# Liquid Nitrogen의 감찰 효과
# The Lubrication Effect of Liquid Nitrogen in Cryogenic Machining [II]

## 공구 마모에 의한 마찰 계수 이론적 전개
## Part 2: Tool Wear and Chip Microstructures

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## Abstract

This paper presents some indirect physical evidences indicating that reduced friction occurs in an economical cryogenic machining process, in which LN2 is applied selectively in well-controlled jets to the localized cutting zone. These evidences include cutting force components, tool wear rate and chip morphology. LN2 reduced the tool wear rate to a great extent and elongated the tool life up to four times compared to emulsion cooling. The friction reduction was further reflected in larger shear angle and less secondary deformation in the chip microstructures. This study also found that the effectiveness of LN2 lubrication depends on the approach how LN2 is applied.

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## 1. Introduction

Generally, lubricants can be broadly defined as materials which are used for one or more of the following purposes: to reduce friction, to prevent wear, to prevent adhesion, to aid in distributing the load, to cool the moving elements, and to prevent corrosion [1]. LN2 is well known for its cooling power due to its cryogenic temperature. We would like to see how it will affect the friction in the cutting process and the tool wear. Unfortunately, many factors are involved in an actual cutting process, the friction on the tool-chip interface cannot be measured directly. Therefore we will rely on indirect evidence to support the claim of lubrication effect by LN2. Cutting forces may provide some clue, as friction force is playing a role in the cutting process. Tool wear is another, lower friction in the cutting process should result in less wear to the tool. Then the chip, the workpiece material after the machining process, has been subject to some deformation due to the friction in the cutting process, should have some residual trace indicating the level of friction it has been subjected to. It seems cutting forces, tool wear, and chip morphology can provide indirect physical evidences to verify that friction was reduced by LN2 in cryogenic machining when compared to dry cutting.

The improved tool life in cryogenic machining has been mostly attributed to the cooling effect of LN2 because lower temperature reduces hot softening of the tool and enhances the tool hardness for wear resistance. Yet no investigation have been attempted to reveal the possibility of lubrication effect by LN2 in metal cutting processes and to maximize the lubrication effect to a full extent in the tool life improvement.

Since LN2 is so different in nature from conventional cutting fluids, a new vision must be used to introduce the lubrication effect of LN2 to cryogenic machining. In order to make LN2 effective as a lubricant, an adequate design for applying LN2 to metal cutting has to be developed. An economical cryogenic machining process developed by Hong [2] has a unique way of delivering LN2 to the tool-chip interface. Through a specially designed nozzle, this process provides a possibility to achieve the LN2 lubrication effect. However, there is a need to collect evidences to prove the existence of lubrication in cryogenic machining.

This paper will emphasize on the indirect physical evidence involved in actual cryogenic machining. Cutting forces will be measured, tool wear will be examined, and chip will be inspected during or after the machining tests.

## 2. Experiment Result and Discussion : Tool Wear

One major purpose for using a lubricant in the metal cutting process is to reduce tool wear, and hence improve tool life. In a cryogenic cutting, LN2 achieves the tool life improvement by reducing the tool-chip interface temperature to enhance the tool resistance against various wear mechanisms and by producing a lubrication effect to reduce the friction on the tool-chip interface. Therefore a charting of the tool wear development in cryogenic cutting process can demonstrate the frictional behaviors properly.

Tool wear is generated in a cutting process in two distinct forms, namely, crater wear and flank wear. The crater wear occurs in a form of crater on the tool rake face, and results from the friction of the chip flowing along the tool face. The flank wear produces a wear land on the tool flank, and is formed by the rubbing action of the newly generated work surface.

Based on an international standard on tool wear and tool life testing [3], the crater wear and flank wear for turning operations can be represented by the maximum depth of the crater valley, *KT*, and by the maximum width of the flank wear land, or *VBmax*, respectively. In the current study, a dial indicator with a resolution of 0.0127 mm (or 0.0005 in) was applied to measure the crater wear by using a needlepoint tip to reach the deepest point of the crater valley. A tool microscope (from Kennametal Inc.) was used to measure the flank wear. A tool insert is considered to fail if either *KT* becomes greater than 0.136mm (rake failure) or *VBmax* greater than 0.610mm (flank failure), whichever comes first.

