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Effect of Main Cut and Multiple Trim Cuts on Surface Integrity of 2379 Steel

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Abstract. Wire electrical discharge machine (WEDM) is commonly used in producing tool and die parts. However, it rarely achieves the optimum machining condition due to the inappropriate selection of WEDM machining parameters. In this study, 2379 steel which own properties equivalent to SKD 11 was used as die material. Four main wire electrical discharge machine (WEDM) cutting parameters, namely pulse on time, pulse off time, servo voltage, ignition pulse current has been experimentally studied and optimized at both levels, main cut and multiple trim cuts using Taguchi Method. Based on Taguchi Method optimization and analysis of variance (ANOVA), the result found that pulse on time and pulse off time give significant effect on white layer thickness for both main cut and multiple trim cuts. According to Signal to Noise (S/N) ratio response, the optimal combination of A2B3C2D1 and A1B3C3D1 gave the lowest white layer thickness for main cut and multiple trim cuts respectively. It also has been found that the hardness of machined surface with multiple trim cuts is higher compared to main cut.

Keywords: WEDM, 2379 steel, white layer thickness, multiple trim cuts

1. Introduction

Tool steel is a common material that often been used in a tool and die making industries due to the tremendous mechanical properties that it has such as high wear resistance, high compressive strength, high hardness and greater dimensional stability. However, the high carbon and high chrome that consist in this material makes it difficult to be machined. Generally, instead of using conventional machining techniques which are difficult and costly, the non-conventional machining technique likes WEDM is used for producing the parts. No direct contact between electrode and workpiece give the machined area zero stress. WEDM also capable to cut any conductive material regardless of their hardness and ductility with intricate and complex shape. Thus, it makes this machine popular in manufacturing industries [1]. However, since the machine uses the thermal energy as a medium to cut the workpiece, the inappropriate selection of WEDM machining parameters often affects the surface quality of the machined surface [2].

Surface integrity is an indicator of machining quality, which describes the surface condition of a workpiece after it has been modified by a manufacturing process. This performance measure is commonly studied by many researchers in order to evaluate the surface quality of machined surfaces. It reveals the surface condition of a workpiece after being modified by various mechanical and thermal loads during manufacturing process and most likely changes the material's properties. One part of surface integrity of machined surface is about the surface texture which affects the surface roughness. While the other one is surface metallurgy which changed the material properties in the subsurface area



[1]. The thermal effects from wire sparking during machining process produce heat affected zone (HAZ) at the machined surface and it includes the recast layer or white layer which has been studied in this paper. White layer was formed by the re-solidified melted material which adheres to the surface area when repeating rapid heating and cooling cycle occurred during cutting process. Most of the re-solidified debris were stuck back at the edge of the shallow crater that formed due to current spark. Surface defects such as white layer problem will decrease the fatigue strength and wear resistance of the workpiece and it's become main problem for tool life deterioration [3].

Surface integrity of machined surface is influenced by various WEDM machining parameters including pulse on time, pulse off time, servo voltage, ignition pulse current, wire tension, wire speed and dielectric pressure [4-5]. Selection of optimal parameter combination is a great challenge due to the presence of large numbers of variables. Over a decade, various researchers have tried to optimize the machining parameters of various materials to analyze the surface integrity. Rao, et al. [6] used Taguchi Method to optimize the machining parameter of Aluminum 2014T6 alloy for the performance measure of surface properties, surface quality and surface roughness. Kapoor, et al. [7] studied the effect of cryogenic treated brass wire on surface roughness and material removal rate of WEDM by various machining parameters. Dhobe, et al. [1] and Manjaiah, et al. [8] had reported that the white layer thickness was affected by the machining parameter mostly pulse on time current and servo voltage. Singh and Pradhan [9], optimized the process parameter for D2 steel. B.Kiran Kumar [10], Manjaiah, et al. [8] and Patel and Rathod [11] had investigated the effects of four machining control parameters, namely pulse peak current, pulse on time, pulse off time and wire tension on the material removal rate and surface roughness. In other work, Ikram, et al. [12] added another factor i.e. kerf width to be considered and they add more parameters including wire feed velocity, dielectric pressure, open voltage and servo voltage. Lodhi and Agarwal [13] have conducted single objective optimization i.e. surface roughness on D3 steel. Noted that all of these studies have only focused on the main cut of the WEDM process.

