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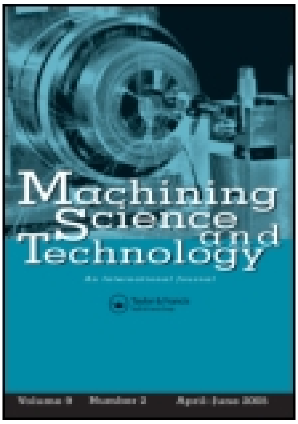

Machining Science and Technology: An International Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/lmst20

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Published online: 07 Feb 2007.

To cite this article: Shane Y. Hong (2006) LUBRICATION MECHANISMS OF LN2 IN ECOLOGICAL CRYOGENIC MACHINING, Machining Science and Technology: An International Journal, 10:1, 133-155, DOI: 10.1080/10910340500534324

To link to this article: http://dx.doi.org/10.1080/10910340500534324

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*Machining Science and Technology*, 10:133–155

ISSN: 1091-0344 print/1532-2483 online
DOI: 10.1080/10910340500534324

# LUBRICATION MECHANISMS OF LN2 IN ECOLOGICAL CRYOGENIC MACHINING

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□ *Cryogenic machining is considered an environmentally safe alternative to conventional machining where cutting fluid is used. In cryogenic machining, liquid nitrogen (LN2) is well recognized as an effective coolant due to its low temperature, however, its lubrication effect is less well known. Our previous studies of the change in cutting forces, tool wear, chip microstructure, and friction coefficient indicate a possible lubrication effect of LN2. This paper proposes two mechanisms on how LN2 can provide lubrication in the cutting process. To verify these proposed LN2 mechanisms and distinguish them, idealized disk-flat contact tests were performed. A low temperature can alter the material properties and change the friction coefficient between the specimens. However, from the test results, this lubrication mechanism was dependent on the material pairs. An uncoated carbide insert with a low carbon steel or titanium alloy disk test showed reduction of friction under LN2 cooling, but a coated insert increased the friction force. LN2 injection to form a physical barrier or hydrodynamic effect between two bodies is always effective in reducing the friction force.*

**Keywords** Cryogenic machining, Lubrication, Liquid Nitrogen, Friction force

## INTRODUCTION

In conventional machining, water-based cutting fluids are frequently used to increase cooling and lubricating properties. Neat cutting oils, fatty oils, or extreme pressure soluble oils are used in many machining operations. Among the operative lubrication mechanisms, hydrodynamic lubrication, a solid-film lubrication, is common. However, boundary lubrication and extreme pressure lubrication are considered the main lubrication mechanisms for conventional cutting fluids. In boundary lubrication, polar materials are added to mineral oil, causing an organic film to bond chemically or physically to the interacting surfaces, resulting in a bonded film much more firmly attached to the metal surface than that of the purely physical barrier of oil alone. In extreme pressure lubrication,

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chlorinated or sulphurized additives chemically react with the metal surface. These metallic derivatives generated by the reaction form a low friction protective film between the interacting surfaces which prevents drastic wear and welding. But these additives are very toxic (1), and although oils and emulsions are common cutting fluids in machining, they are environmental pollutants and health hazards as well.

Cryogenic machining, which uses liquid nitrogen (LN2) as a coolant, was considered to be an environmentally safe alternative to conventional machining since nitrogen is naturally recycled without damage to the environment. In past research studies in cryogenic machining, longer tool life (2–6) and improved chip breaking (7, 8) were reported. With the proper LN2 injection method (9), the consumption of LN2 can be minimal and the cryogenic machining can be even more economical than conventional emulsion cooling (10). However, the improved machinability in cryogenic machining has usually been attributed to the cooling effect of LN2. The function of LN2 as lubricant has rarely been considered for cryogenic machining.

As reported in previous publications, our studies in cryogenic machining indicate that LN2 may have a lubrication effect based on changes in cutting force, tool wear, and chip morphology (11, 12). The mathematical evaluation of the apparent coefficient of friction in the metal cutting process also indicates a reduction in friction when the process is cooled by LN2 (11). Similarly, a friction test in which the workpiece disk rotates against a tool insert under a speed and load similar to that of regular cutting conditions proves that LN2 is effective in reducing the friction coefficient (13).

Tribological behaviors of some materials at low temperatures were studied by W. Hubner et al. (14) with cryotribometer (CT1) which has a rotating sample steel (AISI 304) disk and a pin as counter bodies in a vacuum chamber. Their sliding friction test at low speeds (0.2 m/s) showed a low coefficient of friction and good wear resistance at low temperatures with polymers and composites, as well as with TiN coating under cryogenic coolants. However, the carbon coatings failed at the interface between substrate and coatings due to the mismatch of the thermal expansion coefficients. In that study (14) the low friction coefficient was considered to be due to reduction of adhesion at low temperatures. Michael et al. (15) experimentally studied the friction behavior of several materials at low temperatures and found velocity-independent friction and time-independent hardness behavior for silicone rubber sliding on epoxy at cryogenic temperatures. For the metallic (Indium) friction test, the friction behavior at the lowest temperature (4.2 K) featured velocity-independent friction values. However, at near 77 K, the friction is almost constant at higher velocities, but negative friction-velocity slope was predominantly at very low speeds. The results of both Hubner and Michael provide additional information for understanding low temperature tribology. With a different emphasis, this study will look into how LN2 provides the lubrication function in cryogenic machining.

