Experimental investigation of workpiece deformation due to WEDM

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Abstract. Deformation of stainless steel AISI 316 which machined by wire electrical discharge machining (WEDM) was studied in this work. First, the temperature distribution in a workpiece due to WEDM single discharge was calculated using the finite element method, and the result was used to estimate residual stress. It was found that the residual stress in the radial direction, \( \sigma_r (z) \) along the center axis of the single discharge crater was distributed non-linearly in the thickness direction from the top surface of the workpiece. Then, in structural analysis, the result of \( \sigma_r (z) \) was imposed within web part model. This study aims to investigate the deformation of AISI316 material during WEDM discharging by taking a discharge current, pulse on time, pulse off time, and heat input to a workpiece as input parameters. As temperature increases due to increase in discharge current during the process caused residual stresses induced by the machining lead to plastic deformation. To explain the deformation of the workpiece, additional models of the uniform rectangular beam were built. As a result, the non-linear distribution of residual stress was found to be the main reason that causes the non-uniform curvature of the workpiece.

Keywords: WEDM, thermal stress, residual stress, surface quality, deformation.

1. Introduction
Electrical discharge machining (EDM) has the ability to produce micro components with complex features on any electrically conductive materials regardless of hardness. However, deformation of EDM workpiece at certain sizes and geometries influences component’s dimensional stability and accuracy which limits further miniaturization of the process. There are two kinds of residual stress which might cause the deformation. One is residual stress that exists within the workpiece prior to machining [1], and the other one is residual stress caused by EDM itself [2]. The stress that exists prior to machining is the result of plastic deformation processes such as forging. This kind of residual stress can be released by annealing before the machining operation [1]. On the other hand, during EDM only part of the zone on the workpiece where the temperature is above melting point is removed and the remaining molten zone is left in the crater to form a recast layer. While the area near crater is in a molten state, no residual stress will be formed due to free movement. However, at the end of discharge, the recast layer solidifies and the cooling process begins. At the cooling zone, the tensile residual stress is formed, causing the zone near the crater to contract [2] [3] [4]. In wire EDM, fabricated fins started to bend when the fin
thickness was less than 100 µm in rough cutting condition, and it was considered that the occurrence was due to the EDM [2].

For thin part components, WEDM might be a solution. However, few researches have focused on the thermal deformation phenomenon which usually appears when machining the thin-walled components in WEDM. The thermal deformation cannot be neglected due to its considerable influence on the mechanical performance and microstructure of the components during service life [5–7], especially machining the thin-walled components. One reason for thermal deformation is always neglected is due to non-macro cutting force during the WEDM process. However, as a matter of fact, thermal effects play the dominant role in WEDM except for ultrashort discharges. The thermal deformation may be caused by two kinds of residual stress [8]. One is the residual stress exists in the workpiece before machining which can be released by annealing in the pre-processing, while the other one is the residual stress generated by the WEDM process which is not yet explained clearly.

Finally, the influence of residual stress on workpiece deformation has never been calculated by other researchers. Consequently, in this work thermal and structural analysis are studied in order to understand the deformation. Residual stress due to a single discharge is studied by using the model of heat conduction within the workpiece. Then, the studied residual stress is imposed within the web part workpiece model in structural analysis to understand the non-uniform deformation of the web part.

2. Literature Review

Since the early seventies, researchers worldwide tried to investigate the workpiece deformation by wire electrical discharge machining and search out the residual stress that causes the workpiece deformation in the material AISI 316.

G. spur et al. [2] studied the influence of the maximum discharge current and the pulse on time on the dimensional stability of the teeth and found the tooth edge deviation occur at a tooth width of 50 µm. This shape deviation results from the melting of the basic material under tensile residual stress, so that the elastic limit of the stressed tooth cross-section is exceeded and a plastic deformation.

M. Zahiruddin et al. [9] studied 2D surface machining by micro EDM to investigate the analysis of micro-fin deformation after calculating the temperature distribution in a workpiece due to micro EDM single discharge and using the result to calculate the residual stress. It was found that the residual stress in the radial direction, σ_r(z) along the center axis of the single discharge crater was distributed non-linearly in the thickness direction from the top surface of the workpiece. Then, in structural analysis, the result of σ_r(z) was imposed within micro fin model. In addition, it was found that the summation of calculated deflections after three sequential discharges was almost equal to the measurement result. As a result, the non-linear distribution of σ_r(z) was found to be the main reason that causes the non-uniform curvature of micro fin. From obtained result the fin straight near the tip and curvature is larger near the root. On the other hand, workpiece deformation occurs at the tip of the beam workpiece in the case of WEDM is comparatively different than micro EDM.

