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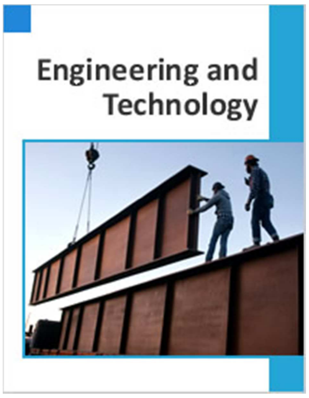

Surface Layer Analysis of Hot-Forging Dies After Die-Sinking Electrical Discharge Machining Using Copper and Titanium Electrodes

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Abstract

Electrical discharge machining (EDM) is a popular unconventional method for manufacturing tools, molds, and dies. Currently, the surface layer of the hot die after EDM needed to be polished to remove the layer of ≈ 50 µm. This research is aimed at the investigation of performance and structure of the surface layer in hot-forging die following die-sinking EDM. The machining conditions included the use of copper (Cu) and titanium (Ti) as electrode materials. A cross-sectional micrographic and hardness analysis was performed, as well as surface roughness measurements, in order to research the thermally affected zones of the hot-forging die surface layer of the SKD61 steel after EDM using oil as the dielectric fluid. The results showed that the performance of the die was reduced due to changes in the hardness and the chemical composition of the workpiece surface. The surface quality of hot-forging die after EDM with Ti or Cu electrode are similar. In this case, EDM using Ti electrode to improve the quality of hot die surface layer was unreasonable. And future trends of hot-forging die surface layers's modification has also been introduced.

1. Introduction

Electrical discharge machining (EDM) is a reproductive shaping process in which the form of the tool electrode is mirrored onto the work piece. In EDM, removal of the unwanted material occurs by melting and vaporization. And there are no physical cutting forces between the electrode and the workpiece hence the tool need not be harder than the workpiece. This process use is particularly widespread in applications where very complex shapes in hard materials with a high geometrical and dimensional accuracy are required [1]. Therefore, EDM is widely used in the production of forging dies. However, the usefulness of the process is limited by its low machining efficiency and the poor surface finish that results [2]. The machined surface layer produced by EDM usually has different characteristics from those of the base metal and those of machined surfaces produced by conventional machining processes.

The surfaces can be quite complicated. The surfaces produced by EDM tend to contain cracks and a "recast layer" [3]. The surface integrity describes the mechanical, metallurgical, topographical, and chemical conditions of the surface region and encompasses features such as heat-affected zones, micro-hardness, micro-cracking, residual stresses, surface roughness, tool/carbon material diffusion, etc. The cracks and the thicker recast layers deteriorate the tolerances and usable lifespan of the workpiece [4]. The topography, metallurgical properties, and physicochemical properties of the surface layer change considerably during EDM [5]. The studies on the effects of EDM on the surface integrity of the surfaces have been carried out by many researchers [6, 7]. In particular, the EDMed surface has a white layer featuring microscopic cracks and a low toughness [8]; this degrades the performance of the working dies since the surface properties greatly influence the working ability of machine parts such as: frictional resistance, corrosion resistance, wear resistance, etc. This variation in surface quality reduces the efficacy of the mold, so methods for increasing the surface quality are required. Traditional machining processes (grinding, polishing, buffing, etc.) are typically used to remove surface-layer damage after die sinking by EDM.