Figure 1 and 2 show the developments of the rake crater depth *KT* and flank wear width *VBmax* for cutting Ti-6Al-4V at a surface cutting speed of 1.5m/sec. The dry cutting undergoes a catastrophic jump with the rate of both the flank wear and crater wear at the later phase of the tool life span. This may be due to the intense tool-chip interface temperature produced in the dry cutting, which makes the titanium chip strongly adhesive and diffusive to the tool rake, leading to a rapid blunting of the tool edge. The blunted tool edge reduces the effective flank clearance angle, resulting in a flank-work contact of high normal stress and friction, therefore, an accelerated flank wear, as also observed in [4].

Yet for cryogenic cuttings of Ti-6Al-4V either with primary nozzle on or with 2 nozzles on , the rake crater depth *KT* and flank wear *VBmax* approach the tool failure criteria line *KT*=0.136mm or *VBmax*=0.610mm only gradually. It can also be found, from a comparison of the Figure 1 and 2, that the tool rake fails prior to the flank failure for dry cutting, while the cryogenic cuttings result in a very slow rate of the rake crater wear, leading to an considerably earlier flank failure than the tool rake. This is also true for cutting speeds of 1.0m/sec, 2.0m/sec and 2.5m/sec, as demonstrated by our cutting tests of full tool life charted in Figure 3.

The significantly reduced rate of rake crater wear for the cryogenic cuttings with primary nozzle on alone also serves as evidence of the LN2 lubrication effect by the LN2 jet on the tool rake. Since the extended tool life is determined by the reduced rate of the tool flank wear for cryogenic cutting, the application of an additional LN2 jet directly to the tool flank (i.e., 2 nozzles on) has also led to a significantly further improvement in the flank life, due to the enhancement of the cooling effect by the LN2 jet from the secondary nozzle.

For the dry cutting operations of AISI1008, the flank always fails prior to the tool rake, and for cryogenic cutting of this material no essential rake crater wear was observed. Therefore, the tool failure is determined exclusively by the tool flank wear. Figure 4 shows the development of the tool flank wear for cutting AISI1008 at a surface speed of 8m/sec. Although the work cooling results in a lower maximum temperature on both the tool rake and flank than the chip cooling, it produces a high rate of the flank wear than the latter. This may be due to the fact that the primary deformation zone is also cooled overly by the work cooling. Because of the strong temperature dependency of AISI1008 yielding strength, the overly cooled primary deformation zone makes the work more resistance to shearing, producing considerably increased cutting force, which corresponds to a larger normal and friction force on the tool flank. This considerably increased cutting force will partially cancel the cooling effect by LN2 on the tool flank, which enhances the tool toughness against the abrasive friction. The cryogenic cutting with primary nozzle on , although producing a higher temperature on both the tool rake and flank than the work cooling, leads to a significantly reduced rate of the flank wear. This may be because the lubrication effect by the primary LN2 jet on tool-chip interface tends to prevent an essential rake wear (either rake crater wear or rake edge wear), which helps to maintain a sharp cutting edge, reducing the friction of the newly cut workpiece surface against the tool flank.

## 3. Experiment Results and Discussion
## : Chip Microstructures

In a cutting process, the chip is formed by removal of a material layer from the workpiece. This chip forming process includes two steps. (1).The formation of the chip starts in an area called primary deformation zone, which extends from the tool cutting edge to the junction between the surfaces of the chip and workpiece, and is characterized by a heavy shear deformation. (2).The chip slides on the tool rake face with a high normal load, undergoing a heavy friction by the tool rake face and resulting in a secondary deformation beneath the chip face which is in contact with the tool rake face. The heavy shearing in the primary deformation zone and the heavy friction in the secondary deformation zone will change the morphology of the chip grains tremendously. The primary deformation produces distinguishable parallel slip lines of the deformed material grain throughout the chip thickness while the secondary deformation leads to a further bending of the slip lines in a shallow layer of the chip, which is adjacent to the tool face. Therefore, a microscopic inspection on the chip structure provides an approach to tracing into the tool-chip friction. Obviously, the larger the friction on the tool-chip is, the thicker is the zone that is influenced by the friction. Furthermore, the friction on the chip also damps the chip flow on the tool face and therefore tends to increase the slip line angle [5]. These facts justify an evaluation of the tool-chip friction based on the slip line angle of the chip body and on the thickness of the secondary deformation zone. Since both the primary and the secondary deformations are plastic in nature, it suffices to perform the microscopic inspection on the chip samples that are collected after the cutting process.