J. P. Kruth, Ph. Bleys et al. [10] observed up to a thickness of 0.4 mm, the beams show no deflection because of a sufficient ratio of thickness to stress penetration, which prevents deformation. On the other hand, the beam of 0.2 mm and 0.1 mm show warping to the left, i.e. towards the last machining path. It must be noted that the beam of 0.1 mm seems to bend to the right, but this phenomenon is caused by dielectric flushing combined with an undercut in the corners, severely weakening the structure. In addition, he found the measurement of residual stress profiles for rough and finish WEDM of tool steel show that the maximum tensile stress is reduced with increasing number of finishing steps.

3. Experiment

3.1. Workpiece preparation

Stainless steel AISI316 is selected as the workpiece material and the standard size from suppliers was 200mm × 100mm × 3mm as shown in Figure 1. The designed web beam for cutting operation as shown in Figure 2. The brass wire electrode diameter (0.25 mm) was used as the tool electrode.
3.2. Machine
The workpiece was machined using AQ327 WEDM machine of Sodik Europe ltd as shown in Figure 3 with an isopulse generator and deionized water was used as dielectric liquid with Sodik’s new lp control, it can import parasolid (solid models) files directly into the controller. This unique feature maximizes cutting efficiency, reduces the work flow and reduces programming. Figure 4 illustrates the setup of EDM wire cut machine.

3.3. Material properties
The chemical composition for the stainless steel grade AISI 316 is indicated in table 1. Also the thermal and mechanical properties are set out in table 2.

| Chemical Composition of AISI 316 at room temperature |
|---------------------------------------------------|
| Element   | Mn | Si  | P  | S  | Cr | Mo | Ni | N  |
| Content % | 2  | 0.75| 0.045| 0.03| 18 | 3  | 14 | 0.10 |

Figure 1. Workpiece material used in Standard size

Figure 2. The designed web thickness

Figure 3. EDM wire cut machine

Figure 4. Setup of EDM wire cut machine
Table 2. Thermal and mechanical properties

| Thermal properties | Values         |
|-------------------|---------------|
| Thermal conductivity | 17W/mK        |
| Co-efficient of Thermal Expansion | 18*10^-6     |
| Specific Heat      | 530 J/kgK     |
| Density            | 800Kg/m³      |
| Melting Temperature| 1673K         |

| Mechanical Properties | Values |
|-----------------------|--------|
| Modulus of Elasticity | 193GPa |
| Poisson’s Ratio       | 0.275  |
| Tensile Yield Strength| 515MPa |

3.4. Machining conditions used
Table 3 demonstrates the values of the input parameters which used in the experiment, and cover the reasonable range of the input parameters available according to the characteristics of WEDM. Other parameters such as frequency constant, discharge voltage and spark radius were kept constant.

Table 3. Process parameters used for modeling

| Sr. no | Parameters                  | Values         |
|--------|----------------------------|----------------|
| 1      | Discharge Voltage, V       | 45 V           |
| 2      | Spark radius, R            | 100µm          |
| 3      | Workpiece polarity         | Anode          |
| 4      | Frequency constant, Kf     | 2.4            |
| 5      | Material                   | AISI 316       |
| 6      | Dielectric medium          | water          |
| 7      | Reference (ambient) temp. To| 298K           |
| 8      | Discharge Current, I       | 6, 25, 40A     |
| 9      | Heat input to workpiece, P | 0.15, 0.2, 0.25 kw |
| 10     | Pulse on time, T_on        | 100, 210, 260 µs|
| 11     | Pulse on time, T_off       | 160, 200, 265µs|
| 12     | Electrode                  | Brass          |

