

The influence of Span-20 surfactant and micro-/nano-Chromium (Cr) Powder Mixed Electrical Discharge Machining (PMEDM) on the surface characteristics of AISI D2 hardened steel

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Abstract. The application of powder mixed dielectric to improve the efficiency of electrical discharge machining (EDM) has been extensively studied. Therefore, PMEDM have attracted the attention of many researchers since last few decades. Improvement in EDM process has resulted in the use of span-20 surfactant and Cr powder mixed in dielectric fluid, which results in increasing machinability, better surface quality and faster machining time. However, the study of powder suspension size of surface characteristics in EDM field is still limited. This paper presents the improvement of micro-/nano- Cr powder size on the surface characteristics of the AISI D2 hardened steels in PMEDM. It has found that the recast layer in PMEDM improved by as high as 41-53 % compared to conventional EDM. Also notably, the combination of added Cr powder and span-20 surfactant reduced the recast layer thickness significantly especially in nano-Cr size. This improvement was great potential adding nano-size Cr powder to dielectric for machining performance.

1. Introduction

Electrical discharge machining (EDM) has been used extensively in machining difficult-to-cut materials particularly in mould and die industry. As one of the advanced machining techniques, EDM is able to machine difficult-to-cut or hard materials such as hardened steels, Inconel, titanium, etc. However, due to low cutting speed and hence productivity will be lower, machining practitioners must consider the machining conditions and parameters such as voltage, peak current, pulse duration, flushing and dielectric medium before executing any new machining process. Most research has been studied on the effect of changes of the machining conditions and parameters but there were very few studies on the improvement of the machining speed by implementing the higher current and voltage and at the same time try to maintain the good quality of surface integrity and reduced tool wear in EDM operation. High speed or high performance EDM is really desired by any metal fabrication industries which is very profitable by reducing lead-time of production.

However, the material removal mechanism is achieved by the melting and evaporation of workpiece material at each electrical discharge spot, which are then ejected and flushed away by the dielectric fluid. Due to the rapid high temperature melting and cooling process, subsurface defects such as



cracks, spalling, porosity, residual stress, metallurgical transformations, and heat affected zones (HAZ) are easily found on the machined surface of the workpiece. To restore the machined surface properties and remove the surface defects, the technique of fine powder mixed into the dielectric fluid of EDM, called the powder mixed EDM (PMEDM), is thus proposed.

Despite the various improvements offered by PMEDM, the important issue of effects of using powder suspended in dielectric fluid in PMEDM processes on machining time, surface quality, and accuracy still needs to be improved and investigated. The addition of powder suspended in dielectric fluid in PMEDM together with high concentration of powder in the dielectric fluid was found as a viable method to improve surface quality and reduce machining time. The electrical conductivity of powder was linked to increase the overall conductivity of dielectric fluid thus decreasing the dielectric strength of the dielectric fluid and widening the sparking gap distance between the tool electrode and the workpiece. The increase in sparking gap distance together with the high concentration of powder in the dielectric fluid facilitates the discharging process to be more uniform and reduces the need to back off the tool electrode because of short circuiting and arcing, which result in lower machining time. Also, the suspension of powder produced a high sparking gap size, which led to reduction of electric discharge power density, hence low in explosion force due to the powder size.

Powder mixed of EDM (PMEDM) machining is a revolutionary technique originally developed to achieve higher machining rates and better surface finish compared to conventional EDM. Most of the studies were conducted to evaluate the process performance in terms of machinability and surface integrity in relation to the machining process parameters. Sharma (2010) [1] investigated the effect of aluminium powder addition in dielectric during EDM of hastelloy on machining performance using reverse polarity. It was observed that the addition of aluminium powder in the dielectric fluid obtained material removal rate increase sharply. It is because of the fact that with addition of powder particles in dielectric, the spark gap is filled up with additive particles. Kumar and Davim (2011) [2] studied the role of Silicon powder in EDM machining of Al-10%SiCp metal matrix composites. It was observed that when Si powder is suspended into the dielectric fluid of EDM, the machining rate improves. The reason for enhancement of machining rate is mainly that the conductive powder particles when added into the dielectric fluid of EDM lower the breakdown strength of the dielectric fluid. Kansal et al (2005) [3] was studied the effect of silicon powder addition in dielectric during electric EDM machining of EN-31 steel. It was observed that the value of material removal rate (MRR) increases with increase in peak current. It was further reported that with increase in concentration of the powder, the MRR tends to increase. This is because the added additive causes bridging effect between both the electrodes, facilitates the dispersion of discharge into several increments and hence increases the MRR. The maximum MRR is obtained at highest level of concentration of added silicon powder (2 g/l) and peak current (12 A). Kung et al (2009) [4] studied the effect of aluminium powder mixed in EDM machining of cobalt-bonded tungsten carbide. It was reported that the MRR generally increases with an increase of aluminum powder concentration. This trend is valid up to a maximum value, after a certain limit, the increase of aluminum powder concentration leads to the decrease of MRR. Both MRR and electrode wear rate (EWR) increase with an increase of the grain size.

