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Design of an Experiment to Study the Corner Collapse in Wire EDM

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Keywords : wire EDM, wire deflection, discharge gap, corner collapse

ABSTRACT

The error from corner cutting is significant in wire Electrical Discharge Machine (abbr. EDM). Most studies focus on the cause of wire deflection, but there is no study on the discharge gap variation when the cutting parameters adjust in corner cutting. This paper studies the cutting parameter that affects the wire deflection and discharge gap at different cutting speeds using experimental designs. The effects of different cutting parameters on the wire deflection and discharge gap were separately investigated. The experimental results show that the processing of the corner should condiser the amount of wire deflection and effect of the discharge gap to obtain the best cutting parameters. Reducing the cutting parameter of ON to 30% of the original speed can signficantly improve the corner accuracy. This study has been applied in Accutex wire EDM and improved the corner cutting significantly.

INTRODUCTION

In a wire Electrical Discharge Machine (abbr. EDM) design, the error from corner collapse is the most important accuracy issue to engineers. Past experience and research data show that wire deflection is the main cause of corner error. Thus, there are many studies on the measurement of wire deflection. Dauw et al. (1989) focused on the analysis of the wire vibration phenomenon and developed a measurement and acquisition system. Yamada et al. (1997) analyzed the measured values of a wire electrode displacement with normal vibration modes and investigated the fundamental characteristics of the vibration system through statistical analysis. Habib and Okada (2016) used high-speed camera to directly observe the movements of the wire electrode in the discharge process. The results showed that the vibration amplitude and frequency mainly depended on the wire tension and amplitude direction. The wire vibration mode was also analyzed and could be varied with the machining position of the thin workpiece.

Dauw and Beltrami (1994) proposed an on-line tracking and control of the wire position. The deviation of the wire position relative to the programmed wire path position is continuously measured and corrected during the machine cutting. These papers cannot easily and precisely measure the wire deflection in all cutting conditions. In fact, wire deflection can easily decrease by slowing down or suspending the movement in corner cutting, but a decrease in speed of the movement will expand the discharge gap and enlarge the corner collapse because the discharge continues.

Some studies focus on reducing the corner error by adjusting the cutting parameter. Puri and Bhattacharyya (2003) used Taguchi method, which involved thirteen control factors with three levels for an orthogonal array L27 (3^{13}), to explore the corner cutting of machining parameters to improve the corner error. Sanchez et al. (2004) proposed a hybrid computer-integrated system to improve the corner cutting accuracy by combining the experimental knowledge of the process and numerical simulation. However, both studies can only be applied in limited cutting conditions.

Some studies have examined the kerf width in the WEDM. Liao et al. experimentally studied the variation of the machining parameters on the MRR, gap width and surface roughness. Although their work attempted to determine the level of importance of the machining parameters on the MRR, the levels of importance of the gap width and surface roughness were not introduced. The change in gap width and surface roughness with machining parameters were presented in simple graphical forms.

Tosun et al. (2004) used Taguchi's approach to investigate and optimize the effects of the dielectric flushing pressure, pulse duration, wire speed and open circuit voltage on the kerf and MRR for AISI 4140 steel, and they inferred that the highly significant

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factors for both MRR and kerf are the open voltage and pulse duration, whereas the dielectric flushing pressure and wire speed are less prominent factors. All studies related to the kerf width focus on general machining but not the corner errors that are affected by the kerf width variation. There is no relevant study on the cutting parameter in corner machining related to the gap kerf variation.

In the accuracy cutting application, the workpiece is cut at least 2 or 3 times; the 1st cut is a rough cut for the shape, the 2nd cut is a trim cut for accuracy, and the 3rd cut is a trim cut for both accuracy and roughness. Thus, the shape error must be trimmed in the 2nd or 3rd cut. The major error originates from the gap change or wire deflection in the corner machining. In practical application, we do not expect that the entire corner error can be completely eliminated in the 1st cut, but we want to control the error in an acceptable range, so that the cutting error can be better trimmed in the 2nd or 3rd cut. Sanchez et al. (2007) studied the corner geometry generated by the successive cuts (roughing and finishing). The errors in different zones of the corner are identified and related to the material that was removed in each cut. The limitation of the cutting speed enables certain control on the amount of material that is actually removed by the wire. The effect of different aspects such as work thickness, corner radius and number of trim cuts is discussed. The main conclusion is that a corner accuracy optimization procedure must consider the errors generated by the previous cuts.