White layer elimination is required in order to increase the fatigue strength of tool parts, particularly at machined surface. Many of manufacturers execute secondary process like grinding, polishing, and lapping for improving the surface properties. However, these steps are time consuming and consequently will burden the cost to the customers. WEDM has an operational function, namely multiple trim cuts that capable to cut the previous cut path of the main cut with low discharge energy. In general, the high discharge energy produced during the main cut maximizes the material removal rate but decreased the machined surface quality. The formed of white layer in surface and sub-surface area due to the high discharge energy can be reduced by executing the multiple trim cuts [14-16]. Jangra, et al. [17] investigated the effect of main cut and multiple trim cuts on surface roughness for the four types of material, namely WC-Co composite, HCHCr die steel, Nimonic-90 and Monel-400. The results show that the surface roughness was improved significantly due to lower discharge energy which gives less thermal effect to the machined surface. Jangra [18] also reported that un-machined area named as surface objection which was produced during main cut can be eliminated by multiple trim cuts. An advantage of multiple trim cuts of WEDM also has been used to improve the surface roughness and die corner accuracy of material Monel 400 alloy as reported by Selvakumar, et al. [19].

JIS SKD 11, AISI D2 steel and Assab XW41 are common tool steel for die making [12][20]. In developing countries like Malaysia, local die makers may choose alternative material such as 2379 steel which has similar properties but is more economical. Unfortunately, from the literature survey, only a few studies on multiple trim cuts on 2379 steel are found. It is found that no extensive study has been done on surface integrity of the work material 2379 steel by using multiple trim cuts in order to eliminate or reducing the effect of white layer. Thus, there is a need to investigate the effect and optimization of WEDM machining parameters on surface integrity for main cut and multiple trim cuts by using Taguchi Method. In this study Analysis of variance (ANOVA) and signal to noise (S/N) ratio are used to analyze the significant process parameters for achieving the optimal performance measure. The findings of this study would be useful for the tool and die maker in determining the best combination of WEDM

parameters for producing die with high surface quality that would improve production output and extend tool life.

2. Methodology

2.1. 2379 steel preparation

Workpieces size of 25mm x 25mm x 3mm are prepared from 2379 steel bar, which has similar characteristics to SKD 11 steel. The composition of the materials is shown in Table 1. The prepared workpieces are heat treated to obtain a final hardness of 60 ± 2 HRC. For the WEDM experiments, 0.2 mm zinc coated brass wire is used as the electrode, capable of sustaining high discharge energies. The WEDM cut is conducted on a 4-axis CNC WEDM (AG400, Sodick Inc).

Table 1. Chemical composition of 2379 steel

C	Si	Mn	P	V	Cr	Mo	S	Fe
1.50- 1.60%	0.10- 0.40%	0.15- 0.45%	0.030%	0.90- 1.10%	11.0- 12.0%	0.60- 0.80%	0.030%	Balance

2.2. Machining parameter

Table 2 shows the level and WEDM machining parameters in this study which have been chosen through extensive review from literatures [1-3, 8, 9]. Two types of cutting methods were investigated, i.e. main cut and multiple trim cuts. In the main cut experiments, the process would consist of only a single cutting pass. While for the multiple trim cuts, the cutting process would consist of a single main cut followed by four trim cuts running along the same cutting path as the main cut, but with additional dimensional offset to obtain the final cutting dimensions. Figure. 1 illustrates the multiple trim cuts for the WEDM process. Table 3 shows combination of the machining parameters for the main cut experiments according to $L_9 3^4$ orthogonal array. While for the multiple trip cuts experiments, the same parameters were used for the 1st main cut, while the subsequent four trim cuts were automatically selected by the machine to use lower discharge energy parameters.

Table 2. Level and WEDM parameters control parameters

No	Parameter	Level 1	Level 2	Level 3
1	Pulse on time (μ s)	0.3	0.5	0.7
2	Pulse off time (μ s)	5	7	9
3	Servo voltage (V)	15	25	35
4	Ignition pulse current (Amp)	8	12	16

