공구와 칩 사이에서의 Liquid Nitrogen의 마찰 효과

Friction on the Tool-chip Interface Under Liquid Nitrogen Cooling

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Abstract

A cutting fluid can improve machining quality and tool life by maintaining the tool toughness and by providing a lubrication effect to reduce the friction between the chip and tool interface. Although liquid nitrogen as an environmentally safe coolant has been widely recognized in cryogenic machining, its function as a lubricant is plausible due to its chemical inertness, physical volatility and low viscosity. Since a reduced friction is a direct witness of the lubrication effect from a tribological viewpoint, this paper presents an evaluation of the apparent friction coefficient on the tool-chip interface in cryogenic cutting operations to prove and characterize the lubricity of LN2 in cryogenic machining. The mathematical approaches have been formulated to derive the normal and frictional forces on the tool-chip interface for the oblique cutting tests.

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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. Conventionally various cutting fluids have been used in cutting operations to sustain a proper machinability for most metal materials. A conventional cutting fluid, such as an emulsion, can be expected to improve tool life by reducing the temperature rise in the cutting area to maintain the tool toughness and by providing a lubrication effect to reduce the friction of the chip and work on the tool faces. This suggests that a conventional cutting fluid can serve as both a coolant and a lubricant in cutting operations. Liquid nitrogen (LN2) as an environmentally safe coolant has been widely recognized in cryogenic machining while its function as a lubricant is plausible due to its chemical inertness, physical volatility and low viscosity. Therefore, the tool life improvement in cryogenic machining, as reported widely in other researches[1-6], have been mainly attributed to the super-cooling effect of LN2 in a belief that almost all types of tool wear mechanism are governed by the tool-chip interface temperature and can be considerably reduced if the LN2 is properly applied to the cutting area. The cryogenic cooling principle in tool-chip interface is illustrated in Figure 1.

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.

From a tribological viewpoint, a reduced friction is a direct witness of the lubrication effect on a pair of interacting surfaces. This fact suggests that the friction on the tool-chip interface can better characterize the function of LN2 as a lubricant in a cryogenic cutting operation. Yet the friction on the tool-chip interface cannot be measured readily because of a complicated engagement of the tool with the workpiece material that is typical for a real-life industrial cutting process. Therefore, a mechanical model has to be formulated to derive the friction on the tool-chip interface from those cutting force components measured by an assembly of the toolholder and dynamometer.

2. Evaluating the Normal and Frictional Forces

Since the cutting force component are usually measured experimentally by a three dimensional dynamometer in the tool-in-use coordinate system [7], *i.e.* in the directions of cutting, feeding and thrusting for turning operations, resulting in three force components named cutting force *Fcutting*, feeding force *Ffeed* and thrusting force *Fthrust*, respectively, a mechanical model has to be formulated to derive the normal load and frictional forces from these directly measured force components. For an idealized orthogonal cutting, the normal and friction forces can be calculated readily from the cutting force measurements in terms of the rake angle in a two-dimensional hodograph [8].

In vector manipulation approach all forces are considered as a vector in x-y-z coordinate. The unit frictional force vector is defined as *eF* and the unit normal force vector is *eN* . The direction of the major cutting edge can be represented as a unit vector, *emajor*, and a unit vector *eminor* is also defined along the minor cutting edge. The schematic relations in oblique cutting are presented in Figure 2. The components of the unit major cutting edge vector *emajor* in x-y-z coordinate are

$$e_{major} = [\cos i, -\sin i, 0]^T \quad (1)$$

while the unit minor cutting edge vector *eminor* is identified. Conventionally, tool geometry is specified by an end cutting edge angle *Ce*, rake angle and oblique angle *I*. Angle *Ce** is the difference between the end edge angle *Ce* and the side edge angle *Cs* due to a tool rotation (*Ce** = *Ce* - *Cs*). Then angle can be calculated from.

$$\tan\lambda = \frac{\overline{AD}}{\overline{OA}} = -(\tan\gamma + \tan C_e{}^* \tan i)\cos C_e{}^* \quad (2)$$

Then the unit minor cutting edge vector can be represented by angle and *Ce** as follows

$$e_{\min or} = [\cos\lambda \sin C_e{}^*, \sin\lambda, \cos\lambda \cos C_e{}^*]^T \quad (3)$$