In this study, the metallurgic micrograph technique has been used to inspect the microscopic features of the chip samples. In order to obtain a high quality metallurgical micrograph that reflects the chip microstructure clearly and accurately, the chip face influenced by the tool-chip friction was perpendicularly oriented to the viewing surface. For this purpose, the chip was encased firstly in an epoxy resin at room temperature to obtain two-dimensional rectangle faces. After the chip-embedded resin was cured fully, it was hot-mounted in a ruling model with Bakelite powder under a pressure of 4200PSI and a temperature of 150o for about 20 minutes.

The pre-treatment process of the specimen consisted of a four-stage manual grinding with the series of water-lubricated papers. The direction of grinding was rotated by 90o with each change of the abrasive paper grade so that the removal of the previous grinding scratches was well guaranteed. Excessive grinding at any grade of abrasive paper was avoided because it can cause a subsurface deformation that would leads to significant artifacts and not be eliminated by succeeding grades of abrasive paper. The grinded specimen was then polished by using an aluminum slurry with a 0.3-micron grain size in water on medium-nap cloth and by using a BUEHLER polishing machine at low speed. This eliminated an extra stress layers on the specimen surface so that a scratch-free surface was obtained. In order to achieve a clear specimen surface, a water polishing without any other abrasives media was added was performed, which lasted 3 to 5 minutes.

The specimen was etched using a Nital solution (4ml HNO3, 100ml ethanol) for 30 to 50 seconds at room temperature. With this chemical treatment, the sharpness and the contrast of the microstructure morphology were found to be in high resolution even under 1000X magnification. A metallurgical microscope was used to photograph the specimens microstructure under a bright-field illumination with a green color filter.

Figure 5 (a) and (b) show the chip microstructures (with a magnification 200X) for a dry cutting and cryogenic cutting of AISI1008 at a cutting speed of 6m/s, respectively. The cryogenic cutting was performed by cooling the tool rake ( primary nozzle on ). The slip lines that occur at the shearing plane can be seen clearly throughout the chip thickness for both the dry and cryogenic cuttings. For the dry cutting, the grain structure is deformed severely, compared to the cryogenic cutting. The slip line angles for the cryogenic cooling is approximately 48o, smaller than that for the dry cutting (57o). Correspondingly, the reduced slip line angle for the cryogenic cutting leads to a reduced thickness of the chip body. More importantly, it can be seen that the cryogenic cutting results in a reduced thickness of the secondary deformation zone.

Figure 6 (a) and (b) show the chip microstructures for a dry and a cryogenic cutting of Ti-6Al-4V at a cutting speed of 1.5m/s, respectively. The cuttings were performed with a feed of 0.25 mm (0.01 in.) and a cutting depth of 1.27 mm (0.05 in.). For the cryogenic cutting, LN2 was applied to both the tool rake and flank ( 2 nozzles on ). The slip line angle for the cryogenic cutting is 37o, lower than 54o for the dry cutting. The significantly reduced slip line angle has decreased the chip thickness in the cryogenic cutting. The thickness of the secondary deformation zone for the dry and cryogenic cutting is 34 *m* and 17 *m*, respectively.

The reduced slip line angle, chip thickness and secondary deformation in cryogenic cutting of these two materials served as a evidence of the reduced friction on the tool-chip interface, implying a lubrication effect of LN2 in cryogenic machining which is expected by applying LN2 in fine jets of high pressure to the localized tool faces.

## 4. Conclusion

From the observations made on tool wear development and chip microsructure, which are critical behaviors in a cutting process and influenced by LN2, the following conclusions can be derived;

(1) Tool wear rate, which is determined partially by the friction on the tool face, has been reduced by a margin, which is dependent on the cooling approach. The application of a LN2 jet to the localized tool rake face is essential for reducing both tool rake and flank wear.

(2). The thickness of the chip body and the secondary deformation zone, the slip line angle, which are influenced mainly by the friction on the chip by the tool face, can be reduced distinguishably in a cryogenic cutting, compared to a dry cutting.

(3). The reduced friction on the tool-chip interface in cryogenic cutting, as demonstrated by these experimental observations, may serve as an indicator of the lubrication effect of LN2 in the cryogenic machining, which uses the cooling approach proposed in this paper.