A complete improvement of the corner error is not easy because in wire EDM machining, a change in cutting parameter will also simultaneously cause a change in amount of wire deflection, machining ability and size of the discharge gap. There is no study related to the machining ability, wire deflection and gap size in corner machining. The corner errors measured from the test punch are combined with the wire deflection and gap kerf variation.

Liang and Liao (2014) proposed a Cross-Section-Measurement (CSM) method to precisely measure the wire deflection error in different conditions. The error range is approximately 120-140 μm at 50 mm thickness for the SKD11 workpiece. From the CSM method, the wire deflection value can be easily measured. Using the CSM method, this study examines the effect of the discharge parameters on the wire deflection and size of the discharge gap. With the experimental method design, the effects of the machining parameters on the wire deflection and gap size can be separated. The experimental data show that the best cutting parameter to improve the wire deflection is not also the best parameter to simultaneously improve the discharge gap difference. The factor that minimizes the effect of total corner collapse must simultaneously consider the parameters that affect the wire deflection and gap difference. The relation can get by regression. Then, by selecting the suitable cutting parameter and using multiple cutting can obtain a high-accuracy workpiece. This study has been applied and significantly improved the corner accuracy in the Accutex wire EDM.

THE EXPERIMENTAL METHOD

In wire EDM machining, the gap between the electrode and the workpiece is notably small only several tens of micrometers and emerges in de-ion water. Moreover, the gap is obstructed by the electrode and workpiece~~,~~ which makes the observation of the wire movements difficult. In this paper, we attempt to find the effect of the machining parameters that affect the wire deflection and gap size through the experimental design, and we select the best cutting parameter to optimize the corner machining. We design the experiments to measure the wire deflection and gap difference at different cutting speeds. The first experiment group uses the Cross-Section-Measurement (CSM) method to measurement the wire deflection. The second experiment group sets the cutting parameters identical to those of the first experiments and cut the test punch to measure the gap variation. The experimental methods are as follows:

Method 1 : Wire deflection experiments and CSM method

We used the CSM method to measure the wire deflection in different cutting conditions. The CSM method is briefly described as follows:

A machining path is designed as shown in Figure 1. Before cutting, it must make a wire electrode verticality calibration to ensure that the wire electrode is perpendicular to the top plane of the work-piece.

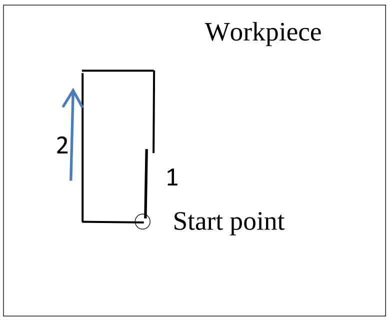

Fig. 1(a) Cutting path designed for the CSM Method.

Because the measurement must use the top plane as the reference plane when After the workpiece machining is completed. Then, we precisely setup the workpiece and prepare machining. From the start point, we start up path 1 cutting and maintain the stable machining. When path 1 approaches the end point, we suddently turn off the discharge power to preserve the wire shape of cutting path 1.

Next, we return the machine to the start point and start to cut path 2 with a half-groove offset compared to path 1. Normally, if the brass wire is 0.25 mm, the kerf width is approximately 0.33 mm; then, the offset of path 2 is 0.165 mm.

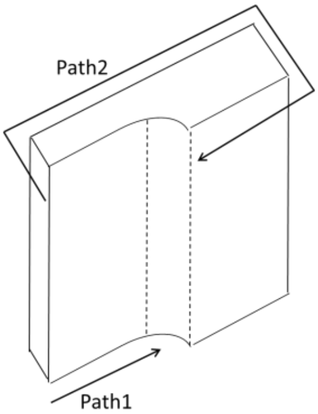

Fig. 1(b) 3D drawing of the punch.

A punch can be taken as shown in Fig. 1(b). Fig. 2 shows the top view of the punch at the intersection of paths 1 and 2. Because the offset is half of the groove width, path 2 must cut across the tip point of path 1. The wire deflection can be preserved in the residual groove of path 1.

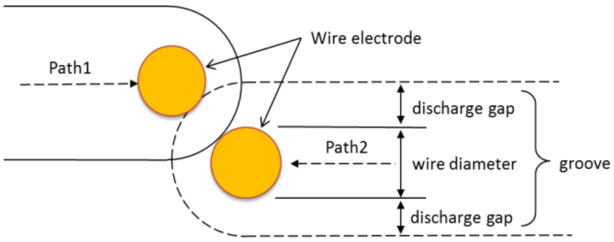

Fig. 2. Top view of the cross section.

