Surface assessments of EDMed mould steel

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Abstract. To meet the requirement of the mould industry, the new mould steels are sprung out to improve its properties such as toughness, corrosion resistance etc. However, there are some defects on the finish surface such as cracks, pores etc. In the paper, the two mould steels are chosen to study, one of which has nitrogen element while the other doesn’t have. The relationship between current, pulse on duration and EDM characteristic for two material are studied, and the influence of nitrogen on the cracks and pores are analysed as well. The results show that larger peak current will cause rough surface and little crack in the surface, while the high pulse on duration will increase the surface roughness and crack density. The existed of nitrogen achieves more pores on the surface, and the quantity of pores increases when lengthens the pulse on duration and weaken the peak current.

Keywords. Electrical discharge machining (EDM); mould steel, surface crack; surface pores; machining characteristics

1. Introduction

Plastic products have been widely used in many fields such as clinical products, electronic parts etc. Therefore, the demands for plastic mould are increased [1]. And as it is well known that the performance of those mould is dominantly influenced by quality and reliability of surface. Hence, new plastic mould steels and new techniques of plastic mould have been developed to demonstrate superior quality and desired performance to meet the increasingly demands of mould steel. Generally, the mould steel possesses the combination of toughness, corrosion resistance and the uniform hardness throughout large cross sections. The nitriding is an efficient technique for mould steel used to improve the wear and corrosion resistance [2] and mechanical properties [3]. Nevertheless, due to above improvements, the hardness of mould steel is at least 33 HRC surveyed from 70% mould steel market [4]. Hence, the difficulty in machining of mould steel has been increasing.

Traditionally, plastic mould is formed by high speed machining (HSM) or electrical discharge machining (EDM), the cavity is HSM-ed for rough which can drastically reduce the machining times, while EDM is for finishing [5, 6]. Nevertheless, some defects on surface come with EDM process are the main factors that to influence the performance and service life, therefore, it is needed to be removed to ensure the quality of products. Further, it is necessary to carry out a comprehensive research about the surface characteristics on the EDM surface.
Numerous efforts have been made in past years to investigate the mould steel surface and its surface metallurgical state. The integrity of EDM surface is characterized by the surface roughness, residual stress, cracks, pores [7], and white layer. The white layer is the result of melted zone with some defects its advantage of high hardness, good corrosion resistance [8]. If the equilibrium of between the energy outputted by generator and transferred by material is broken, the heat will mainly transfer into the material, as the heat flows are non-homogeneity, the residual stresses generates [7], as a result, the crack is formed on the surface [9]. G.Cusanelli et al.[8] investigated the white layer’s properties such as its sublayer, microstructure, hardness and etc. on material of W300, it is found that white layer, whose hardness is twice as hard as the steel, in dielectric oil presents dendritic and columnar structure, and the crack propagation starts at the austenite/martensite interface and continue to outer surface. Bülent Ekmekci [7] found that residual stresses increase as non-homogeneities within increases of white layer, whereas phase transformations contribute little. B. Bhattacharyya et.al [10] developed a response surface methodology model to study the correlation between peak current, pulse on duration and surface integrity. The results show that the optimal parameter combinations of 2A/20μs, 2A/20μs and 9A/20μs can give minimum surface roughness, white layer thickness and crack density respectively. The influence of surface roughness, white layer, and residual stress on the cracks’ formation were studied with changing current and pulse on duration, and it is found that the formation of cracks can be avoided in machining D2 and H13 by EDM when suitable combination of parameters was selected [11]. Y.H. Guu [12] carried out experiments on D2 to study the surface characteristics of EDM and developed formulations at different machining conditions to evaluate the surface roughness, white layer thickness, residual stress and EDM damage. Similar works on EDM of H13 tool steel also has been done to achieve the desired surface [13]. Meanwhile, surface cracks and white layer in AISI D5 tool steel by WEDM was also studied [14]. Despite such works have been studied on the mould steel, there are still rare works on nitrogenous mould steel by EDM.

Thus, this paper aims to the EDM-ed surface of nitrogenous mould steel, and the correlation between input parameters such as current and pulse on duration and surface characteristics was investigated. The surface characteristics investigated were surface roughness, micro-cracks, as well as the pores on the surface.

2. Materials and equipment

The specimens of two different mould steel were selected in this study, the first group (named MS1) doesn’t have element of nitrogen while another group (named MS2) has. The thickness is about 10mm, and the detailed compositions are shown in table 1. An electrical discharge machine tool (CHARMILLES ROBOFORM 35) carried out the all experiments. The geometrical form of the machined surface after the machining process was observed with the scanning electron microscope (SEM) JSM-7600M (Made in Japan). Then the surface roughness (SR) of the machined surface was measured by a Mitutoyo profilometer (Model: SURFTEST SJ-301). An optical microscope, Nikon EPIPHOT 300, was utilized to check the white layer.