In machining applications, LN2 has properties that are very different from those of conventional cutting fluids. LN2 evaporates quickly and has a very low viscosity. It is difficult to keep LN2 between contact areas. LN2 also does not possess polar properties. Thus it cannot act as an additive in boundary lubrication. It is inert, making chemical reactions to form a film on the interacting surfaces impossible. Therefore, understanding the lubrication mechanisms of LN2 requires a new concept. The following two possible mechanisms are suggested:

1. LN2 is already known as an effective coolant, which can change the mechanical properties of material due to the low temperatures induced. Altered material properties by LN2 cooling can reduce adhesion between interacting surfaces or enhance wear resistance by hardened surfaces, resulting in a low friction coefficient.
2. Despite the fact that LN2 has non-wetting and low viscosity properties, using LN2 injection to form a physical barrier or thin lubrication film between two bodies may be possible to reduce friction.

In order to verify and distinguish different LN2 lubrication mechanisms, an idealized tribological testing setup is conceived as shown in Figure 1. This test setup consists of a rotating disk that slides on a flat surface. Two possible LN2 lubrication mechanisms, the temperature effect and the hydrodynamic effect, can be differentiated by different LN2 applications to the test setup.

The hypothesis of LN2 lubrication due to the temperature effect is mainly based on the changes of material properties as its temperatures decreases. If LN2 can be applied only to the disk, the flat, or both, without any LN2 supply at the contact area between their contacts, LN2 will just alter the material properties. The friction coefficient change will indicate the level of the lubrication provided by the LN2 cooling effect. On the other hand, if LN2 is jetted between the two contact samples, the friction reduction is most likely caused by the hydrodynamic effect. Thus a matrix of various combinations of LN2 application methods will provide additional information for which of these mechanisms involved and its level of effectiveness in lubrication.

## TESTING DESIGN AND SETUP

The experiment setup is shown in Figure 2, where a rotating disk rubs on a flat specimen with a controlled normal force. This disk-flat sliding contact test setup was arranged horizontally to reduce complication in

