiment groups, the independent variables of group \( i \) were \( x_{i1}, x_{i2}, x_{i3} \). Similarly, the measured micro-texture width of group \( i \) was expressed as \( y_i \). So it could gotten the formula (4):

\[
\begin{align*}
y_1 &= b_0 + b_1 x_{11} + b_2 x_{12} + b_3 x_{13} \\
y_2 &= b_0 + b_1 x_{21} + b_2 x_{22} + b_3 x_{23} \\
\vdots \\
y_{12} &= b_0 + b_1 x_{121} + b_2 x_{122} + b_3 x_{123}
\end{align*}
\]

(4)

Matrix form could be obtained \( Y = bX \), as follow:
According to the least square method, it could get the formula (5):

$$b = (X^T X)^{-1} X^T Y$$

The data in Table 2 and Table 3 were logarithm zed to obtain the matrices of Y and X respectively (6):

\[
Y = \begin{bmatrix}
2.097 \\
2.061 \\
2.053 \\
2.041 \\
2.049 \\
2.021 \\
2.029 \\
2.054 \\
2.078 \\
2.065 \\
2.037
\end{bmatrix}, \quad X = \begin{bmatrix}
1 & 1.544 & 2.301 & 0.699 \\
1 & 1.544 & 2.243 & 0.602 \\
1 & 1.544 & 2.176 & 0.477 \\
1 & 1.544 & 2.097 & 0.301 \\
1 & 1.477 & 2.301 & 0.602 \\
1 & 1.477 & 2.243 & 0.477 \\
1 & 1.477 & 2.176 & 0.301 \\
1 & 1.477 & 2.097 & 0.477 \\
1 & 1.398 & 2.301 & 0.301 \\
1 & 1.398 & 2.243 & 0.301 \\
1 & 1.398 & 2.176 & 0.699 \\
1 & 1.398 & 2.097 & 0.602
\end{bmatrix}
\]

Using MATLAB software to solve and calculate, the value of formula function coefficient b was obtained:

\[
b = \begin{bmatrix}
1.3815 \\
0.2571 \\
0.1025 \\
0.0829
\end{bmatrix}
\]

Therefore, the function formula between the width of micro-texture and the WEDM parameters was established by the least square method, in which \(C=24.0713\), \(\alpha=0.2571\), \(\phi=0.1025\), \(\sigma=0.0829\), the function formula (1) of the prediction model of micro-texture width was equal to:

\[
W = 24.0713 \cdot T_{on}^{0.2571} \cdot T_{OFF}^{0.1025} \cdot I_{IP}^{0.0829}
\]

From the functional relationship between the size of micro-texture width and WEDM parameters, if only considering the exponents of WEDM parameters, it could found that the exponent of pulse width was the largest, which indicated that pulse width was the most important factor affecting the width of micro-texture fabricated by WEDM.

4. Conclusion
By using NC WEDM technology to fabricate micro-texture on tool surface, good experimental results had been obtained. The micro-texture size fabricated by WEDM was micron scale. Only considering
micro-texture size, the micro-texture fabricated by WEDM met the size requirements. In the experiment, the effects of three WEDM parameters, that was pulse width, pulse stop and current, on the fabrication of micro-texture were discussed. The prediction model of micro-texture size was established by least square method. It was found that the most important factor affecting the micro-texture width was pulse width. This test provided a theoretical and practical basis for the application of WEDM technology in the field of micro-texture tool fabrication.

Acknowledgments
Authors would like to thank the members of the project team for their dedications and efforts, and the teachers and schools for their help.

