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EFFECTS OF ELID-ELECTROLYTIC COOLANT WITH NANOMETER SIZE CARBON PARTICLES ON THE CUTTING PHENOMENA

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Abstract:*To overcome difficulty in machining of a ferrous material with a diamond tool, a new coolant system named* '*ion-shot coolant system*' *was developed utilizing ELID (Electrolytic In-process Dressing) electrolytic coolant and nanometer size carbon particles. A series of experiments conducted to show effects of the ion-shot coolant system on high carbon chromium steeel workpieces with single crystal diamond tools. Experimental results exhibited that the ion-shot coolant system maintained a sharp cutting edge and in turn, stable cutting force and improved surface quality. Furthermore, stable chip formation was observed under new coolant system. All results were compared with cutting under conventional kerosene mist supply.*

Keywords: Ion-shot coolant system, ELID coolant, Nanometer size carbon particles, Ferrous material, Single crystal diamond tool

1 Introduction

In general, a diamond tool has been used for precision machining due to a very sharp cutting edge and longer tool life. With increase demand on precision molds for various applications such as medical devices, micro-fluidic devices, alternative energy components, etc., the usability of the diamond tool becomes significant. However, machining of the ferrous workpiece material with a diamond tool has been avoided due to severe tool wear. Many studies reported significant wear of the diamond tools due to carbon diffusion into the ferrous workpiece [1, 2]. Therefore, it is necessary to develop new machining technology to utilize full benefits of the diamond tools.

A special coolant system called 'ion-shot coolant system' was developed, which consists of electrolytic liquid and nanometer size carbon particles. In this experiment, ELID-electrolytic coolant was used for electrolytic coolant [3, 4]. Applying ELID-electrolytic coolant on the cutting interface of the ferrous workpiece material induced chemical reaction on the work surface including pitting that may change crystallographic behavior of the workpiece. The ion-shot coolant system also contains nanometer size carbon particles that may prevent the diamond tool wear. The preliminary research showed various benefits of this system such as consistent tool shape, improved surface quality, and effective chip discharge [5, 6]. This study introduces the additional research and the mechanisms for such benefitial phenomena of the ion-shot coolant system against a ferrous material with a diamond tool.

2 Benefits of Ion-shot coolant system

2.1 Experimental Setup

The schematic of the ion-shot coolant system is shown in Figure 1. The ELID liquid with density controlled nano-carbon particles are supplied through carbon electrodes where the coolant is electrolyzed. The electrolytic coolant included nanometer size carbon particles is dripped to the cutting point with a volume of about 30ml/min. High carbon chromium steel (Hv800) that has a high chemical affinity to the single crystalline diamond cutter (nose radius, R=800 μm) was used for experiments. An ultra precision CNC machine (NANO100) was used. Planer cutting method was applied with cutting speed of 150 mm/min and peek feed of 5 μm/pass.

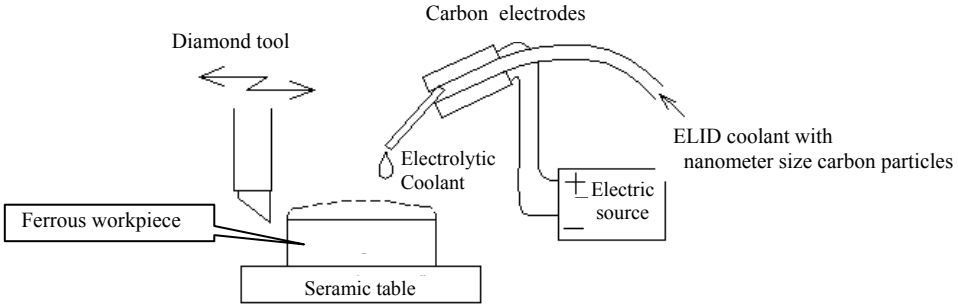


Fig. 1 : Schematic of the ion-shot coolant system.

Four types of coolants were used for comparison purpose. Conventional kerosene mist coolant (KM) which has a good chemical affinity with the diamond tool and the work material was used as a reference coolant, ELID coolant (EC), EC with nanometer size carbon particles (NCC: Nano-Carbon Coolant), and electrolyzed NCC (NCEC: Nano-Carbon Electrolytic Coolant). Nano-carbon particles were added to improve lubrication at the cutting interface and minimize the tool wear. Average carbon particle diameter was about 100 nanometer and it was diffused into pH-7 water at 20 wt%. Then, it was diluted into the ELID coolant (50:1 ratio). In NCEC, the coolant was electrolyzed by passing through the carbon electrodes for surface modification by chemical reactions. Electrolytic conditions were 15V for open voltage, 1.7A for peak current, and 1μs for each on and off pulse. During experiments, the cutting interface was enclosed in the coolant except KM.

