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Research Article

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Surface improvement of SKD61 die steel material after electrical discharge machining with graphite electrode

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ABSTRACT

Electric discharge machining (EDM) is widely used for machining difficult to cut materials, complex shapes and products requiring high precision work. The limitations of this process are the low productivity and low surface quality after machining. Therefore, to overcome these limitations of EDM process is an utmost concern of the present study. This paper presents the study of the influence of titanium powder mixed in dielectric fluid on the surface quality of SKD61 steel machined by EDM process. The machined surface was characterized for surface roughness, thickness of heat-affected zone, chemical composition, microhardness and topography. Results of the characterization shows that powder mixed in dielectric medium can be a solution to improve the quality of machined surface.

Keywords: PMEDM, Surface roughness, Heat affected zone, Topography, Microhardness.

INTRODUCTION

EDM is one of the non-traditional machining processes which find applications to machine complex geometries, and small size holes with high precision requirements. Basically material removal in EDM process takes place by precise control of spark generated in gap between the tool electrode and the workpiece immersed in a dielectric fluid. EDM process uses thermal energy to melt the material and evaporate the machined material. During the process the temperature is raised in the range of 10000 to 12000 °C. EDM process has advantages over traditional method that, this process does not have negative affect on the quality of processed products due to vibration, deformation and mechanical stresses. However, the use of thermal energy during machining leads to the changes in the metallurgical properties of the surface of the material compared to the base material. The past research studies showed that the surface layer after EDM machining consists of large number of microscopic cracks, white layer thickness and high surface roughness values. This affects the performance characteristics of the EMD process. Therefore, there is a lot of scope in improving quality of machined surface after EDM process.

The results of past research have shown that, powder mixed electrical discharge machining (PMEDM) is very effective to improve the productivity, quality and precision machining of workpiece. Pecas and Henriques machined SKD61 steel by EDM with silicon powder mixed in oil dielectric fluid. They found that the surface roughness values and structure of the machined surface gets affect by silicon powder [1]. Pecas and Henriques developed a mathematical model to predict the thickness of the white layer, shape and depth of surface roughness [2]. Furutani et al. used Ti powder (≤36µm) mixed in oil dielectric fluid for machining AISI 1049 steel in EDM process. They found that a TiC layer of thickness 150 µm was created and the layer has a microhardness value of 1600 HV [3]. Simao et al. obtained a coating formation conditions on the steel surface after PMEDM [4]. Furutani et al. used PMEDM and deposited tungsten carbide coating on the machined surface of the steel mould made of materials namely, OHNS, D2 and SKD61 [5]. Kumar and Batra research showed that the microhardness of machined surface has increased to 100% compared to the base material microhardness, and this can be a very viable research in improving durability of forging moulds, dies[6]. Furutani and Shiraki used MoS_2 powder for surface coating of bearings steel and found that the machined surface roughness values were significantly improved [7]. Furutani used titanium Powder (≤38μm) mixed dielectric fluid and obtained TiC coating having 1900HV microhardness on steel surface [8]. Ganachari et al. used two different powders that is aluminium and silicon carbide powder in dielectric medium to explore which one provides best quality of machined surface [9]. Parkash et al. used copper and graphite powder mixed into the dielectric fluid to check its affect on the tool wear rate. They found that by using graphite powder in dielectric medium provide less tool wear rate than copper powder in dielectric medium. The tool wear rate reduction will improve the electrode durability and precision machining [10]. Syed and Kuppan used aluminium powder mixed in water dielectric fluid for machining steel W300 mould. They found that the thickness of white layer got reduced in comparison to without powder in dielectric fluid. And an increased concentration of powder reduces the thickness of the white layer [11]. Govindharajan et al. used graphite and nickel powder mixed in dielectric fluid. They found increased material removal rate, reduced the tool wear rate, and improved precision and quality of machined surface [12]. Singh et al. used Al powder mixed in dielectric fluid during machininf of SKD61 steel and they found that the increase in the concentrations of powder reduces the surface roughness values [13]. Khedkar et al. studied the material migration and surface improvement of OHNS die steel by machining using tungsten powder mixed dielectric medium in die sink EDM [14]. Kumar et al. studied the affect of material and size of the powder on productivity aspects and surface intergity of the EN31 steel material [15]. Razak et al. used silicon powder mixed in dielectric fluid and they concluded that MRR is increased, TWR and Ra is reduced which in turn reduces the machining time [16]. Long et al. used copper and graphite electrode during machining of hot forging die steel in EDM. They found that mechanical properties and microstructure of mould was affected by machining by copper and graphite electrode [18, 20]. Long et al. used titanium powder mixed in dielectric fluid in EDM with copper and graphite as tool electrode. They found that MRR is increased very high, TWR and Ra decreases [19, 21]. It can be seen from the literature review that the material, size and concentration of powder used in EDM process still needs to optimize for improving the productivity and quality of machined surface. In view of this, the present study aims at evaluating the influence of titanium powder mixed in dielectric fluid on to the quality of machined surface. The characteristics of surface quality was measured in terms of surface roughness (Ra), the heat affected zone, surface hardness, chemical composition and surface topography. In this analysis, the diffusion of powder onto to the machined surface after EDM was also evaluated.