Wu et al. (2005) [5] obtained the improvement of surface finish on SKD steel in EDM machining with aluminium and surfactant added dielectric. It was observed that the surface roughness status of the workpiece has been improved up to 60% as compared to that EDMed under pure dielectric with high surface roughness Ra of 0.434 mm. Peças and Henriques (2008) [6] investigated the effect of silicon powder concentration and dielectric flow in the surface morphology in EDM machining on AISI H13 with powder mixed dielectric. It was observed that the crater diameter, crater depth and the white-layer thickness are reduced by the use of silicon powder particles suspended in the dielectric. Chow et. al (2000) [7] studied the performance of EDM in micro-slit machining of titanium alloy using SiC and aluminium as additive in the kerosene dielectric medium. Addition of additives increased the gap distance, which resulted in better MRR and produced better surface finish. Further, it was observed that using SiC, better material removal was obtained in comparison to aluminium powder as

additive. Al (5 g/l) and SiC (25 g/l) produced the highest material removal. Klocke et al. (2004) [8] study the effects of aluminum and silicon powder suspended dielectrics on the thermal influenced zone by electrodischarge machining with small discharge energies. They found that powder additives change the thermal material removal mechanism. They used High speed framing camera (HSFC) in this research capture the single discharge EDM. By comparing the intensities of Al and Si powders additives the result is that silicon additive intensity is higher than the aluminum additive.

From the literature, it can be inferred that powder mixed of EDM or PMEDM has the potential of becoming a useful and cheap alternative process for surface modification particularly in machining difficult-to-cut materials. In addition, with incorporating magnetic and membrane filtering system, it is highly potential to improve machining speed which leads to higher productivity especially in advanced material processing technology. However, assessing the powder concentration uniformity and powder agglomeration and deposition in the machining tank were the problem that was investigated. Furthermore, powder agglomeration and deposition in the machining tank is costly and varies the powder concentration during machining. In order to avoid powder aggregation and deposition, and to ensure the homogenous suspension of particles in the dielectric fluid, the addition of surfactant to the powder mixed dielectric was proposed [5]. Kolli (2017) [9] found out that the addition of surfactant to dielectric fluid (electrical discharge machining oil and graphite powder) improved the material removal rate and surface roughness. It was noticed to have reduced the recast layer thickness and agglomeration of graphite and sediment particles. Material migrations between the electrode and the workpiece surface were identified, and migration behavior was powerfully inhibited by the mixing of surfactant. Surfactant added into dielectric fluid played an important role in the discharge gap, which increased the conductivity, and suspended debris particles in dielectric fluid reduced the abnormal discharge conditions of the machine and improved the overall machining efficiency.

In this study, the experimental works were explored the effects of Span-20 surfactant and Chromium (Cr) powder mixed electrical discharge machining (PMEDM) of AISI D2 hardened steel. In addition, the effects of powder size influencing the recast layer thickness were also discussed.

2. Experimental methods

The study adopted Sodick EDM AQ55L, a sinking EDM machine developed to perform the experiment as shown in Figure 1 and schematic diagram of high performance electrical discharge machining (HPEDM) are shown in Figure 2. A self-made cycling system was mounted on the EDM machine, and span-20 surfactant was added to dielectric. The dielectric was filtered and could be used repeatedly by the cycling system. Experiments were conducted in this study by using a 99.9% purified electrolytic copper of 10 mm diameter as an electrode material with 100 mm in length and 8 mm in diameter. AISI D2 steel in the dimensions 50 mm x 50 mm x 10 mm was used as the workpiece. Table 1 showed the chemical compositions of AISI D2 hardened steel material and Table 2 showed the specifications of Cr powder used. The powder used in this experiment was Chromium (Cr) with size 45-55 μ m and 70-80nm as shown in Table 3.