2.2 Surface quality

Machined surfaces with the same width of cut (total 1mm) and the depth of cut (2 μm x 3 times) under KM and NCEC are shown in Figure 2(a). The machined surface under KM reproduced scratch marks and disordered lines as shown in right cutting lines in Figure 2(a) and enlarged images in Figure 2(b). Some of these defects were caused by crystal grain of the work material [7]. Simoneau *et al.* reported that dimples were created when cutting moved from a pearlite to ferrite grain using finite element analysis [8]. In general, as the depth of cut becomes smaller, the material behaves as an anisotropic and inhomogeneous material so that unstable cutting occurs when the tool crosses the grain boundary, which was the case of cutting with KM.

However, when cutting with NCEC, the material behaved as an isotropic and homogeneous material as in the conventional cutting so that uniform cutting paths and smooth surface were produced, Figure 2(a) (left side). Some chemical reaction during cutting may cause change in microstructure of the work material favorable to cutting and it may result isotropic and homogeneous cutting. In micromachining, the microstructure of the work material plays a significant role in cutting performance because the material cannot be treated as statistically isotropic and homogeneous material as in conventional machining due to discrete crystallographic orientation change over grains.

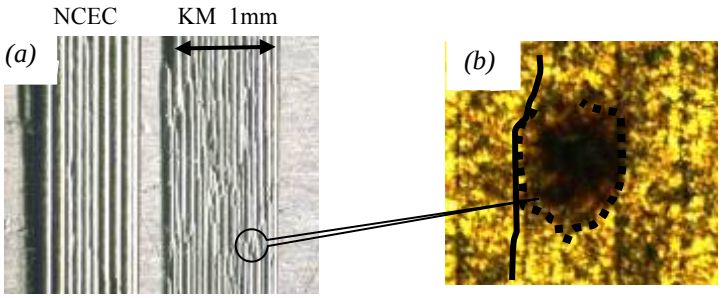


Fig. 2 : Machined surfaces under KM and NCEC (depth of cut: 2μm x 3 times).

2.3 Tool condition

One of the important factors to produce fine surface is to maintain a sharp cutting edge during cutting. BUE (Built-up-edge) and tool wear cause unstable cutting and inconsistent surface profile. The debris from the cutting attached to the flank face of the single crystal diamond tool used in the cutting with NCEC first and then KM as shown in Figure 3(a) while the flank face of the other edge of the same tool used in cutting with NCEC only was very clean in Figure 3(b). The chemical reaction in NCEC may create a coated layer on the tool surface and change the friction coefficient and chemical affinity to the iron so that chips are not attached to the surface. This may be also explained with chip discharge function of NCEC in the next section.

The cutting force profile also shows that cutting with NCEC was stable compared with other three coolants, Figure 4. The clean sharp edge of the tool and the low friction coefficient of the coated layer on the rake face produced stable cutting force profile and resulted in fine surface as shown in Figure 2.

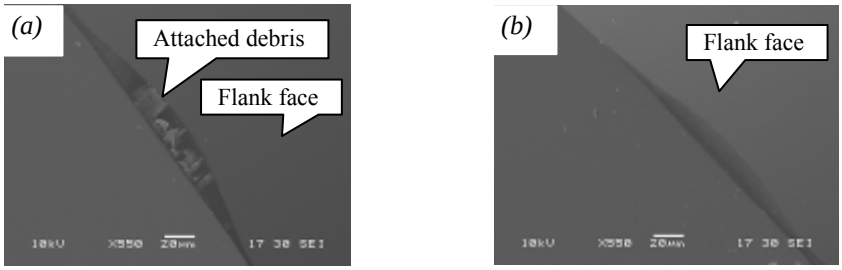


Fig. 3 : Flank surfaces of the single diamond tool after cutting with (a) NCEC(5.3m) + KM(5.4m) and (b) NCEC(7.2m).