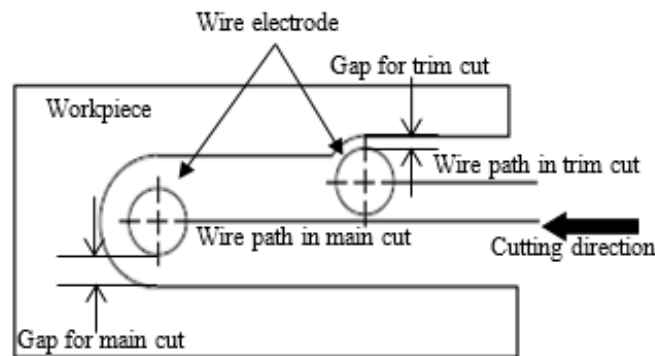


Figure 1. Multiple trim cuts operation

2.3. Design of Experiment

Taguchi method is a powerful statistical technique used to analyze and optimize process parameters. It utilizes orthogonal arrays from design of experiments theory to evaluate the influence of large number of variables on responses with a small number of experiments [10]. In the present work, an L_93^4 orthogonal array is selected to determine the parameter combinations, as shown in Table 3. The S/N ratio would be calculated to measure the impact of noise factors on the performance characteristics. Three different characteristics of S/N ratio are used in Taguchi Method depending on the target of the experiment, namely, smaller is better, nominal is better and larger is better. A high value of S/N ratio indicates that particular control factor setting has minimum effect on the noise factors [13]. In this study, a smaller is better S/N ratio is considered which signify that the lower value of white layer thickness is desirable. The smaller is better S/N ratio can be expressed as follow:

$$S/N \text{ ratio smaller is better} = -10 \log \left[\frac{1}{n} \sum_{k=1}^n y_{ij}^2 \right] \quad (1)$$

Where, n is the number of tests, and y_{ij} is the experimental value of the i th performance characteristic in the j th experiment.

Table 3. Machining parameter (According to L_93^4 orthogonal array)

Exp. No	A (μ s)	B (μ s)	C (V)	D (Amp)
1	0.3	5	18	8
2	0.3	7	25	12
3	0.3	9	35	16
4	0.5	5	25	16
5	0.5	7	35	8
6	0.5	9	15	12
7	0.7	5	35	12
8	0.7	7	15	16
9	0.7	9	25	8

Note: A: Pulse on time, B: Pulse off time, C: Servo voltage, D: Ignition pulse current

2.4. Measurement method

For the thickness of the white layer, which existed due to thermal effects during WEDM cutting process, the measurement was carried out with the scanning electron machine (SEM). Procedure such as surface polishing, drying and etching with Nital 5 % (5% HNO₃, 95% Ethanol) was prior conducted in order to measure white layer thickness. The thickness of white layer is measured from the outermost surface to the border, which differentiate the parent material and the altered area. Nine different places were measured before recorded as average thickness of white layer. While for the hardness tests, it was conducted with Mitutoyo ATK-600 for evaluating the hardness of machined surface. Five different places which located on the center line of machined surface were measured and the average values were recorded.

3. Result and discussion

In this section, the influence of various WEDM parameters for both types of cutting method on the surface integrity such as white layer thickness, hardness and surface topography of machined surface will be discussed.

3.1. Effect on white layer thickness

Due to the thermal effect during cutting process with WEDM, machined surface structure usually will be altered. They made up structure consist of three distinctive layer i.e. white layer/recast layer, heat affected zone and unaffected parent metal which is very difficult to be seen unless after etched with the 5% Nital solution and observed by SEM [20]. White layer or recast layer is an area which can't be resolved by any chemical agent and it remain white colour after etched with etchant while heat affected zone area is difficult to be distinguished. In this study, the white layer which exists in the cross section of machined surface has been measured by using SEM. The non-uniform white layer thickness was observed along the cross section of machined surface area (Figure. 2). Nine readings have been taken and the average result of white layer thickness of 2379 steel for main cut and multiple trim cuts and their corresponding S/N ratio values are shown in Table 4 respectively.

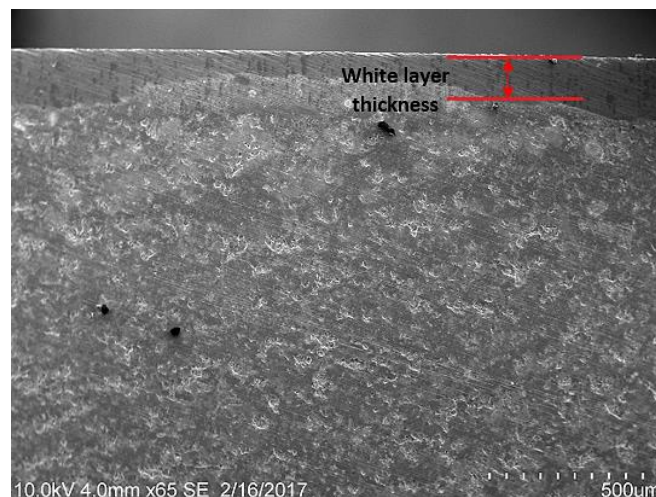


Figure 2. White layer structure in cross section of machined surface.

