Journal of Coating Science and Technology
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Carbon Nanotubes (CNTs) for Prolonging the Life of Micropunch

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Abstract: Carbon nanotubes (CNTs) coated on the WC/Co micropunch with diameter in 150 μm for prolonging the life of micropunch was investigated. Carbon nanotubes were synthesized by homemade method. With scanning electron microscopy (SEM) and transmission electron microscopy (TEM), the morphology and structure of CNTs had been expressed. After the punching test with Ti as substrate, the effect of CNTs for prolonging the life of micropunch on the wear loss and the surface morphology of micropunch had been studied by confocal laser, SEM, digital balance *etc*. Results show the wear of CNTs coated micropunch decreases obviously. Even in the severe wear period the wear loss is less than that of non-CNTs coated micropunch. Compared with the micropunch without CNTs coating, the promising results are due to the formation of a transfer film at the contact region by rubbing of the CNT forest, CNTs produced adheres to the micropunch surface avoiding direct contact during the punching period and providing lubricant properties to the interface by virtue of their graphitic nature. Also, the relevant mechanism was illustrated primarily.

Received on 12-03-2015
Accepted on 20-08-2015
Published on 14-09-2015

Keywords: Carbon nanotubes, micropunch, wear characteristic, WC/Co.

DOI: http://dx.doi.org/10.6000/2369-3355.2015.02.02.5

1. INTRODUCTION

Carbon nanotubes (CNTs) [1, 2] are unique nanosystems with extraordinary mechanical and electronic properties, which derive from their unusual molecular structure. CNTs having wall thickness of one carbon sheet are named single-walled carbon nanotubes (SWCNTs). SWCNTs can be considered as the building blocks of multi-walled carbon nanotubes (MWCNTs), which consist of a coaxial array of SWCNTs with increasing diameter from two to several tens of nanometers, providing very high aspect ratio structures [2].

In the last decade, an enormous amount of work has been devoted to reveal the unique, structural, electrical, mechanical and chemical properties of CNTs and to explore what might be the most interesting applications [3-10]. Carbon nanotubes, showing unique properties such as high tensile and flexural strengths, high elastic modulus, and high aspect ratio, have also been considered as attractive contenders for tribological applications. In this sense, interesting results have been reported with significant improvements in friction and wear rates for nanotubes-polymers [11, 12], ceramics [13, 14], and metal composites [15, 16]. According to theoretical considerations [17-19], friction coefficients between the walls of MWCNTs should be extremely low.

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Due to wear of the WC/Co micropunch, quality of the punched holes deteriorates significantly after about 1000 punching shots [20]. Also, the cost of the punches is high. Therefore, it is desirable to prolong the useful life of the micropunches.

As above-mentioned, CNTs are high in strength and low in friction coefficient, CNTs coated on the surface of micropunches may greatly prolong the tool life by reducing wear loss during punching and enhancing the wear resistance of the punches.

Consequently, in order to long the serving tools in the microfabrication, the effects of CNTs coated on WC/Co micropunches on wear resistance improvement were investigated in this research. In the long run, this research can lead to improving wear resistance properties of such tools made of WC/Co and other engineering materials.

2. EXPERIMENTAL MATERIAL AND PROCEDURES

2.1. Experimental Material

Micropunch (Made by Ultrahardness tools company, Japan) with 75 % volume fraction WC particle and 25 % volume fraction Co particle of 50 μm mean size, 150 μm in diameter was delivered with precisely grinding by experimental requirements. Figure **1** shows the surface texture of micropunch for CNTs coating. Pure titanium sheet with 200

E-ISSN: 2369-3355/15

μm in thickness was used as the substrate. Alcohol with a normal purity of 95 % was purchased from Sigma Aldrich.

