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

물리적 현상에 의한 절삭력
Part 1: Cutting Force Component with Physical Evidences

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Abstract

Machinability improvement by the use of liquid nitrogen in cryogenic machining has been reported in various studies. This has been mostly attributed to the cooling effect of liquid nitrogen. However, No study has been found in discussion on whether liquid nitrogen possesses lubrication effect in cryogenic cutting. In machining tests, cryogenic machining reduced the force component in the feed direction, indicating that the chip slides on the tool rake face with lower friction. This study also found that the effectiveness of LN2 lubrication depends on the approach how LN2 is applied regarding cutting forces related.

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1. Introduction

Cryogenic Machining, which uses liquid nitrogen (LN2) as a coolant, is an environmentally safe alternative to conventional machining, and has been explored since the 1950s. Scattered reports disclosed the advantages of cryogenic machining, such as improving tool life, improving machined surface finish, and reducing cutting forces[1-7]. After 1980s, new trends such as high-speed cutting, concern for the environment, and employee health awareness renewed the interests in cryogenic machining, as reviewed in [8]. There are reasons that people do not consider LN2 as a lubricant. The lubrication mechanisms of conventional cutting fluid include hydraulic, boundary, or extreme pressure lubrications. By no means LN2 falls into any category of them. LN2 has a very low viscosity and evaporates quickly into gaseous state. That makes it very difficult, if not impossible, to form a nitrogen film between the tool and the chip as in hydraulic lubrication. LN2 does not possess polar property either, certainly cannot act as an additive in boundary lubrication. Although at extremely high temperature LN2 may react with titanium to form *TiN* (Titanium Nitride), a low friction substance, nitrogen is a relatively inert medium under a temperature reachable in most metal cuttings. No chemical reaction is expected to form low friction derivatives, as the chlorines or sulfur in extreme pressure lubrication.

2. Geometric Relationship Approach

Figure 1 shows the force diagram in a three-dimensional space where the friction and normal forces are resolved into *Rf*, *Pf* and *Rn*, *Pn*, respectively. *Rf*, and *Rn* can be evaluated from the cutting and feeding force, while *Pf* and *Pn* can be expressed in terms of thrusting and cutting force components. Then the friction force can be written as:

$$F = R_f \cos\eta + P_f \sin\eta$$

Similarly the normal force can be represented as follows:

$$N = R_n \cos i - P_n \sin i$$

The partial components *Pf* and *Pn* can be expressed in terms of the cutting force *Fcutting*, thrusting force *Fthrust* and inclination angle i as follows

$$P_f = F_{thrust}\cos i + F_{cutting}\sin i$$

$$P_n = -N''\sin i$$
$$= -(F_{cutting}\cos i - F_{thrust}\sin i)\sin i$$

where, N is projection component on plane x-y. *Rf* and *Rn* can also be expressed in terms of the feeding force *Ffeed*, cutting force and the normal rake angle as

$$R_f = F_{feed}\cos\gamma + F_{cutting}\sin\gamma - P_f\sin i\sin\gamma$$

$$R_n = F_{cutting}\cos\gamma - F_{feed}\sin\gamma - P_f\sin i\cos\gamma$$

In the case of a small rake and inclination angle, the last term in Equation (13) and (14) can be ignored. After *Rf, Pf, Rn, Pn* in Equation (9) and (10) are substituted by Equation (11)~ (14), the friction force and the normal force can be obtained as follows

$$F = (F_{feed}\cos\gamma + F_{cutting}\sin\gamma)\cos\eta + (F_{thrust}\cos i + F_{cutting}\sin i)\sin\eta$$

$$N = (F_{cutting}\cos\gamma - F_{feed}\sin\gamma)\cos i + (F_{cutting}\cos i - F_{thrust}\sin i)\sin^2 i$$

3. Experimental Setup

Cutting tests were performed on a CNC turning machine of 30 HP (22.4 KW). The CNC controller is capable of keeping the surface cutting speed constant with the changing surface diameter by automatically regulating the RPM speed of the spindle. For cryogenic cutting tests, LN2, with a pressure of 2.4Mpa (350 psi), was supplied through a thermally isolated delivery line, which was a thin stainless steel inner tubing jacketed by an outer tubing with vacuum drawn between them. This delivery line has been used extensively in our past research [8,11,12] and is capable of supplying a stabilized LN2 flow with an average volumetric flow rate as low as 0.9 litter/min (0.2 gal/min).