(Multiple trim cuts A= 0.3 μ s, B=7 μ s, C=25V, D=12Amp)

Based on Table 4, it shows that when the pulse on time value is 0.7 μ s the thickness of white layer is the largest compared to 0.3 μ s and 0.5 μ s. This is because of workpiece was exposed to the high discharge energy in longer period and its lead to form a thicker white layer. The result was in agreement with Cao, et al. [20] and Manjaiah, et al. [8]. For cutting time shorter than 0.7 μ s the results show that, even though after multiple trim cuts were being executed, the thickness of white layer for both cutting types is quite

similar. This probably due to the effect of higher servo voltage that induced higher discharge energy during second cut before it uses low energy at the subsequent cut at third till to fifth cut. In this study the second to the fifth cut of the multiple trim cuts is generated automatically by default setting provided by the machine tool manufacturer.

Table 4. Experimental design and white layer thickness result

Exp. No	Main cut		Multiple trim cuts	
	White layer thickness (μm)	S/N ratio (dB)	White layer thickness (μm)	S/N ratio (dB)
1	168.7	-44.54	159.50	-44.06
2	185.3	-45.36	165.13	-44.36
3	168.1	-44.51	137.71	-42.78
4	166.4	-44.43	169.78	-44.60
5	162.9	-44.24	177.33	-44.98
6	140.7	-42.97	169.44	-44.58
7	251.9	-48.02	175.67	-44.89
8	304.3	-49.67	194.00	-45.76
9	166.8	-44.45	154.84	-43.80

By using Minitab 16, response table for S/N for main cut and multiple trim cuts were generated (Table 5 and Table 6). These response tables give information about the average S/N ratio for each factor level, delta, and rank. Based on the characteristic of smaller is better, the higher value of S/N ratio represents lower value of white layer thickness, which is good for surface integrity performance. Therefore, of all the three levels, for the two types of machining cuts, the optimum level parameter combination is selected based on higher values of S/N ratio. For the main cut, the optimal set of parameters for optimum white layer thickness is obtained at 0.5 μs pulse on time (level 2), 9 μs pulse off time (level 3), 25V servo voltage (level 2) and 8Amp ignition pulse current (level 1). Therefore, the optimal combination is A2B3C2D1. Meanwhile, for multiple trim cuts is obtained at 0.3 μs pulse on time (level 1), 9 μs pulse off time (level 3), 35V servo voltage (level 3) and 8Amp ignition pulse current (level 1). The optimal combination is A1B3C3D1.

Table 5. Response Table for Signal to Noise Ratios (Main cut)

Level	A (μs)	B (μs)	C (V)	D (Amp)
1	-44.80	-45.66	-45.72	-44.41*
2	-43.88*	-46.42	-44.74*	-45.45
3	-47.38	-43.97*	-45.59	-46.20
Delta	3.50	2.45	0.98	1.79
Rank	1	2	4	3

Table 6. Response Table for Signal to Noise Ratios (Multiple trim cuts)

Level	A (μ s)	B (μ s)	C (V)	D (Amp)
1	-43.73*	-44.52	-44.80	-44.28*
2	-44.72	-45.03	-44.25	-44.61
3	-44.82	-43.72*	-44.22*	-44.38
Delta	1.09	1.31	0.58	0.33
Rank	2	1	3	4

Meanwhile, the effect of control parameter on white layer is shown graphically in Figure. 3(a) and (b). From both figures, it can be observed that white layer thickness increases with increase in pulse on time. Increase in pulse on time will increase the discharge energy that allows higher temperature impose and penetrates into the subsurface. At high-temperature point the material melted and vaporized, then re-solidified and stick back to the machined surface during pulse off time. This makes the white layer thickness thicker. The result of this study is in-line with Li, et al. [14]. Contrarily, for pulse off time, the pause time between discharges allows the debris to solidify and be flushed away by dielectric prior to next discharge which leads to increase the sparking efficiency. The thickness of white layer decreases when the pulse off time was increased. However, there is no such significant effect of servo voltage and ignition pulse current on white layer thickness because there is less change in S/N ratio value.