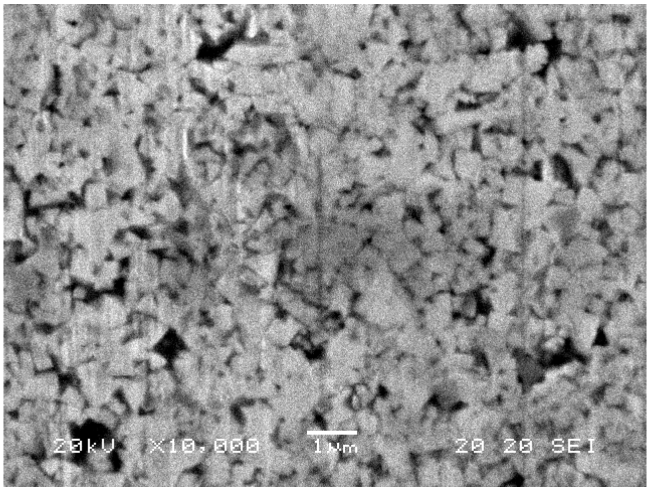


Figure 1: Surface texture of micropunch.

2.2. Experimental Procedures

2.2.1. CNTs Synthesis

The micropunches were cleaned by acetone and pure ethyl alcohol so as to remove any possible contaminant, and carefully put into the vacuum chamber waiting for coating.

For CNTs coating on micropunch, first of all, the catalyst (Fe) was deposited on the micropunch working section by electron cyclotron resonance (ECR) (Made by Elionix, Japan), and the related processing parameters are listed in Table **1**. At the same time, remain of the micropunch was covered by Al foil to avoid the effect of Co distributed in micropunch itself because pure Ni, Co, or Fe, and their alloys or compounds are widely acceptable catalysts for the growth of CNTs [21, 22].

Table 1: ECR Processing Parameters for Fe Deposition

Substrate	WC/Co Micropunch
Catalyst	Fe
Irradiation time	60 s
Accelerated voltage	2500 V
Ion current density	12.0 mA/cm^2
Gas	Ar
Gas flow rate	0.6 SCCM
Vacuum	1.5×10^{-4} Pa

After catalyst deposition, CNTs were synthesized by homemade method. The schematic diagram of the self-designed equipment for CNTs synthesis with alcohol chemical vapor deposition (CVD) is shown in Figure **2**. The size of vacuum chamber and the heater is *Φ*100×150 mm and 50×30 mm respectively. The electrical resistance is taken as the heating resource. Alcohol in a ceramic container is located under the heater, and the specimen is placed on the heater in the vacuum chamber. A DC power supplier is applied to heat the specimens in the vacuum (1×10^{-2} Pa) under 38~40 A.

2.2.2. Micropunching

The prepared pure titanium sheet was properly cleaned by acetone and pure ethyl alcohol so as to remove any possible contaminant, and carefully put into the microdie. Thereafter, specimens were punched by the microprocessing machine MP50 (Made in Japan) with 20 pulses per minute, and feedrate of 2 mm.

The effect of CNTs on the wear loss and the surface morphology of micropunch were investigated by confocal laser, scanning electron microscopy (SEM), digital balance *etc*.

3. RESULTS AND DISCUSSION

3.1. CNTs Coated on Micropunch

The synthesized CNTs are shown in Figure **3**. It demonstrates that the length of CNTs is about 15 μm. Moreover, CNTs are compacted tightly resulted in curve aligning. The relevant TEM image is shown in Figure **4**. It shows that CNTs is multi-wall nanotubes, and the diameter of the synthesized MWCNT was about 3~5 nm.

3.2. Wear Loss of Micropunches

The wear loss of non-CNTs and CNTs coated micropunches is shown in Figure **5**. It illustrates that the weight of both kinds of micropunches (each for 5 times) decreases with the increment of punching number in the initial, which means the wear of both micropunches in the initial was significantly increased, and the effect of CNTs on the wear loss is not remarkable.

With the punching in progress, the wear of non-coated/coated micropunches is in the quasistable period with a little wear loss as shown in Figure **5**, especially for punching number from 500 to 1200 for Non-coated micropunches and from 450 to 1400 for CNTs coated micropunches. In this period, the effect of CNTs on the wear loss of micropunch is sound obviously.

During the severe wear period, with the punching numbers increasing further, such as over 1200 for Non-coated micropunch and over 1400 for CNTs coated micropunch, the wear of micropunch is increased distinctly (Figure **5**). At the same time, the effect of CNTs on the wear loss decreases.

