Experimental investigations on wire electro-discharge machining (WEDM) of TiN/Si3N4 Nano-complex ceramics

Zhang Da1*, Zhang Chengmao2
1College of Automation and Electronic Engineering, Qingdao University of Science and Technology, No.99 Songling Rd, Qingdao, Shandong, P.R. China, 266061
2College of Electromechanical Engineering, Qingdao University of Science and Technology, No.99 Songling Rd, Qingdao, Shandong, P.R. China, 266061
qdzd721@163.com

Abstract. In this paper, the surface characteristics of TiN/Si3N4 nano-complex ceramics cut with wire electro-discharge machining are studied. The effect of single pulse energy on surface properties is investigated in detail. The microscopic observation of the surface appearance with the scanning electron microscope shows that the longer the pulse discharge time, the greater the pulse discharge current, the greater the single pulse energy, the deeper the surface discharge pit, the larger the size, the surface melting and re-solidification phenomenon is more serious. The micro-observation of the cross-section of the surface processed shows that the surface metamorphic layer includes the melting and re-freezing layer and the white layer, the thickness of surface metamorphic layer is about 1 to 10 µm. The longer the pulse discharge time, the greater the single pulse energy, the greater the thickness of the surface metamorphosis layer. Due to the randomness of the discharge process, the metamorphic layer is not uniform.

1. Introduction
As having excellent properties such as high hardness, high temperature resistance, wear resistance and corrosion resistance, ceramic materials have been widely used in space technology, machinery industry, oil industry and other fields. However, because of high hardness and brittleness, ceramic materials are difficult to mechanical processing and their application is limited in many cases. Multiphase compounding is one of the main means of material modification for the improvement of material performance. As having excellent mechanical properties in both normal and high temperature environments, nano-complex ceramic has very broad application prospects [1-5]. Therefore, the study of wire electro-discharge machining (WEDM) process for nano-complex ceramics has important theoretical and practical significance.

2. Analysis of TiN/Si3N4 nano-complex ceramics surface processed by WEDM using scanning electron microscope
From the macroscopic view, even though the processed surface cut by wire electro-discharge machining has processing stripes, there is no obvious cut mask like mechanical cutting on the surface. The depth of the processing stripes and the distance between the stripes are mainly related to factors such as the discharge pulse energy, the feed speed and the way the electrode wire is removed. The stripes on the surface processed by the high speed wire electro-discharge machining are more obvious
[6, 7]. Black-and-white streaks can be formed easily when the aqueous solution of emulsified soap is used in processing.

TiN/Si3N4 nano-complex ceramics surface cut by WEDM is shown in Figure 1. It can be seen that, the surface of the work piece is formed by the overlap of many discharge marks. As every pulse discharge in the processing forms a discharge mark, continuous discharge overlaps discharge marks and forms the surface without obvious cutting marks. The depth and size of discharge marks depend mainly on the energy of the single pulse discharge. Because the pulse discharge voltage is generally about 25V, the single pulse discharge energy is mainly determined by discharge current and pulse discharge time. Single pulse discharge energy, material eroded by single pulse and discharge mark increase with the pulse discharge current and the pulse discharge time.

![Figure 1. SEM photo of TiN/Si3N4 nano-complex ceramic surface processed by WEDM.](image)

Figure 2 shows the SEM photos of surfaces processed by different single discharge energy. The power supply peak voltage is 75V. The pulse discharge peak current is 15A. The pulse interval is four times of the pulse discharge time. Water solution emulsified is utilized as working solution. In Figure 2 (a), the pulse discharge time is 15µs. In Figure 2 (b) the pulse discharge time is 57µs. In Figure 2(c) the pulse discharge time is 100µs.

![Figure 2. SEM photos of surfaces processed by different single discharge energy.](image)
The energy of single discharge pulse increases with pulse width. As the energy of a single discharge pulse increases, the depth and size of the pits formed by the processing increase slightly, and the surface roughness also increases slightly (as shown in Figure 2). As the ceramic materials have high melting point and complex erosion mechanism, the rate of increase in roughness is much smaller than that of metal materials.