As a base for comparison, cutting tests on dry running or emulsion-cooling were also performed. The emulsion used in the testing was a general-purpose synthetic emulsion diluted to 6% in water. It is free of sulfurized or phosphorized substances, but mixed with extreme pressure additives such as chlorinated paraffin. Therefore, boundary lubrication or extreme pressure lubrication[13] can be expected to become effective, depending on the normal load generated on the tool-chip interface. The emulsion was supplied through the built-in coolant system of the machine tool and by flooding the cutting area as common practice in industry.

The two work materials tested are Ti-6Al-4V, a titanium alloy, and AISI1008, a low carbon steel, which demonstrate various mechanical properties under a low temperature, and will described in the subsequent sections

Rhombic shape tool inserts are used with a tool holder MCLNL-164C (from Kennametal Inc.). The geometry and grade of each insert were selected as suggested by tool makers for each material and will be described later respectively.

For cryogenic cutting, a new LN2 delivery device as shown in Figure 2 was used. It provides two nozzles, namely, the primary nozzle which is built into the obstruction-type chip breaker, and the secondary nozzle which is located inside the clearance of the tool flank and workpiece surface. For an insert with a grooved chip breaker, which are used mainly for machining of carbon or alloy steels, the actual LN2 delivery nozzle is a modified design of what is illustrated in Figure 2. For such inserts, the grooved tool rake makes up a natural LN2 channel to the tool-chip contact area with a LN2 supply cap that sits on the tool face and is connected to the LN2 delivery line. The most important requirement for a LN2 nozzle design is to allow for LN2 jet to be delivered with high pressure or velocity to the sub-millimeter cutting zones adjacent to the tool cutting edge.

In our previous research[11,12], two cooling strategies, namely, the localized chip cooling and workpiece cooling were already proposed for the purpose of chip breakability improvement in machining a low carbon steel, AISI1008. In this paper these two cooling strategies will also be studied from a tribological viewpoint together with the new cooling approach presented.

4. Experiment Result and Discussion

LN2 as a coolant will alter mechanical properties of the workpiece materials, and usually influence the shearing force on the primary deformation zone, therefore changing the friction on the tool-chip interface due to a corresponding change in the normal load. One the other hand, LN2 as a lubricant will also directly modify the inherent frictional behavior on the tool-chip interface and usually reduce the friction force. Therefore an investigation into the force components can provide a qualitative evaluation of the effect of LN2 on the frictional behaviors in cryogenic cutting.

In the current study, the force components, *FC*, *FF*, *FT* , in the direction of cutting, feeding, and thrusting, respectively, were measured using a Kistler 3D dynamometer, which feeds the signal to a data acquisition system to log the force data in a form of time series. Digital smoothing techniques were utilized to eliminate the electronic or mechanical fluctuations contaminating the logged data. As the three force component measured will be definitely shifting with the tool wear development, a fresh tool insert was used for each cutting.

5. Testing Results for Ti-6Al-4V

All the cutting tests on this material were performed for outer surface turning. The feed and the depth of cut were 1.27mm and 0.254mm, respectively. Due to the super-cooling property of LN2, the high surface cutting speed was allowed, which exceeded the industry suggested speed limit (1.0ms) and ranged from 1.0m/s to 2.5m/s. The cutting tool was an uncoated CNMA 432-K68 flat insert from Kennametal Inc. (or equivalently ISO K05-K20, M10-M20), which is made of the tungsten carbide-cobalt alloy (WC/CO) and has been the leading choice adopted in aerospace or airplane industry for titanium machining.