References
[1] Raj, D. A.; Senthilvelan, T. Empirical Modelling and Optimization of Process Parameters of machining Titanium alloy by Wire-EDM using RSM [J]. Materials Today Proceedings, 2015, 2 (4-5): 1682 - 1690.
[2] Nourbakhsh, F.; Rajurkar, K.P.; Malshe, A.P.; et al. Wire electro-discharge machining of titanium alloy[C]/ Elsevier B.V. 2013, 13 - 18.
[3] Sharma, P; Chakradhar, D.; Narendranath, S. Evaluation of WEDM performance characteristics of Inconel 706 for turbine disk application [J]. Materials & Design, 2015:S0264127515304457.doi: 10.1016/j.matdes.2015.09.036.
[4] Dabade, U.A.; Karidkar, S.S. Analysis of Response Variables in WEDM of Inconel 718 Using Taguchi Technique [J]. Procedia CIRP, 2016, 41: 886 - 891.
[5] Priyadarshini, M.; Pal, K. Grey-taguchi Based Optimizationof EDM Process for Titanium Alloy [J]. Materials Today: Proceedings, 2015, 2 (4-5): 2472 - 2481.
[6] Ishfaq, K.; Ahmad, N.; Jawad, M.; Ali, M.A.; M. Al-Ahmari, A. Evaluating Material’s Interaction in Wire Electrical Discharge Machining of Stainless Steel (304) for Simultaneous Optimization of Conflicting Responses. Materials, 2019, 12, 1940.
[7] Sanchez, J. A.; Conde, A.; Arriandiaga, A.; Wang, J.; Plaza, S. Unexpected Event Prediction in Wire Electrical Discharge Machining Using Deep Learning Techniques. Materials, 2018, 11, 1100.
[8] Mukhopadhyay, A.; Barman, T.K.; Sahoo, P.; Davim, J.P. Modeling and Optimization of Fractal Dimension in Wire Electrical Discharge Machining of EN 31 Steel Using the ANN-GA Approach. Materials, 2019, 12, 454.
[9] Chaudhari, R.; Vora, J.J.; Mani Prabhu, S.S.; Palani, I. A.; Patel, V. K.; Parikh, D. M.; de Lacalle, L.N.L. Multi-Response Optimization of WEDM Process Parameters for Machining of Superalastic Nitinol Shape-Memory Alloy Using a Heat-Transfer Search Algorithm. Materials, 2019, 12, 1277.
[10] Wang, J.; Sanchez, J. A.; Iturrioz, J.A.; Ayesta, I. Geometrical Defect Detection in the Wire Electrical Discharge Machining of Fir-Tree Slots Using Deep Learning Techniques. Appl. Sci. 2019, 9, 90.
[11] So, J.Y.; Bae, W.G. Fabrication of Superhydrophobic Metallic Surface by Wire Electrical Discharge Machining for Seamless Roll-to-Roll Printing. Metals, 2018, 8, 228.
[12] Verma, V.; Sajeeveran, R. Multi Process Parameter Optimization of Diesinking EDM on Titanium Alloy (Ti6Al4V) Using Taguchi Approach [J]. Materials Today Proceedings, 2015, 2581 - 2587.
[13] Saha, A.; Mondal, S.C. Multi-objective optimization in WEDM process of nanostructured hardfacing materials through hybrid techniques: [J]. Measurement, 2016, 94: 46 - 59.
[14] Nayak; B.B.; Mahapatra, S.S. Optimization of WEDM process parameters using deep cryo-treated Inconel 718 as work material [J]. Engineering Science & Technology An International Journal, 2016, 19 (1): 161 - 170.
[15] Klink, A.; Guo, Y.B.; Klocke, F. Surface Integrity Evolution of Powder Metallurgical Tool Steel
by Main Cut and Finishing Trim Cuts in Wire-EDM [J]. Procedia Engineering, 2011, 19: 178 - 183.

[16] Sugihara, T.; Enomoto, T. Crater and flank wear resistance of cutting tools having micro textured surfaces [J]. Precision Engineering, 2013, 37 (4): 888 - 896.

[17] Sugihara, T.; Enomoto, T. Improving anti-adhesion in aluminum alloy cutting by micro stripe texture [J]. Precision Engineering, 2012, 36 (2): 229 - 237.

[18] Kümmel, J.; Braun, D.; Gibmeier, J.; et al. Study on micro texturing of uncoated cemented carbide cutting tools for wear improvement and built-up edge stabilisation [J]. Journal of Materials Processing Technology, 2015, 215: 62 - 70.

[19] Obikawa, T.; Kamio, A.; Takaoka, H.; et al. Micro-texture at the coated tool face for high performance cutting [J]. International Journal of Machine Tools & Manufacture, 2011, 51 (12): 966 - 972.

[20] Ryk, G.; Etsion, I. Testing piston rings with partial laser surface texturing for friction reduction [J]. Wear, 2006, 261 (7): 792 - 796.

[21] Etsion, I.; Sher, E. Improving fuel efficiency with laser surface textured piston rings [J]. Tribology International, 2009, 42 (4): 542 - 547.

[22] Lei, S.; Devarajan, S.; Chang, Z. A study of micropool lubricated cutting tool in machining of mild steel [J]. Journal of Materials Processing Tech, 2009, 209 (3): 1612 - 1620.

[23] Kawasegi, N.; Sugimori, H.; Morimoto, H.; et al. Development of cutting tools with microscale and nanoscale textures to improve frictional behavior [J]. Precision Engineering, 2009, 33 (3): 248 - 254.

[24] Sugihara, T.; Enomoto, T. Crater and flank wear resistance of cutting tools having micro textured surfaces [J]. Precision Engineering, 2013, 37 (4): 888 - 896.

[25] Chang, W.L.; Sun, J.; Luo, X.C. Investigation of microstructured milling tool for deferring tool wear [J]. Wear, 2011, 271 (9): 2433 - 2437.

[26] Zhang, J.; Li, Q.; Zhang, H.; Sui, Y.; Yang, H. Investigation of Micro Square Structure Fabrication by Applying Textured Cutting Tool in WEDM. Micromachines, 2015, 6: 1427 - 1434.