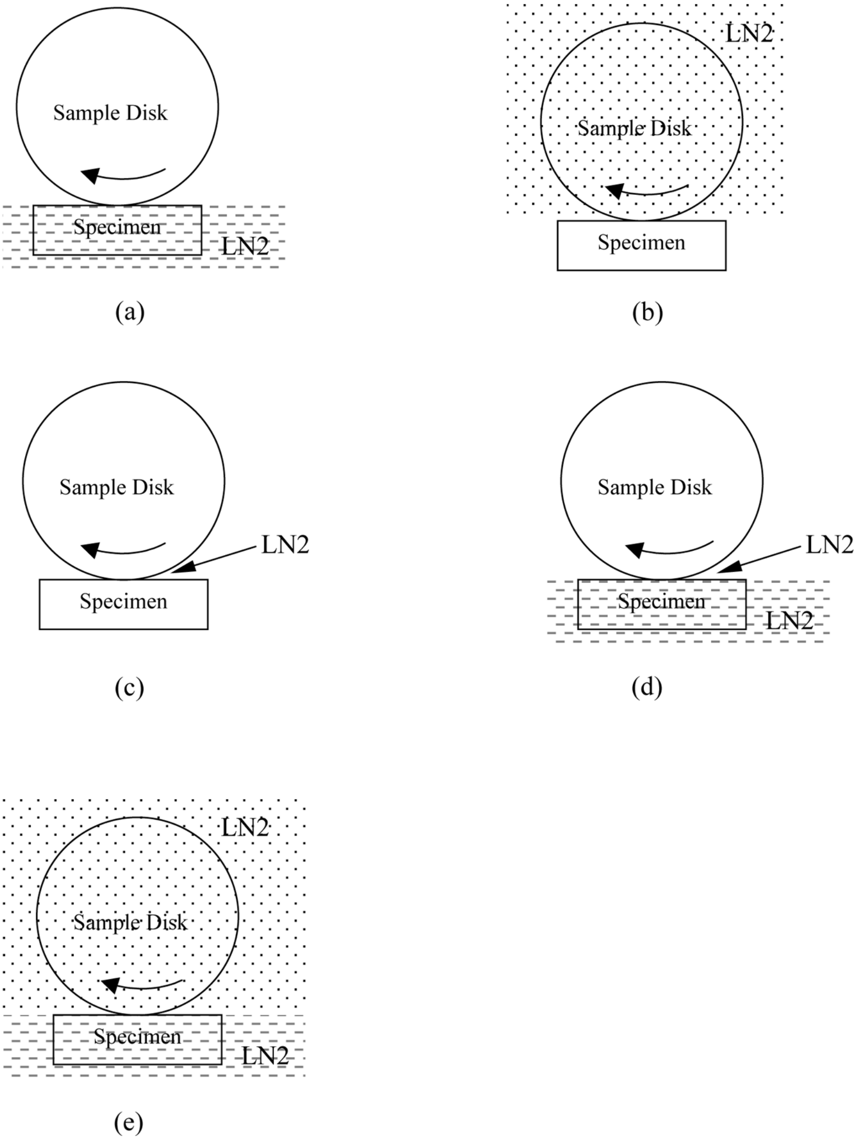
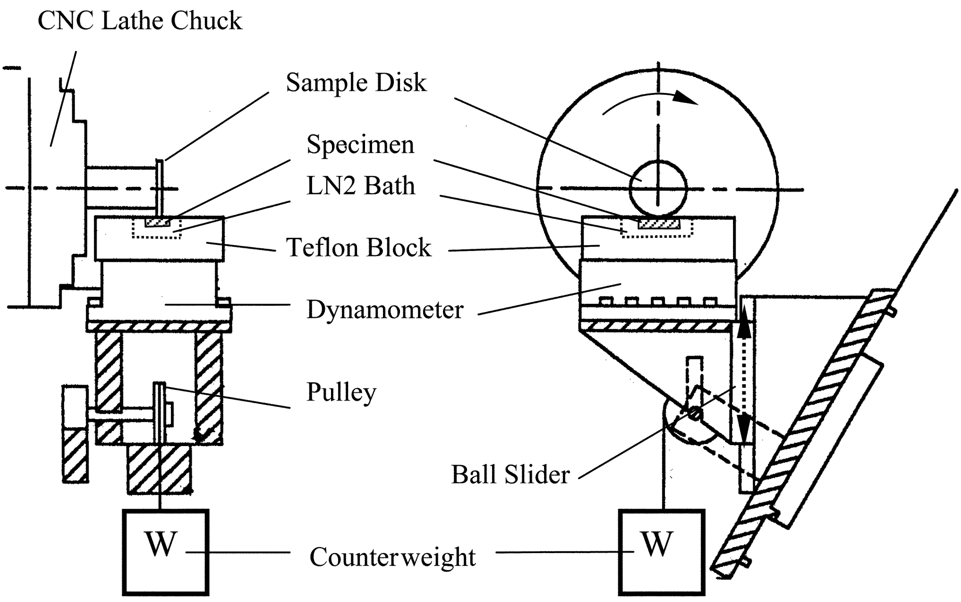
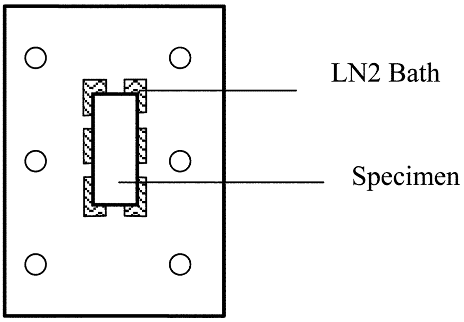


**FIGURE 1** Five cases of LN2 application between two materials for distinguishing lubrication mechanism. (a) Specimen under LN2 cooling (No. LN2 at contact); (b) Sample disk under LN2 cooling (No. LN2 at contact); (c) LN2 jetting between specimen and sample disk; (d) Jetting and cooling a specimen; (e) Specimen and sample disk under LN2 cooling without LN2 at contact.

the acting direction of the force and the influence of gravity. To maintain a reliable and uniform normal force, a counter weight was used since the gravitational force from the counter weight is the most fundamental method to provide a well-calibrated force. The normal and friction force were measured by a 3D dynamometer directly. The test was performed



(a) Schematic of experiment setup



(b) Top view of Teflon block

**FIGURE 2** Experimental setup for direct sliding contact.

under low speed and normal loads to isolate or reduce any factors, such as frictional heat at contact, which may change the results.

The whole assembly floated on a vertical ball bearing slide to reduce friction and the upward motion and normal force were controlled by counter weights via a pulley with normal loads which ranged from 6.7 to 26.7 N.

In this study, two disk samples were made of AISI 1018 low carbon steel and Ti-6Al-4V. The former is commonly used for mechanical parts and the latter is widely used in the aerospace industry. The wheel was a disk of

56 mm in diameter and 2.5 mm in thickness and was mounted on the spindle chuck of the CNC lathe. The peripheral surface was conditioned prior to the tests to guarantee concentricity and uniform surface roughness.