Three cryogenic cooling strategies have been tested, that is, primary nozzle on for cooling the tool rake, secondary nozzle on for cooling the tool flank, and two nozzles on for cooling both tool faces, and compared to emulsion-flood cooling.

Figure 3, 4, 5 show the cutting, thrusting and feeding forces versus the surface cutting speed for Ti-6Al-4V machining, respectively, with the emulsion as a basis for comparison. Obviously the additional tool flank cooling (two nozzles on) does tend to increase the cutting fore, compared to the tool rake cooling alone (primary nozzle on). But it is interesting to note all of the cryogenic cooling strategies lead to only a slightly increased cutting force although the mechanical properties of Ti-6Al-4V, such as its shear yielding strength or ductility, can vary significantly with the temperature[12, 13]. For example, at the surface cutting speed of 1.0m/s, simultaneous cryogenic cooling of the tool rake and flank has increased the cutting force component only by less than 6%, in comparison with the emulsion cooling. This is mainly because that the Ti-6Al-4V workpiece is not exposed to directly to the LN2 cooling and the temperature on the primary deformation zone is not reduced significantly due to a poor thermal conductivity of the Ti-6Al-4V.

The thrusting force component is mainly contributed by the plastic plowing action of the tool flank against the newly cut surface of the workpiece, which occurs when the tool cutting edge is not absolutely sharp. The thrusting force changes with the surface cutting speed less drastically than the cutting force. All the cryogenic cooling strategies produces a smaller thrusting force compared to emulsion cooling. The secondary nozzle on and two nozzles on cooling strategies in cryogenic cutting have both a lower thrusting force than the primary nozzle on cooling. This means that the flank cooling exerts a more significant influence on the thrusting force than the rake cooling. The reduced thrusting force in a cryogenic cutting may imply that the cryogenic cooling on the newly cut surface of the workpiece suppress the Ti-6Al-4V plasticity due to a low temperature.

The feeding force component in an oblique cutting operation is more closely related to the frictional force on the tool-chip interface [14]. As shown in Figure 5, the feeding force component can be reduced significantly in cryogenic cutting if the tool rake is cooled, as in the case of the primary nozzle on or two nozzles on cooling strategies. Cooling the tool flank alone with secondary nozzle on will not change the feeding force substantially. This implies that the tool-chip interface friction can be reduced considerably by delivering a LN2 jet to the tool-chip interface.

6. Testing Result for AISI1008

Because AISI1008, as a low carbon steel, has mechanical properties highly dependent on temperature, the use of liquid nitrogen can significantly influence the chip-tool contact length and mechanical interactions on the tool-chip interface, therefore change the frictional behaviors in the cutting zone. The chip cooling, workpiece pre-cooling, which were originally used for improving chip breakability [9,10], and the tool rake cooling (primary nozzle on) have been tested in the current study to demonstrate the effect of LN2 on the cutting force components and compared with dry cutting, the common cutting operation for this material in the industry.

The cutting tests on AISI 1008 were performed using a depth of cut of 1.5 mm and a feed of 0.254 mm. The cutting speed ranged from 4 m/s to 11m/s, and the tool insert was CNMA432-KC850 (with a flat rake), which is composed of a tri-phase coating (TiN-TiCN-TiC) and cobalt-enriched substrate.

Figure 6 and 7 show the cutting force and feeding force components measured in AISI1008 cutting tests. Since workpiece pre-cooling influenced the workpiece without any cooling effect on the tool-chip interface, it has produced the highest cutting force component over the whole speed range used. This is attributable to the increased shearing strength of AISI1008 caused by the substantial cooling effect on the primary deformation zone. On the contrary, the cryogenic rake cooling (primary nozzle on) did not lead to a considerable increase in the cutting force component, compared to the dry cutting, because LN2 was applied only to the very localized tool rake without causing a substantial cooling effect to the workpiece material. Furthermore, it is interesting to note that the cryogenic rake cooling resulted in lowest feeding force component. This corresponds to a reduced friction on the tool-chip interface by a LN2 shooting to the tool face, implying a lubrication effect of LN2 on the tool-chip sliding contact.