Figure 1. Sodick High Speed EDM Die Sink (AQ 55L) with Powder mixed dielectric circulating system.

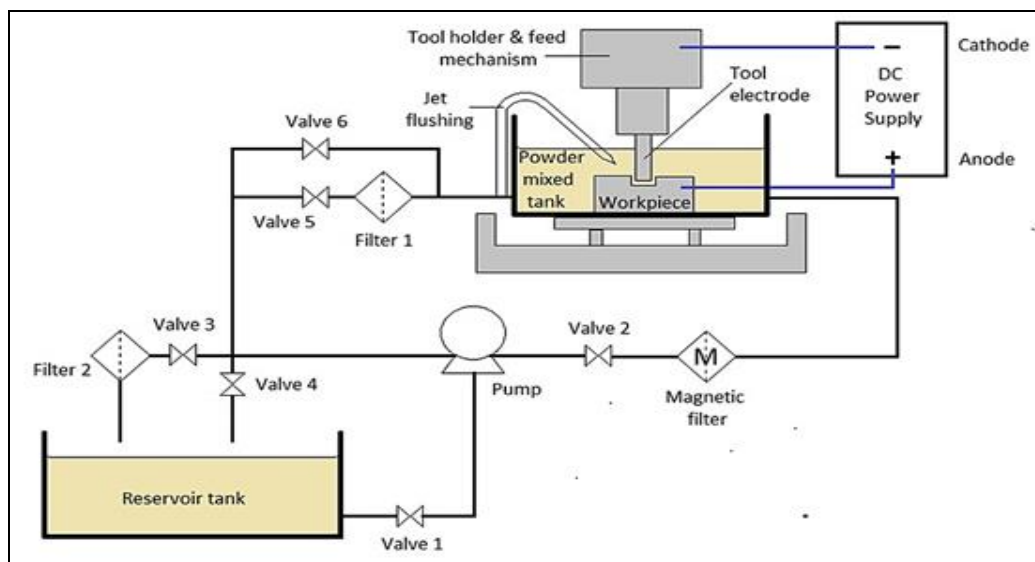


Figure 2. HPEDM schematic diagram.

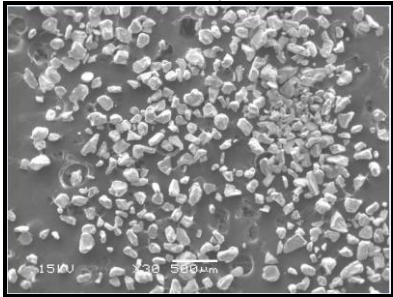
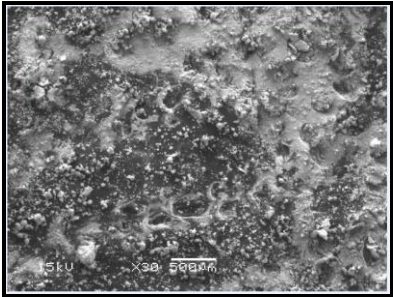
Table1. The chemical composition of AISI D2 Hardened steel.

Element	C	Cr	Si	Mn	Mo	P<	S<	V<
Content (%)	1.40-1.60	11.00-13.00	0.40	0.60	0.80-1.20	0.030	0.030	0.20-0.50

Table 2. Specifications of Cr powder used.

Cr%	C%	S%	P%	Si%	Al%	Fe%	Sieve Analysis
99%	0.01%	0.015%	0.090%	0.08%	0.01%	97%	-325 Mesh

Table 3. Shape and profile of different Cr powder particles in PMEDM tests.

Range for particle sizes	Medium-size	Nano-size
Powder sizes	45-55 μm	70-80 nm
Appearance (SEM image)		
Powder colour	Grey	black
Shapes	angular, spheroidal irregular	agglomerate of particles, clusters

In this study, die-sinking EDM at a depth of 3mm were conducted using 10mm electrode on the surface of AISI D2 hardened steel under different machining condition shown in Table 4.

Table 4. EDM machining parameter.