In this experiment, the wire diameter is 0.25 mm. The total groove width is equal to the sum of the wire diameter and discharge gap. The groove width can be exactly measured by cutting a square punch, and the value is approximately 0.33 mm. Therefore, by designing path 2 with a cutting offset of 0.165 mm shift to path 1, the shape of the section can be retained as a quarter circle as shown in Fig. 3.

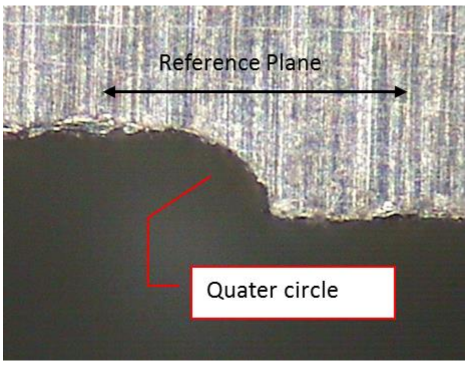

Fig. 3. CCD picture of the cross section from the top view.

We put the workpiece under the CCD camera and set the top plane of the workpiece as the reference plane, which is perpendicular to the wire electrode. From the upper side of the meet point, we draw a line perpendicular to the reference plane as a reference line. The reference line on the cross section can be built as shown in Figs. 4 and 5. The wire deflection can be measured by the distance between the actual edge point and the reference line, as shown in fig. 6.

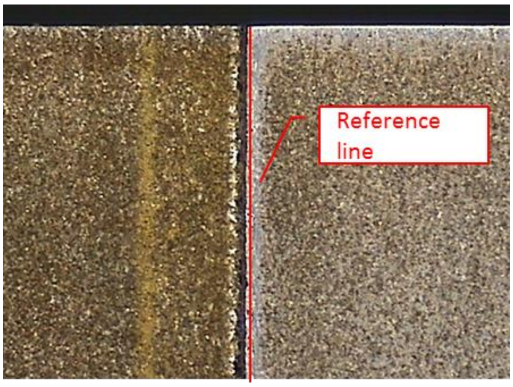

Fig. 4. Cross section using CCD X40.

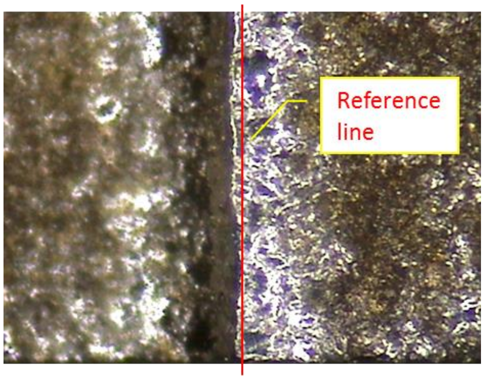

Fig. 5. Cross section obtained using CCD X180.

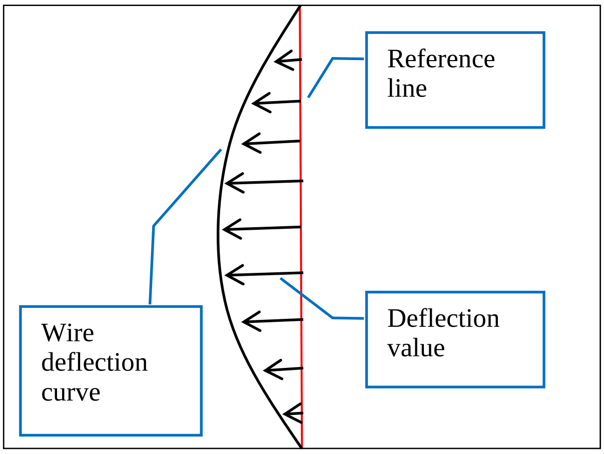

Fig. 6. Topology of wire deflection by CSM

Method 2: Gap difference experiments

We design a 4*8 square test punch as shown in Fig. 7, cut the test punch and measure the discharge gap.