Also, due to CNTs coated on micropunches, the start of quasistable period is advanced. On the contrary, the end of quasistable period is postponed as shown in Figure **5**. It elucidates the effective quasistable period is longer than that of non-coated micropunches. For CNTs coated

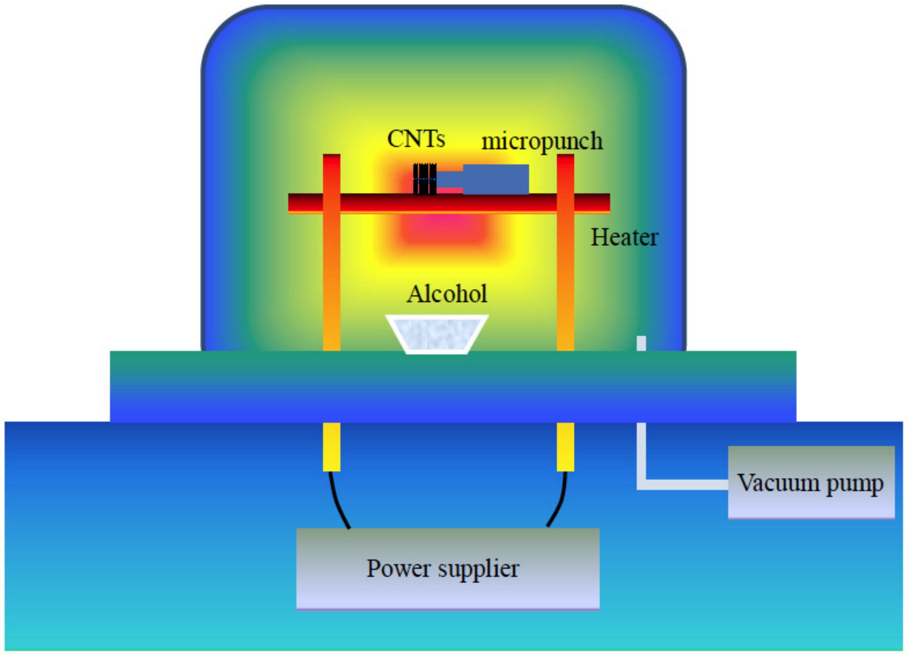


Figure 2: Equipment for CNTs synthesis.

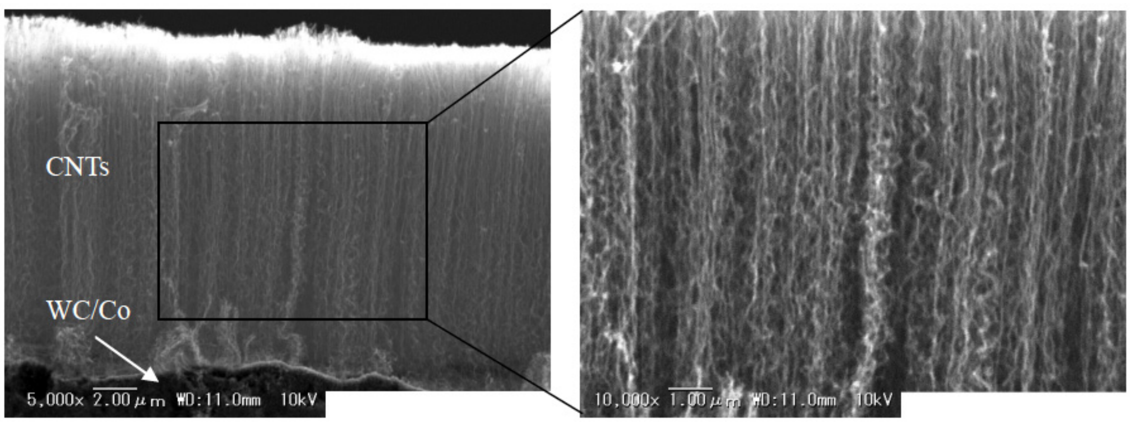


Figure 3: Synthesized CNTs coated on Micropunch.