Working Parameters	Description
Workpiece	AISI D2 (50x50x10) mm
Electrode	Copper ,Cu (Ø 10mm)
Dielectric	Kerosene + Cr powder
Grain size of Cr powder	45-55 μm (Micro-Cr powder) 70-80nm (Nano-Cr powder)
Cr powder concentrations, C_p	0-4 g/L (45-55 μm) 0-0.6 g/L (70-80nm)
Span-20 surfactant concentrations, C_p	0-10 g/L (45-55 μm) 0-1.0 g/L (70-80nm)
Polarity, P	Reverse Polarity
Peak Current, I_p	40A
Pulse-on, P_{on}	50 μs
Duty Cycle	80%
Voltage	120V
Depth of Cut	3 mm
Flushing rate	3.5lmm ³ /hour

3. Results and Discussions

3.1 Comparison of recast layer thickness provided by span-20 surfactant and micro-/ nano- Cr powder.

Figure 3 and Figure 4 shows the percentage of improvement of recast layer thickness comparing with conventional EDM of different Cr powder particle sizes. It was found that proper addition of Span-20

surfactant and Cr powder particles helps to enhance the machining efficiency by further stabilising the electric discharge. The improvement in process stability resulted from a reasonably large gap size that reduces the arcing frequency through lower debris concentration and a more even debris distribution in the interspace.

Additionally, when comparing the minimum-maximum recast layer thickness ($C_p=0$ g/L/ $C_s=10$ g/L - $C_p=2$ g/L/ $C_s=10$ g/L), the value of recast layer thickness is observed to decreased dramatically from 30.80 μm to 18.00 μm and increased to 22.47 μm , respectively as shown in Figure 3 for micro-Cr PMEDM. As for comparison conventional EDM, the minimum recast layer thickness peaked at 18.00 μm ($C_p=2$ g/L/ $C_s=10$ g/L) which shows a reduction of 41.56 % from conventional EDM. Recast layer is an unwanted layer created by an EDM process that is composed by deposition for other elements on the workpiece surface. This layer formed by the deposition of the molten metal solidifying in the crater of machined surface. The molten material is rapidly quenched by the dielectric. The recast layer is hard but brittle contain of micro-crack. The improvement of recast layer thickness value clarify that the potential of addition of span-20 surfactant and Cr powder into dielectric fluid ability to gives a notable potential to be utilized as one of the advanced and innovative technique to eliminate the some of the disadvantages of conventional EDM method and enhanced EDM capability [10, 11].

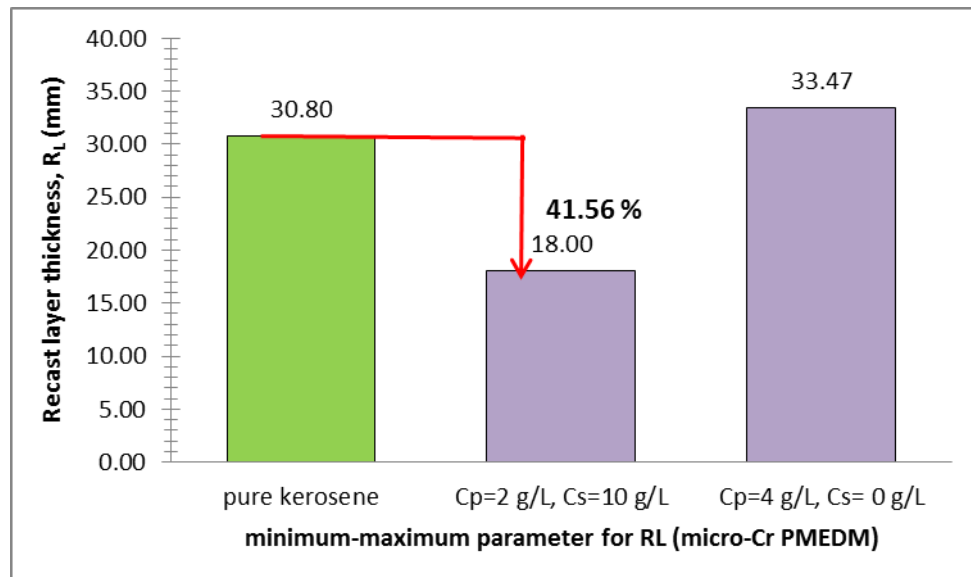


Figure 3. Material removal rate on minimum ($C_p=0$ g/L/ $C_s=10$ g/L)–maximum ($C_p=2$ g/L/ $C_s=10$ g/L) recast layer thickness for micro-Cr PMEDM.