In forging process the lifespan of die is very important due to manufacturing cost and technical performance. The failure causes influencing working capacity of die are thermal fatigue, plastic deformation, wear, etc. In this causes, wear is the main factor affecting in hot forging process. Although wear cannot be eliminated, its effects can be minimized in some cases by electroplating, physical vapor deposition, or chemical vapor deposition. Prior research has shown that, during machining of the workpiece, material is transferred from the electrode material through the plasma onto the surface of workpiece is also appreciable [9]. The field of surface modification using EDM process with electrode materials or with powder mixing in the dielectric fluid also carried out. The researcher carried out experimental investigation to research the effects of composite electrodes on die life in EDM, Ti powder was used for the material of electrodes. They showed that the hardness of the layer containing TiC is much higher than that of base material which lead to improve wear resistance of die surface by a factor of three to seven times [10]. Investigated the effect of urea powder mixing into distilled water used as the dielectric fluid of EDM on machining surface of titanium, TiN deposition on the machined surface occurred, which improved the hardness and wear resistance of the machined surface [11]. When a titanium-in-kerosene dielectric medium was used, a titanium carbide layer with a micro-hardness 1600HV on carbon steel was obtained with copper electrode of 1mm in diameter [12]. Surface modification during EDM is one of the many methods for improving a workpiece's surface properties [13] and represents a future direction for EDM and surface modification research. In PMEDM, titanium powder mixed into the dielectric fluid at suitable concentration, that improves material removal rate, increases machining surface quality, and reduces tool wear electrode [14-16]. This improves productivity and accuracy, and also reduces machining time in parts manufacturing. The intrusion of titanium powder and carbon materials from the solvents and the electrode material into the surface layer of the billet changes the physical properties and chemical composition of the surface layer after EDM. A new research trend, using PMEDM and combining suitable electrode materials with powder materials (powders and electrode materials are titanium or tungsten) to improve the quality of the material surface has recently gained importance.

In this research, the performance and properties of the surface material layer of a hot-forging die of SKD61 hardened steel after die sinking EDM are evaluated using the titanium and copper electrodes. In this analysis, the performance of the machined surface and the amount of material transferred from the electrode to the workpiece surface was observed. The EDM with Cu electrode is carried out to evaluate the effect of die-sinking EDM to surface quality of hot-forging die and this is the choice of direction for the next finishing machining. Ti electrode was tested to investigate the feasibility of the hot-forging die surface layer improvement by EDM using this metal.

2. Experimental Procedure

The experiments were conducted using a die-sinking EDM platform, model NC EDM 850 Suzhou Zhonghang Changfeng CNC Technology Co., Ltd., Jiangsu, China. The material used for workpiece was SKD61 (Japanese Industrial Standard) hot–die steel that is used extensively for hot-forged dies. The constituents of the steel, as determined by a chemical analysis, were: 0.40% C, 0.47% Mn, 0.98% Si, 0.14% Ni, 4.90% Cr, 0.83% V, 1.15% Mo, 0.016% Co, 0.00012% S, 0.018% P, and the balance was Fe. The workpiece dimension was 70×70×15 mm^3. Before machining, the raw material had a micro-hardness of 490÷547 HV. The hot-forged die neck seal bearings of Honda motorbike had the shape shown in Figure 1.

The electrode materials selected for this investigation were Ti and Cu. Copper has excellent electrical and thermal conductivities and it is a major commercial material. Titanium compounds have been applied extensively as materials for surface modification because of their hardness, abrasion resistance, high melting point, and low coefficient of friction [4]. The dielectric fluid used was oil (HD–1). Machining parameters are selected according to the requirements of the Pho Yen Mechanical Joint Stock Company of Viet Nam; these are provided in Table 1.

Table 1. *Machining conditions.*

Parameter	Value
Intensity of discharge (A)	4
Pulse-on time (μs)	100
Pulse-off time (μs)	3
Dielectric	Kerosene oil
Polarity	Positive
Machining time	1h 13'27"
Voltage of discharge (V)	150
Electrode material	Copper, Titanium