EXPERIMENTAL SECTION

In this study SKD61 (Japanese Industrial Standard) hot-die steel was considered as workpiece material that is extensively used for hot-forged dies. The workpiece dimension was $100 \times 80 \times 25$ mm^3. Before machining, the raw material had a microhardness of 490 to 547 HV. 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 tool material selected for this study was graphite. The electrode had the circular cross-section as shown in Figure 1. Graphite has excellent electrical and thermal conductivity and is a commercial used material. Titanium powder was used to mix in dielectric fluid in EDM. Titanium is chosen as the powder material due to its high hardness, abrasion resistance, high melting point, and low coefficient of friction (Figure 2). For uniform distribution of titanium powder mixed in dielectric fluid a stirrer was continuously rotated at 300 rpm with the help of a motor. To remove the debris from the cutting zone and to avoid mixing with the dielectric medium, the permanent magnets are placed at the bottom side of the workpiece. This further improves the efficiency of the process. Figures 3 shows the schematic diagram of experimental setup and figure 4 shows the actual photo of experimental setup. Table 1 depicts the process parameters used for the experimental runs. Experiments were repeated twice to take the average values for each EDM output characteristics. After conducting the EDM experiments, samples were subjected to chemical composition test, microstructure analysis, surface hardness surface roughness and surface topography. The surfaces of the samples were cleaned prior to scanning electron microscope (SEM, model JSM 6490, JEOL, Japan) analysis and the images were captured at two different magnifications that is 50× and 1000×. The chemical compositions of the machined surfaces were analyzed using energy-dispersive X-ray spectroscopy (EDS, model JSM – 6490LA, JEOL, Japan).To analyze the phase composition of the surfaces, selected workpieces were analyzed using X-ray diffractometry (XRD) over a 2θ range from 5° to 80° with a model Axiovert 40MAT from Carl Zeiss, Germany. Microhardness was measured on microhardness tester (model Indenta Met 1106) from Buehler, USA. Surface roughness of samples was measured using a SJ-301 model of Mitutoyo make, Japan.