As Figure 4 stated above, for the nano-Cr PMEDM lead to 51.67% reduction in recast layer thickness comparing with conventional EDM case when comparing the minimum-maximum recast layer thickness ($C_p=0$ g/L/ $C_s=0.5$ g/L - $C_p=0.6$ g/L/ $C_s=0.5$ g/L) from 30.80 μm to 14.27 μm and 27.07 μm , respectively. This results revealed that nano-Cr PMEDM exhibits better reduction in recast layer thickness compared to micro-Cr PMEDM. The highest percentage of reduction in recast layer thickness was at the smaller particle sizes. This can be attributed to the amount of molten metal solidified on the machined surface is much higher in micro-Cr PMEDM. Thus, thicker recast layer thickness formed. This is occurred due to discharge distribution in micro-Cr PMEDM is lower compared to nano-Cr PMEDM, which caused the current density in micro-size particle more than nano-size particle.

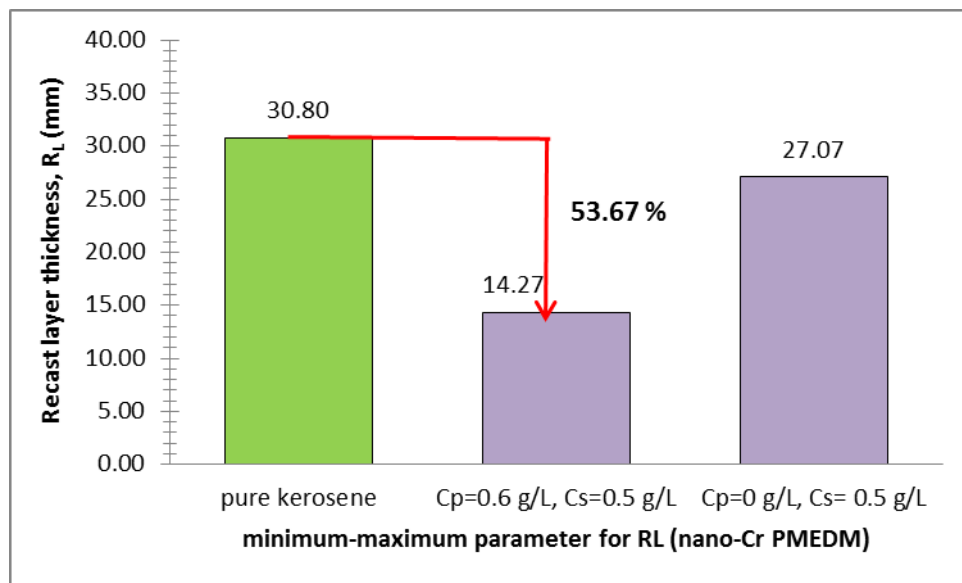


Figure 4. Material removal rate on minimum ($C_p=0$ g/L / $C_s=0.5$ g/L) –maximum ($C_p=0.6$ g/L / $C_s=0.5$ g/L), recast layer thickness for nano-Cr PMEDM.

Subsequently, Figure 5 and Figure 6 shows surface morphology of machined of AISI D2 surface and sub-surface when minimum-maximum recast layer thickness, it was observed that the EDM produces much damages on the surface and sub-surface like micro-cracks, micro-holes, metallurgical transformations and heat affected zones are happened on the workpiece samples due to rapid melting of work surface during electrical discharge process and then rapid cooling of work surface [5] [4]. As it is observed in Figure 5 and Figure 6, the machined sample using Cr powder, micro-holes are decreased and also the surface density of cracks is relatively less when added of Cr powder. However, the surface density of cracks increased at Cr powder concentration of 4 g/L due to exceeds of Cr powder in dielectric, which increased the rapid melting and cooling of work surface, thus also increased the hardness of EDMed surface [12]. In order to maintain or even improving these properties and decreasing the surface and sub-surface defects, the technique of addition of Span-20 surfactant and Cr powder has been applied in this investigation. It is observed that the thickness of the recast layer having performed EDM by the dielectric with Cr powder and span-20 surfactant is smaller than that of pure kerosene. This is due to the fact that surfactant can improve the viscosity of tar and the surface tension of kerosene. When dielectric flows easily between electrode and workpiece, the dreg removal rate is improved, and the discharged energy is also evenly distributed. The phenomena of unstable concentrated discharge are also decreased.