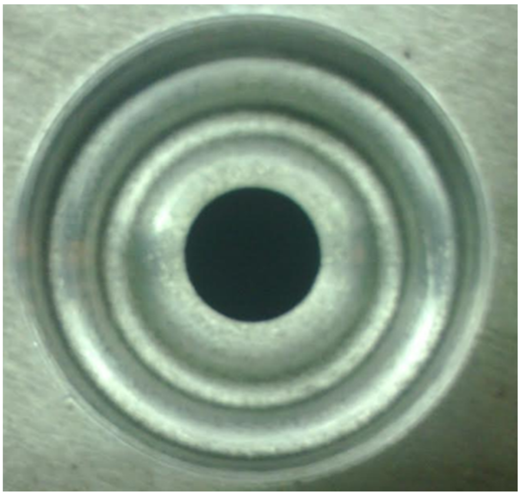

Figure 1. *Hot-forged die geometry used in this research.*

The following material parameters were studied during the course of this experiment: chemical composition, micro-structure, surface hardness, surface roughness, and surface appearance. Three readings were taken for each work specimen to compute the final, average measurement. Surface roughness was measured using a SJ–400 from Mitutoyo, Japan. After EDM, the samples were cleaned and the cross-section of die-sink surface was machined. An optical micro-scope was used to research the change in the micro-structure of the EDMed surface. The rest of the analysis was carried out on six samples using a scanning electron micro-scope (*SEM, model JSM 6490, JEOL, Japan*). The surfaces of the samples were cleaned prior to SEM analysis at three different magnifications: 100×, 500×, 1000×. To analyze the phase composition of the surfaces, selected workpieces were analyzed using X–ray diffractometry (XRD) over a 2θ range from 5° to 85° with a model Axiovert 40MAT from Carl Zeiss, Germany. Micro-hardness was measured on micro-hardness tester (*model Indenta Met 1106*) from Buehler, USA. The chemical compositions of the machined surfaces were analyzed using energy-dispersive X-ray spectroscopy (*EDS, model JSM–6490LA, JEOL, Japan*).

3. Results and Discussion

3.1. Cross-Section Analysis Following EDM

The cross-sectional structure of the SKD61 steel surfaces fabricated using EDM with the titanium or copper electrodes exhibited three layers, as shown in Figure 2: the white layer, the heat-affected zone (HAZ) and the base metal. The white layer was the outermost light-colored layer with a relatively high thickness (Table 2): 12.03÷21.79 µm for the Cu electrode and 11.25 ÷ 22.77 µm for the Ti electrode, and it was distinct from the other layers. This layer forms when some of the molten material (from both the electrode and work piece) is not removed and is rapidly quenched by dielectric fluid. The white layer contains a high density of micro-scopic cracks that run across the total depth of the white layer, only seldom continuing into the layers beneath. The cracks are mostly perpendicular to the surface of the work piece. The larger micro-scopic crack size in the die fabricated using Ti electrode as compared to that produced using Cu electrode is evident from Figure 3.

The micro-hardness values of the white layer in both types of specimens were quite similar (Figure 4): 453.7 HV for the Cu electrode and 464.1 HV for the Ti electrode. The values are lower than those obtained in the heat affected zone and base material. The forging dies and hot-mold dies always operate in high-temperature environments and under high shock pressure. Choosing the correct type and hardness of the die material and the surface-layer coating is very important for improving the working accuracy and functionality of the dies. Given the above results, the white layer presence reduces the working capacity of hot-die sinks.

The HAZ zone was located beneath the white layer and is was difficult to observe clearly the properties. It wasn't so thick as the white layer and the thickness is pointed in Table 2: 8.68 ÷ 13.84 µm Cu electrode and 8.54÷11.12 µm for the Ti electrode. In this layer, the material has been heated below the melting point of the material as in the recast layer. There were a few micro-scopic cracks with small depths in the heat-affected zone layer that were not parallel to the machined surface. The micro-hardness of the heat-affected zone was very high: 627.1 HV for the Cu electrode and 646.0 HV for the Ti electrode; these values were higher than that of the white layer and the base metal (570.5÷588.8 HV). The properties of the HAZ may alter the performance of the hot-forging die.