3.5. Method to cut the workpiece
Figure 5 shows a method to cut the thick plate workpiece. The plate workpiece was held horizontally. In order to explain the method, Figure 5a. is referred. First, the tool was moved downward to the starting position in the direction of cutting depth, cd; approximately 10000µm (10 mm) for the workpiece which was held horizontally. Then the tool was relatively moved towards the plate side surface perpendicularly and cutting begins. In this work, the tool electrode was moved during the thick plate cutting so that excessive too electrode wear does occur at only one side of the tool electrode surface which may severely influence the cutting progress. After the first slot cutting, the tool electrode was returned to the starting position, and then it was moved in the y- direction relative to the plate. Then, the tool was moved again towards the plate side surface to begin the 2nd slot cutting. Here, movement in the y- direction is important to control the part thickness, pt. Workpiece with plate thickness, Th equal to 3000µm (3mm). In this work, the web part with size of 10mm × 3mm × 0.2mm was obtained by using the cutting method in this section.
4. Methodology

4.1. Theory of the formation of residual stress and workpiece deformation
Figure 6a. tensile stress is formed and remains at both sides of the 1st slot after the first cutting. During the 2nd slot cutting, the stress of part surface at the adjacent area of the 1st slot is released. At the same time, in the region on the part surface at the adjacent area of the 2nd slot, tensile stress is formed. When the part width, \( p_w \) is sufficiently small, the tensile stress at the adjacent area of the 2nd slot will cause the part to be bent toward this slot as shown in figure 6c. To obtain quantitatively the part bending due to WEDM, it is necessary to conduct the structural analysis to calculate the workpiece deformation caused by the thermal stress. [9]

4.2. Residual stress due to single discharge
The power input of EDM single discharge is required to build the heat conduction model. In WEDM, discharge energy per unit time distributed at workpiece under each unit area of circular surface heat source so-called power density, \( P_r \) was used as a measure of the power input. It is calculated as follows:

\[
P_r = X \cdot i_e \cdot u_e / (\pi \cdot d^2/4)
\]

Where:

\( d \) - diameter of the wire
\( i_e \) - discharge current
\( u_e \) - discharge voltage

Figure 6. Theory of the formation of residual stress and workpiece deformation
• \(i\) and \(u_e\) are discharge current and discharge voltage, respectively which are measurable during discharging.

• \(X\) is the ratio of energy distributed into workpiece with respect to the total discharge energy, and it can be expected between the case of micro and macro EDM [9].

• \(d\) is plasma diameter. In macro EDM, plasma diameter expands about 5 times of crater diameter \((dm = 68.4\mu m)\) within the first 2\(\mu s\) of \(t_e\) [10]. In this work \(t_e\) was 100 \(\mu s\) which is significantly longer than 2\(\mu s\). Thus, \(d\) in this work was assumed to be 342 \(\mu m\) [11].

All the parameters that are required to determine \(P_e\) in WEDM are shown in table 4, and in this work, they will be used for the thermal stress analysis. The physical model of heat conduction to estimate the residual stress was built using ANSYS; finite element analysis software. In this work, stainless steel AISI316 was used as the workpiece because its high thermal conductivity makes it suitable to function as a tool workpiece in EDM wire cut machine. However, though the toughness of stainless steel is relatively high, stainless steel workpiece are vulnerable to thermal deformation. The energy input as shown in Table 4 was used to model the power density on the workpiece. Figure 7 shows an overview of the axisymmetric model, with 10 mm in radius and 3 mm in thickness. All surfaces were assumed adiabatic except the discharge area.

| Parameters                                      | Values       |
|------------------------------------------------|--------------|
| Discharge current, \(i_e\) [A]                 | 12           |
| Discharge voltage, \(u_e\) [V]                 | 20           |
| Discharge duration, \(t_e\) [\(\mu s\)]       | 100          |
| Energy distribution ratio into workpiece, \(x\) [%] | 34          |
| Plasma diameter at end of \(t_e\), \(d\) [\(\mu m\)] | 342 [11]    |
| Power density on workpiece, \(p_e (t_e)\) [Gw/m\(^2\)] | 0.7          |
| Crater diameter, \(dm\) [\(\mu m\)]            | 68.4         |

Figure 7. Overview of heat conduction model of satinless steel workpiece

Figure 8 shows the magnification of the discharge zone. The zone in the workpiece where the temperature exceeds boiling point was assumed to vaporize immediately, and thus each element in the zone was removed from the model. Accordingly, the power density location was changed as shown in Figure 8.
After the end of discharge, the simulation was continued to allow cooling before obtaining the residual stress. Figure 9 shows the temperature distribution at the end of cooling ($t = 265 \mu s$ after the ignition of discharge). As shown in the figure, the maximum temperature of the workpiece model drops to 100 °C which is only 75 °C above the initial temperature. This can be considered sufficiently low for the residual stress calculation.