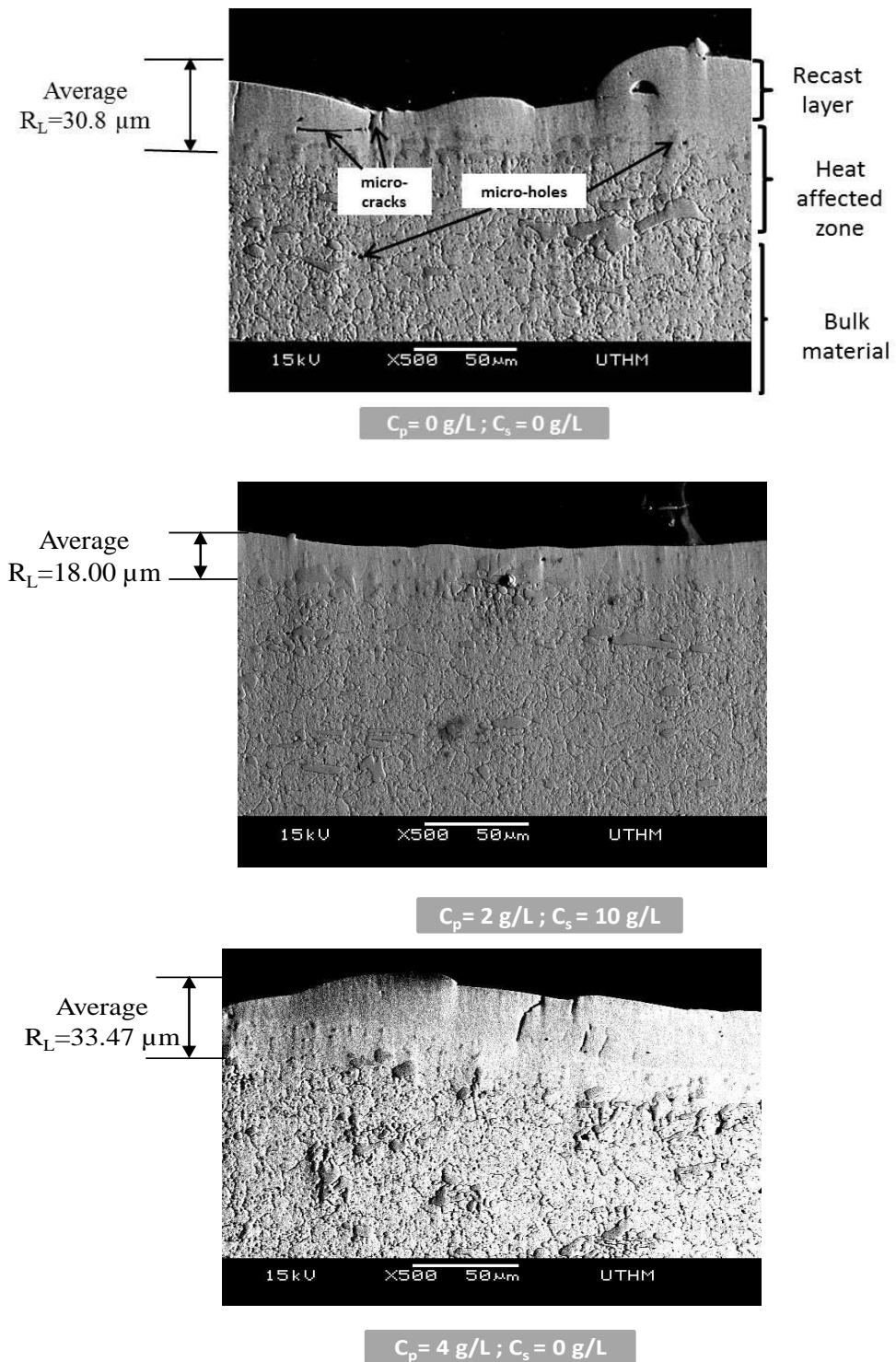


Figure 5. Recast layer of minimum-maximum recast layer thickness for micro-Cr PMEDM; (a) pure kerosene, (b) minimum recast layer ($C_p=2 \text{ g/L}/C_s=10 \text{ g/L}$), (c) maximum recast layer ($C_p=4 \text{ g/L}/C_s=0 \text{ g/L}$).