Table 2. *Depth of altered-metal-zone layers.*

Altered metal zone layers	Depth (µm)	
	Cu electrode	Ti electrode
White layer	12.03 ÷ 21.79	11.25 ÷ 22.77
Heat affected zone (HAZ)	8.68 ÷ 13.84	8.54 ÷ 11.12

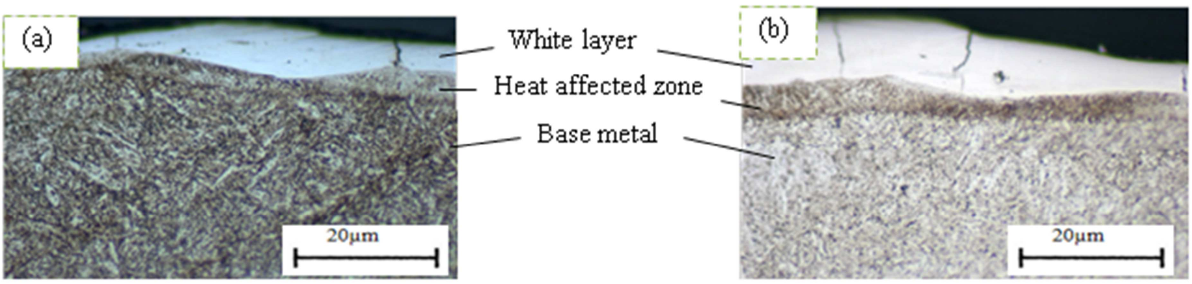

Figure 2. *The different layers formed on of the hot-forging die surface (a), Ti electrode (b), Cu electrode.*

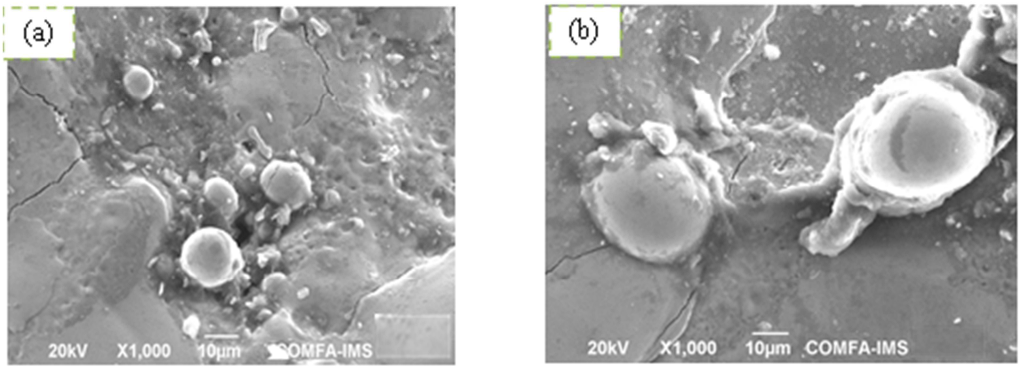

Figure 3. *Cracks on of the hot-forging die surface (a), Ti electrode (b), Cu electrode.*