## 5. References

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[5]. ANSI/ASME B94.55M-1985, Tool Life Testing with Single-Point Turning Tools, sponsored and published by ASME.

# 저 자 소 개

전성찬 : Cornell Univ.에서 석사, Columbia Univ.에서 박사 학위를 취득하였으며 현 Columbia Univ. 에서 post doctoral research fellow 로 재직 중임. 주 관심 분야는 MEMS, cryogenic machining, re-solidification 에 의한 표면 처리

정우철 : Columbia Univ.에서 석사, 박사 학위를 취득함. 주 관심 분야는 metal cutting.

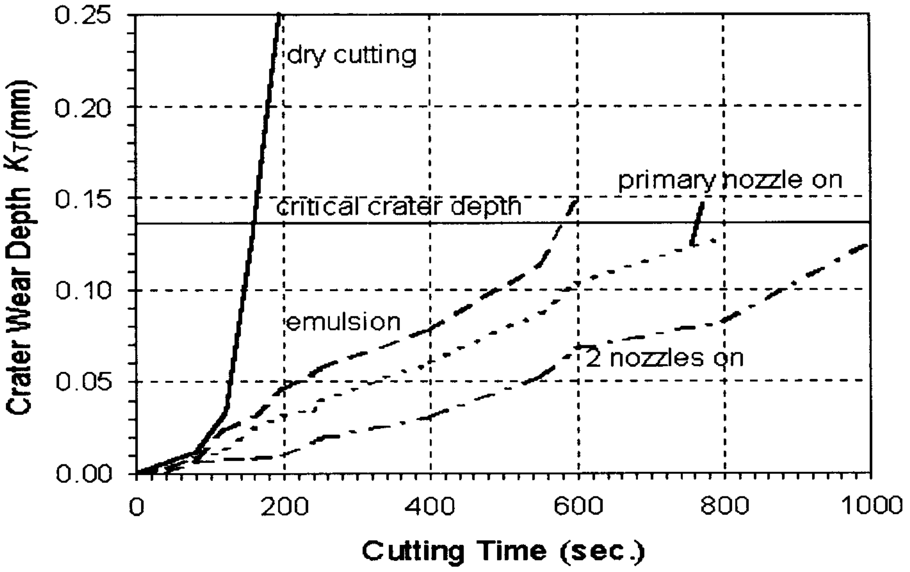


Figure 1 Crater Wear for Cutting Ti-6Al-4V at 1.5mm/s

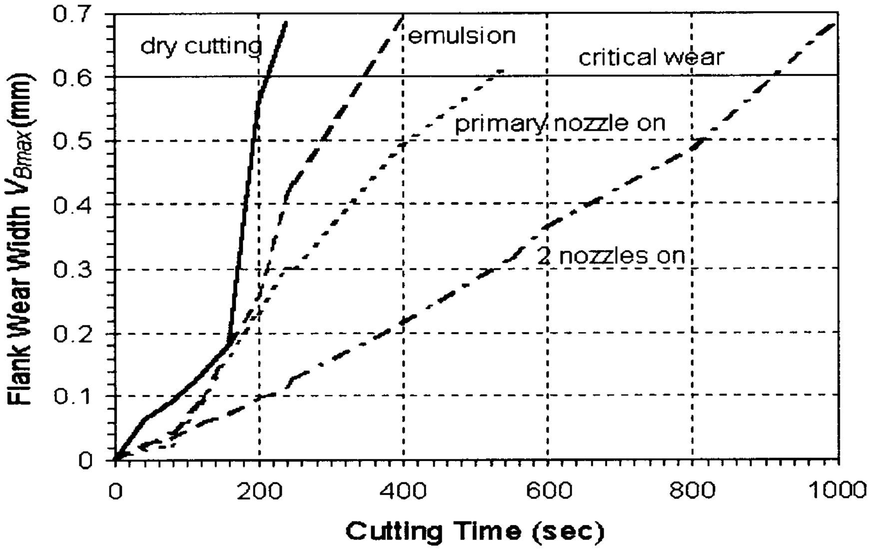


Figure 2 Flank Wear for Cutting Ti-6Al-4V at 1.5mm/s

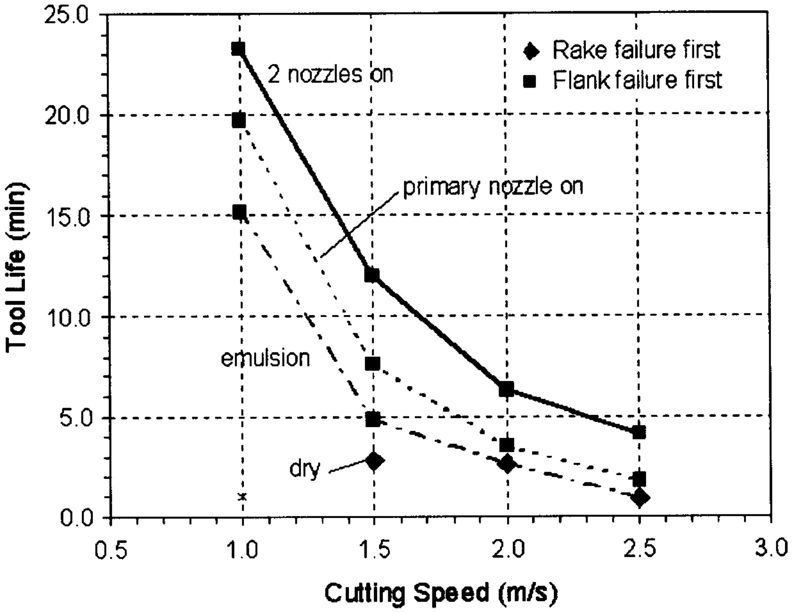


Figure 3 Tool Life for Cutting Ti-6Al-4V

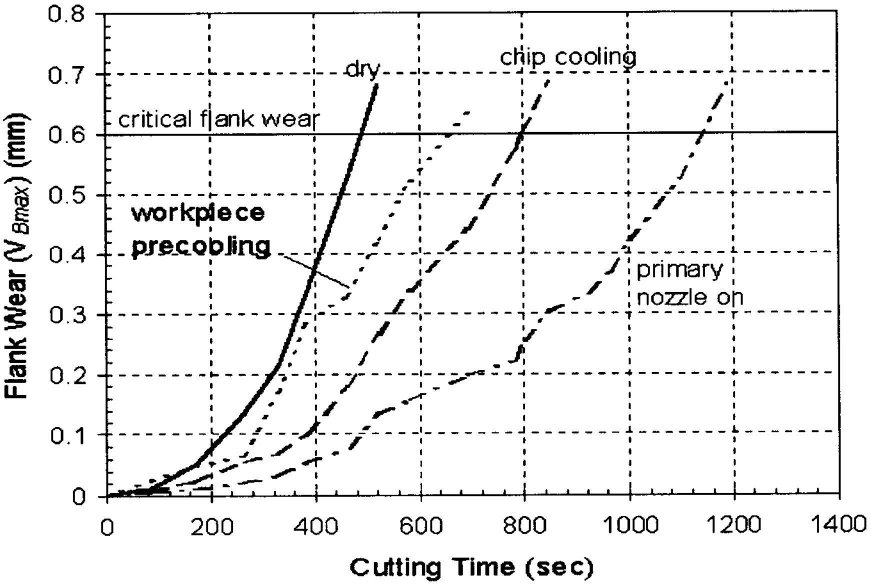
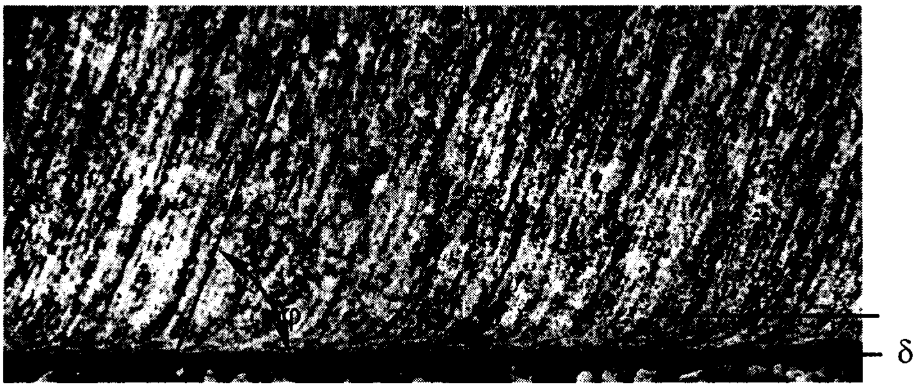
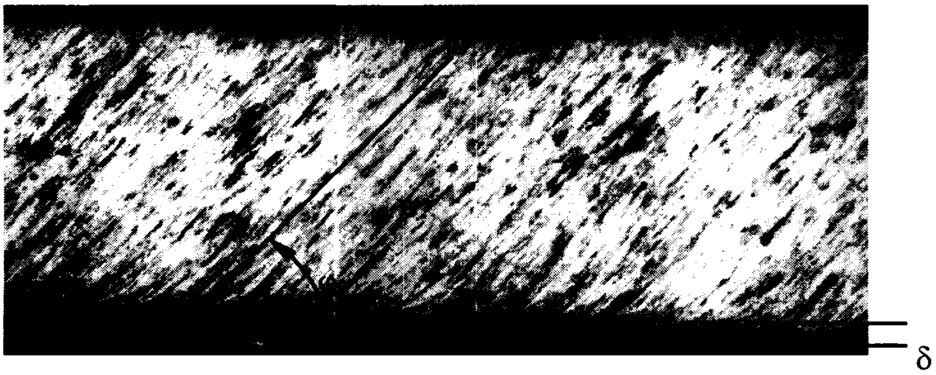