Three materials are used to make the flat surface for the disks described above to rotate against: low carbon steel 1018, carbide, and coated carbide. The flat specimen for AISI 1018 is a rectangular piece 19 mm × 50.8 mm × 6.4 mm. For tool specimens, both coated and uncoated carbide inserts were mounted on a slot on an adaptor plate of the same size as 1018 specimen. This 1018 or tool specimen was placed in the cavity on a thick Teflon block (125 mm × 150 mm × 50 mm), which is used for insulation. This block was mounted on a 3D Kistler dynamometer. Before testing, the dynamometer was calibrated by using a spring force gauge and known weights. The frictional force and normal force were measured and logged by a PC-based data acquisition system. The force components were continuously recorded for about 30 seconds. The average forces over the period were used to calculate the coefficient of friction by dividing the friction force by the normal load. The sliding speed was controlled by using a rotational speed of 104 rpm that resulted in a relative sliding speed of 0.3 m/s on the sample.

Based on the fundamental setup described above, three different LN2 cooling setups were used in the experiment: specimen cooling in the LN2 bath, disk cooling in the LN2 saturated enclosure, and LN2 jetting to the interface of the disk and the flat specimen.

For specimen cooling in the LN2 bath, the cavity of the Teflon block was continuously filled by LN2 and the level of LN2 was maintained to prevent overflow. The specimen was cooled on every side except the top surface where no LN2 existed between the disk and tool. The test setup is schematically illustrated in Figure 3.

For cryogenic cooling of the disk, an LN2 chamber was made of a polystyrene foam cup to cover the disk and LN2 mist was sprayed into the chamber. A polyethylene foam sheet served as a thermal insulator between the disk and the specimen to prevent cooling of the specimen, and as a barrier to prevent penetration of any LN2 spray between the disk and specimen. The test setup for the disk cooling is shown schematically in Figure 4.

In jet cooling, LN2 was introduced between the disk and the specimen using another test setup. The LN2 nozzle was closely positioned near the wedge angle between the sample disk and the specimen and LN2, with a pressure of 2.4 Mpa (350 psi), was supplied through a thermally isolated delivery line, consisting of a thin stainless steel inner tubing jacketed by an outer tubing with a vacuum drawn between them. Figure 5 presents a schematic view of the LN2 jet cooling test setup.

The LN2 jet may introduce an impinging force or reaction force to the experiment setup which would influence the measured friction force, and thus, may lead to an erroneous value of the friction coefficient. Since the

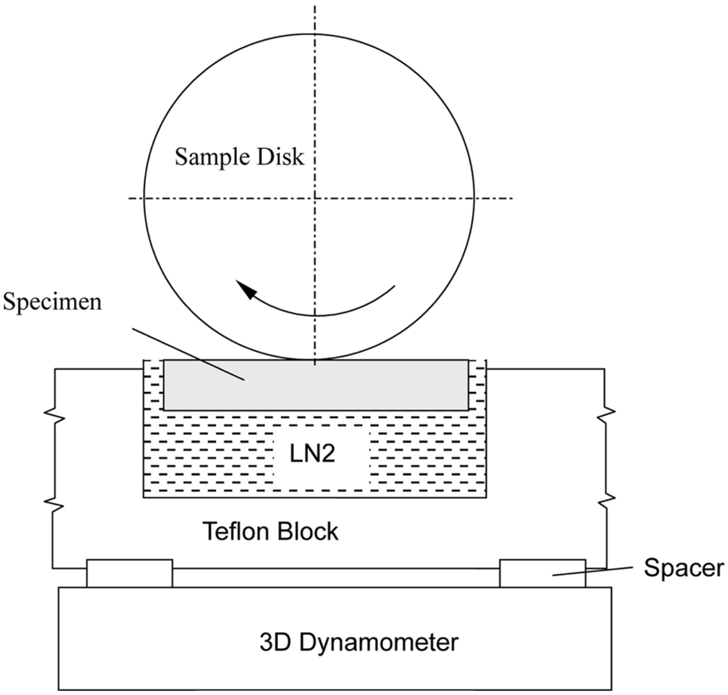


**FIGURE 3** Schematic of specimen cooling in LN2 bath.

impinging force (measured prior to the experiment) was in the range of 6–7 N, it can influence the coefficient of friction by from 0.2 to 0.8 depending on the normal loads. Therefore, to eliminate the effect of the impinging force and of any reaction force, the LN2 jet was first applied before the disk rotation, and then the dynamometer was reset so that the force measurement during the test will not reflect the impinging force component.

## EXPERIMENT RESULTS

To study the LN2 lubrication effect on materials, five pairs of materials were used to conduct the friction test: AISI 1018 disk vs. AISI1018 flat, AISI 1018 disk vs. uncoated insert, AISI 1018 disk vs. coated tool insert, Ti-6Al-4V disk vs. uncoated carbide insert, and Ti-6Al-4V vs. coated carbide insert.