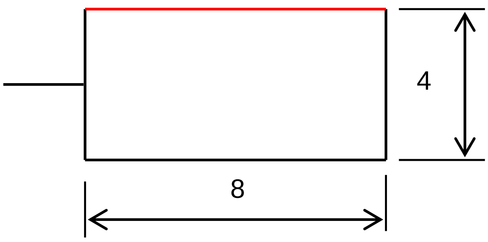

Fig. 7. Test punch sample for the gap variation experiment.

We cut a test punch without the wire diameter compensation and design the original length as 4 mm. The difference between the original path and the measured test punch size is the discharge gap plus wire diameter, as shown in fig. 8. Three side cuttings use the standard cutting parameters, and only one side cutting uses the experimental cutting parameters. By measuring the size of different punch cuttings based on different setting parameters, we can obtain the gap difference. In this experiment, the major purpose is to measure the difference in test punch size under different cutting conditions, so the size of the test punch is not important.

From the CSM method, we can know that the wire deflection is zero at the upper position of the punch, so we must measure the punch size in the up position to eliminate the wire deflection as shown in fig. 9.

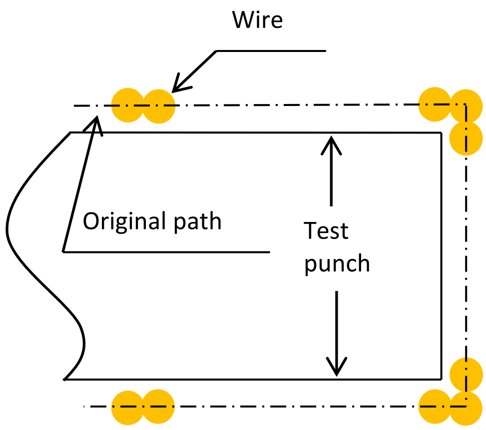

Fig. 8. Discharge gap between the original path and the test punch.

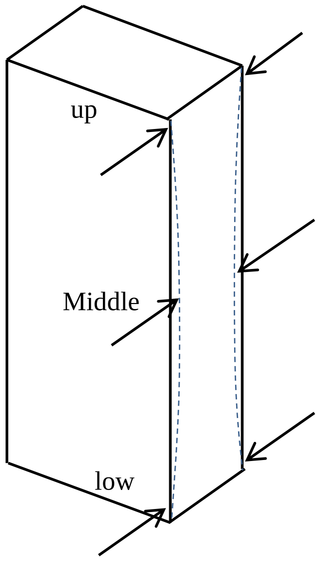

Fig. 9. Measuing point of the punch to eliminate the wire deflection factor

EXPERIMENTAL WORK

In the Accutex wire EDM machine, the factors that affect the corner error are: OV (ignited voltage), ON (discharge time), OFF (discharge off time), WF (wire feed speed), WT (wire tension), WP (water pressure), and SG (servo gain). In corner machining, a change in WF or WT will easily cause wire break and induce a wire mark. The WP parameter will make the flushing unstable and easily breaks the wire. Thus, these 3 parameters are not use for corner adjustment in industrial applications. The OV cannot effectively affect the cutting speed. It is not a suitable parameter in our experiments. Thus, the following experiments use ON, OFF, and SG as the control factors. During the experiments, only one control factor is changed at a time to obtain different cutting speeds. A set of reasonable cutting parameters was used as the standard, and we set the cutting speed as 100%. By changing the control factor, we obtained different cutting speeds of 80%, 70%, 60% and 50% of the original setting. Then, we cut the sample workpiece and measured the amount of wire deflection under different conditions using the CSM method. Similarly, with the identical control factor, we obtained the cutting speed of 80%, 70%, 60% and 50% of the original setting. By cutting a 4*8 square workpiece and measuring difference sizes of the workpiece, we derived the gap difference.

All experiments were performed using the ACCUTEX AU series wire EDM machine. The wire EDM was designed with an iso-energy power circuit, and the controller is a PC-based system.

Fig. 10. Accutex AU series wire EDM machine.

Experimental condition:

Workpiece : SKD11

Thickness : 50 mm

Wire : 0.25 mm brass wire CU63%/ZN 37%

OV (ignition voltage) = 90 V

ON (discharge time) = 13 (0.65 μs)

OFF (discharge off time) = 9 (9 μs)

Wire tension =1200 g

Wire speed =10 m/min

Gap voltage = 44 V

Feed rate = 2.5 mm/min

SG (servo gain) = 6.0

Figure 11 includes the discharge voltage wave and current wave, which shows the meaning of the cutting parameters ON, OFF and OV. ON and OFF are constant-time operator setting in every discharge.

