Performance Evaluation and Microstructural Characteristics Of Improved Tool Steel Alloy XW42 By WEDM

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Abstract. M3 is a newly improved cold die steel, an upgrade from the familiar cold die steel XW42. Only little information of these steel is available in literature for its machining characteristics since it is a newly improved die steel. This paper attempts to show the effects of machining factors on the responses consist of material removal rate (MRR), surface roughness (SR) and cutting speed (CS) of WEDM-ed M3 die steel. The machining factors that had been investigated were pulse on time (T_{on}), Voltage (V) and wire tension (WT). Other wire electrical discharge machine (WEDM) performance characteristics such as white layer thickness formation, microstructural and metallurgical alterations were also investigated. The technique of analysis of variance (ANOVA) was used to confirm the variables affecting the responses. The experimental results revealed that T_{on}, V and WT greatly influenced the MRR and SR. With high toughness of M3, no micro cracks were observed on the machined surface. Debris and craters were significantly reduced at low T_{on}, medium V and high WT. SEM analysis of white layer thickness exposed a deterioration about 53% from the base material (XW42) while maintaining the surface roughness at 192μm.

1. Introduction

In a down-stream industries including die making industry, which will usually be affected by any technological changes, it is novel to produce various kinds of dies. In order to produce quality die, an improved die material and die-making processes are continuously being introduced by the die-making industry. M3 is a newly improved cold die steel from Universiti Technical Malaysia (UTE-M). It is an upgrade over the known cold die tool steel XW42. M3 removes the disadvantages of insufficient toughness, resulting from the lack of material composition and XW42 high temperature tempering. Very little information is available in literature for its machining characteristics since M3 is a new developed die steel.

[1] labelled that the selection of optimal process parameters for obtaining higher cutting efficiency or accuracy, material removal rate (MRR), lower white layer thickness (WLT) and surface roughness (SR) is still not fully solved, even with the most up to date Computer Numerical Control (CNC) WEDM. This is mainly due to the large number of process variables and complicated stochastic process mechanisms in WEDM as captured by [2]. Despite this, the correlation of process parameters and machining performance are difficult to be established precisely.

[3] reviewed the literature from the period and found that lower WLT, good SR or MRR can be gained through the selection of optimum cutting parameters. Improper selected parameter may also
result in short circuiting of wire, wire rupture, high SR, lower CS and low MRR. The issue has recently grown in importance where more investigations have been carried out to improve these outcomes. Conversely, the problem in WEDM process is still unambiguous. The aim of this study is to clarify several aspects of the machining factors on pulse on time (T_{on}), voltage (V) and wire tension (WT) of WEDM-ed M3 die steel. Machining response includes material removal rate (MRR), surface roughness (SR) and cutting speed (CS). Analysis of variance (ANOVA) is used to study the effects of these machining factors. Another objective of this paper is to acquire the best machining parameters to obtain the lowest white layer thickness of M3 in WEDM. This indicates the need to understand the various perceptions of these improved materials within the WEDM parameter since information is either unavailable or scanty.

2. Experimental study

Figure 1 shows a typical newly cast M3 steel alloy through double austenitisation heat treatment process including tempering to relief internal stresses. All samples were examined for microstructural examinations and mechanical testing after grind and machined to the dimension of 10 mm x 10 mm x 20 mm for hardness and white layer thickness through WEDM and 10mm x 10 mm x 55 mm for Charpy impact test.

![Figure 1. A newly cast M3 material consists of cerium, lanthanum and niobium](image)

SF, MRR, and CS would be the dependable variables while independent variables would be the T_{on}, V and wire tension [28]. The compositions of the improved cold work tool steel based on XW42 as shown in Table 1 was in range of AISI D2 or SKD 11. The weight of the material would be measured to identify the MRR. The M3 had a bulk hardness of 52.3HRC with the toughness of 2.94J while the base of XW42 was 51.8HRC and 6.84J in toughness.