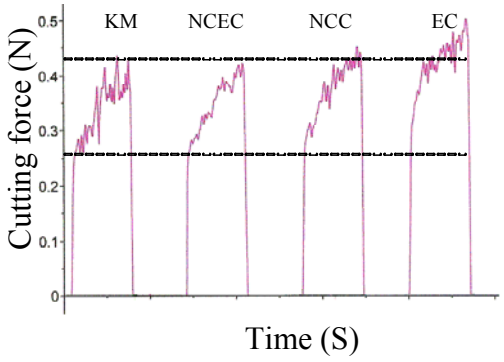


Fig. 4 : Main cutting force profile with various coolants.

The tool life experimental result with varing cuttind speed in NCEC was shown in Figure 5. From this result, longer tool life was observed at higher cutting speed. Tool wear volume was measured using the 3-dimensional CAD volume calculation software. And removal rate was defined as cut removal volume divided by the tool wear volume.

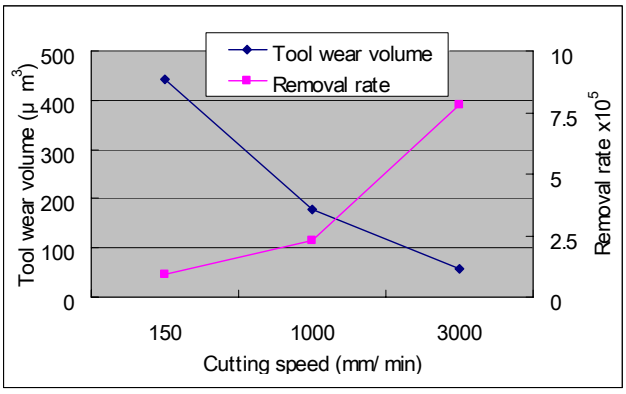


Fig. 5 :Relation between cutting speed and diamond tool wear.

2.4 Chip formation

When NCEC was applied, the long continuous chips were made, Figure 6(a), while the segregated chips formed under KM condition, Figure 6(b). Continuous chip reprents stable cutting and improved surface quality. Furhter, by adjusting NCEC condition, chip breakability characteristics was improved, Figure 6(c). Figure 6(c) shows broken chip of about 1.5 μm width and 30 μm length. This chip formation may be also explained with the relation for chlorine compound of NCEC in the next section.

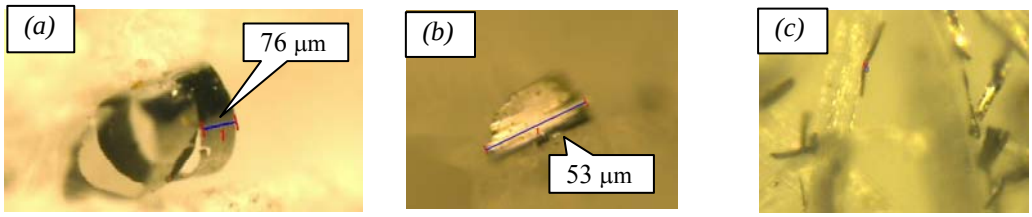


Fig. 6 : Minute chip forms in (a)NCEC, (b)KM and (c)chip breakability characteristics under NCEC.

2.5 Chip transportation

The minute chips from the cutting with NCEC transported to the edge of the workpiece during the cutting, Figure 7(a). Although the image does not show details, the minute chip from NCEC cutting were attached and aligned in order at the edge of the workpiece. This may be caused by electrostatic force. With a small amount of NCEC supply (30ml/min), chips were effectively removed from the cutting interface and the machined surface. In order to understand this, iron powder was deposited to NCEC and NCC coolant, Figure 8. In Figure 8(a), iron powder tightly gathered at the edge of the coolant in NCEC. In case of NCC, iron powder was distributed toward the coolant edge, Figure 8(b). The figure also shows that the contact angle of NCEC coolant was higher than that of NCC. Therefore, NCEC seemed to modify the surface of the workpiece to be more hydrophobic. This may be related to chemical reaction on the surface. Hydrophobic molecular tends to be non-polar and prefer neutral molecules. Alkanes are typical hydrophobic compound. Interestingly, NCEC was pH-10 and NCC was pH-9 during cutting.