In the controller design, SG is designed to adjust the servo gain as follows:

$$\text{Feed rate} = SG * K *(GV-SV) , \tag{1}$$

where GV is the gap voltage, SV is the servo voltage, and K is a system coefficient. The feed rate increases and the difference between GV and SV decreases if SG increases.

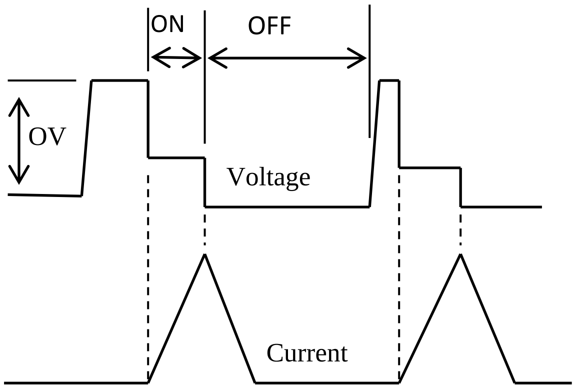

Fig. 11. The explanation of power discharge wave

We set the wire deflection experiments into three A groups:

Table 1 Groups of wire deflection experiments

	SG	ON	OFF
Wire Deflection	A1	A2	A3

Group A1: for the 1st cut, we use the experimental cutting condition and change the SG to adjust the cutting speed to the desired value; then, we cut the workpiece and measure the wire deflection using the CSM method.

Table 2 Adjusting only the SG for A1 experiments.

Feed rate %	100%	80%	70%	60%	50%
Feed speed mm/min	2.5	2.0	1.75	1.5	1.25
SG	6	4.4	3.8	2.9	2.2

Repeating Group A1 experimental process, we make the A2 experiments by changing only ON to adjust the cutting speed to the desire value. We make A3 experiments by changing only OFF.

Table 3 Adjusting only the ON for A2 experiments.

Feed rate %	100%	80%	70%	60%	50%
Feed speed mm/min	2.5	2.0	1.75	1.5	1.25
ON	13	11	10	9	8

Table 4 Adjusting only the OFF for A3 experiments.

Feed rate %	100%	80%	70%	60%	50%

Feed speed mm/min	2.5	2.0	1.75	1.5	1.25
OFF	8	10	11	12	14

Similar to the wire deflection experiments, we set the gap difference experiments into three B groups:

Table 5 Groups of gap dfference experiments

	SG	ON	OFF
gap variation	B1	B2	B3

Group B1: cut an 8X4 square punch; for the 1st cut, use the experimental cutting condition and change the SG to adjust the cutting speed to the desired value; then, measure the size of test punch in micrometer to obtain the gap difference. All experimental cutting conditions of group B are identical to those of group A.

RESULT and ANALYSIS

All experimental data are as follows:

Table 6 Experimental results

Feed rate %	100%	80%	70%	60%	50%
Feed speed mm/min	2.5	2.0	1.75	1.5	1.25
Size of test punch (results of Group B) unit :mm					
SG	3.669	3.658	3.65	3.646	3.639
ON	3.668	3.676	3.679	3.68	3.684
OFF	3.669	3.663	3.662	3.66	3.656
Wire deflection (results of Group A) unit :mm					
SG	-0.103	-0.09	-0.068	-0.052	-0.038
ON	-0.103	-0.09	-0.087	-0.085	-0.076
OFF	-0.103	-0.068	-0.068	-0.065	-0.049

The maximum difference of the test punch size is 45 μm (3.684-3.639 mm) at the cutting condition of 50% feed rate. Fig. 12 shows the feed rate vs. punch size, where we observe:

1. When the cutting speed is decreased by the parameter of OFF or SG, the size of the workpiece decreases, which implies that the discharge gap increases. When we use OFF or SG to decrease the cutting speed in corner cutting, the corner collapse may worsen because the discharge gap increases.
2. When the cutting speed is decreased by the parameter ON, the size of the workpiece increases, which implies that the discharge gap decreases. When we use the ON to decrease the cutting speed in corner cutting, the corner collapse can be compensated because the discharge gap decreases.

The maximum difference of the wire deflection is 38 μm (76 μm -38 μm) at the cutting condition of 50% feed rate. The wire deflection can be reduced by up to 65 μm by changing the SG and only to 27 μm by changing the ON at 50% feed rate. Thus, the best factor of wire deflection is a change in parameter of SG and not ON. Fig. 13 shows the feed rate vs. wire deflection.