From this model, the residual stress distribution along the center axis of a crater due to WEDM single discharge was measured. Figure 10 shows measured residual stress and penetration depth for three different machining situations. As shown in the figure, the distribution of residual stress is non-linear, coinciding with the results obtained by other researchers [3] [4]. In later section the influence of non-linear distribution of residual stress on part beam deformation will be observed.
4.3. Criterion of workpiece deformation

An exploratory experiment was carried out to observe the workpiece deformation in WEDM. Stainless steel plate with standard size from supplies was 200mm × 100mm × 3mm as shown in Figure 1. The workpiece was cut off with fixed dimensions as shown in Figure 2. The part beam was machined using WEDM with taking a discharge current, pulse on time, pulse off time and heat input to a workpiece as input parameters, the applied machined path is shown in figure 11a. In order to study the complex phenomenon accurately, the part beam with size of 10mm × 3mm × 0.2mm were selected as experiment specimen. Moreover, the criterion of workpiece deformation is performed. Generally, the beam deflection could be used to express the deformation behaviour. Through the magnitude of deformation during the WEDM process is micron scale, the beam deflection was measured directly by the KEYENCE VH-Z500R digital microscope. Therefore, the beam deflection is selected as the criterion of workpiece deformation as shown in Figure 11b.

| i₀ [A] | tₚ [μs] | Wₑ [mJ] |
|-------|---------|---------|
| 6     | 100     | 3       |
| 6     | 210     | 35      |
| 40    | 260     | 370     |

Figure 10. Measured residual stress vs. depth for three different machining situations.

Figure 11. Method to produce stainless steel beam workpiece

5. Results and discussions

5.1. Preliminary experiment
In order to get the beams deformation after machining WEDM, beams thickness was selected from 0.3 mm to 0.1 mm. Figure 12 shows the problem of deformations when machining very thin parts by WEDM.

![Figure 12. WEDM of thin parts results in considerable deformation](image)

Up to a thickness of 0.25 mm the beams show no deflection, because of a sufficient ratio of thickness to stress penetration, which prevents deformations. The damage observed at the tip of 0.1 mm beam. The beams of 0.2 mm and 0.1 mm on the other hand show warping to the right, i.e. towards the last machining path. It is clear this makes further finishing of the part impossible, thus limits the thickness of structures that can be machined first by WEDM before finishing. It must be noted that the beam of 0.1 mm seems to bend to the right, but this phenomenon is caused by dielectric flushing combined with an undercut in the corners, severely weakening the structure (figure 12, sample 1). Figure 12 should not lead to the interpretation that the structures shown on the figure cannot be correctly machined by WEDM.

5.2. Deformation after machining WEDM
Experiments were run with a stainless steel AISI 316 as used in conventional EDM and a wire diameter of 250 µm. The experiments served to examine the influence of the maximum discharge current ($i_e$) and pulse on time ($t_e$) on the dimensional stability of the part beam. The generator parameters were varied for these investigations in such a way that the total machining spectrum could be examined. At the first, the settings were selected in a way that the share of open-circuit impulses, predominated during machining. Later, the settings were gradually varied until further machining became impossible due to the high portion of short circuits.

![Figure 13. Part beam workpiece](image)  ![Figure 14. Part beam deformation](image)

Figure 13 shows that a decreasing part thickness leads to a deflection in shape from the programmed workpiece contour. The tensile residual stresses induced during machining of the increasing part beam flank and their depth of indentation into the sub-surface layer exert a major influence on the intensity of the deflection.
The deflection was observed clearly in figure 14, where $\lambda = 0.62 \text{ mm}$, while the basic body of the sample prevents a deformation during machining of the increasing flank (figure 13, flank A), the part beam over during machining of decreasing flank (figure 13, flank B). The shape deflection results from the melting of the basic material under tensile residual stress, so that the elastic limit of the stressed part beam cross-selection is exceeded and a plastic deformation. However, the deflection was observed clearly in figure 14, where $\lambda = 0.62 \text{ mm}$. Figure 15 shows the measured deflection of the part workpiece with respect to its thickness, where the deflection of the workpiece increased when the workpiece thickness was reduced.