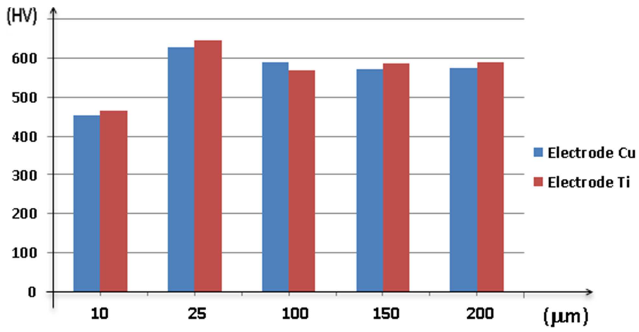

Figure 4. *Micro-hardness measurements across transverse sections.*

3.2. Chemical Composition and X-ray Diffraction Patterns of Machined Surfaces

The chemical composition of the machined surface layer was determined using EDS. The compositions and the XRD patterns of the surface layers are shown in Figures 5–7. The compositions of the HAZ and base metal were unchanged in a result of EDM. The EDX analysis, employing the ZAF method for standardless quantitative analysis, of the chemical composition of the white layer indicated that it changed significantly. The EDX analysis of the white layer showed the presence of major constituent elements Fe, C, Mn, Si, V, Cr, and Mo in addition to Cu (from the Cu electrode) and Ti (from the Ti electrode), as shown in Figure 5. The carbon content in the white layer increased greatly from 0.40% to 13.76% for Cu electrode and to 11.43% for Ti electrode. This is because, during the pulse, the thermal energy of the emitted sparks generated carbon cracking oil, thereby creating the carbon that entered the machined surface. The increase in carbon content improves the hardness and strength of the surface but reduces the toughness and ductility. The appearance of the electrode materials on the machined surface – Cu electrode: from 0.054 to 0.32%, Ti electrode: from 0.053 to 1.98% – is the result of the melted and evaporated electrode materials moving and sticking to the surface of the workpiece. Increased Cu and Ti contents can improve the corrosion resistance. The peaks corresponding to the different elements are shown in Figure 6 for both types of electrode materials. The Ti and Cu peaks confirm the presence of electrode material in the deposited layer. The intensity of Ti peak was greater than that of the Cu peak in workpiece. This indicates that more Ti accumulated at the surface and that the inner layer was richer. This situation is desirable since it produces a harder surface.

The XRD analysis was carried to confirm the transfer of electrode material from the electrode and carbon from the dielectric fluid to the workpiece surface and, also, to identify the phases of the compounds formed during the EDM process; these results are shown in Figures 6a and b. Several compounds formed on the workpiece surface. The pattern indicated the presence of iron carbides (Fe_7C_3 and Fe_3C) and molybdenum carbide (Mo_3C_7). The presence of Fe_7C_3 and Fe_3C increase the hardness of the machined surface. The corrosion resistance and hardness of the machined surface can also be improved by Mo_3C_7. Large amounts of Ti and C migrate from the electrode and dielectric fluid to the hot-forging die surface. However, TiC did not form on the machined surface layer.

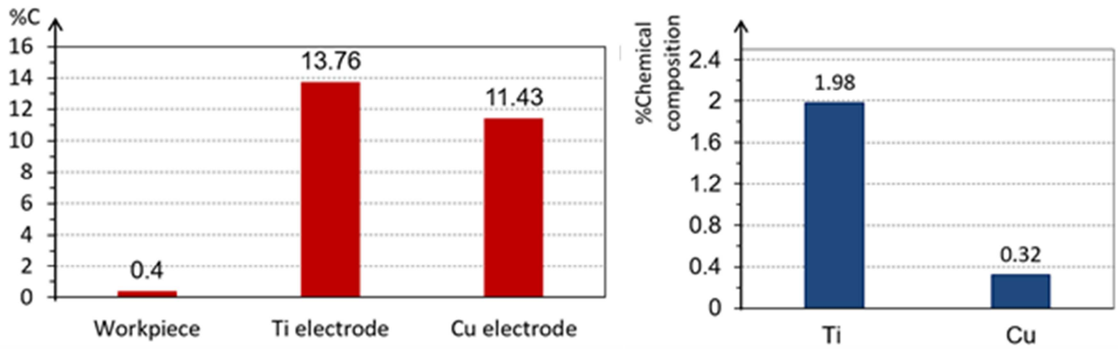

Figure 5. *Chemical composition (C, Ti and Cu) of the machined hot die (a), %C (b), % electrode materials.*