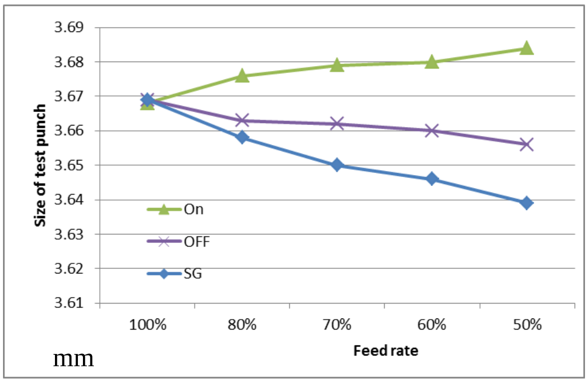

Fig. 12. Test punch size at different cutting speeds

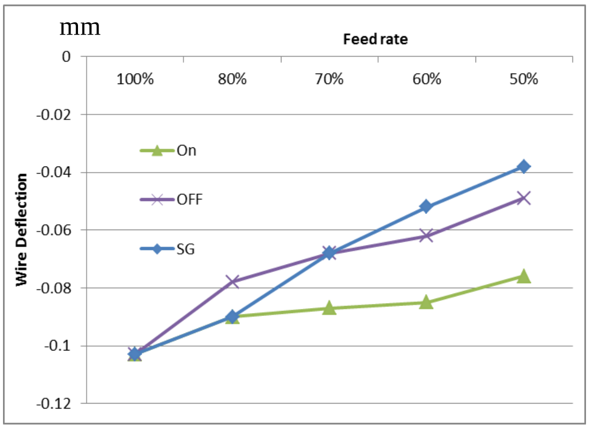

Fig. 13. Wire deflection at different cutting speeds

Yan and chuang (2002) have discuss the relationship between corner collapse and wire deflection. We define the symbols as:

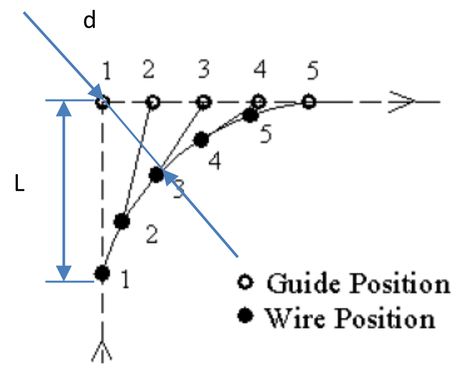

Fig. 14. Wire deflection and corner collapse

d: corner collapse
L: wire deflection
g: gap difference

The relation between the corner collapse (d) and the wire deflection (L) is appropriate : d=0.707 L. We only consider that wire deflection affects the corner collapse without other possible factors. A change in discharge gap changes will also affect the corner collapse. The relationship between corner collapse (d) and gap difference (g) is shown in Fig. 15, and the equation is: d=1.414 g.

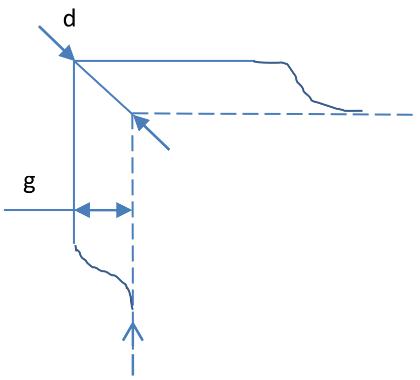

Fig. 15. Gap variation and corner collapse

We calculated the difference in test punch size as shown in table 10. We defined the 100% feed rate as the origin; a positive value indicates a size increase, and a negative value indicates a size decrease.

Table 7 Defference of the test punch size

Feed rate %	100%	80%	70%	60%	50%
On	0	0.008	0.011	0.012	0.016
OFF	0	-0.006	-0.007	-0.009	-0.013
SG	0	-0.011	-0.019	-0.023	-0.03

Unit :mm

When the machine cut the path to the corner position, the cutting EDM conditions will be changed, and wire deflection will occur. Both wire deflection and gap difference will affect the corner collapse. At the beginning of the experiment design, we separate the factors of wire deflection and gap difference. To considering the physical machining, we attempt to superpose the effect of wire deflection and gap difference as follows:

$$d= 0.707*L+ 1.414 *g. \qquad (2)$$

The corner collapse value is derived from equation (2) and shown in table 8 and Fig. 16.