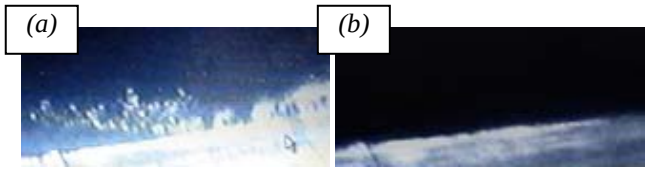


Fig. 7 : Minute chip deposited to the edge of the workpiece in (a) NCEC and (b) NCC.

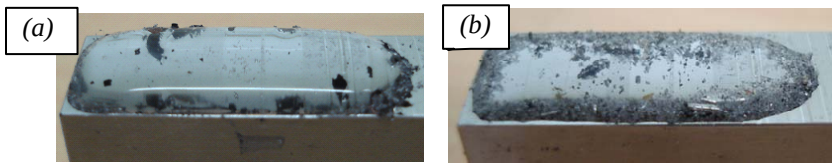


Fig. 8 : Iron powder on NCEC and NCC coolant.

3 Fundamental Mechanism of the ion-shot coolant system

The ion-shot coolant system showed various benefits for a diamond cutting on the ferrous workpiece material, which will have a possibility to overcome conventional problems for such a combination. At this chapter, several mechanisms are introduced for such beneficial phenomena of the ion-shot coolant system against a ferrous material with a diamond tool.

When cutting with NCEC, the cutting force was stable. Nanometer size carbon particles may act as a solid lubricant as a graphite layer that has a very low friction coefficient. They may also act as a protective coating so that the typical diffusion wear was prevented. Figure 9 shows the thin film of the diamond rake face after one hour of cutting with NCEC. This thin film was analysed using EPMA. For easier analysis, thin film was gathered by a needle as shown in Figure 10(a). EPMA result showed that main content of the thin film was carbon, Figure 10(b). EPMA result also shows silver from the eletrode coating material and copper from the base plate of EPMA. This analysis may give the possibility of producing the graphite layer or a layer with similar structure of the typical solid lubricant, the friction coefficient of the tool would be very low and assist a stable cutting.

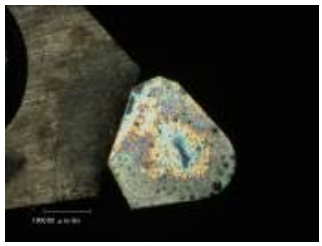


Fig. 9 :Thin film formation on the diamond tool under NCEC cutting.

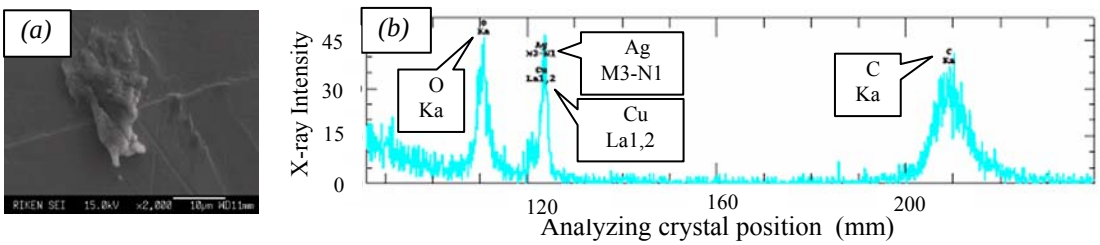


Fig. 10 :Thin film analysed particles and the data used by EPMA.

ELID coolant is water based liquid with ionized chemicals. It contains chlorine ions that are the cause of corrosion of the work surface. Chlorine ions penetrate the grain boundaries and the defects on the surface, and then weaken the surface integrity. During cutting, NCC coolant exhibited pH-9 while electrolyzed ELID coolant became pH-10. The value of pH certainly affects chemical reaction on the tool and work surface. It may create a different type of oxidized layers through complicated chemical reaction under different pH value. Some oxidized layers are solid and others are in molten status. If ELID coolant at pH-10 creates a molten status of surface layer, the surface would become amorphous and the material would respond isotropically and homogeneously to the cutting in NCEC.

The micro hardness of the work surface with NCC increased while it decreased with NCEC, Figure 11. Without electrolysis, a certain chemical reaction on the surface during the cutting may produce harder surface layer (ex. Fe_2O_3). As the coolant is electrolyzed, the pH value of the coolant may change and promote a different chemical reaction on the surface that may produce somewhat molten surface and thus softer surface layer (ex. $FeCl_3$ in the water). The thickness of those modified surface layers were about 200 nm by using the nanometer indentation depth analysis, Figure12. The difference in micro hardness of each surface resulted in the difference of the machined groove shape. The burr height on the groove edge of the work surface with NCC was over 3 times larger than the one with NCEC.