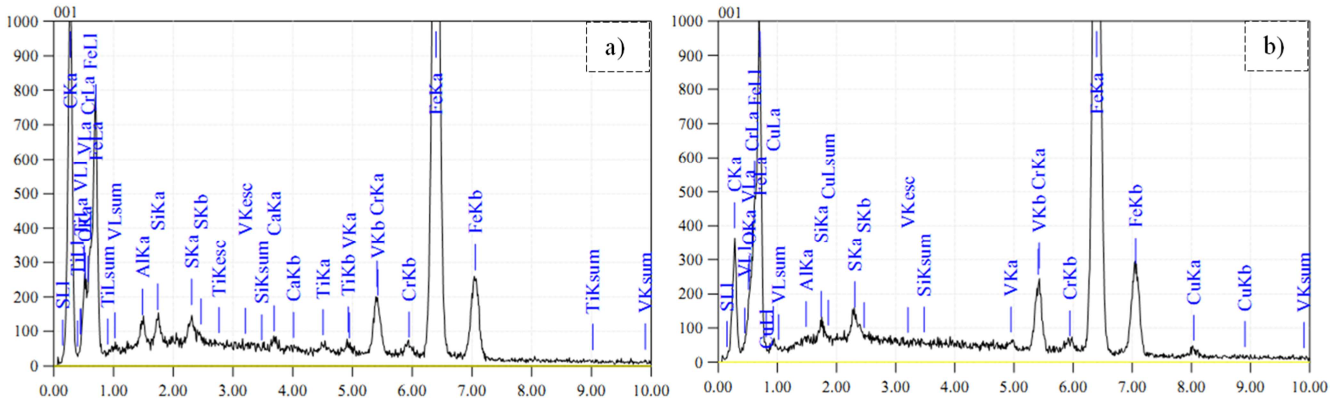

Figure 6. EDX analysis of the hot-forging die surface layer (a), Ti electrode (b), Cu electrode.

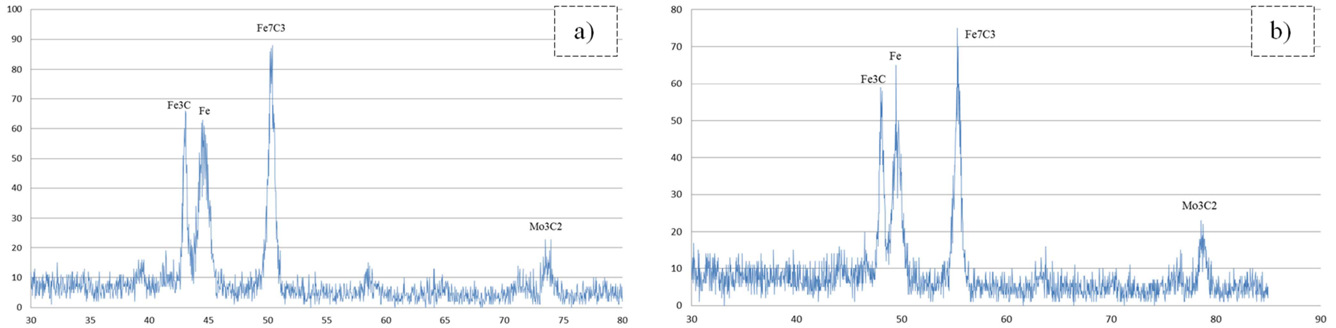

Figure 7. XRD patterns of the hot-forging die surface layer (a), Ti electrode (b), Cu electrode.

3.3. Topography of the Machined Surface

Assuming that each spark leads to the formation of a spherical crater on the surface of the workpiece, the volume of metal removed per crater will be proportional to the cube of the crater depth. The surface accumulated many large craters created by the sparks generated during the pulse cycle, as shown in Figure 8a. The craters were on the radius of curvature (indicated by the arrows in Figure 8b) created when the melting and evaporating materials affected by the dielectric fluid were simultaneously quenched and caused the outer surface tension. Many small hard particles appeared on the processed surface and adhered to it, causing an increase in the surface roughness. These spherical protrusions are particles of molten metal that were expelled molten workpiece and small amounts of electrode material form spheres during the discharge and later spatter and solidified on the workpiece surface. The particles formed as a result of the molten metal removal must be solidified at an extremely high rate. Otherwise, the molten metal surface tension would have rounded off the sharp edges. The cracks were formed due to the high thermal stresses prevailing at the specimen surface as it was cooled at fast rate after the discharge process. The average surface roughness of the hot-forging die surface after the die-sinking EDM process was 23.1÷26.3 µm. This result demonstrated that further polishing is required before use.