An uncoated carbide tool insert (K68) was obtained from Kennametal, equivalent to ISO class M05-K20 or M10-M20, and is a low-cobalt (5.7%) unalloyed grade with intermediate carbide grain size. Its impact strength, transverse rupture strength (TRS), and hardness at cryogenic temperatures have been reported by Zhao and Hong (16). Generally, it retained its impact strength and TRS, while its hardness increased. K68 is commonly used for machining Ti-6Al-4V.

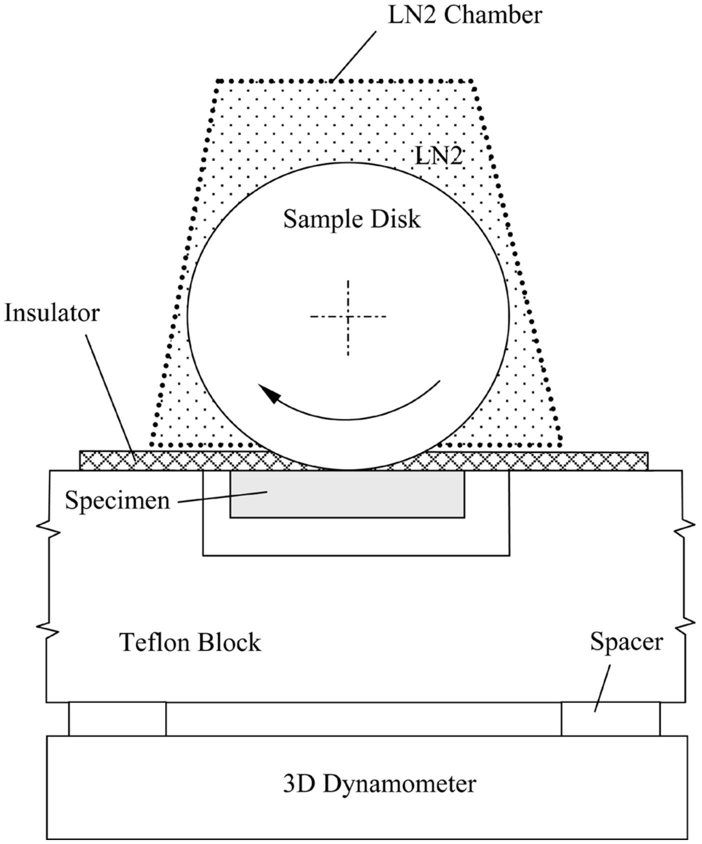


**FIGURE 4** Schematic of LN2 disk cooling.

A chemical vapor deposition (CVD) coated carbide tool insert (KC 850) from Kennametal, equivalent to ISO M30-M45 or P25-P45, has a triple phase coating with layers of TiN, TiCN, and TiC. Coatings on tools, generally 5–10 μm (200–400 μm) in thickness, are applied by various techniques. An outer layer TiN coating, which is gold in color, has a low coefficient of friction, high hardness, resistance to high temperatures, and good adhesion to the substrate. Its hardness is 18500–27500 $HV_{0.025}$ (Mpa), and its coefficient of thermal expansion is $8.3 \times 10^{-6}$ (°$C^{-1}$). A composite layer of TiCN has advantages of both TiN and TiC, and it serves as a buffer to reduce thermal stress. A backing layer of TiC, which is gray in color, has high flank wear resistance and high transverse rupture strength values. The hardness for TiC is 32000–40000 $HV_{0.025}$ (Mpa) and its coefficient of thermal expansion is $6.7 \times 10^{-6}$ (°$C^{-1}$).

To distinguish between the possible lubrication mechanisms, the workpiece disk and tool specimen were cooled by LN2 with five different

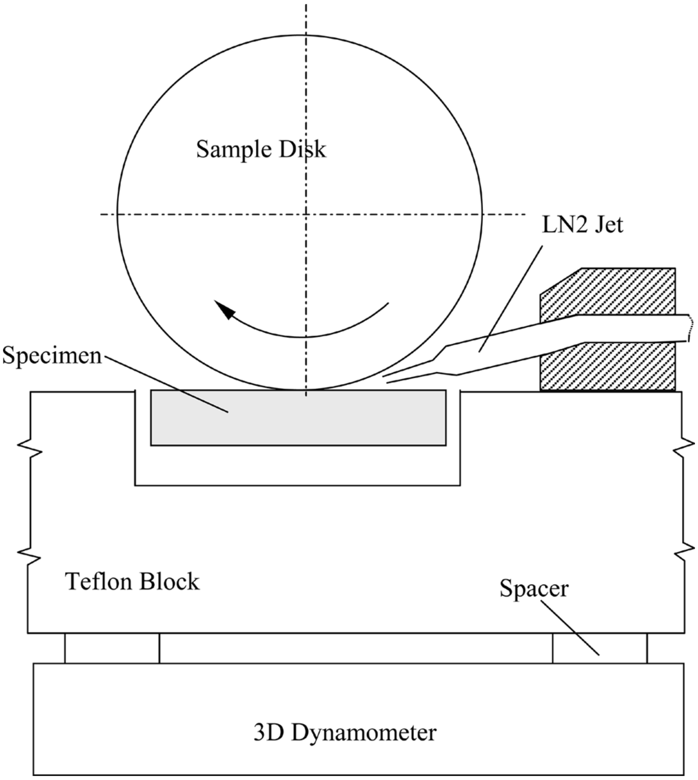


**FIGURE 5** Schematic of LN2 jet cooling.

combinations as shown in Figure 1 for each of the material pairs in the friction tests:

(a) Only LN2 bath cooling for the specimen to study the effect of cryogenic temperatures on the tool material,
(b) Only the disk was exposed to the LN2 saturated enclosure to study the effect of cryogenic temperatures on the workpiece material,
(c) LN2 was jetted between the disk and the specimen to study hydrodynamic effects on the contact and local cooling,
(d) Both the disk and the specimen were cooled by LN2 but without jetting in between for comparison with the results from (a) and (b),
(e) Combined LN2 jet and bath cooling to study the combined effect of the hydrodynamic film and the low temperature tool.

A dry run friction test was also conducted for comparison. Normal loads between 6.7 to 26.7 Newtons were applied by adding a counter weight. The disk was driven by the CNC lathe spindle at 104 rpm to create a relative linear sliding speed of 0.3 m/s between the disk and the flat tool specimen. The normal and frictional forces were measured and the coefficients of friction were then calculated.

### AISI 1018 Disk vs. AISI 1018 Specimen

Using the same workpiece material for both the test specimen and the sample disk, the influence of LN2 on the workpiece material's friction behavior can be studied without the complication of the interaction between two different contacting materials. In the friction test for the AISI 1018 disk running against the AISI 1018 specimen, the normal force applied by the counter weight and the resulting friction force are listed in Table 1. The standard deviation of the friction force indicates the spread of measurement fluctuation. Calculated from the mean value and standard deviation, the coefficient of variation provides a normalized measure of the spread. The friction coefficient was calculated and plotted in Figure 6 for various normal loads.

**TABLE 1** Experimental Data for AISI 1018 vs. AISI 1018

| | | | Friction force | | | |
|---|---|---|---|---|---|---|
| Material pair | Cooling conditions | Normal force (N) | Mean (N) | Standard deviation | C.V. (%) | Friction coefficient |
| AISI 1018 vs. AISI 1018 | Dry | 6.67 | 0.85 | 0.11 | 12.8 | 0.13 |
| | | 13.34 | 1.98 | 0.27 | 13.4 | 0.15 |
| | | 20.02 | 2.88 | 0.27 | 9.4 | 0.14 |
| | | 26.69 | 4.29 | 0.39 | 9.2 | 0.16 |
| | Bath cooling | 6.67 | 1.11 | 0.16 | 14.8 | 0.17 |
| | | 13.34 | 2.07 | 0.31 | 15.2 | 0.15 |
| | | 20.02 | 2.95 | 0.31 | 10.5 | 0.15 |
| | | 26.69 | 4.03 | 0.38 | 9.4 | 0.15 |
| | Disk cooling | 6.67 | 1.08 | 0.15 | 13.8 | 0.16 |
| | | 13.34 | 2.14 | 0.31 | 14.7 | 0.16 |
| | | 20.02 | 3.08 | 0.30 | 9.8 | 0.15 |
| | | 26.69 | 4.19 | 0.38 | 9.1 | 0.16 |
| | Disk and bath cooling | 6.67 | 1.23 | 0.18 | 14.5 | 0.18 |
| | | 13.34 | 2.33 | 0.33 | 14.2 | 0.18 |
| | | 20.02 | 3.68 | 0.36 | 9.8 | 0.18 |
| | | 26.69 | 4.72 | 0.40 | 8.4 | 0.18 |
| | Jet cooling | 6.67 | 0.32 | 0.04 | 12.8 | 0.05 |
| | | 13.34 | 0.77 | 0.09 | 11.7 | 0.06 |
| | | 20.02 | 2.23 | 0.22 | 9.7 | 0.11 |
| | | 26.69 | 3.51 | 0.34 | 9.6 | 0.13 |
| | Jet and bath cooling | 6.67 | 0.40 | 0.06 | 14.3 | 0.06 |
| | | 13.34 | 0.99 | 0.10 | 10.4 | 0.07 |
| | | 20.02 | 2.34 | 0.23 | 9.8 | 0.12 |
| | | 26.69 | 3.65 | 0.32 | 8.7 | 0.14 |