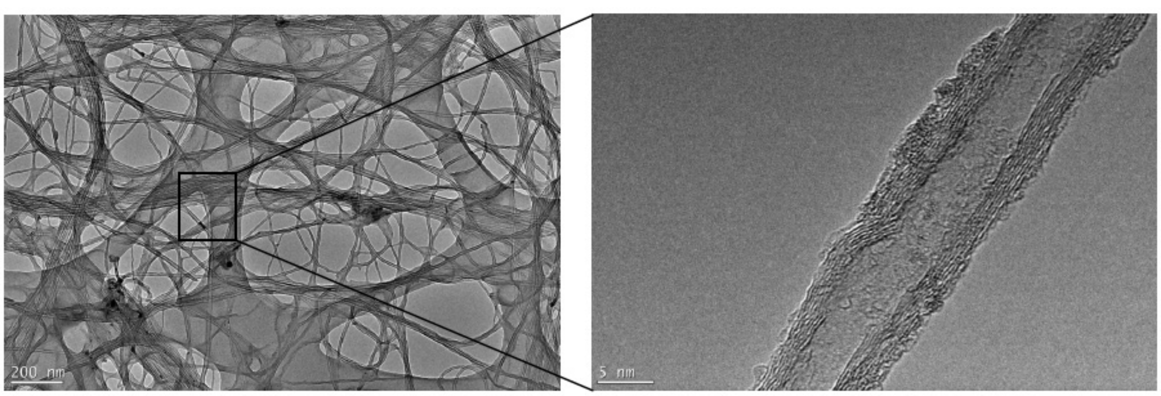


Figure 4: TEM image of synthesized CNTs.

micropunches, it is 1400 – 450 = 950. By comparison, for non-coated micropunches, it is 1200 – 500 = 700. Furthermore, the total wear loss of CNTs coated micropunches is less than that of non-coated micropunches. It demonstrates that the life of micropunch is improved or prolonged evidently.