Figure 1 Graphite electrode

Figure 2 Titanium powder

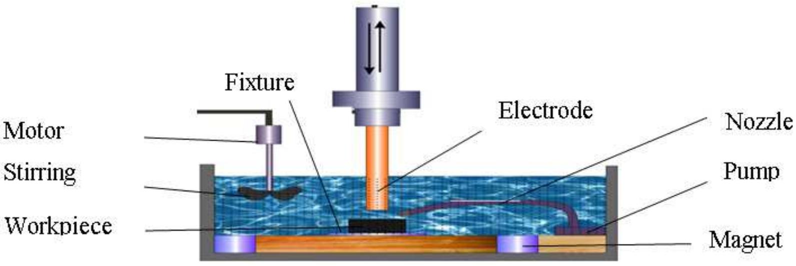


Figure 3 Schematic diagram the experimental setup

Figure 4 Photograph of the experimental setup

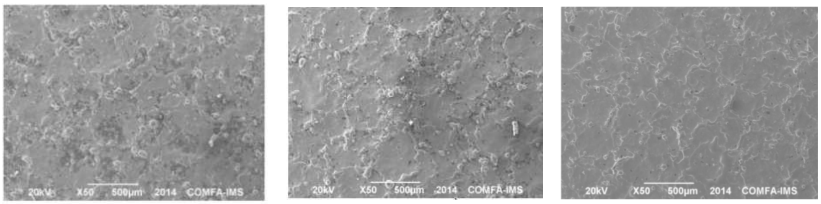
Table 1 Machining conditions

Variable	Set-up
Intensity of discharge(A)	15
Pulse-on time(µs)	50
Pulse-off time(µs)	85
Dielectric	HD-1
Polarity	Positive (EDM process)
Machining time	15 minutes
Voltage of discharge (V)	150
Tool material	Graphite (Ø25mm)
Flushing	10 liters/min
Powder	Titanium: - grain size 45µm. - concentration: 0,5,10,15,20 g/l.

RESULTS AND DISCUSSION

3.1. Topography and Surface roughness of the machined surface

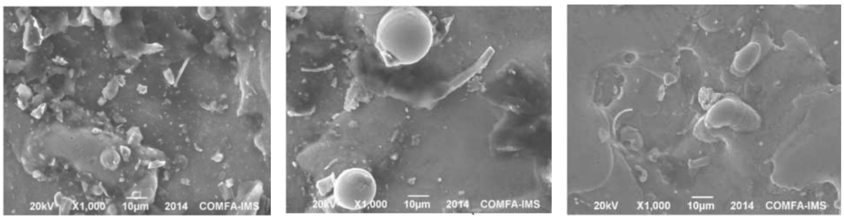
The machined samples were checked for surface roughness based on centre line average method and topography of the surfaces were checked by the SEM. Figure 5 (a), (b), (c), (d) and (e) shows the topography of machined surface for without powder, with 5 g/l, 10g/l, 15 g/l and 20 g/l powder respectively, which were taken at 50X magnification at SEM. It is clear from the image that machined surface are composed of many craters. By addition of titanium powder mixed in dielectric fluid lead to increase in the number of craters but the diameter and depth of them were decreased. Further increasing the concentration of powder led to the number of craters increase, while the diameter and depth of it constantly decreased. This has helped to improve the smoothness of the machined surface. The same is obtained from the surface roughness values of the machined surface as shown in the table 2. Topography of the surface structure will cause less stress concentration; this is because the bottom of the craters is curved which will increase the fatigue strength of the surface layer. Micro-cracks are observed on the machined surface, but the number of micro-cracks is reduced by addition of titanium powder in the dielectric fluid. The numbers of micro-cracks are inversely proportional to the value of the powder concentration. The craters, micro-cracks are formed and uniformly distributed on machined surface; this has created favorable conditions for the lubricating oil retention on the machined surface. This in turn improves the corrosion resistance of the surface. Figure 6 (a), (b), (c), (d) and (e) shows the microstructure of the machined surface for without powder, with 5 g/l, 10g/l, 15 g/l and 20 g/l powder respectively. It can be seen that large numbers of spherical metal particles are sticking to the machined surface. The reason is that the metal wich got melt was cooled very fast by the dielectric fluid and got stick on the machined surface. The metal adhesion is more in case of without use of powder in dielectric fluid. The adhesion decreased as increase in the concentration of powder is increased in the dielectric fluid. This adhesion of re-melt metal on to the machined surface increases the roughness of the surface. But with the increase in powder mixed in dielectric fluid reduces the surface roughness of machined surface. The same is obtained from the surface roughness values test as shown in the table 2.



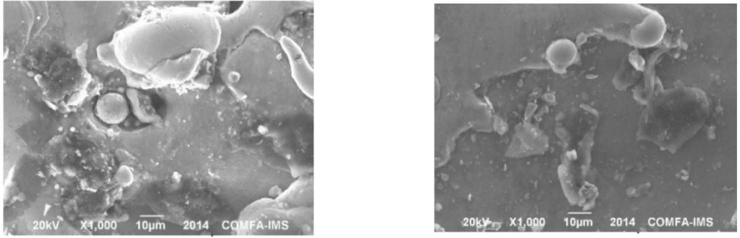
a) No powder **b) 5g/l** **c) 10g/l**

d)15g/l **e) 20g/l**

Figure 5 Topography of machined surface



a) No powder **b) 5g/l** **c) 10g/l**



d) 15g/l **e) 20g/l**

Figure 6 Microstructureof machined surface

Table 2 Surface roughness values of machined surfaces

Trial no	Ra (µm)	Concentration (g/l)
1	7.13	No
2	5.69	5
3	4.61	10
4	4.25	15
5	4.18	20