7. Conclusions

From the observations made on the force components, which are critical behaviors in a cutting process and influenced by LN2, the following conclusions can be derived.

(1). The use of LN2 generally increases the force component in the cutting direction, due to the temperature-dependent mechanical properties of the workpiece materials. But the unfavorable increase in the cutting force components strongly depends on the cooling approach used and can be minimized by applying LN2 only to the localized tool faces.

(2). The feeding force component in cryogenic machining of AISI1008 and Ti-6Al-4V can be always reduced substantially by applying a LN2 jet to the take face, indicating a reduced tool-chip friction, which contribute to the feeding force.

8. References

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저자 소개

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 표면처리

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

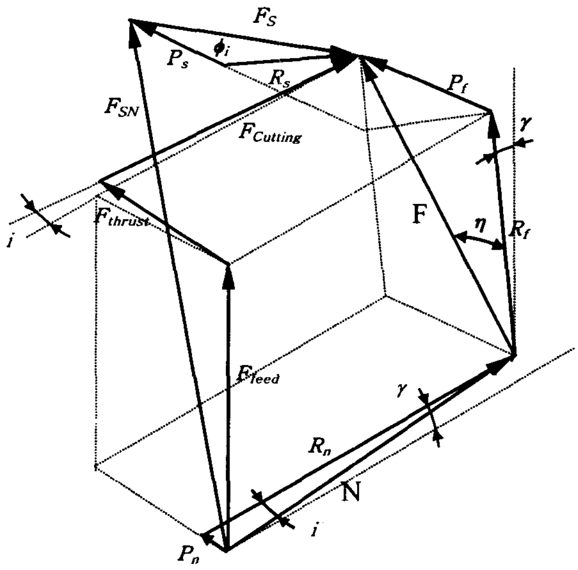

Figure 1 The Force Diagram in Oblique Cutting Model