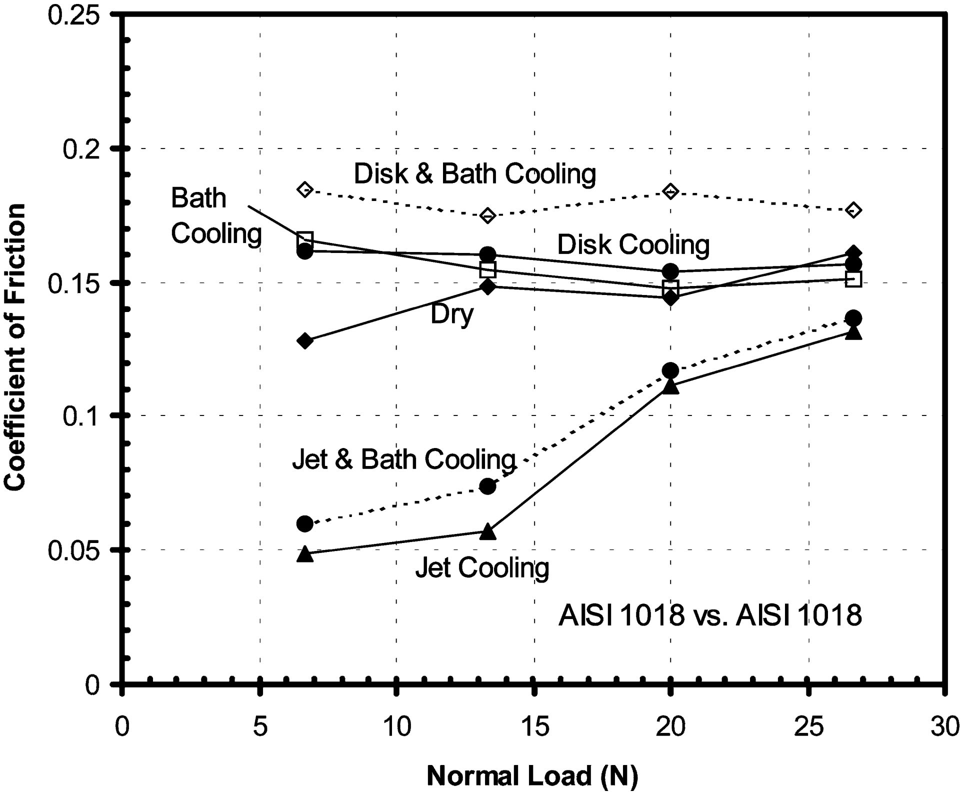


**FIGURE 6** Coefficient of friction for AISI 1018 against AISI 1018 under various LN2 approaches at 0.3 m/s.

From the test result, the AISI 1018 material sliding on identical material had a coefficient of friction ranging from 0.13 at normal loads of 7 Newtons to 0.16 at loads of 27 Newtons. Both the friction force and the friction coefficient increased as the load increased. The AISI 1018 specimen cooled in a LN2 bath showed an almost constant friction coefficient (about 0.15) with applied normal loads. The AISI 1018 sample disk cooling produced a similar friction coefficient to that of specimen cooling. Both bath and disk cooling seemed slightly higher than that of dry but very close to each other. A combined disk and bath cooling resulted in the highest friction coefficient (0.18) among the LN2 approaches. It seems that additional LN2 cooling makes the workpiece material more abrasive. Jet application showed effectiveness in reducing the friction coefficient. The friction coefficient ranged from 0.05 to 0.13, and increased as the load increased, indicating that the hydrodynamic layer degraded as heavier pressure tended to squeeze the lubricating film out. Additional cooling by placing the specimen in the LN2 bath did not help but yielded a slightly higher friction coefficient. This result showed that there is no advantage in cooling the workpiece, but, rather worsening in terms of friction.

## AISI 1018 Disk vs. Uncoated Carbide Insert

The normal force and measured mean friction for AISI 1018 against the uncoated carbide insert are listed in Table 2. The coefficient of friction was calculated and is shown in Figure 7.

The AISI 1018 sample disk sliding against uncoated insert had a high friction coefficient, dropping as the load increased, from 0.34 to 0.22 as load increased from 7 N to 27 N in the dry run. The uncoated insert cooled by LN2 bath lowered the friction coefficient ranging from 0.24 at the normal load of 7 N to 0.20 at 27 N. The LN2 sample disk cooling also reduced the friction force compared to the dry test, but was not as effective as cooling the tool insert. Combined disk and bath cooling showed a slightly lower friction coefficient (0.21–0.24) than the LN2 disk cooling alone, but the performance was not any better than mere bath cooling of the tool insert.