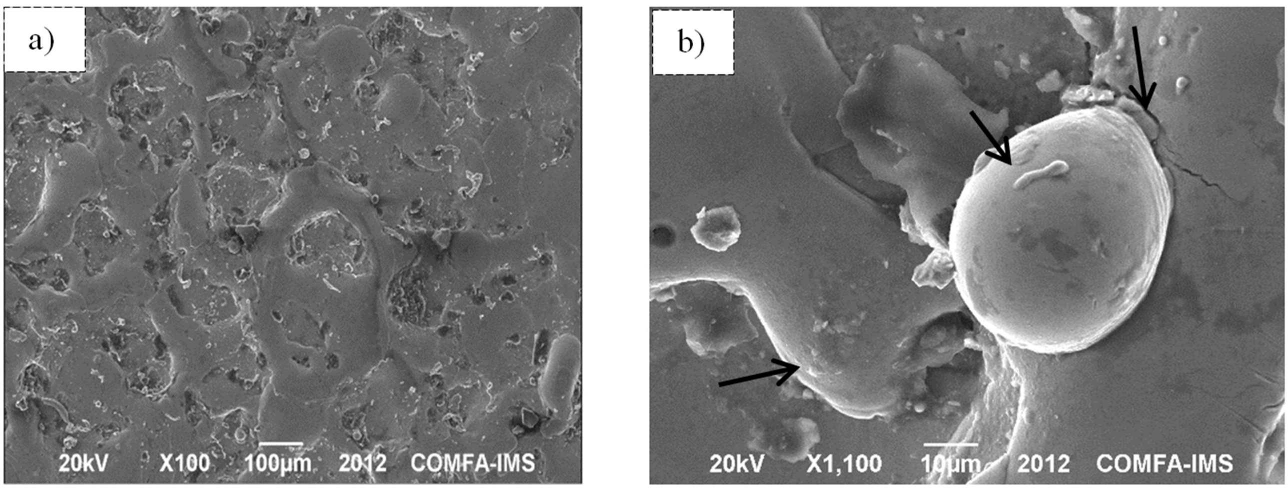

Figure 8. Micro-structures of the hot-forging die surface (a), Surface photographs (b), The form of craters and debris particles.

4. Conclusion

The white layer had a low hardness and significant cracking that is detrimental for the forging die functionality. Thus, it is necessary to determine the effect of various parameters in order to reduce or eliminate the white layer formation on the machined surface. The thickness of the surface in polishing (≈ 50 μm) is not reasonable. This has removed HAZ layer, its hardness is highest, and it led to the durability of the mold is reduced and caused material losses. The results have shown that the use of Ti as an electrode material is not efficient. Besides, titanium is expensive, as compared to many other metals, is characterized by complexity of the extraction process, difficulty to melt that causes problems during fabrication. The machinability of titanium and its alloys is generally poor owing to several inherent properties of the materials. Therefore, the choice of electrode Ti is unreasonable in this case. The surface was covered with a hard layer produced in the EDM process consisting of carbides (TiC, WC, TaC, WC-Co, etc.) that enhanced the surface characteristics of the workpiece. These results indicate a promising direction for the EDM research using electrodes TiC, WC and other carbides for successful surface modification. The research studies have shown that if metal powder or alloy powder is suspended in a suitable dielectric fluid during EDM then successful surface modification can occur. These results indicate a fruitful direction for EDM research.

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