Thus, the unit normal force vector *eN* and the unit friction force vector *eF* can be calculated based on the emajor and emajor. The vector, *eN*, is perpendicular to the rake face. The unit normal vector, *eN*, to the rake face can be determined as the cross product of these two unit vectors, which are defined by the major and minor cutting edges.

$$e_N = e_{major} \times e_{\min or} \quad (4)$$

T$e_{major} - e_N - e_{F'}, e_{major} - e_N - e_{F'}$ can be calculated by the cross product of *eN* and *emajor* because the *eN* is already perpendicular to *emajor*. Therefore we have can be defined on the rake face to evaluate the unit vector eF and eF, and the local coordinate he frictional force occurs on the rake face in the direction of chip flow. A unit vector eF can be used to indicate the direction of the friction force. For the sake of convenience, a local coordinate,

$$e_{F'} = e_N \times e_{major} \quad (5)$$

Thus, the unit frictional force vector in local coordinate *eF local* can be represented by chip flowing angle .

$$e_{F\,local} = [\sin\eta, 0, \cos\eta]^T \quad (6)$$

Oe_F $e_{F\,local}$ $e_{major} - e_N - e_{F'}$ on the tool face can be denoted by *ex* - ey - ez and *emajor*, *eN*, and *eF* is evaluated in *ex* - *ey* - *ez* coordinate, asin local coordinate by the coordinate transformation. The local coordinate in ex - ey - ez coordinate can be represented from bviously, the unit vector

$$\begin{bmatrix} e_x' \\ e_y' \\ e_z' \end{bmatrix} = \begin{bmatrix} e_{major}^T \\ e_N^T \\ e_{F'}^T \end{bmatrix} \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} \quad (7)$$

and the transformation matrix [T] is

$$[T] = [e_{major}, e_N, e_{F'}]^T \quad (8)$$

Now obviously, *eF local* can be transformed to *eF* by [*T*].

$$e_{F\,local} = [T]\, e_F$$
$$e_F = [T]^{-1}\, e_{F\,local}$$
$$e_F = \left([e_{major}, e_N, e_{F'}]^T \right)^{-1} e_{F\,local} \quad (9)$$

With the unit vector *eN* for the normal force *N* and *eF* for the friction force *F* ready, the following equations apply

$$N = [F_{thrust}, -F_{cutting}, F_{feed}]\, e_N^T \quad (10)$$

$$F = [F_{thrust}, -F_{cutting}, F_{feed}]\, e_F^T \quad (11)$$

In geometric relationship approach Figure 6 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:

$$F = R_f \cos\eta + P_f \sin\eta \quad (12)$$

Similarly the normal force can be represented as follows:

$$N = R_n \cos i - P_n \sin i \quad (13)$$

3. Experimental Setup

Cutting tests were performed for both dry and cryogenic cutting of Ti-6Al-4V and AISI1018 on a 30HP (22.4kW), CNC turning machine. The CNC controller is programmed to keep the surface cutting speed constant by adjusting the RPM of the spindle automatically with respect to the work diameter. The cutting tool used for both of the materials is an uncoated CNMA432-K68 insert. For Ti-6Al-4V, the depth of cut and the feed are selected constantly as 1.27mm (0.05 inch), 0.254mm (0.01 inch), respectively, and the surface cutting speeds range from 1.0m/s, 1.5m/s, 2.0m/s to 2.5m/s. For AISI1018, the depth of cut is changed to 1.52mm (0.06 inch), while the surface cutting speed elevated to a range from 4m/s to 11m/2. To characterize the possible lubrication effect by LN2, different cooling approaches are tested for cutting Ti-6Al-4V, namely, (1) dry cutting (or emulsion cooled cutting), (2) cutting with the primary nozzle shooting LN2 jet to the tool-chip interface (primary nozzle on), (3) cutting with the simultaneous use of the primary and secondary nozzles (2 nozzles on). For all those cutting tests which were performed without activating the primary nozzle (such as in the case of dry cutting, emulsion cooled cutting), the primary nozzle (actually a modified chipbreaker) was still kept in place, but with its LN2 channel blocked, so that the same action of the chipbreaker on the chip flow was in effect for all the cutting tests.