Table 8 Compound corner collapse

Feed rate %	100%	80%	70%	60%	50%
On	-0.073	-0.052	-0.046	-0.043	-0.031
OFF	-0.073	-0.064	-0.058	-0.057	-0.053
SG	-0.073	-0.079	-0.075	-0.069	-0.069

Unit :mm

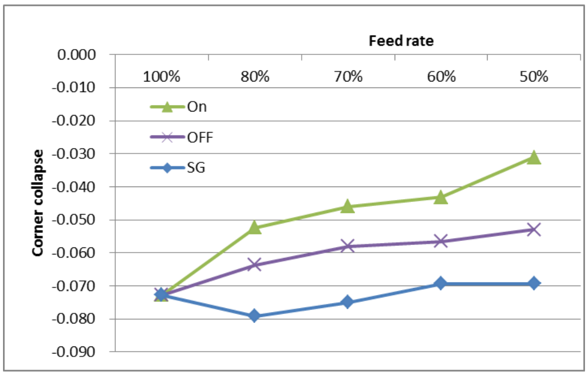

Fig. 16. Compound corner collapse

Fig. 16 shows that the best factor to improve the corner collapse is parameter ON. Although parameter SG has the best improving effect in wire deflection, considering the total effect of corner collapse, it is not a good parameter to improve the corner accuracy. The parameter OFF does not have good effect compared to the factor ON. In practical application, the corner cutting has too many cutting conditions such as the cutting angle, wire diameter, material thickness... For a design engineer, selecting only one parameter to improve the corner accuracy is easiler to make application than multiple parameters. Thus, we select the best improving parameter (ON) for the following experiments and varifications.

Using ON as the major control factor, table 9 shows the experimental results,

Table 9 Experimental results of parameter ON

Feed rate %	100%	80%	70%	60%	50%
Difference of test punch size Unit :mm					
ON	0	0.008	0.011	0.012	0.016
Wire deflection Unit :mm					
ON	-0.103	-0.09	-0.087	-0.085	-0.076

From table 9, the equation of corner collapse can be derived by regression analysis as:

L=-0.0625714*x-0.0441619, (3)

g=-0.0328571*x+0.0321905, (4)

d= 0.707*L+1.414*g

= -0.09069791*x+0.01429490, (5)

x is the feed rate percentage controlled by the factor of ON. The cofficients of determination R_L^2=0.9478762 and R_g^2= 0.9223503 are notably close to unity, so the derived mathematical model is sufficient to represent the real cutting status. Based on these mathematical models, the gap difference, wire deflection and corner collapse can be correctly predicted. By setting x in equation 5 from 0.5 to 0.2, we derive the corner collapse d as shown in table 9.

Table 10 Derivation of the corner collapse at different feed rates by changing the parameter ON

x	d (mm)
0.5	-0.0311
0.4	-0.0220
0.3	-0.0129
0.2	-0.0038

If the feed rate is decreased to 50%, the corner collapse can be reduced to 31.0 μm . If the feed rate is decreased to 30%, the corner collapse can be reduced to 12.9 μm by changing the parameter ON.

RESULT VERIFICATION

Cutting a 90-degree workpiece to verify the corner collapse is identical to the aforemention situatiom. The CCD picture of corner collapse at the feed rate of 50% by ON is shown in Fig. 17. Because ON is gradually reduced at the corner inlet position, which is operated by the controller function, and the discharge gap gradually decreases. Thus, the workpiece at the inlet of the corner will gradually grow over the boundary line.

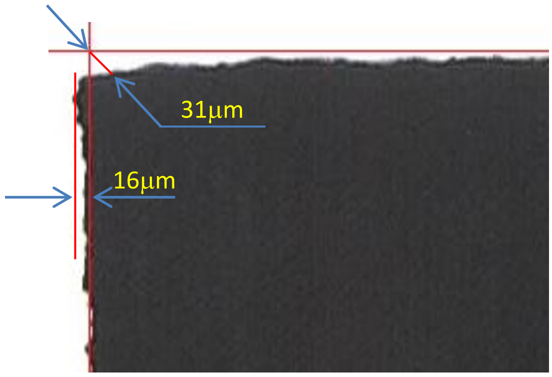

Fig. 17. CCD picture of corner collapse at 50% of the feed rate by adjusting ON

Repeat the experimental verification by adjusting ON to 30% feed rate. The CCD picture of corner collapse at 30% of the feed rate by ON is shown in Fig. 18.