![Figure 15. Measured deflection of part workpiece with respect to its thickness](image)

5.3. *Effect of residual stress on the workpiece deformation*

First, it is fully understood that the larger residual stress accompanies with the larger deformation. In fact, since the workpiece material is heated, molten and removed at the high temperature during the pulse discharge process, the thermal stress appears in the workpiece surface and leads to thermal deformation. In the heating process, the elastic deformation appears at first. Once if the thermal stress within the material is beyond the yield strength of materials, the plastic deformation takes place. Then cooling process comes after the pulse discharge process, and the recast layer begins to form in the cooling process so that the tensile residual emerges in the recast layer surface. It is mentioning worthy that the residual stress distributed at the top of the thin part beam should balance with that force on the bottom. If not, the thin part beam will keep on deforming until the residual stress is balanced by the internal force of materials.

Finally, the results of experiment in this work as shown previously in Figure 14. During the experiment, one side of stainless steel AISI 316 workpiece was rigidly supported, and WEDM results in non-linear residual stress distribution within the workpiece as shown in Figure 10. The non-uniform deformation as shown in Figure 17 can be observed.

5.4. *Non-linear deformation in thin part beam*

There is a non-linear deformation phenomenon in the WEDM processing the thin part beam component as shown in Figure 14. This deformation is placed non-linear from fixed end to free end along the beam direction. The non-linear deformation phenomenon needs to be further analysed to determine the deformation characteristics. Therefore, the deformation data are measured at each interval of 50 microns from the fixed end to free end of the cutting beam. As shown in Figure 16, it can be clearly seen that there exists the maximum deformation as well as the maximum deflection angle at the tip of the beam. With the increase of the beam thickness along the cutting direction, the deformation decreases rapidly and presents the strong non-linear characteristic, which is exactly consistent with the research results of Zahiruddin and Kunieda [9]. This might be attributed to that when the wire tool is beginning to cut into the workpiece, the pulse discharge status hardly keeps stable as well as more the ratio of abnormal discharge (namely arc discharge, transition discharge, short circuit, open circuit) increases dramatically.
Figure 16. The relationship between part beam thickness and deformation

Additionally, the debris has been flushed away at a high speed in the first cutting so that the debris has little influence on the pulse discharge process, which leads to much more strong input discharge energy directly acting on the workpiece surface. The reasons which mentioned above probably produce the large thermal deformation at the tip of the beam. Moreover, another probable reason is that the tip of the beam is a free end without any constraints, therefore the residual stress in the workpiece material needs to be balanced by enough strong inner force from the larger deformation generated. On the contrary, after the wire tool cutting into the workpiece for some distance away from the free end, the pulse discharge status comes to be relatively stable. Correspondingly, the residual stress of the material decreases and uniformly distributes along the cutting direction. On the other hand, the tail of the beam is a fixed end which can constrain the deformation and balance the residual stress.

6. Conclusion
Workpiece deformation due to WEDM has been studied and the work can be concluded as follows:
1. Up to a thickness of 0.25 mm, the beams show no deflection because of a sufficient ratio of thickness to stress penetration, which prevents deformation.
2. On the other hand, the beams of 0.2 mm and 0.1 mm show warping to the right, i.e. towards the last machining path.
3. The curvature was observed at the tip of the beam workpiece.
4. Non-linear distribution of residual stress was found to be the main reason that causes the non-uniform curvature of the workpiece.
5. The deflection of workpiece increased when the workpiece thickness was reduced.
6. Imposed residual stress was non-linearly distributed in the thickness direction below WEDM crater.
7. As a consequence, a non-uniform bending of web part workpiece along its length due to WEDM can be observed.
8. To understand the workpiece deformation, it must be comparison the curvature of machined web beam workpiece with the curvature of simulated web beam workpiece and also, a comparison between the distribution of residual stress generated by multi-discharges in the depth direction and distribution of residual stress generated by single discharge.
9. As temperature increases due to increase in discharge current during the process caused residual stresses induced by the machining lead to a shape deflection of contour elements.
10. The deflections was measured, where $\lambda = 0.62$ mm. This result indicates that the deflection of the workpiece increased when the workpiece thickness was reduced.

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