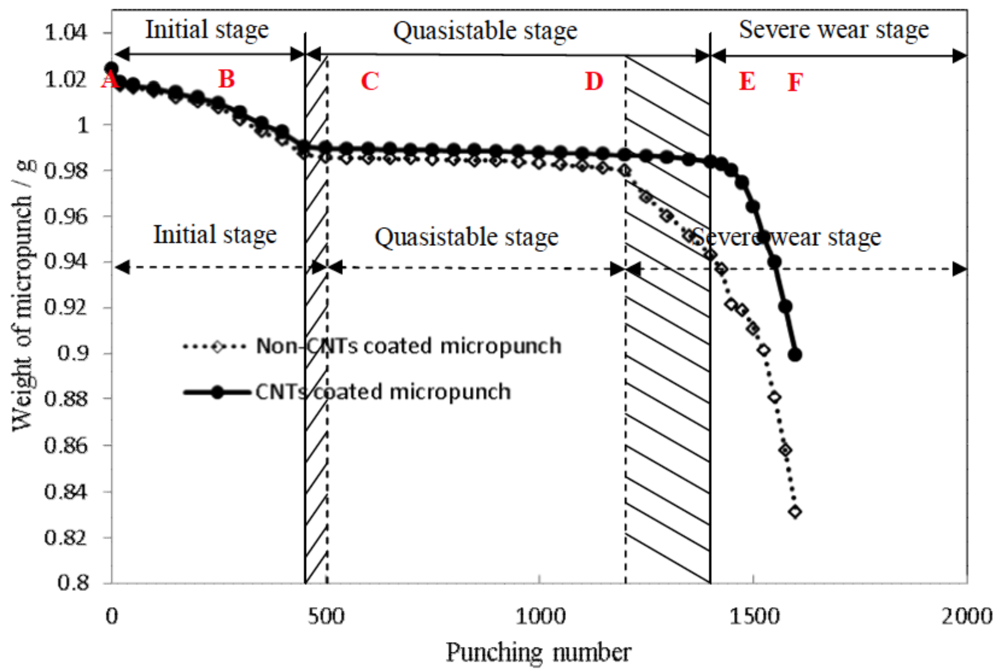
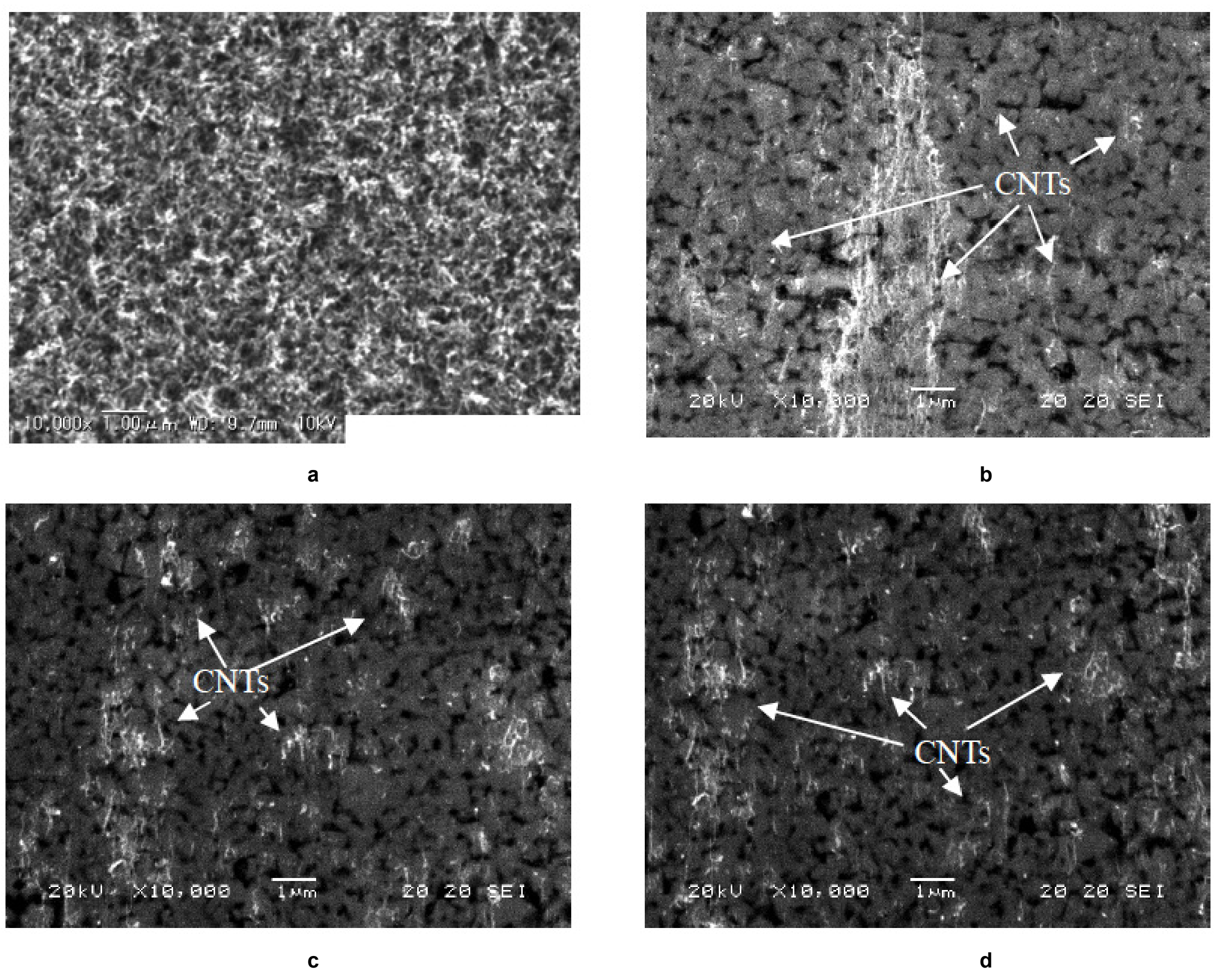
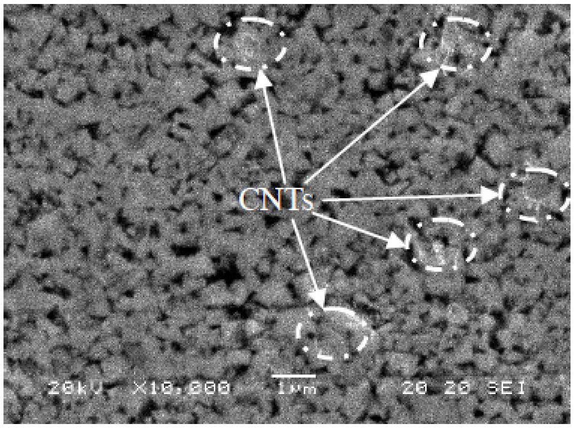