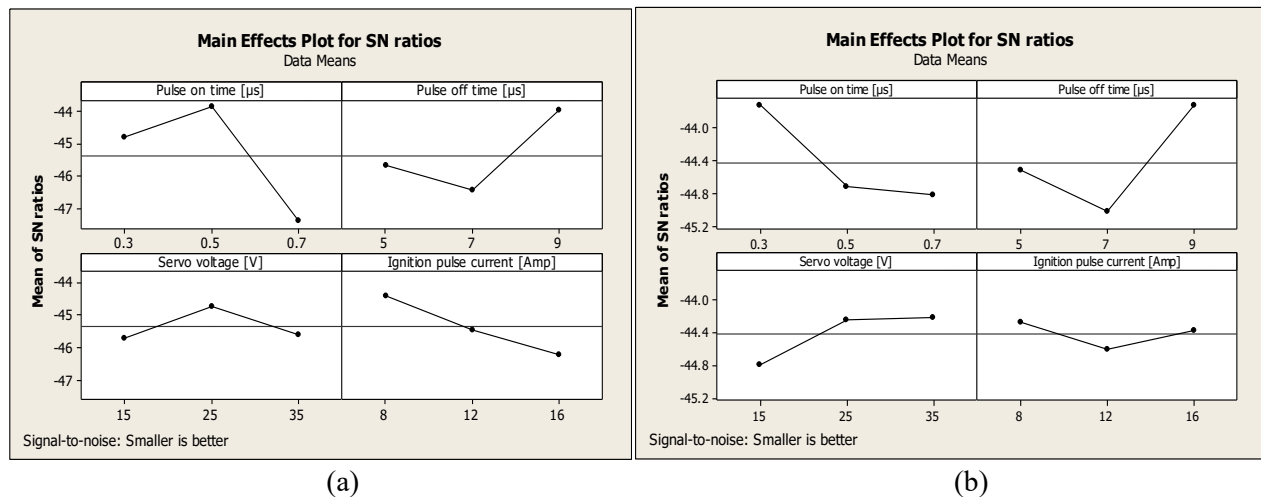


Figure 3. Mean S/N ratio for white layer thickness at each level for all the parameters. (a). Main cut, (b). Multiple trim cuts

3.1.1 ANOVA. Analysis of variance (ANOVA) has been performed to determine the level of significance of the control parameters on the performance characteristics of white layer thickness. The summary of the result percentage is indicated using R-squared (R-Sq) as shown in Table 7. Considering the value of the percentage that shows the significant factors influenced white layer thickness, it can be determined that the pulse on time with the highest percentage of 60.74% is the most significant factor, followed by pulse off time 27.20%, servo voltage 8.37%, and ignition pulse current 3.69% for the main cut. It can be understood that to get a surface with minimal effect of the white layer thickness, the pulse

on time should be set at shorter time which is in agreement with Manjaiah, et al. [8] who mentioned that white layer thickness is related to WEDM parameter mainly pulse on time.

For the multiple trim cuts, the pulse off time is found to be the major factor that affecting the white layer thickness (46.77%). Then followed by pulse on time, servo voltage and ignition pulse current with 38.69%, 11.40%, and 3.15% respectively. The longer pulse off time gave the chance of debris and melted material to be flushed away by the dielectric fluid. It also improves the dielectric fluid circulation for the cutting channel. Additional four trim cuts with a distinctive machining parameter value which available in multiple trim cuts may the reason make each parameter has a various contribution for the surface roughness compared to main cut which has only single rough cut.

Table 7. One-Way ANOVA for white layer thickness

Factors	Main cut		Multiple trim cuts	
	R-Sq (%)	Rank	R-Sq (%)	Rank
A (μ s)	55.29	1	38.69	2
B (μ s)	26.33	2	46.77	1
C (V)	4.76	4	11.40	3
D (Amp)	13.61	3	3.15	4

Note: A: Pulse on time, B: Pulse off time, C: Servo voltage, D: Ignition pulse current

3.1.2 Confirmation test. For the Taguchi Method, the confirmation test needs to be executed for validating the result that was determined during the optimization stage. Separate experiments were conducted to investigate the optimal parametric combination and the result of both types of cutting were 86.54 μ m for main cut and no white layer thickness was seen in multiple trim cuts. The value for white layer thickness for main cut is 38.49% less than the minimum value of white layer thickness obtained (140.70 μ m) during the parametric test. While for the finish cut, no white layer thickness was seen and it improved significantly. The multiple trim cuts work to eliminate all the recast layer which exists during main cut. It confirms that the optimal combination parameter gave a better result compare to parametric test.