4. Experiment Result and Discussion

The measured cutting force components in titanium machining were converted to the friction force and normal force. Figure 3 and 4 show the friction coefficients versus the cutting speed for cutting Ti-6Al-4V with different cooling conditions. Obviously, the application of the LN2 to the tool flank together with shooting a LN2 jet to the tool rake (2 nozzles on) can produce an additional lubrication effect to the cutting area, leading to more significant reduction in the friction coefficient, compared to the application of LN2 to the tool rake alone (primary nozzle on). Therefore, the lubrication effect depends considerably on the approaches of the LN2 delivery in cryogenic machining. The lubrication effect by LN2 for these cryogenic cutting approaches is due to the greatly changed material properties in the tool-chip contact area, which change a friction mechanism dominated by shearing and galling in the secondary deformation zone of the chip into one that is characterized only by pure sliding. This explains why an additional application of LN2 jet to the tool flank has produced a significant reduction in the friction coefficient at high cutting speeds. On the other hand, the application of LN2 jet to the tool-chip interface may have a tendency of increasing lubrication film by external high pressure between the chip and the tool rake. Therefore, it can be reasonably expected that the generation of a lubrication layer by the LN2 delivery pressure and the change in the material properties at low temperature are combined to reduce the tool-chip friction essentially, with the lubrication effect playing the dominating part.

Based on cutting force tests in AISI 1018 machining, the friction coefficient evaluated by the three analytical approaches are presented in Figure 5 and 6, where the friction coefficient for the emulsion cooled cutting operations is also included for comparison. Compared with the dry or emulsion-cooled cutting, all cryogenic approaches have reduced the friction coefficient considerably at high cutting speeds. Since the hardness and yielding strength for AISI 1018 can be drastically increased with a decreasing temperature, the chip abrasiveness against the tool rake can be considerably enhanced by the low temperature to an extent which overwhelms the positive change in the friction mechanism. This explains why an extra cooling to the tool flank can not necessarily reduce the friction coefficient for cutting AISI1018 at the lower cutting speeds, compared to the mere application of LN2 to the tool-chip interface alone (i.g. primary nozzle on).

There can be various mechanisms by which the application of LN2 influences the frictional behaviors in cryogenic machining. The application of LN2 tends to reduce the adhesion and chemical reactions between tool rake and chip face, therefore the chip may become less abrasive against the tool face. The substantially reduced tool-chip interface temperature in cryogenic machining can also help in attenuating the degradation of the tool rake, therefore maintaining the surface integrity of the tool rake even at high cutting speed.

In all the cutting tests for these two workpiece materials, the friction coefficient tends to decrease with the surface cutting speed. Since the tool-chip interface temperature increases with cutting speed, this tendency can be attributed to the decreased yielding strength of chip, which has lessened the asperity shearing of the chip and tool surface. Therefore, the high speed cryogenic machining can be a good approach to enhancing the lubrication effect of LN2.

5. Conclusion

Based on the observation of the frictional behaviors of the tool-chip interface in cryogenic cutting tests, the following conclusion can be drawn

(1). The friction coefficient in cryogenic machining can generally be reduced, depending on the LN2 injecting method.

(2). As long as LN2 is delivered to the tool-chip interface, the friction coefficient can be reduced significantly, compared to the dry or emulsion-cooled cutting operations, especially at high cutting speeds.