Figure 5: Relationship between wear loss and punching numbers.



(Figure 6). Continued.



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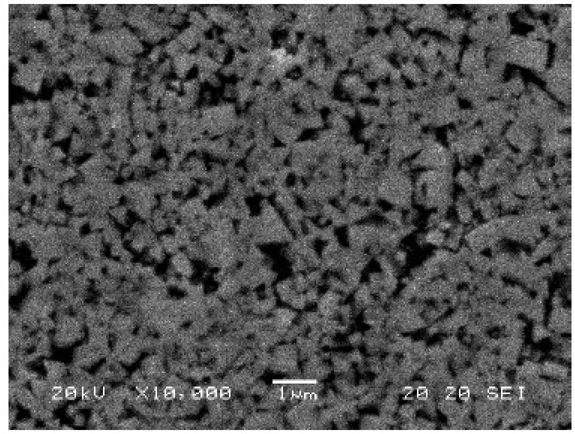

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Figure 6: Surface texture of micropunch in various conditions (**a**) Initial surface texture of CNTs coated micropunch, (**b**) Surface texture of CNTs coated micropunch in the initial stage, (**c**) Surface texture of CNTs coated micropunch in the initial quasistable stage, (**d**) Surface texture of CNTs coated micropunch in the quasistable stage, (**e**) Surface texture of CNTs coated micropunch in the sever wear stage, (**f**) Surface texture of CNTs coated micropunch in the last sever wear stage.

3.4. Surface Texture of CNTs Coated Micropunch

Figure **6** shows the surface textures of CNTs coated micropunches during various punching periods. Figure **6a** shows the initial surface texture of CNTs coated micropunch (see point A in Figure **5**). Carbon nanotubes forest is synthesized and distributed successfully on the surface of micropunch, and tangles mutually.

With the punching being in progress in the initial stage, the distribution of CNTs is shown in Figure **6b** (Point B in Figure **5**). It shows that CNTs distribute on the surface non-uniformly and a bulk of CNTs attaches on the surface by the punching rubbing effect. When the punching is in the quasistable period, the surface texture of micropunch is shown in Figures **6c** and **6d** (See point C and D in Figure **5**). It illustrates that CNTs distributes uniformly on the micropunch surface which form a transfer film between micropunch and substrate (Ti foil) during the punching process. It is just due to the formation of this transfer film at the contact region by rubbing of the CNT forest, CNTs or debris produced adheres to the micropunch surface (or the mating surfaces) avoiding direct contact during the punching period and providing lubricant properties to the interface by virtue of their graphitic nature. Results presented are agreed with results shown in Figure **5** and promising for prolonging the life of micropunches.

With the increment of punching number, the surface texture of micropunch is shown in Figures **6e** and **6f** (See point E and F in Figure **5**). It shows that CNTs distribute sparsely, and disappear finally (Figure **6f**). It is noted that the promising effect of CNTs is lost resulted in severe wear of micropunch.