3.2. Effect on surface hardness

The thermal effect of the discharge energy altered the surface mechanical properties. The hardness of machined surface has changed due to the thermal effect [1]. To get a better understanding of the thermal effect on the machined surface, the hardness of it was measured with hardness testing machine Mitutoyo ATK-600. Measurements were conducted at five points along the center line of the machined surface. The average of hardness for main cut and multiple trim cuts is shown in Table 8.

Table 8. Machined surface hardness for main cut and multiple trim cuts

Cutting type	Cutting condition								
	#1	#2	#3	#4	#5	#6	#7	#8	#9
Main cut [HRC]	60.9	60.8	60.6	60.5	60.8	59.9	60.5	60.4	60.6
Multiple trim cuts [HRC]	61.2	60.9	60.9	60.9	61.2	60.7	60.8	61.0	61.0

Delta	0.3	0.1	0.3	0.4	0.5	0.7	0.3	0.6	0.3
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The impact of thermal during repetitive heating and rapid cooling, produced a several layers at the machined surface. These formations also depend on the cutting process and workpiece properties. At the outermost area, the changed structure, namely recast layer or white layer altered the hardness of machined surface. As seen from Figure. 4, multiple trim cuts show higher hardness for all cutting conditions compared to the main cut at the machined surface area. This is due to the time for thermal exposure for multiple trim cuts, which is longer about 70% compared to main cut. Increases the time for heating and rapid cooling will increase the carbon content in recast layer. Consequently, increase the surface hardness. At the same time, the oxides element which is formed during machining and adhered to machined surface may explain why the multiple trim cuts have a higher hardness compared to main cut [8].

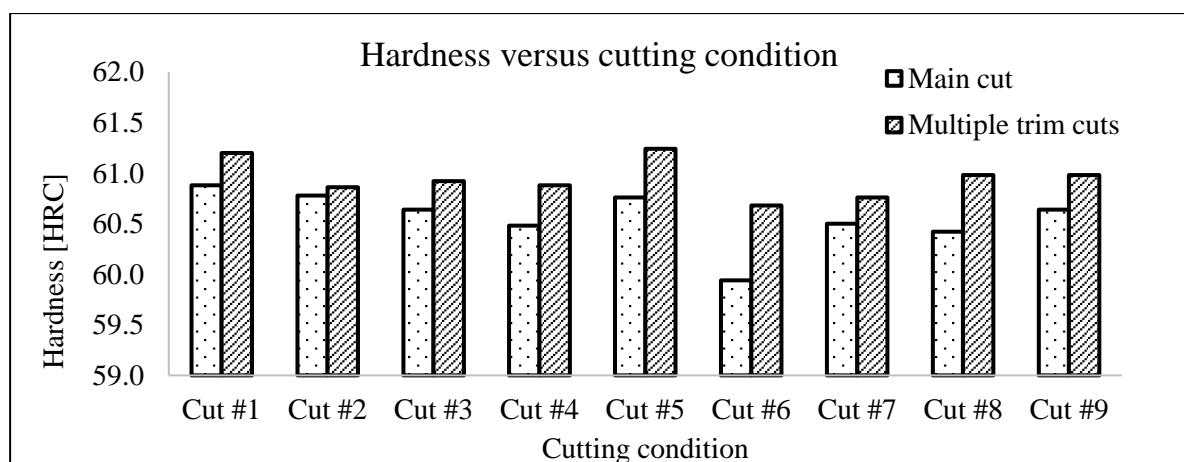


Figure 4. Hardness of machined surface area

3.3. Surface topography

Good machined surface plays a main role in extending the life period of a product. It will determine the fatigue strength of a product. Therefore, understanding the surface characteristics of machined surface is important. In WEDM, the effect of heat from discharge energy causes the deformation of machined surface particularly during main cuts. The surface topography characteristics of the samples of 2379 steel for both types of cutting types are shown in Figure 5.