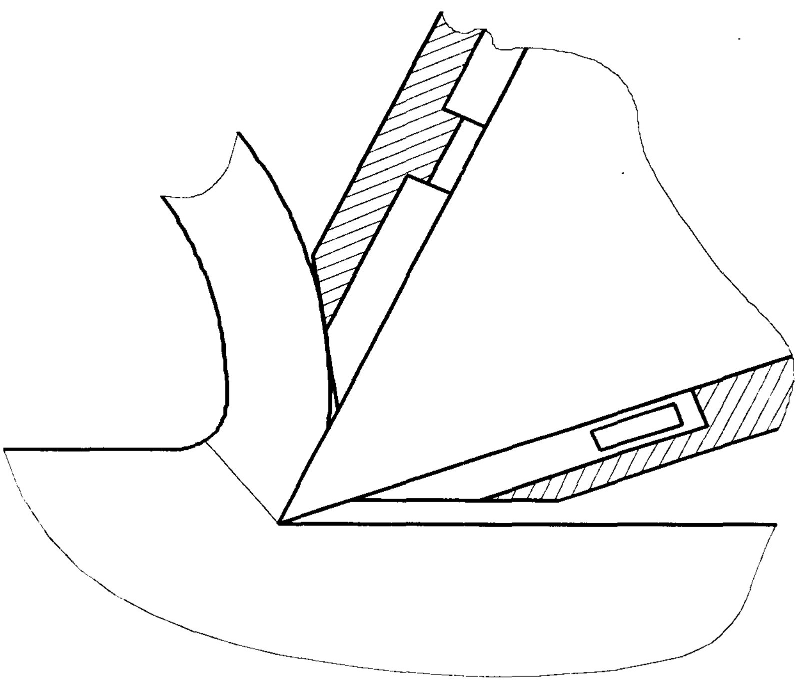

Figure 2 Effect of LN2 on Cutting Zones

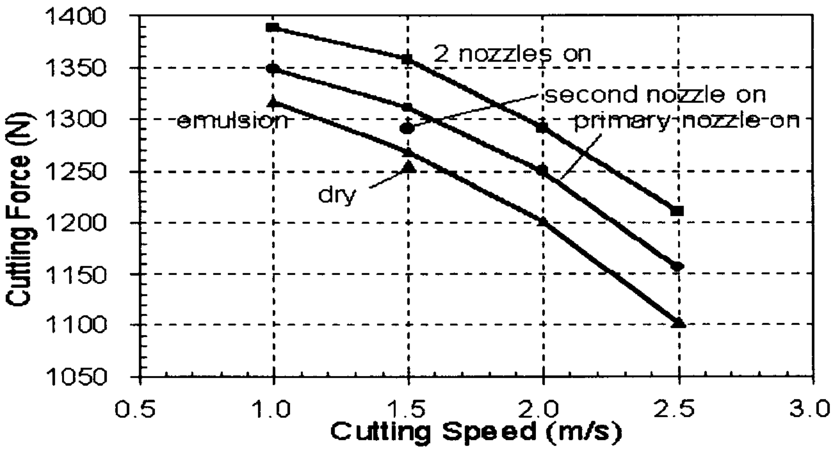

Figure 3. Cutting Force versus Speed for Ti-6Al-4V

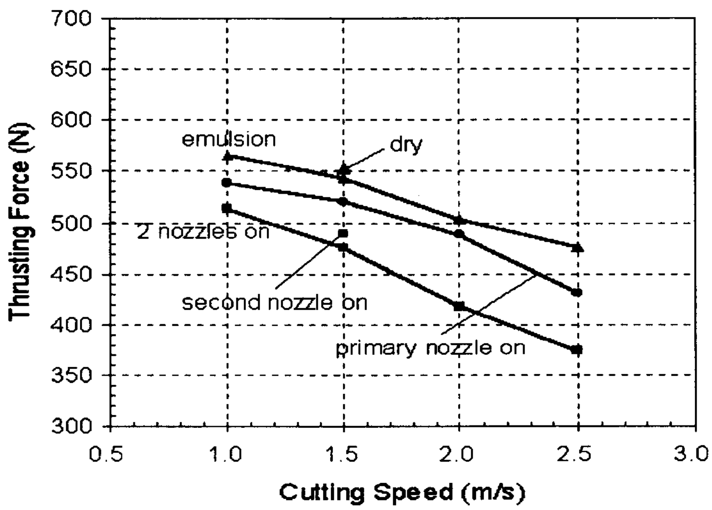

Figure 4. Thrusting Force versus Cutting Speed for Ti-6Al-4V

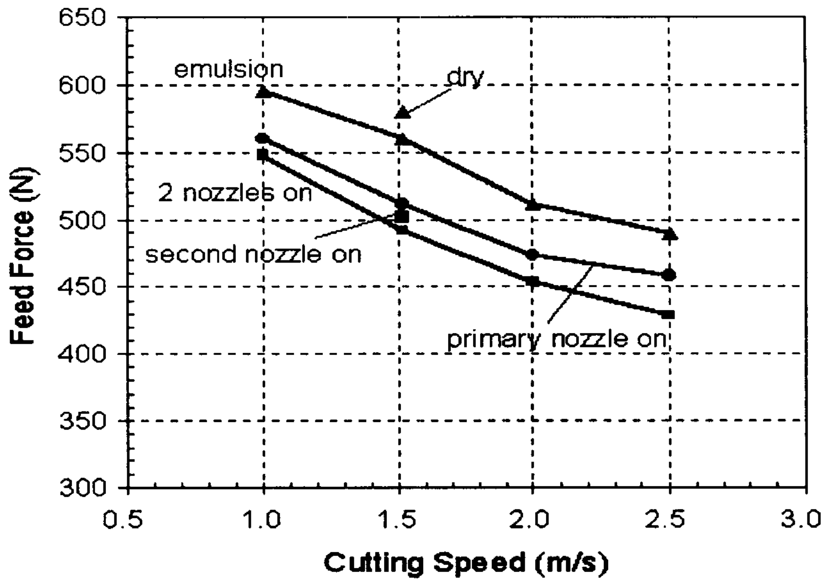

Figure 5. Feeding Force versus Speed for Ti-6Al-4V

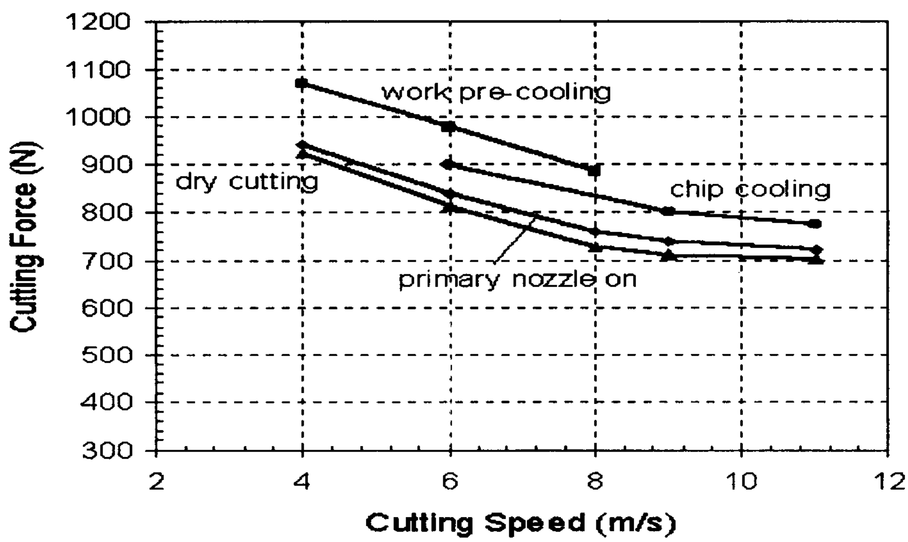

Figure 6. Cutting Force versus Speed for AISI1008

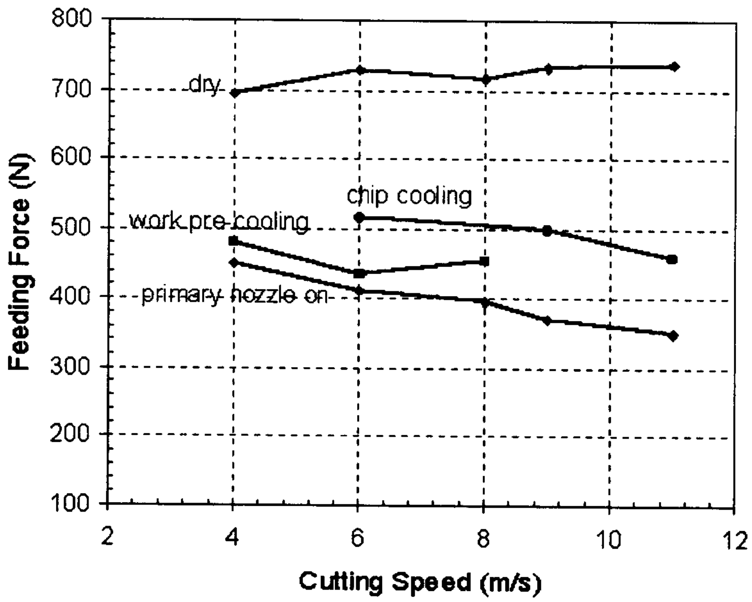

Figure 7 Feeding Force versus Speed for AISI1008