3.2. Surface integrity of machined surface

After machining, the surface gets modified and three different layers are formed on the surface. Figure 7 shows the cross-sectional view of SKD61 steel surface consisting of three different layers namely, white layer, heat affected layer and base material. White layer is formed by the workpiece material, electrode material and the metal powder melts and got deposited which have not been swept away by the dielectric fluid and it is adhesion on the surface machining. Figure 8 a), (b), (c), (d) and (e) shows the white layer thickness for without powder, with 5 g/l, 10g/l, 15 g/l and 20 g/l powder respectively. Micro-cracks appear in the white layer and its depth is approximately equal to the thickness of this layer. A powder mixed in dielectric fluid reduces the white layer thickness and it is more evenly distributed on the machined surface as shown from figure 8. This is due to the presence of powders in the dielectric fluid which increases the number of electric sparks in a single pulse. This reduces the thermal energy of each electric sparks impact on machined surface. The thickness of the heat-affected layer is reduced with increasing concentrations of powder. This is due to the increase in powder concentration in the dielectric fluid. And it will lead to the increase the number of electric sparks and hence reduces the energy of each electric sparks. The presence of metallic powder in the dielectric medium will lead to formation of electric sparks more evenly throughout the surface of the workpiece. This will help to stabilise the pulses of thermal energy which leads to more uniform formation of white layer thickness and more evenly distributed over the machined surface. White layer contains a mirco-cracks which will negative affect the ability of the working surface after machining. Heat affected layer is present beneath the white layer and heat-affected layer is difficult to observe. And the thickness of this layer is smaller than the white layer. This layer is formed by the thermal energy of the electric sparks which affects the base material during the machining phase. Number of microscopic cracks in the heat-affected layer is very less with small depth.

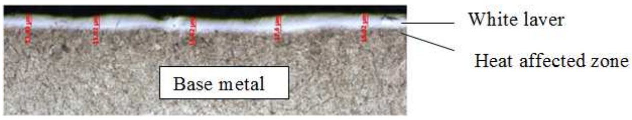
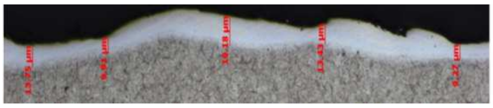


Figure 7 Layers were formed in machined surface

a) No powder (t_{min}= 8.31 µm,t_{max}= 22.69µm)

b) Gr+ 5g/l (t_{min}= 3.20 µm,t_{max}= 4.79 µm)



c) 10g/l (t_{min}= 4.48 µm,t_{max}= 11.19 µm)

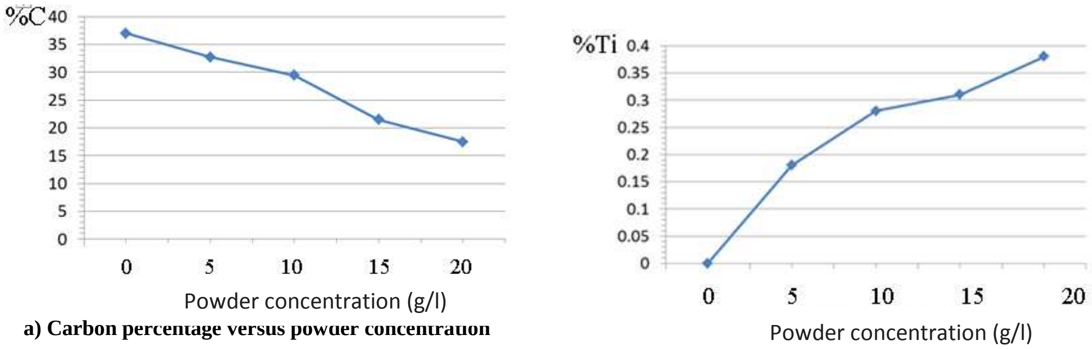
d) 15g/l (t_{min}= 8.67 µm,t_{max}= 10.61 µm)

e) 20g/l (t_{min}= 6.71 µm,t_{max}= 13.75 µm)