6. References

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저자소개

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

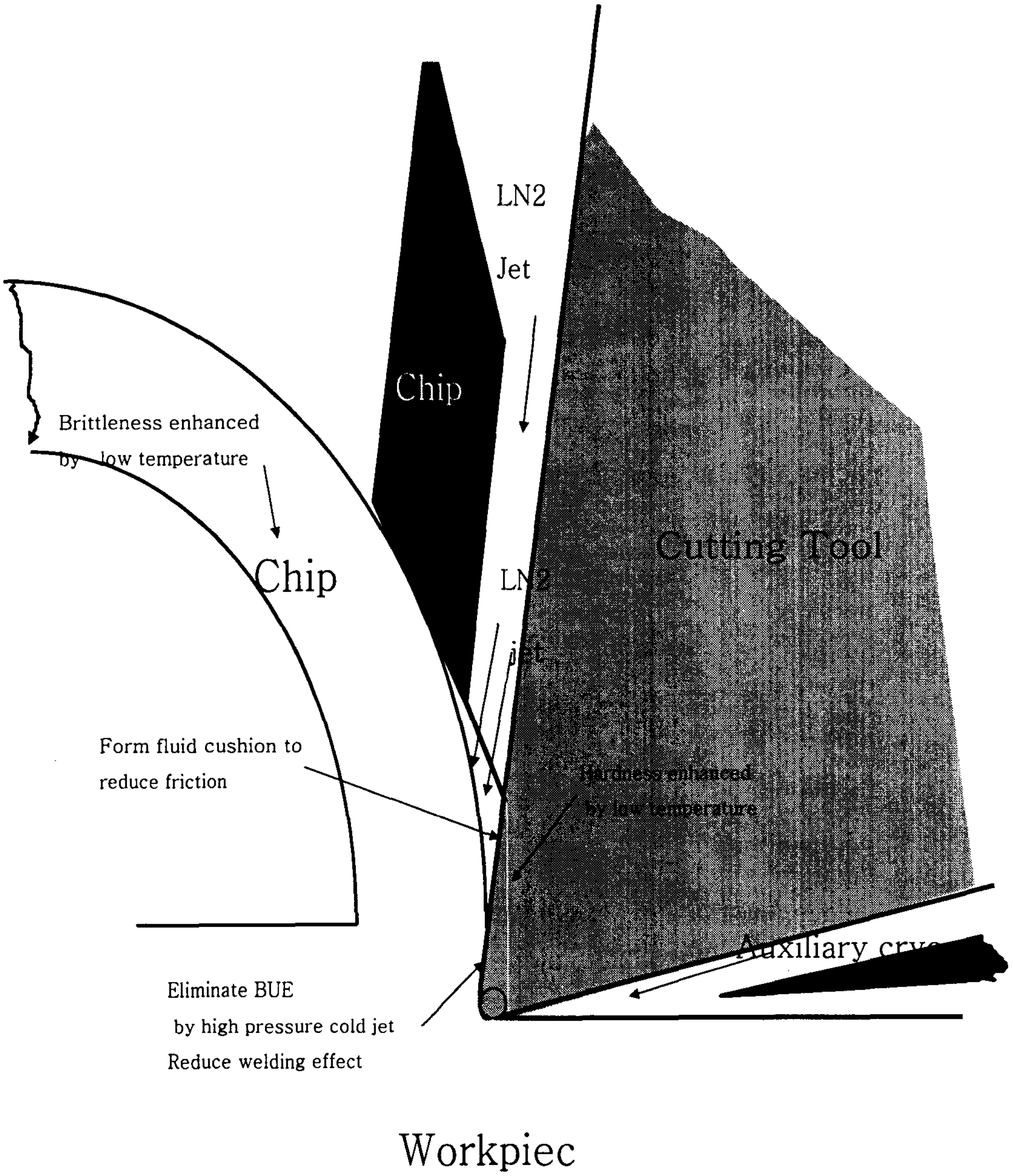

Figure 1. Schematic and principle of economical cryogenic cooling

