Determination and Analysis of Residual Stress for AISI L2 Tool Steel in Electric Discharge Machine (EDM)

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Abstract. Electric discharge machine is one of the most important non-traditional cutting processes conducted without contact between the workpiece and tool electrode. Each cutting process was associated with residual stresses, and these stresses are significant in determining life and product performance. This study aimed to determine the residual stress produced in the electric discharge machine (EDM) using the X-ray diffraction method. The used EDM parameters in this study are current $I_p$ (10, 20, 30) A, pulse on-time $T_{on}$ (50, 100, 150) $\mu$s, and pulse off-time $T_{off}$ (6.5, 12, 25) $\mu$s these parametric divided into 27 specimens. Full factorial was used to analyze the result using Minilab 17 software. The result showed that approximately between the experimentally and predict result. Also, the result illustrated that the residual stress was increasing with increases in each parametric EDM used. Maximum tensile residual stress is (838.86 Mpa) at a higher value of machine parameters, while the best residual stress achieved is compressive residual stress at low machine parameters, and it reaches 201 Mpa.

Keywords. Electrical discharge machining (EDM), Factorial, X-ray diffraction, Residual stress.

1. Introduction
An electric discharge machine is a cutting process electric spark mechanism to convert electrical energy to thermal energy to produce many sparks on the workpiece with a dielectric liquid. Resulting from the high-temperature gradients, EDM produces residual stresses and metallurgical changes. Such stresses are always generated where regions of material were non-homogeneous plastically deformed in such a permanent way strain incompatibilities happen [1]. These stresses are contained much more than the material's yield point and, depending on the crystal structure, causing severe slip, twining, and cleavage [2]. The maximum value of residual stresses at the top surface decreases until it reaches zero in the sub-surface [3]. Figure (1) explains the variation of residual stress by the plasma column; from the figure, we can see that the residual stress is affected only on the heated affected zone. This means that the residual stress in EDM is depended on the heated affected zone and is associated with depth [4]. Residual stress can be classified into two types compressive residual stresses and tensile residual stresses. The compressive residual stresses are more important for product performance and life, promoting service and preventing crack nucleation. The compressive residual stress value takes a negative signal [5]. Tensile residual stress increasing service stresses and leads to failure of components, distortion, corrosion, and cracking. The tensile residual stress value is taken positive signal [6]. Many types of research in this field is done. Mohanty showed that residual stress increased...
sharply with increasing current and pulse on time, often slowly increasing residual stress and duty factor [7]. S.N. Joshi and SD Pande showed high-temperature gradient zones and high residual stress regions that reach the material yield strength. A large amount of compressive stress is generated inside the crater zone; it decreased along with the depth of the work domain and transited into tensile stress [8]. S. Saxena studied the thermal stress distribution for the electric spark process. It was found tensile stress at the contact area between electrode and workpiece increased in depth, tensile stress converted to comparison stress; this converting also connected with the cooling and heated cycle during the process [9]. B. Nahak studied surface integrity in die-sinking EDM and showed the residual tensile on the surface due to the abrupt surface temperature difference due to the fast thermal cycle and the consolidated layer's thermal expansion [10].

Figure 1. Effect of plasma column on residual stress distributions[11].

2. Residual stress measurement
Residual stress was a crucial factor when assessing engineering components' integrity and welded assemblies [12-13]. Residual stresses occur in many manufactured structures and components. Over the years, various approaches have been developed to calculate residual stress for different materials to achieve accurate evaluation. Numerous technical methods have developed over many decades. Their practical implementations have greatly benefited from the advancement of complementary technology, particularly in material cutting, full-field deformation measuring techniques, computational methods, and computing power [14]. Many methods were used to measure residual stress, such as destructive, semi destructive, and non-destructive techniques depending on their applications and the availabilities of those techniques. X-ray diffraction method was used in this study on a device XRD-6000, which was found in Structural Research and Development Laboratory/Baghdad/ Iraq. We use XRD methods because it is used for ductile material and small components. Also, the XRD method has good accuracy and inexpensive, and it is considered a non-destructive test.