Figure 8 Thickness of white layer in machined surface

3.3. Chemical composition and X-ray diffraction patterns of machined surfaces

Figure 9 (a) shows that the percentage of carbon increased greatly in the machined surface after EDM process. This is due to the cracking of carbon from hydrocarbon oil and migration of carbon from electrode material to the machined surface. And the absence of powder mixed in dielectric fluid led to the largest carbon percentage. This shows that the amount of electrode erosion is the largest and cracking of carbon from hydrocarbon oil was high. And the same is observed in the case of no powder mixed in dielectric fluid where the machined surface of the workpiece contains the largest percentage of carbon (%), C_{max} = 36.99. The percentage of carbon on the machined surface reduced when titanium powder is mixed into the dielectric fluid. This is due to the reduced thermal energy of the electric sparks and which reduced the dissociation of carbon from the dielectric fluid and minimization of tool wear rate. Due to increased in concentrations of titanium powder reduced the percentage of carbon which indicates minimization of tool wear rate. This increases the efficiency of the process and increases the precision of machining. Figure 9 (b) indicates the presence of titanium elements on to the machined surface. This is due to melting of the titanium powder and constantly entering to the SKD61 steel surface during EDM process. This shows the migration of material from dielectric on to the machined surface. The increase in the concentration of titanium powder increases the percentage of titanium on to the machined surface. This increase in titanium increases the surface hardness of the machined surface and improves the corrosion resistance of surface. Figure 10 shows that during EDM with titanium electrodes it is observed that the migration of titanium is more (%Ti ≈1.58%) and the amount of titanium migrating the surface is higher than the amount of titanium (%Ti ≈0.38%) migrating from the powder mixed in dielectric fluid. However, titanium migrating from the titanium powder mixed in dielectric fluid there is an uniform distribution on the machined surface as shown in figure 11.Therefore, the use of powder mixed in dielectric fluid can be improve the strength and hardness of the surface is more evenly. However, Figure 12 shows that, TiC was not formed on the machined surface.



a) Carbon percentage versus powder concentration

b) Titanium percentage versus powder concentration

Figure 9 The composition of elements C and Ti in machined surface

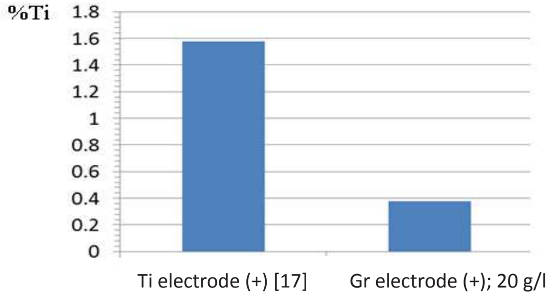
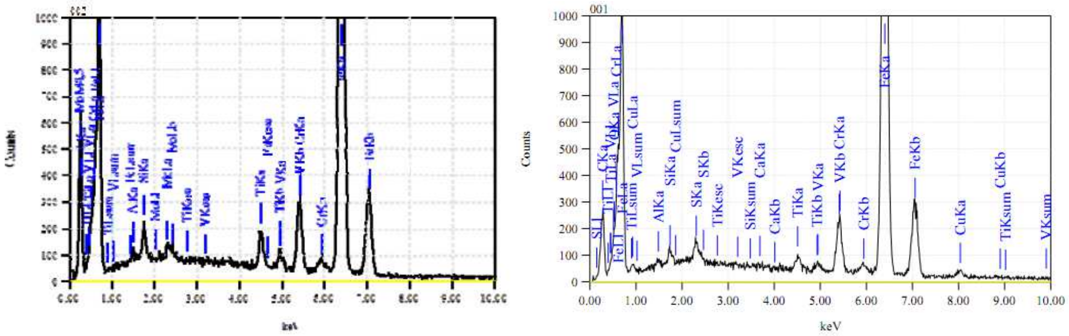