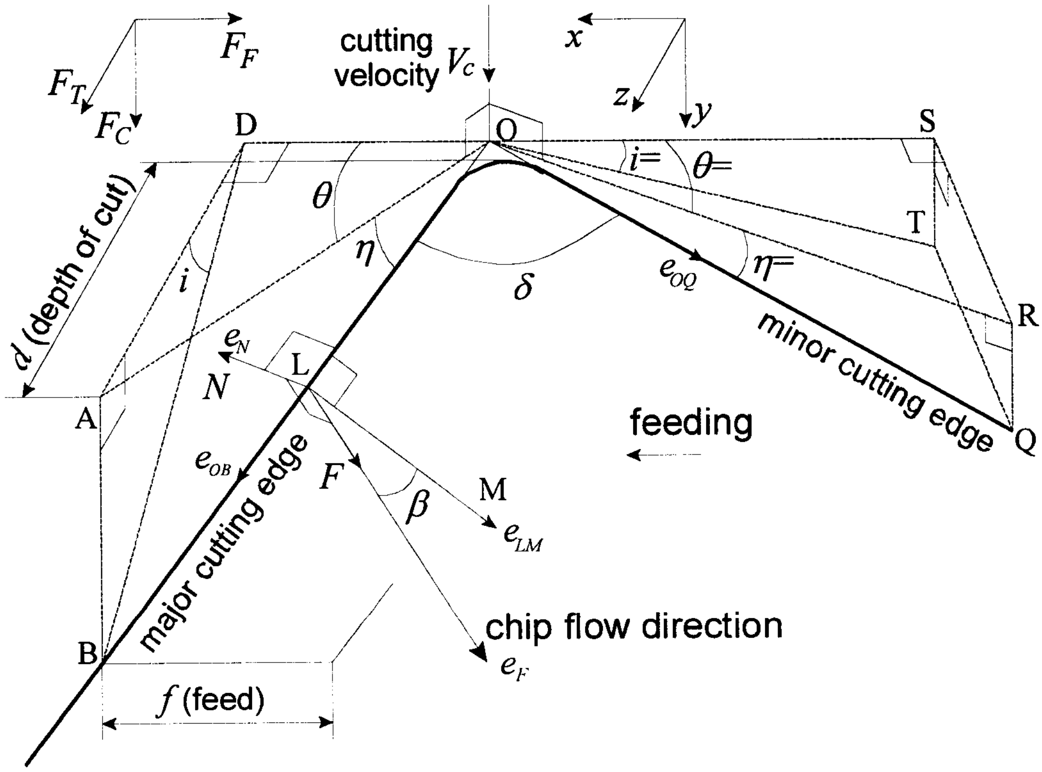

Figure 2 Hodograph for General Oblique Cutting

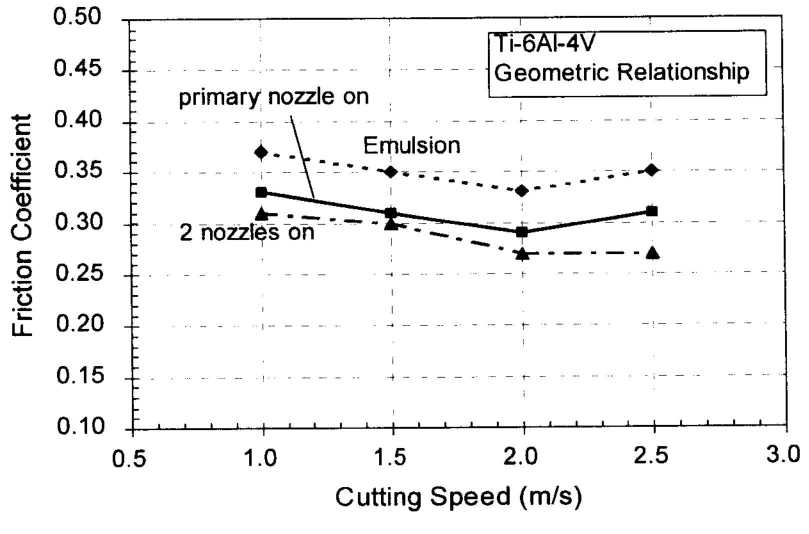

Figure 3. Friction Coefficient for Cutting Ti-6Al-4V (by geometric relationship)