3. Experimental procedure

The workpieces and electrodes were polished before EDM, and the sandpaper of 400#, 600#, 800#, 1200#, 1500#, 2000# and 3000# were chosen as a polish tools and used by sequence of abrasive particles size. Surface roughness of workpiece and electrode end face were reached Ra 0.03 and Ra 0.02 respectively. The workpiece and electrode were setup on the machine and adjusted, and the flatness of the workpiece surface was adjusted so that the depth of cut is uniform during machining; moreover, the electrode must be perpendicular to the workpiece surface.
Table 1. Chemical Composition of experimental materials in wt. %.

|     | C   | Mn | Cr  | Mo | V   | Si  | Ni | N  |
|-----|-----|----|-----|----|-----|-----|----|----|
| MS1 | 0.38| 0.5| 13.6| -  | 0.3 | -   | -  | -  |
| MS2 | 0.21| 0.45| 13.5| 0.6| 0.25| 0.9 | 0.6| 0.087 |

The machining depth was set to 1mm, and the machining program was generated by program expert, and then the process files was set to satisfy the requirements. The full factorial design upon the current and pulse on duration, so there are totally 27 sets of experiments. The following value of current were used: 1.5, 3 and 6 A, with pulse on duration of 6.4, 12.8 and 25 \( \mu \text{s} \) while the voltage was held at 200V and 0.67 at duty factor. In all experiments, the copper electrode was connected to the negative and kerosene was selected as dielectric.

In order to measure and quantitatively analyse the crack on the surface, surface crack density is defined as the crack length per unit area [11]. The SEM photo were imported into CAD software package to depict the all cracks in same scale, and then the total length of cracks and the area of photo were calculated. Furthermore, the result of the crack density is the ratio of the total length of cracks and area of photo.

4. Results and discussions

4.1. Surface roughness

The average surface roughness \( R_a \) of the machined surface is measured using a Mitutoyo profilometer (Model: SURFTEST SJ-301). \( R_a \), also known as arithmetical mean roughness, is the arithmetic mean value of the absolute value of profile deviation within the reference length [15].

![Surface Roughness](image)

Figure 1 shows the variation of the surface roughness with respect to the peak current and pulse on duration. It can be found that surface roughness value increases as the peak current value increases for all materials; whereas combination of small peak current and all pulse on duration values cause very slight increase in surface roughness. Especially, when the peak current is 1.5 ampere, the surface roughness is almost same in the all pulse on duration. The increase of peak current will expand the discharge channel diameter and hence increase the diameter and depth of crater in the formed the new surface, which in turn can roughen the surface [16]. Figure 1 also indicates that the surface roughness...
has a nearly same increase slope as pulse on duration change from 6.4\mu s to 12.8\mu s, and then have a
different increase slope in material of MS1. When the nitrogen exists in the mould steel, surface
roughness is sensitive to the pulse on duration, thus the bigger roughness is achieved by material of
MS2 at the longer pulse on duration.

4.2. Surface defects
During the EDM process, the heat generated by power supply melt the material in pulse on duration,
and then fluid cool the material in pulse interval, and in turn the material is drastically heated and
melted, rapidly solidified; therefore, the non-unified temperature make material expand and contract in
different area, thus the internal thermal stress is generated[17]. When this stress is greater than the
material’s tensile strength, thus the crack is formed. As the material blasted out from the surface, there
also are much bubbles attributed to pyrolysis of dielectric; as soon as those bubbles are expelled from
the molten area, it can cause pores on the surface. Cracks and pores are popular defects in the EDM
process, those defects can fail the working parts or shorten the life of products such as mould, dies and
etc.

4.2.1. Cracks. In order to measure the cracks density, surface crack density is defined as the crack
length per unit area. Fig.2 shows that crack density in relation to peak current and pulse on duration.
From the Fig.2, it is found that crack density is obviously abundant using smaller peak current and
longer pulse on duration. It means that the crack density can be decreased by increasing the peak
current and decreasing the pulse on duration. This may be explained as follow: the heat cannot be
transferred to deep surface when shorter pulse on duration is selected, therefore, the white layer is thin,
and the residual stress is less than the tension stress of material, thus, the quantity of crack is few;
otherwise, the pulse on duration is longer, the more energy is generated and transferred to the deeper
surface, which makes the white layer thicker. After end of a spark, the upmost surface solidifies
sharply, but the inner solidifies slowly and gradually, so the internal stress is concentrated and tear the
upper surface. Whereas the larger peak current causes a larger current density of the discharge channel
and makes the great number of melted materials expelled from the pool, thus the non-uniformed stress
distribution of solidification layer is suppressed, and consequently, the crack density in surface is
prevented.