The melting and re-freezing phenomenon on the TiN/Si3N4 nano-complex ceramic surface processed by WEDM is shown in Figure 3. The power supply peak voltage is 75V and the pulse discharge time is 57µs. Water solution emulsified is used as the working solution. For Figure 3 (a) and (b), the pulse discharge current is 5A. For Figure 3 (c) and (d), the pulse discharge current is 35A.

As shown in Figure 3 (a) and (b), there are many pores on the processed surface and solidified phase after melting. As the discharge current is small, the discharge energy of the pulse is small. Therefore, the heat generated by discharge and the impact of the explosion are small. Melting and gasification of ceramic material are the main modes of erosion. The ceramic material that is melted but not thrown off the work piece surface solidifies in the discharge gap due to the decrease of heat. Sleek discharge pit forms on the edge and is eroded by the next electric spark discharge. In this case, the processing speed is slow and the surface quality is better.

When the discharge current increases to a certain extent, due to the increase of single pulse discharge energy, the material erosion mode begins to be mainly in the way of thermal stripping. Particles of overall removal become more and larger. Multi-prism area and larger discharge pit form on the processed surface. It can be seen from Figure 3 (c) and (d), as a result of the increased single pulse discharge energy, roughness of the processed surface increases.
Figure 3. Melting and re-freezing phenomenon on TiN/Si$_3$N$_4$ nano-complex ceramic surface processed by WEDM.

3. The metamorphic layer of TiN/Si$_3$N$_4$ nano-complex ceramic surface processed by WEDM

The processing of WEDM is an electrical and thermal physical process, that is, the local transient high temperature action makes the surface layer material of the work piece melting and gasification. The melted material is thrown off the surface of the work piece, thus enabling the erosion of the work piece material.

The molten material which has not been thrown off the surface of the work piece is solidified again due to the sharp cooling of the coolant and remains on the work piece surface. The physical properties of these materials left on the surface are different from those of the original material. These molten and re-solidified materials join together to form metamorphic layers. Generally speaking, when the electro-discharge machining is processed with the larger single pulse energy, the metamorphic layer is thicker [8].

Figure 4 is the photo of the cross-section of TiN/Si$_3$N$_4$ nano-complex ceramic surface processed by WEDM. The outermost layer of the processed TiN/Si$_3$N$_4$ nano-complex ceramic surface is melting and re-solidification layer. The lower layer beneath the melting and re-solidification is called the white layer. The white layer occurs because TiN/Si$_3$N$_4$ nano-complex ceramic is melted and then cooled quickly under the action of coolant. The metamorphic layer of WEDM mainly refers to the area from the surface to the white layer. The area beneath the white layer is less heated. And this area is commonly referred to as the thermal affecting zone. Due to the randomness of the discharge, the thickness of the metamorphic layer is not completely uniform.

Figure 4. Cross-sectional image of TiN/Si$_3$N$_4$ nano-complex ceramic processed by WEDM.

The thickness of the metamorphic layer is related to the type of work piece material and the process parameters. Microscope images of cross section of TiN/Si$_3$N$_4$ nano-complex ceramic processed by
WEDM are shown in Figure 5. The power supply peak voltage is 75V and the pulse discharge peak current is 15A. Water solution emulsified is used as the working solution. The pulse discharge times of Figure 5 (a), (b), (c) and (d) are 15µs, 57µs, 79µs and 100µs separately. As can be seen from Figure 5, the longer the pulse discharge time, the greater the energy of a single discharge pulse, the greater the distance from the white layer to the surface, the greater the thickness of the metamorphic layer. In general, the thickness of the metamorphic layer is between 1 and 10µm.

![Cross section images of TiN/Si₃N₄ nano-complex ceramic processed by WEDM.](image)

### 4. Conclusion

As TiN/Si₃N₄ nano-complex ceramic is conductive, it is easy to be processed by WEDM. The depth and size of the discharge pits of the processed surface increase with the discharge energy of single pulse. The quantity of the single pulse discharge energy depends mainly on the pulse discharge current and the pulse discharge time. The surface of the work piece is covered with a melting and refreezing layer. And there is a clear white layer beneath the melting and refreezing layer. The surface metamorphic layer is composed of melting-refreezing layer and white layer and more brittle than the substrate material. The thickness of surface metamorphic layer is about one to ten micrometer and not uniform.

### References

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