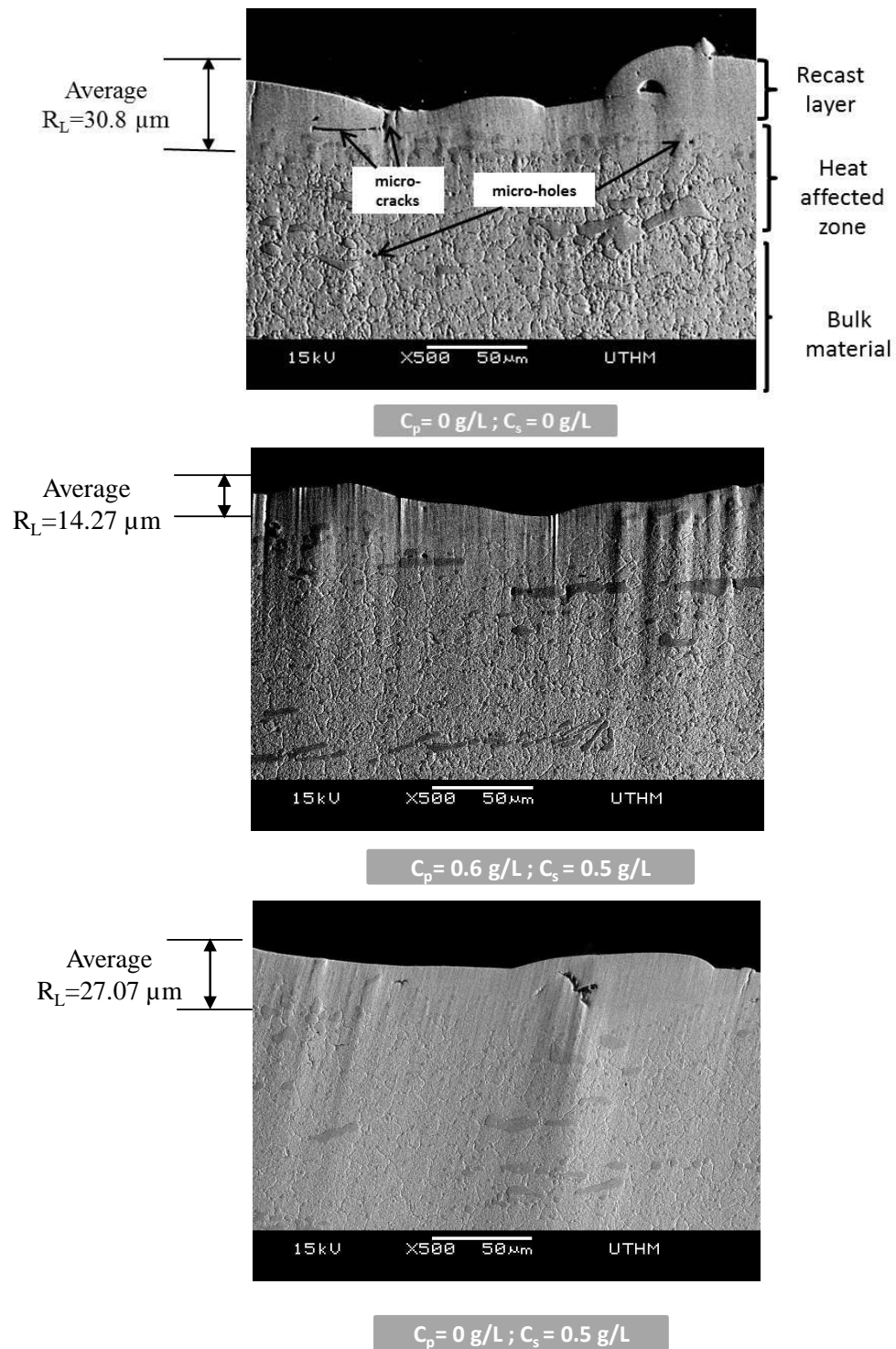


Figure 6. Recast layer of minimum-maximum recast layer thickness for nano-Cr PMEDM; (a) pure kerosene, (b) minimum recast layer ($C_p=0.6 \text{ g/L}/C_s=0.5 \text{ g/L}$), (c) maximum recast layer ($C_p=0 \text{ g/L}/C_s=0.5 \text{ g/L}$).

4. Concluding remarks

In this study, the influences of Cr powder and span-20 surfactant are significant on the recast layer thickness. It has found that the recast layer thickness in combination Cr powder and span-20 surfactant improved by as high as 41-53 % compared to conventional EDM. In addition, the damages on the surface and sub-surface like micro-cracks, micro-holes, metallurgical transformations and heat affected zones are happened on the workpiece also decreased when Cr powder and span-20 surfactant added into the dielectric.

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