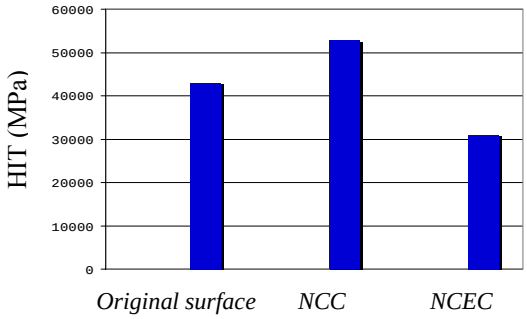


Fig. 11 : Micro hardness of the original surface and machined surfaces with NCC and NCEC.

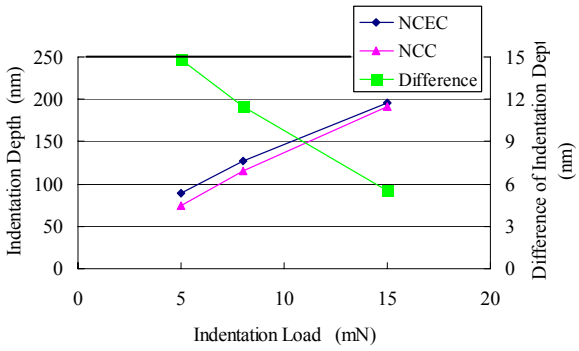


Fig. 12 : Relations on indentation load and depth for NCC and NCEC.

From the observation of the ploughing area of the surface under NCEC, existence of pitting was found at the boundaries and inside of the crystal grains, Figure 13. Besides, from the observation of the minute chip under NCEC, nano-meter sized wrinkles of which directions are normal to the cutting direction were found in Figure 14(b). Thses nano-meter sized wrinkles are similar to the lamellar chip structure which is generally produced from amorphous structural material. Distance indicated by the arrows in Figure 14(b) is 1 μm. Therefore, chemical process under NCEC condition weakens surface brittleness and it loosen discrete crystallographic orientation characteristics. It may be due to chlorine compound in the coolant. Hypothetically, the work surface was pitted by ionized chlorine, which weakens grain boundaries and crystal structure. Additionally, chemical reaction may modify crystal structure of the surface resulting in amorphous layer. It is similar to the role of the slurry in the CMP (Chemical Mechanical Polishing) process.

In order to understand the relation between nano-meter sized wrinkles and chlorine compound, electrolyte liquid withoht chlorine compound was used for NCEC and the chip formation was compared. In this case, sodium sulfate (Na_2SO_4) solution with 0.5mol/ l density was chosen and nanometer size carbon particles also gave electrolytic energy. Figure 15 shows the chip formation under the condition of sodium sulfate solution. The figure shows a straight shape chip formation at about 20μm width and 430 μm length without wrinkles instead of curly shape. From this experimental result, chlorine compound included in ELID coolant has great influence on chip formation and chip breakability by changing material behavior isotropic and homogeneous under micro cutting.

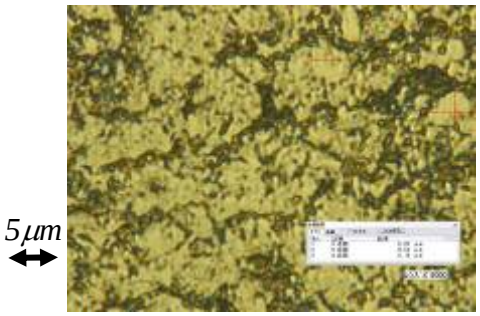
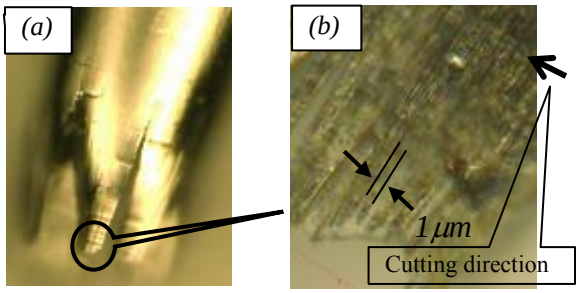


Fig. 13 : Pitting at ploughing area cut with NCEC condition (x5000) .