Figure 4 Flank Wear for Cutting AISI1008

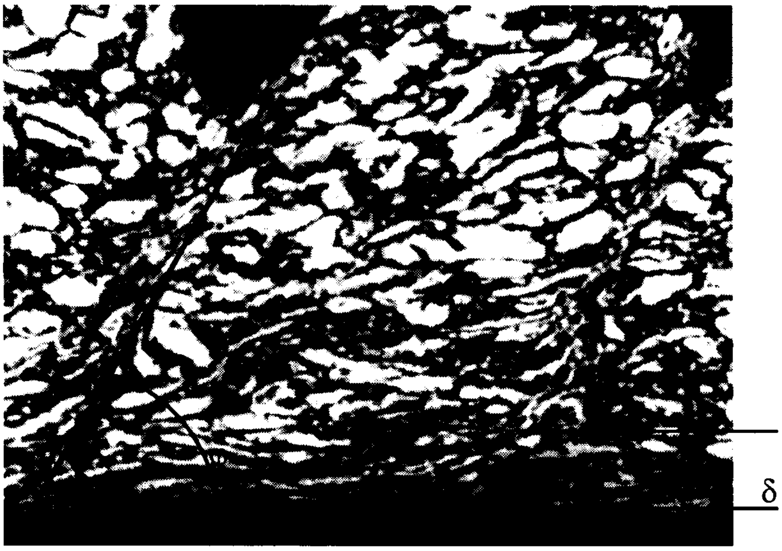


(a) Dry cutting

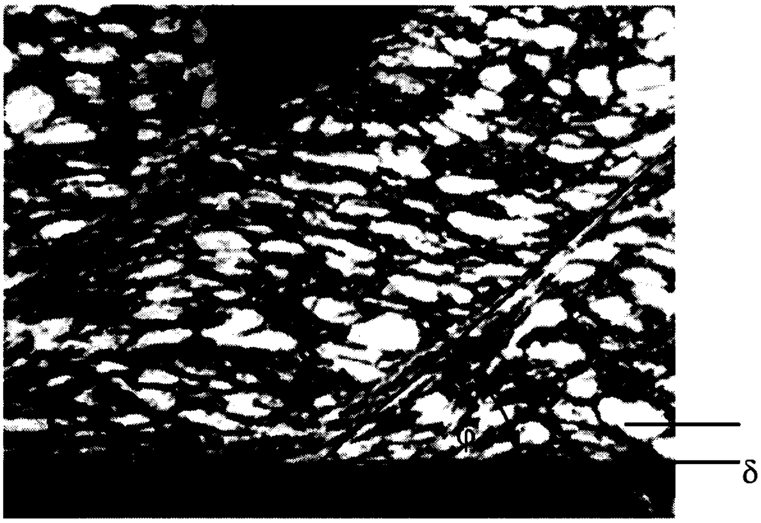


(b) Cryogenic cutting

Figure 5 Chip Microstructure for Cutting AISI1008 at 6m/s



(a) Dry cutting



(b) Cryogenic cutting

Figure 6 Chip Microstructure for Cutting Ti-6Al-4V at 1.5m/s