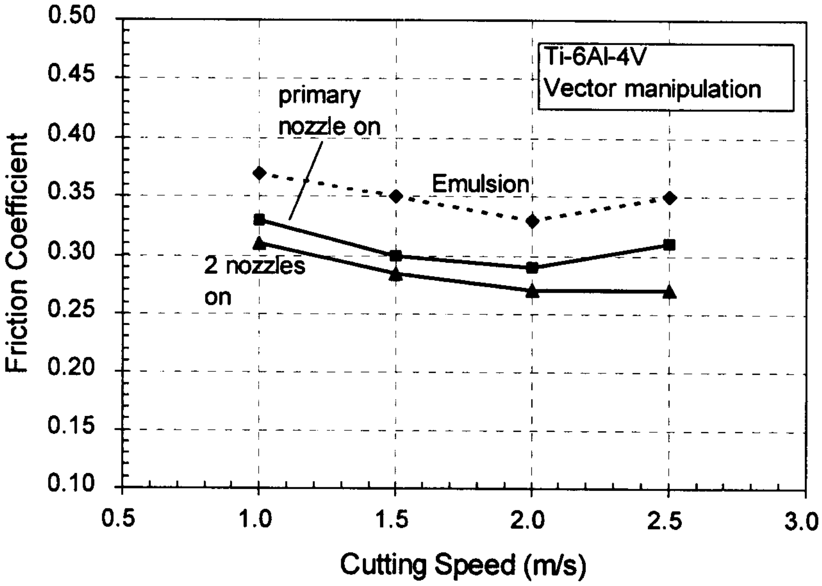

Figure 4 Friction Coefficient for Cutting Ti-6Al-4V (by vector manipulation)

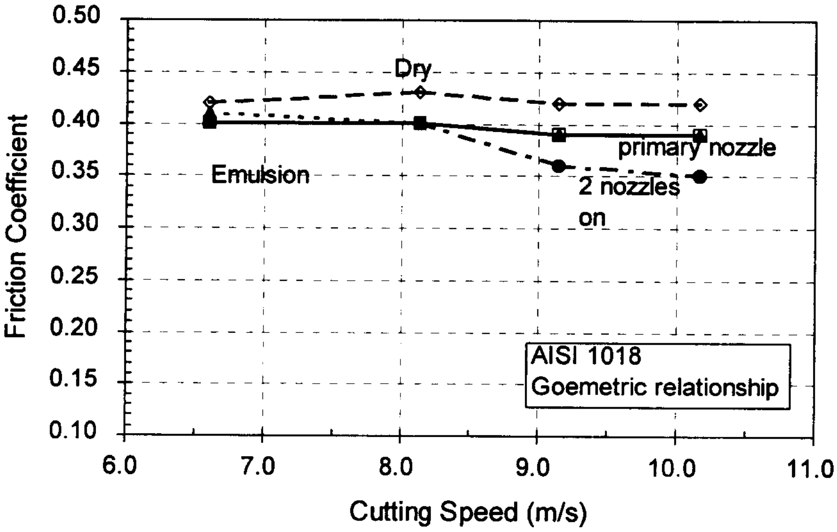

Figure 5. Friction Coefficient for Cutting AISI1018 (by geometric relationship)

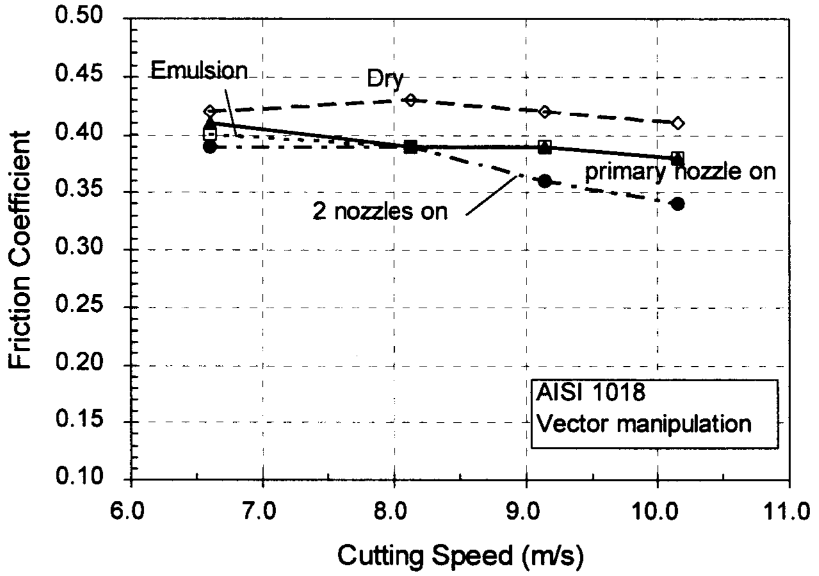

Figure 6 Friction Coefficient for Cutting AISI1018 (by vector manipulation)