3. Experimental procedure
In this study, pure copper is selected as a tool electrode and tool steel AISI L2 as a workpiece. The tool electrode dimensions are 32x27x10 mm³ and the workpiece dimensions are 30x20x3 mm³. After it was cut by water, it gets machined; 10 mm was cut from the end of the sample using EDM, as shown in Figure (2). Chemical composition for the workpiece and electrode are shown in Table (1).
Figure 2. Electrode and workpiece shape.

Table 1. Chemical composition for AISI L2 tool steel and copper electrode.

| Element     | Weight (%) | Element     | Weight (%) |
|-------------|------------|-------------|------------|
| Pure copper | Al         | 0.0023      |
| AISI L2 tool steel | C    | 0.690       |
|             | Si         | 0.276       |
|             | Mn         | 0.406       |
|             | P          | 0.0091      |
|             | S          | 0.003       |
|             | Mo         | < 0.002     |
|             | Cr         | 0.585       |
|             | Ni         | 0.0305      |
|             | Cu         | 99.9        |

The machine parameter can be classified into fixed parameters and changed parameters, such as current, $T_{on}$, and $T_{off}$, as shown in Table (2).

Table 2. Machine parametric value in this study.

| Machining Parameters | Values            |
|----------------------|-------------------|
| Current              | 10, 20, 30 A      |
| $T_{on}$             | 50, 100, 150 μs   |
| $T_{off}$            | 6.5, 12, 25 μs    |
| Polarity             | Positive          |
| Dielectric fluid     | Transformer oil   |
| High voltage (HV)    | 240 V 1.5 A       |
| S code (S CODE)      | 20                |
| Servo feed (SVO)     | 75 %              |
| Working time (WT)    | 0.6 sec           |
| Jumping time (JT)    | 0.8 mm            |
| Gap code (GAP)       | 9                 |
| Depth of cut         | 1 mm              |

4. Results and discussion
The experiment and predicted results for the residual stress with machine parameters are shown in Table (3). Design of experimental is done using full factorial to give (all prospects) 27 number of experiment on program Minilab17 software. The found relationship between the input parameters and the produced residual stress by using DOE is shown in Equation (1).

\[
\sigma_{rs} = 255 - 26.53 I_p - 1.26 T_{on} + 34.9 T_{off} + 0.674 (I_p)^2 + 0.00596 (T_{on})^2 - 1.520 (T_{off})^2 - 0.0092 I_p * T_{on} + 0.957 I_p * T_{off} + 0.0551 T_{on} * T_{off}
\] (1)
Table 3. Experiment and predict value with machine parametric.

| No. | Sample | Ip | T_on | T_off | Exp. Residual stress (Mpa) | Pred. Residual stress (Mpa) |
|-----|--------|----|------|-------|----------------------------|----------------------------|
| 1   | 10     | 50 | 6.5  |       | -226.290                   | -225.421                   |
| 2   | 10     | 50 | 12   |       | -358.200                   | -373.799                   |
| 3   | 10     | 50 | 25   |       | -245.370                   | -252.560                   |
| 4   | 10     | 100| 6.5  |       | -201.900                   | -228.685                   |
| 5   | 10     | 100| 12   |       | 390.000                    | 386.327                    |
| 6   | 10     | 100| 25   |       | 279.386                    | 274.710                    |
| 7   | 10     | 150| 6.5  |       | 279.900                    | 253.984                    |
| 8   | 10     | 150| 12   |       | 402.159                    | 390.233                    |
| 9   | 10     | 150| 25   |       | 375.390                    | 372.876                    |
| 10  | 20     | 50 | 6.5  |       | 239.337                    | 218.995                    |
| 11  | 20     | 50 | 12   |       | 465.039                    | 454.234                    |
| 12  | 20     | 50 | 25   |       | 364.968                    | 377.344                    |
| 13  | 20     | 100| 6.5  |       | 233.150                    | 222.260                    |
| 14  | 20     | 100| 12   |       | 495.200                    | 466.762                    |
| 15  | 20     | 100| 25   |       | 392.150                    | 399.493                    |
| 16  | 20     | 150| 6.5  |       | 216.327                    | 247.559                    |
| 17  | 20     | 150| 12   |       | 431.425                    | 470.668                    |
| 18  | 20     | 150| 25   |       | 517.379                    | 497.660                    |
| 19  | 30     | 50 | 6.5  |       | 365.910                    | 387.121                    |
| 20  | 30     | 50 | 12   |       | 530.379                    | 525.585                    |
| 21  | 30     | 50 | 25   |       | 760.350                    | 740.784                    |
| 22  | 30     | 100| 6.5  |       | 406.280                    | 390.385                    |
| 23  | 30     | 100| 12   |       | 506.000                    | 538.112                    |
| 24  | 30     | 100| 25   |       | 765.600                    | 762.933                    |
| 25  | 30     | 150| 6.5  |       | 421.000                    | 415.684                    |
| 26  | 30     | 150| 12   |       | 569.336                    | 542.019                    |
| 27  | 30     | 150| 25   |       | 838.867                    | 861.100                    |