(a) reverse chip surface (b) sub-μm size wrinkles on the front surface (x5000)

Fig. 14 : Chip observation cut with NCEC condition.



Fig. 15 : Chip observation cut with NCEC using sodium sulfate solution.

4 Conclusion

Using ion-shot coolant system where ELID liquid with nanometer size carbon particles is electrolyzed and supplied to the cutting interface during cutting of the high carbon chromium steel with the single crystal diamond tools exhibited mirror quality surface, longer tool life, and effective minute chip discharge. This method uses very little amount of coolant and contributes to sustainable manufacturing. In summary, the following remarks are concluded;

(1)Mirror surface to the high carbon chromiun steel was obtained by the ion-shot coolant system.
(2)The effects of the nanometer size carbon particles included in ELID-electrolytic coolant were considered as low friction at the cutting interface and the prevention of adhesion between the diamond tool and the ferrous workpiece material.
(3)The effects of ELID-electrolytic coolant with nanometer size carbon particles were considered as the improvement of cutting performance. That is, active chlorine ion, also active hydroxide ion and hydrogen ion generated from the electrolytic reaction on ELID coolant were considered to produce corrosion surfaces with pitting on the ferrous workpiece material. This modified surface was considered to weaken the structural strength of crystal grain boundaries, which reduced the influence of crystal grain boundaries for cutting marks. Also, this chemical reaction was considered to change the extreme surface characteristic to brittleness, which improved the cutting performance and the burr height on the ferrous workpiece material.
(4) Minute ferrous chips were effectively discharged by electrostatic force.

Many assumptions and hypothetical explanations were made in order to explain observed phenomena during cutting experiment using ion-shot coolant system, Figure 16. Some of assumptions made in this study may be susceptible to a misled understanding of the mechanism. However, these would be worth serious considerations for further investigation.

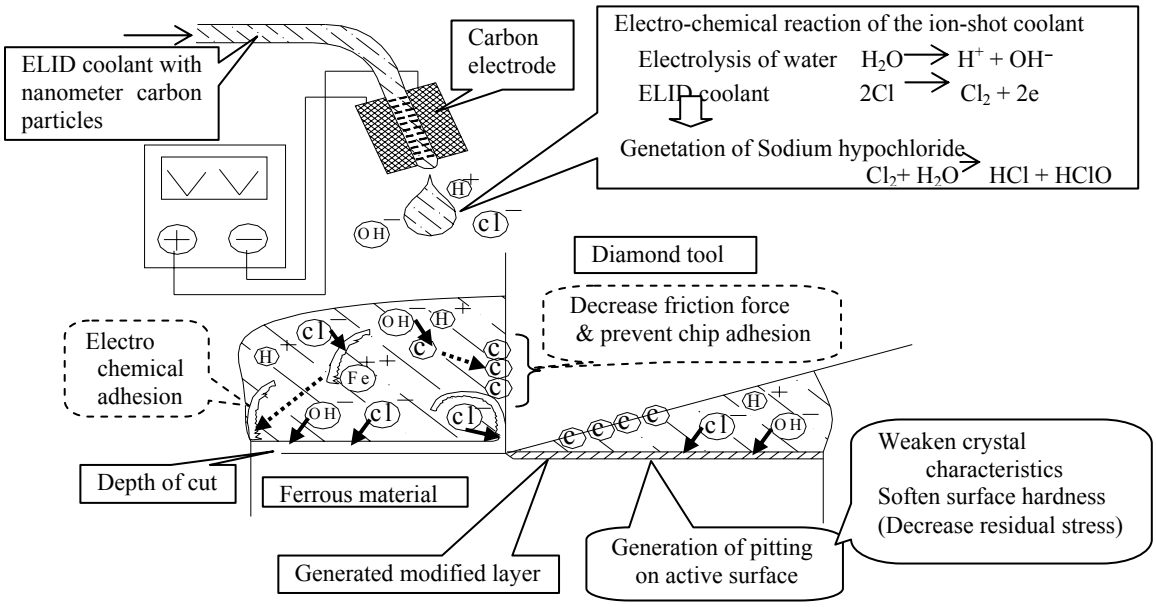


Fig. 16 : Schematic of the hypothetical mechanism for the ion-shot coolant system.

5 Acknowledgement

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