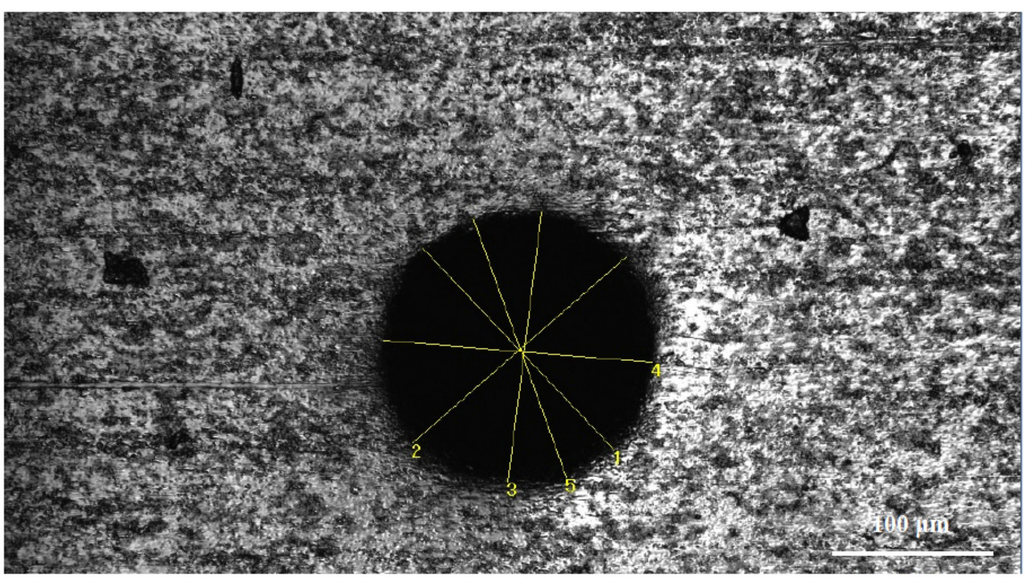

Figure 7: Profile of punched microhole measured by OLS3000.

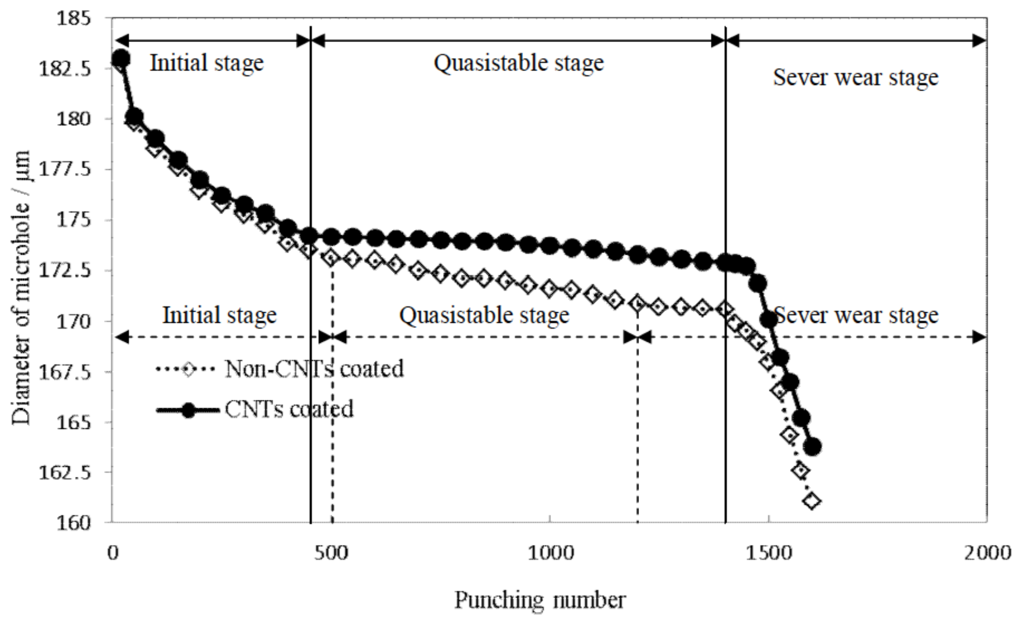

Figure 8: Relationship between diameter of punched microhole and punching number.

3.5. Profile of Punched Microholes

The diameter of the punched microhole by Non-CNTs coated and CNTs coated micropunches was measured by LEXT confocal laser-OLS3000 as shown in Figure **7**. The relevant results (each for 5 times) are shown in Figure **8**. Compared with Figures **5** and **6**, it illustrates that for both cases (Non-CNTs coated and CNTs coated micropunches), in the different wear conditions the diameter of the punched microhole changes correspondingly. In the initial condition, the diameter decreases obviously with the increment of punching number.