Figure 2. Crack density of two materials with varied parameters.

The study of the effects of various material on cracks has also been made. Observed the figure 2,
the crack density has larger tendency to happen in MS2 which exists element of nitrogen. Materials
affects crack sensitive of surface, there are two factors should be considered: the thermal conductivity
of material and effects of additives in material on white layer solidification. The thermal conductivity
of mold steel is different due to its different component, so the EDM characteristics and surface crack sensitive are affected. The alloy steel’s thermal conductivity in room temperature can be calculated by the formulation summarized by previous study [18].

\[ K = 40.50 - 1.21W + 11.12V - 5.46Mo - 1.74Cr - 18.53Cu - 3.73Ni + 6.49Mn - 17.69Si + 26.72C \]

where the element symbol stands for the weight percentage in material. The calculated thermal conductivity of five materials are listed in table 2.

| Material | MS1  | MS2  |
|----------|------|------|
| Thermal conductivity W/(m·K) | 33.51 | 6.91 |

Table 2. Thermal conductivities of materials.

Compared the thermal conductivity and crack density, it can be found that the larger the thermal conductivity is, the less the crack density is. This may be due to the majority of heat is diffused around the melting pool nearly uniform because of its higher thermal conductivity, consequently, the residual stress in surface comes to small, and thus the crack density can be diminished. The thermal conductivity of MS2 is less than MS1. Nevertheless, the crack density is vice versa, this caused by the content of Ni which can refine grain in the material, all of those can prevent the formation of crack [19].

Since amount of chromium, molybdenum in the material, surface of EDM are trend to crack [20]. The content of chromium and molybdenum in MS1 and MS2 are approximately same. The element of nitrogen and chromium will combine and cause the volume expansion, as a result, the crack is formed due to the residual stress because of expansion of material [21].

4.2.2. Pores. From the figure 3, there are many pores in the surface, and pores in MS2 is abundant, only very little pores in MS1. It is same to the order of nitrogen percentage in materials. This may be that nitrides will be pyrolyzed to nitrogen gas and expelled from the surface under the high temperature, thus the pores are formed.

In fact, in the experiments, it also can be found in figure 3 that parameters combination also has a significant influence on the quantity of pores. The quantity of pores in surface increases as pulse on duration increases and peak current decreases. Since the pulse on duration increases, the energy flux exerted on the surface is enhanced as well, the more nitride in molten material is pyrolyzed, and thus the pyrolytic nitrogen is more. Meanwhile, the nitrogen will be expelled from the white layer in the upper surface, so there are many pores are formed on the surface. Otherwise, the pulse on duration is short, the parts of nitrogen has no enough time to be expelled from the white layer, then voids are formed in the white layer.

In order to make sure that the formation process of pores is mainly caused by nitrogen, the Energy Dispersive Spectrometer analysis was done to test the nitrogen percentage before and after electrical discharge machining under the condition of ie=1.5A, te=25 μs, the result is shown in figure 4. It indicates that much of nitrogen is emitted from the materials because the nitrogen percentage of pre-machining is larger than the machined ones.
Figure 3. SEM of pores in EDM-ed surface.
Figure 5 shows cross section of MS1 and MS2 after EDM. It can be found that the larger peak current is, the thicker the white layer is, and there are many pores are in the white layer. It is also found that there only little pores on surface under the large peak current, this may be due to the large energy flux is exerted on the surface, therefore, the more material is molten and re-solidified, thus, the more nitrogen gas and the thicker white layer is formed; nevertheless, high energy brings the high pressure in the channel, which makes the nitrogen gas cannot expelled from the surface and holds the gas in the inner of white layer. So, the large peak current can lead to much pores in the white layer, while the little pores on the surface.

Figure 4. Change of nitrogen content.

Figure 5. White layer after machining.
5. Conclusion
In this paper, two different mould steel was selected to study on the characteristics of EDM, and the surface defects as well. There are such conclusions can be drawn as follow:

- Surface roughness value increases as the peak current value increases for all materials;
- whereas combination of small peak current and all pulse on duration values cause very slight increase in surface roughness;
- The crack density will increase with increment of pulse on duration and decrement of peak current. The higher thermal conductivity can prevent the crack’s formation in EDM.
- Under the same conditions, the exist of nitrogen achieves more pores on the surface, and the quantity of pores increases when lengthens the pulse on duration and weaken the peak current.

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