| Element | Mat. C | Si | Mn | P | S | Cr | Mo | Ni |
|---------|-------|----|----|---|---|----|----|----|
| Cu      | M3    | 1.95 | 0.34 | 0.32 | 0.01 | 0.02 | 12.7 | 0.95 |
| Weight, Wt (%) | 0.35 | 0.12 | 0.1 | 0.85 | 0.01 | 0.01 | 82.1 |

A numerically controlled WEDM machine, Sodick AG600L would be used. Electrode wire was wound at constant speed where current was being supplied into the wire. The new features of the WEDM automatically adjusted the wire tension and speed to avoid machine breakdown due to wire rupture. Brass wire of 0.20 mm diameter was mainly used for electrode. Working fluid (de-ionized water) was supplied from both top and bottom. These machining conditions were chosen based on machine maker manual and recommendation. Three responses were considered for the experiment including material removal rate (MRR), surface roughness (SR) and cutting speed (CS). The samples mass were measured before and after the machining process. The machining time could be obtained from the machine monitor. From these parameter, one could gain the MRR.

The SR could be achieved through the aid of Portable Mitutoyo Surface Roughness Measurement SJ 301. Five readings were taken and the final reading would be the average value of the SR. The CS value could be obtained from the monitor system of the WEDM machine.
The specimens for microstructural observations were prepared using standard metallographic polishing techniques with 0.05 µm Nano-polish Alumina and cleaning with ethanol (after ultrasonic bath to remove foreign embedded particles). This was followed by etching with 2% Nital (5 ml Nitric acid + 100 ml Ethanol) and then with Murakami reagent for 10 s each [4] were done with grinder and polisher double platen and ultrasonic cleaning. Scanning electron microscope (SEM) equipped with energy dispersive x-ray spectroscopy (EDS) was employed for morphology, microstructure and elemental analysis.

Preliminary work on WEDM based on full factorial design (FFD) was undertaken by [5]. For this current research, three factors including $T_{on}$, $V$, and WT would act as the independent variables [6]. FFD (2k) with no replication, where $k$ was the factor, would be implemented in this experiment. There were three factors as stated above. Low and high levels of each factors were chosen based on machine manual and machine maker recommendations. No replication with number of eight experiments and 4 center points, therefore, the total number of experiment for each sample was 12.

3. Results and discussion

A complete values of factors and responses are shown in Table 2. MRR ranges from 0.19 to 0.23 kg/s, SR ranges from 1.92 up to 3.73 µm while CS ranges from 235 to 398 mm/min. The run order is randomized to offset any lurking variables, such as machine warm-up to satisfy the statistical requirement of independence of observations. Randomization acts as insurance against the effects of lurking time related variables. By randomizing the order of experimentation, it can reduce the chances in mistakenly attribute the happenstance effect to the non-randomized factor.

Table 2. A complete matrix table with factors value

| Run | A  | B  | C  | Material Removal Rate (MRR) (kg/s) | Surface Roughness (SR) (µm) | Cutting Speed (CS) (mm/min) |
|-----|----|----|----|-----------------------------------|-----------------------------|-----------------------------|
| 1   | 6  | 8  | 100| 0.23                              | 3.47                        | 3.98                        |
| 2   | 6  | 8  | 100| 0.21                              | 3.54                        | 3.96                        |
| 3   | 10 | 6  | 120| 0.19                              | 3.62                        | 3.42                        |
| 4   | 2  | 6  | 80 | 0.2                                | 2.03                        | 2.35                        |
| 5   | 2  | 10 | 80 | 0.21                              | 2.08                        | 2.38                        |
| 6   | 2  | 6  | 120| 0.21                              | 1.92                        | 2.41                        |
| 7   | 10 | 10 | 120| 0.21                              | 3.62                        | 3.28                        |
| 8   | 10 | 6  | 80 | 0.25                              | 3.39                        | 2.38                        |
| 9   | 10 | 10 | 80 | 0.23                              | 3.73                        | 3.28                        |
| 10  | 6  | 8  | 100| 0.21                              | 3.33                        | 3.90                        |
| 11  | 2  | 10 | 120| 0.2                                | 3.16                        | 2.41                        |
| 12  | 6  | 8  | 100| 0.23                              | 3.55                        | 3.92                        |