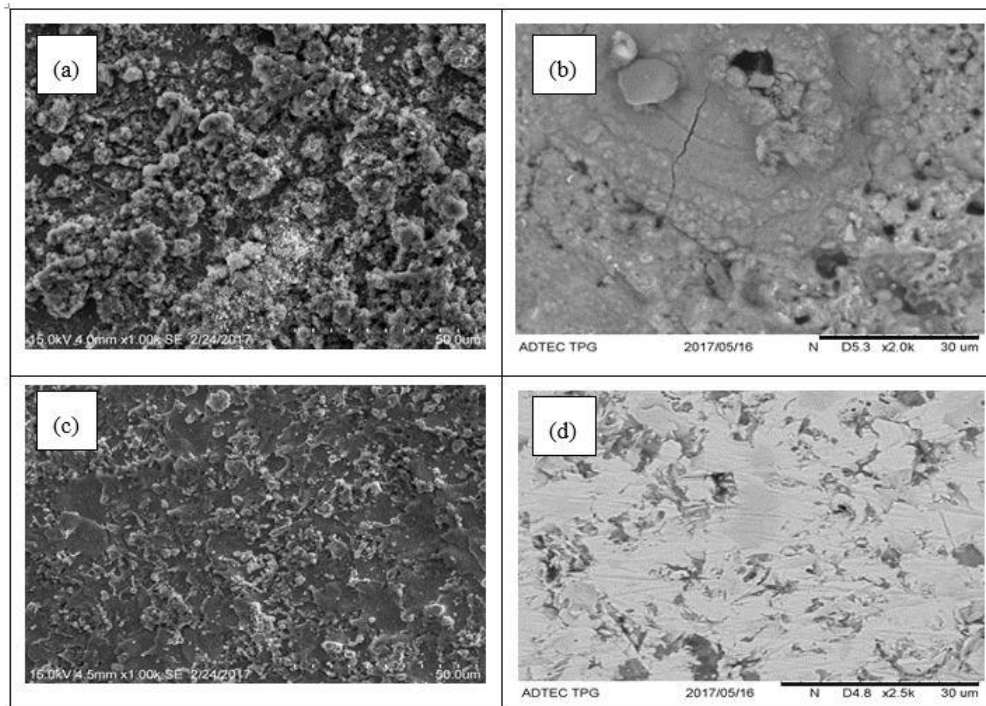


Figure 5. Surface topography characteristics. (a) Main cut (50μm), (b) Main cut (30μm), (c) Multiple trim cuts (50μm), (d) Multiple trim cuts (30μm)

High discharge energy that's been produced during main cut produced the machined surface with porous structure which is consist of shallow craters, voids, micro-cracks and irregular globules (Figure 5 (a) and (b)). High temperature at local region penetrates deeper to subsurface and melt the workpiece material. Molten material later re-solidified due to rapid cooling during pulse off time, stick back and make the surface full with above-mentioned surface characteristics. The coarse surface characteristics of machined surface were decreased after 4th trim cut. Smoother surface was formed with less shallow craters, voids, micro-cracks and irregular globules (Figure 5 (c) and (d)). The low discharge energy used during multiple trim cuts gives less effect to workpiece surface and cut the previous rough surface to the smoother finishing.

4. Conclusion

In this study, effect of four WEDM cutting parameters on the surface integrity of 2379 steel was carried out by using Taguchi method. The following conclusion can be drawn based on the investigation.

1. In the formation of white layer thickness, for the case of main cut, the most significant parameters are pulse on time (60.74%) and pulse off time (27.20%) while the rest was shown no significant effect based on ANOVA analysis. Increase the pulse on time will increase the discharge time, where it will extend the time for current discharged and make more deterioration to the machined surface. Less pulse on time is desirable for lower values of white layer thickness. The optimal machining can be obtained by A2B3C2D1 combination.
2. For multiple trim cuts, the significant factors are as following order, pulse off time (38.69%), pulse on time (46.77%), servo voltage (11.40%) and ignition pulse current (3.15%). For getting the minimum value of white layer thickness the combination is should be set as A1B3C3D1.
3. For the confirmation test, the optimum value of white layer thickness was 86.54μ, which is reduce 38.49% compared to a minimum value during parametric test. While for multiple trim cuts, white layer thickness was clearly eliminated after run with the optimal set of cutting parameter.

4. The hardness of machined surface after multiple trim cuts is harder compared to the main cut machined surface. The increment between 0.1~0.7 HRC was acquired for all cutting conditions. The time exposure to the thermal may the reason of increment of machined surface.
5. Main cut produced surface characteristics consist of shallow craters, voids, micro-cracks and irregular globules and it will reduce the fatigue life of products. While the smooth surface can be achieved by using multiple trim cuts in order to extend the life of products or tools.

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