When the punching process is in the quasistable period, the diameter of the punched microholes keeps stable relatively. With the punching number increasing further, the diameter was decreased remarkably. For CNTs coated micropunch, due to the lack of attached CNTs on the micropunch, the relevant wear characteristic is same as that of non-CNTs coated micropunch. Therefore, the serious wear of the micropunch appears during the micropunching in the severe wear condition. Consequently, the diameter of the punched microholes decreased seriously.

Moreover, results shown in Figure **8** are well agreed with the wear loss of micropunches in the punching period as shown in Figure **5**.

4. MECHANISM OF CNTs' EFFECT

The schematic mechanism of the effect of coated CNTs on the life of micropunches is shown in Figure **9**. It demonstrates that at the beginning of micropunching, because CNTs adhesion to micropunch is relatively low, the coated CNTs are easily detached from the surface of micropunch as shown in inset of Figure **9** (blue circle with dash line).

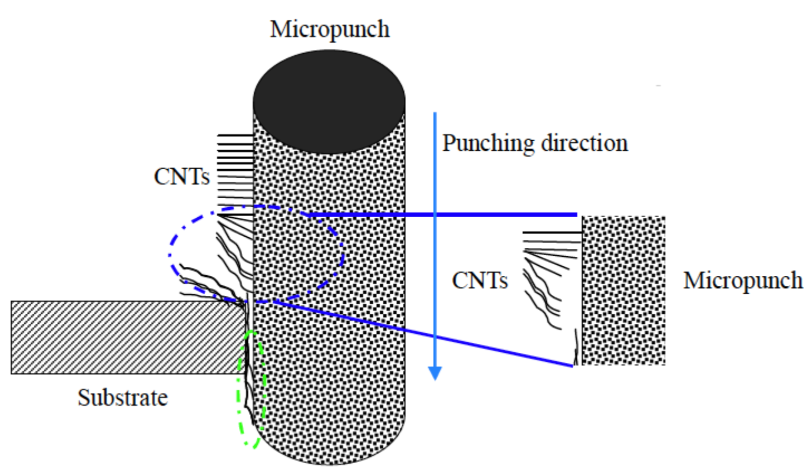

Figure 9: Schematic mechanism of micropunching with CNTs coating.

With the micropunching processed further, the coated CNTs are detached from the surface with more and more large areas. Consequently, only some small fraction of micropunch surface can remain CNTs under the effect of friction between the substrate and the surface of micropunch as shown in Figure **9** (green circle with dash line), which agrees with the results as shown in Figure **6**. Therefore, the ability of CNTs' adhesion to the surface of the micropunch is crucial to the longevity of the micropunch. CNTs with higher adhesion to the micropunch surface are hardly detached from the surface. During the micropunching, CNTs attached on the surface of micropunch and distributed uniformly are the ideal media between the substrate and micropunch to low the friction coefficient. As the results, the wear of micropunch will be decreased significantly and the life of micropunch is prolonged remarkably. Meanwhile, the micropunch coated CNTs with higher adhesion will be more promising for the microfabrication.

5. CONCLUSION

Carbon nanotubes (CNTs) coated on the WC/Co micropunch and its effect on its wear characteristic had been researched. It shows that due to the formation of this transfer film at the contact region by rubbing of the CNTs forest, CNTs produced adheres to the micropunch surface (or the mating surfaces) avoiding direct contact during the punching period and providing lubricant properties to the interface by virtue of their graphitic nature. For CNTs coated micropunches, the punching number in the quasistable period is 950. By comparison, for non-coated micropunches, it is 700. In addition, the total wear loss of CNTs coated micropunches is less than that of non-coated micropunches. As a result, CNTs coated micropunch is evidently promising to improve or prolong the life of micropunch.

ACKNOWLEDGEMENT

The work was fully supported by a grant from City University of Hong Kong (Project No. 7004246).

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