Table 3 shows data in ANOVA including the sum of squares for model and residual on the first column. It is found that the pulse on time ($T_{on}$) contribute the highest with 31.53% while the interaction between voltage ($V$) and wire tension (WT) contribute about 24.36% followed by $T_{on}$ and $V$ interaction 20.89%. The next column shows the degree of freedom corresponding to the sum of squares. Each effect is based on two averages, high versus low, so it contributes 1 degree of freedom (df) for the sum of squares. There are also 3 df for the three effects in the model pool and 8 df for the eight effects in the residual pool. The ratio of sum of square and degree of freedom results in the mean square and the F values are obtained through the ration between MS Model / MS Residual which forms the value of 5.03 for the model. The F value of 5.03 is bracketed by the critical values for 5% and 0.1% risk which end
up with more than 95% confident that MRR is significantly affected by one or more of the effects chosen for the model.

The F-tests for each effect which are based on 1 df as numerators and 8 as denominators, the critical F at 5% for these df (1 and 8) is 5.318. The actual F-values for all three individual effects exceed the critical value F and they are all significantly supporting the half normal plot.

Table 3. ANOVA for material removal rate

| Source | Sum of Squares | df | Mean Square | F Value | Prob>F | Contribution (%) |
|--------|----------------|----|-------------|---------|--------|-----------------|
| Model  | 8.009 E-5      | 3  | 2.670 E-5   | 5.03    | 0.0302 sig. | 31.53          |
| A      | 6.311 E-5      | 1  | 6.311 E-5   | 11.89   | 0.0087  | 64.45          |
| AB     | 4.581 E-5      | 1  | 4.581 E-5   | 8.63    | 0.0188  | 20.89          |
| BC     | 4.875 E-5      | 1  | 4.875 E-5   | 9.18    | 0.0163  | 24.36          |

The model tested in the ANOVA can provide a detail in mathematical equation which can be used to predict a given response in coded form with reference to Table 2:

\[
\text{MRR}= 0.01917 + 0.01 A - 0.025 AB - 0.005 BC \quad \text{(Equation 1)}
\]

The average value of all actual responses is represented by the value for the intercept (β₀) of 0.01917. The factor A (coefficient 0.01) causes a bigger effect than factors AB (coefficient -0.025) and BC (coefficient -0.005) (See Equation 1).

Table 4. ANOVA for surface roughness and cutting speed

| Source | Sum of Squares | df | Mean Square | F Value | Prob>F | Contribution (%) |
|--------|----------------|----|-------------|---------|--------|-----------------|
| Model  | 3.82           | 3  | 1.27        | 7.48    | 0.0104 sig. | 64.45          |
| A      | 3.34           | 1  | 3.34        | 19.62   | 0.0022  | 17.86 |

The model tested in the ANOVA can provide a detail in mathematical equation which can be used to predict a given response in coded form with reference to Table 2:

\[
\text{SR}= 0.29 + 0.26 A - 0.18 B - 0.31 C \quad \text{(Equation 2)}
\]

Since there are very small contribution of voltage and wire tension towards material removal rate, surface roughness and cutting speed, there is no need such clarification in this paper. Table 5 shows that only pulse on time which affect highest contribution towards these responses such as 64.45% for surface roughness and 17.86% for cutting speed. There is no significant changes in all responses due to the changes in all factors in this experiment with respect to cutting speed (CS). The model tested in the ANOVA can provide a detail in mathematical equation which can be used to predict a given response in coded form with reference to Table 2:
The average value of all actual responses is represented by the value for the intercept ($\beta_0$) of 0.29 with factor C causes a bigger effect than factor B (See Equation 2).

Basically, the machine parameters are adjusted based on the machine maker manual with the justification that the cutting process will undergo without the interruption from wire rupture with 3 sets of value which are: $T_{on} = 6\mu s$, $V: 8V$, $WT: 100N$, $T_{on}: 10\mu s$, $V: 6V$, $WT: 120N$ and $T_{on}: 2\mu s$, $V: 6V$, $WT: 80N$.