Residual stress is increasing with an increase in MRR, EWR, and SR. So residual stress increasing with an increase in current from 10 to 30A. This occurred because increasing the current leads to an increase in spark energy between the electrodes. Residual stress also increases with T_on because increasing in T_on leads to high temperature on the workpiece, so increasing in temperature leads to increasing $\sigma_{rs}$. Also, the result shows the highest level of T_off gives maximum residual stresses because higher T_off enhances the re-solidification time in the presence of dielectric medium and results in more significant surface grains, causing higher residual stresses. The effect of current, T_on and T_off on the residual stress is shown in Figure (3).

![Figure 3](image-url)

**Figure 3.** The effect of Current (Ip), pulse on time (T_on), and pulse off time (T_off) on residual stress ($\sigma_{rs}$).
The performance of variance analysis (ANOVA) is organized in Table (4), which includes variation sources, degrees of freedom (DF), the total sum of squares (Adj SS), mean squares (Adj MS), F-values, and P-values to determine whether the factors are significantly related to the response. ANOVA results show that the current has the highest effect on the residual stresses.

Table 4. ANOVA table for $\sigma_{rs}$.

| Source      | DF | Adj SS | Adj MS | F-Value | P-Value |
|-------------|----|--------|--------|---------|---------|
| Model       | 14 | 737874 | 52705  | 64.19   | 0.000   |
| Linear      | 6  | 599871 | 99979  | 121.76  | 0.000   |
| Current     | 2  | 348588 | 174294 | 212.26  | 0.000   |
| $T_{on}$    | 2  | 14997  | 7499   | 9.13    | 0.004   |
| $T_{off}$   | 2  | 236286 | 118143 | 143.88  | 0.000   |
| 2-Way Interactions | 8 | 138003 | 17250  | 21.01   | 0.000   |
| Current * $T_{off}$ | 4 | 126488 | 31622  | 38.51   | 0.000   |
| $T_{on}$ * $T_{off}$ | 4 | 11515  | 2879   | 3.51    | 0.041   |
| Error       | 12 | 9853   | 821    |         |         |
| Total       | 26 | 747728 |        |         |         |

5. Conclusion

The present study discussed the effect of electrical process parameters ($I_p$, $T_{on}$, $T_{off}$) on the residual stresses for tool steel AISI L2 when pure copper is used as a tool electrode. The full factorial model has been proposed to estimate the residual stresses. The result showed that the experimented and predicted values are approximately equal. From the result, it can be concluded that:

- Best residual stresses are compressive stress produced in samples 1, 2, 3, 4, which have negative signals, and this stress appeared at low machine parameters current, pulse on time, and pulse off time. Therefore, the researcher recommends using lower input parameters to achieve safety residual stress.
- Residual stress increasing with increasing the current, pulse on time, pulse off time. The maximum experimental residual stress was 838.9Mpa, and the predicted maximum residual stress was 861Mpa.

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