Adjusting the feed rate to 30% by the parameter ON will induce a large deviation of over 22 μm compared to the original path. The corner collapse has signficant improvement to 13 μm in this condition.

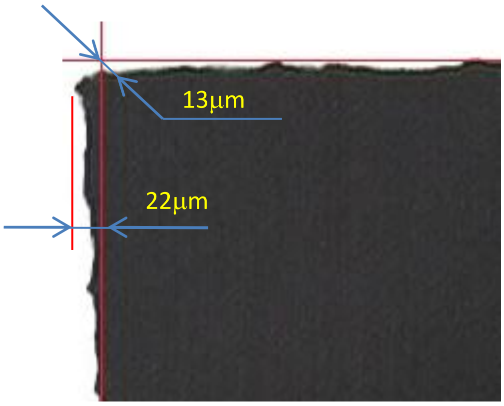

Fig. 18. CCD picture of corner collapse at 30% of the feed rate by adjusting ON

Practical engineering applications normally have multi-cut to obtain the accuracy and roughness. Checking the cutting parameter from the wire cut machine, we obtain the offset compensation value as:

1 cut only : offset = 0.166 mm

2 cuts : 1st cut offset = 0.188mm, 2^{nd} cut offset = 0.132mm

The gap in the 1 st cut is 41 μm (derived from 0.166-0.25/2=0.041 mm) when the machining has 2 cuts, the gap in the 2^{nd} cut is 7 μm (derived from 0.132-0.25/2=0.007 mm), and the trim value at the 2^{nd} cut is 22 μm (derived from 0.188-0.166=0.022 mm).

The operator will drive the machine as fast as possible under the acceptable tolerance. The 2^{nd} cut can trim approximately 20 μm for a single side depending on the cutting energy, so the corner cutting accuracy can be approved by adjusting the parameter of ON to 30~40% feed rate.

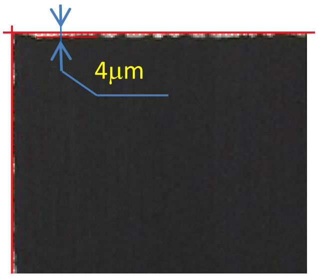

Fig. 19. Corner after 2nd cut when the ON is reduced to 30% feed rate in the 1st cut.

CONCLUSIONS

From the above experiments and results, the following conclusions can be drawn:

1. In wire EDM machining, wire deflection is an important factor that affects the corner accuracy, but it is not the only factor. For the corner accuracy, we must also consider the gap variation when the cutting parameters change for the corner cutting. The effect of the wire deflection and discharge gap variation, which affect the corner accuracy, can be derived from the experimental design.
2. The cutting parameter ON is the most significant factor for the corner collapse. A decrease in cutting speed by decreasing ON can reduce the wire deflection and increase the size of the workpiece to compensate for the error induced by the wire deflection in corner machining. Thus, ON has the best effect for the corner accuracy.
3. The user can adjust the factor ON only to satisfy the required corner accuracy. If the accuracy of the corner is high, the feed rate at corner cutting must be adjusted to a lower speed.
4. Adjusting the parameters OFF or SG also improves the wire deflection. Simultaneously, it will also extend the discharge gap to worsen the corner accuracy.
5. In precise machining, multi-cuts are designed to satisfy the machining accuracy or roughness. The 1st cut does not need to completely erase the corner error because the corner collapse can be trimmed by the 2nd or 3rd cut.

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以實驗方法探討線切割機轉角崩角及改善對策

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摘要

轉角誤差在線切割的加工中是非常重要的，大部分的研究著重在線撓曲因素所造成的誤差，進而探討如何改變加工參數來減低線撓曲量，但是無人探討過轉角加工參數的改變, 對於放電間隙的影響程度；本文以實驗方法，設計二組不同的實驗, 在不同的加工能力下, 分別探討不同放電參數對線撓曲量和對放電間隙的各別影響，據以獲得對轉角崩角量改善的最佳參數。實驗結果顯示, 轉角的加工要同時考慮到線撓曲量和對放電間隙的影響才可獲得最佳的加工參數。 本研究已商品化應用於Accutex線切割機床上，並獲得有效的轉角精度。