Figure 10 The penetration into the machined surface of titanium



a) No powder [17] **b) With powder**

Figure11 The distribution of titanium on the machined surface

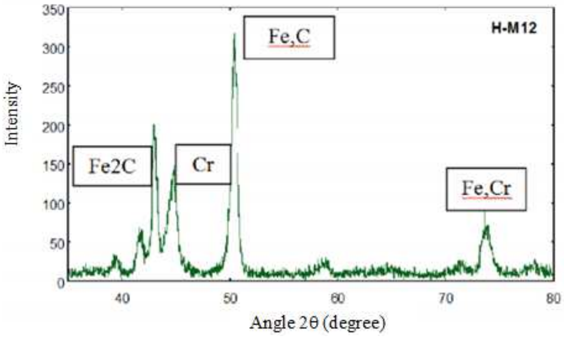


Figure12 XRD of machined surface

3.4. Microhardness of the machined surface

SKD61 steel is widely used in forging hot die, so the hardness of the surface layer strongly affects the ability to do their work. The increase in machined surface hardness leads to improve the abrasion resistance of the machined surface. This can greatly affect the life and accuracy of the moulds. Results of the hardness of the machined surface layer are given in table 3 and figure 13.

Table 3 Micro-hardness of machined surface layers

Concentration (g/l)	Micro-hardness (HV)		
	White layer	**Heat affected layer**	**Base material**
0	502.0	591.0	554.7
5	602.8	596.0	508.7
10	624.3	575.6	540.1
15	650.9	620.5	571.9
20	653.7	598.2	581.6

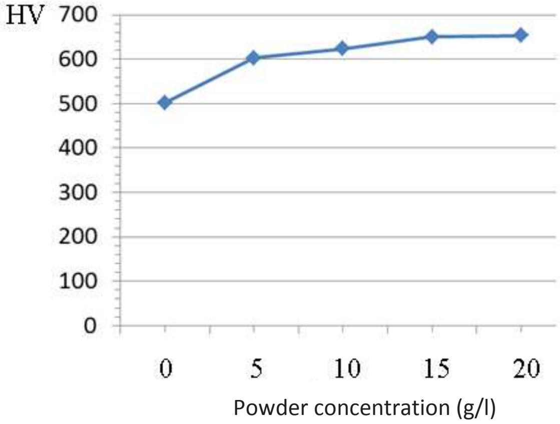


Figure 13 The influence of titanium powder concentration to machined surface hardness

Table 2 shows that when no powder is used in the dielectric fluid the micro-hardness of white layer is very low (≈502.0HV), and its hardness is lower than the hardness of base material and heat-affected layer. Hardness of heat affected layer is the highest (≈591.0HV). Therefore, the choice of suitable material thickness of fine machining to remove all the white layer thickness and retain thickness of heat affected layer to increase ability to work of the moulds. The micro-hardness of white layer is increased by the addition of titanium powder in the dielectric fluid. The micro-hardness of white layer is the highest of three layers in the workpiece surface. The reason is explained by titanium powder mixed in dielectric fluid and carbon from dielectric fluid entered the white layer. Figure 13 indicates that the concentration of titanium powder (0-5) g / l had strongly affected the micro-hardness of white layer. The concentration of titanium powder greater than 5 g/l showed minimum change in the hardness of machined surface. White layer porous structure, containing a number of micro-cracks [17], which has increased the storage capacity of lubricant on the machined surface, increases the life of the moulds.

CONCLUSION

This study included machining of SKD61 steel surface by using titanium powder mixed in dielectric fluid. When no powder was used in the dielectric fluid during machining of SKD61 steel low surface quality is obtained with large number of mirco-cracks. Also, the white layer was not evenly distributed and reduced micro-hardness is observed. When titanium powder is mixed in dielectric fluid is used during machining of SKD61 steel, it was observed that the surface quality of machined surface got improved. The diameter and depth of the craters was reduced and evenly distributed over the machined surface. Also, the deposition of molten metal on the machined surface got reduced. Further, thickness of white layer was evenly distributed and its surface hardness was increased. Thus using titanium powder in the dielectric fluid improves the mechanical properties of white layer and heat affected layer which is a suitable working conditions for die and moulds. Surface layer of SKD61 steel after PMEDM have better characteristics, such as good surface finish, low white layer thickness and the number of micro-cracks were reduced. This will reduce the cost of fine machining, especially when working with small size holes.

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