Figure 2: Comparison of white layer thickness between XW 42 and improved XW 42-M3 with niobium, cerium and lanthanum (Sample 6)

Figure 2 introduces micrographs of white layer for sample XW42 and sample 6 (improved XW42-M3) respectively. Figure 2 (a) and (b) shows that the WLT with the lowest value from both (XW42) and sample 6 (Improved XW42-M3) can be found when the optimal machine set up consists of $T_{on}: 2\mu s$, $V: 10V$ and $WT: 80N$ and $T_{on}: 2\mu s$, $V: 6V$ and $WT: 120N$. On the average, the white layer thickness value for both material is 306.3$\mu m$ for XW42 and the value for improved XW42 is 144.32$\mu m$. These micrographs verify that the maximum width of the white layer is at the lowest levels $T_{on}$ and WT with highest level of V for XW42.

The improved XW42-M3 micrographs proves that the lowest width of the white layer can be achieved with the highest level of WT, mid-level of V and lowest level of $T_{on}$. This is because heat energy increases with $T_{on}$ and V. Therefore, greater heat is produced on the machined surface and leads to greater white layer thickness (WLT) on the machined surface. Based on this, using low $T_{on}$ with medium V and high WT yields the best condition for better cutting and low WLT.

From Figure 3, it can be concluded that larger shallow craters are formed at high voltage which resulted in decreased SR due to expansion of the plasma channel in the discharge gap. It can also be found that some of the SR values are increased with high voltage. This phenomena happens because of the debris presence in the working gap which increases the discharging and melts the particle on the workpiece surface due to low flushing efficiency.

Figure 3: Surface microstructure of sample machined WEDM of XW42 and improved XW42-M3 with lowest surface roughness of 1.92$\mu m$ and 1.92$\mu m$ at $T_{on}: 2\mu s$, $V: 10V$, WT: 80N, and WLT$_{avg}$: 306.3$\mu m$; $T_{on}: 2\mu s$, $V: 6V$, WT: 120N, and WLT$_{avg}$: 144.32$\mu m$
The WED machined microstructure surface shows the formation of debris, craters and cracks but no cracks are found because of higher toughness of improved XW42. As shown in Figure 3 (a), due to higher V and low WT, it can be detected that there are more formations of craters, debris and cracks on the machined surface. Large volumes of molten metal at high discharge energy are flushed away due to pressurized waves and form a large crater on the machined surface. Figure 3 (b) shows that lower craters and debris are formed through the use of lower V and higher WT. At low discharge energy, a small volume of metal is melting very small craters and debris and thus improves the surface quality. Debris are formed during re-solidification where some air get trapped within the melted region and when these bubbles collapse, they form globules or debris.

4. Conclusion

Returning to the question posed at the beginning of this study, it is now possible to state that in order to have an appropriate or thin white layer thickness on the improved XW 42, high carbon high chromium (HCHCr) steel alloy, a low level of pulse on time at 2μs, medium voltage at 6V and high level on wire tension at 120N are required with a very fine surface roughness of 192μm. One of the most significant findings to emerge from this study is that through the addition of rare earth elements consisting of cerium and lanthanum with niobium at weight percentages of 0.01%, the toughness is being increased at 18% even though the bulk hardness deteriorates at 4%. The second major finding to emerge from this study is that the white layer thickness decreases at about 53% in width. Multiple ANOVA analyses reveal that T_on, V, WT and some interactions between T_on, V and WT play an important role in affecting the responses of MRR and SR.

The following conclusion can be drawn from the present study that higher bulk hardness is a promise to gain a thin white layer. It is proven that with bulk hardness value at 52.3HRC of improved XW 42 as compared to the XW42 (51.8HRC), this alloy can have a nice thin white layer of 144.32μm. The current findings add to a growing body of literature on improved cold work tool steel alloy with HCHCr can withstand certain impact toughness and produce good surface finish products if certain improvements are made towards the chemical composition and heat treatment process.

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