**TABLE 2** Experimental Data for AISI 1018 vs. Uncoated Insert

| | | | Friction force | | | |
|---|---|---|---|---|---|---|
| Material pair | Cooling conditions | Normal force (N) | Mean (N) | Standard deviation | C.V. (%) | Friction coefficient |
| AISI 1018 vs. uncoated insert | Dry | 6.67 | 2.24 | 0.24 | 10.7 | 0.34 |
| | | 13.34 | 3.87 | 0.58 | 14.9 | 0.29 |
| | | 20.02 | 5.60 | 0.46 | 8.3 | 0.28 |
| | | 26.69 | 5.85 | 0.54 | 9.2 | 0.22 |
| | Bath cooling | 6.67 | 1.57 | 0.22 | 13.7 | 0.24 |
| | | 13.34 | 2.91 | 0.33 | 11.2 | 0.22 |
| | | 20.02 | 4.70 | 0.45 | 9.6 | 0.23 |
| | | 26.69 | 5.21 | 0.47 | 9.1 | 0.20 |
| | Disk cooling | 6.67 | 1.91 | 0.24 | 12.4 | 0.29 |
| | | 13.34 | 3.34 | 0.37 | 11.1 | 0.25 |
| | | 20.02 | 4.87 | 0.41 | 8.4 | 0.24 |
| | | 26.69 | 6.01 | 0.44 | 7.3 | 0.23 |
| | Disk and bath cooling | 6.67 | 1.47 | 0.21 | 14.5 | 0.22 |
| | | 13.34 | 3.20 | 0.47 | 14.8 | 0.24 |
| | | 20.02 | 4.64 | 0.43 | 9.3 | 0.23 |
| | | 26.69 | 5.70 | 0.56 | 9.9 | 0.21 |
| | Jet cooling | 6.67 | 0.35 | 0.05 | 13.8 | 0.05 |
| | | 13.34 | 0.72 | 0.08 | 11.5 | 0.05 |
| | | 20.02 | 2.26 | 0.21 | 9.5 | 0.11 |
| | | 26.69 | 3.52 | 0.31 | 8.9 | 0.13 |
| | Jet and bath cooling | 6.67 | 0.34 | 0.05 | 15.2 | 0.05 |
| | | 13.34 | 0.97 | 0.14 | 14.3 | 0.07 |
| | | 20.02 | 2.70 | 0.26 | 9.8 | 0.14 |
| | | 26.69 | 3.96 | 0.37 | 9.3 | 0.15 |

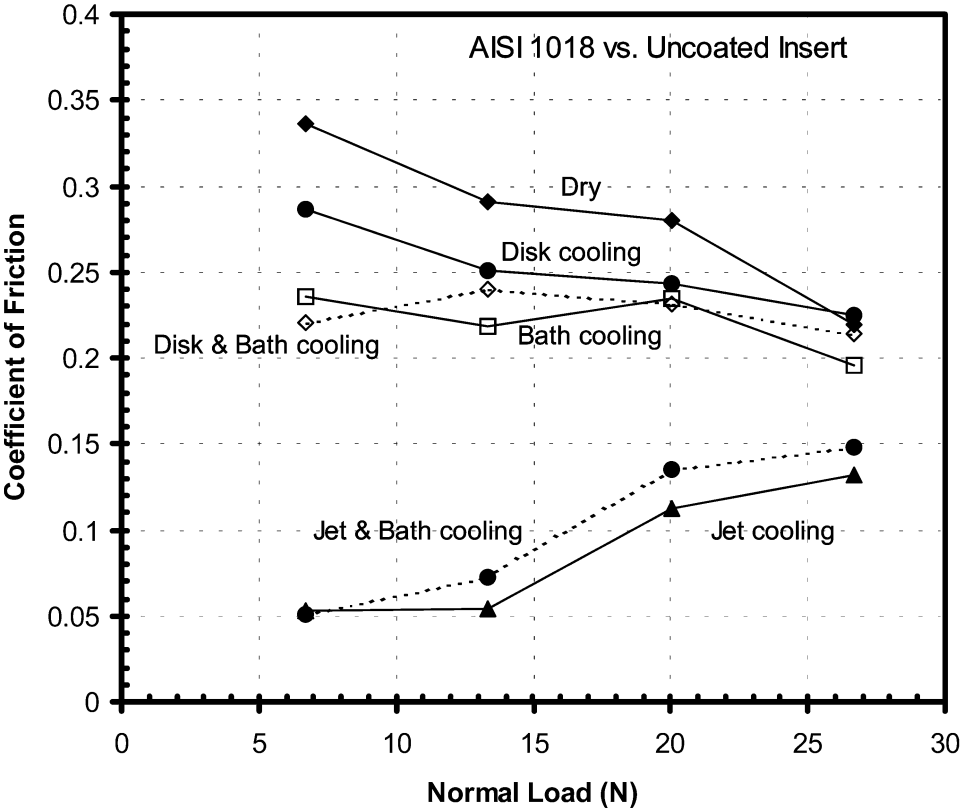


**FIGURE 7** Coefficient of friction for AISI 1018 against uncoated insert under various LN2 approaches at 0.3 m/s.

Jet cooling between the disk and the tool insert achieved the best friction reduction. The coefficient of friction can be as low as 0.05 at low loading when hydrodynamic lubrication dominates. However, the friction coefficient increased as the load increased, similar to the case of 1018 vs. 1018. Cooling to the uncoated insert with an LN2 bath in addition to the jet cooling did not improve the friction, but instead resulted in a slightly higher coefficient.

## AISI 1018 Disk vs. Coated Carbide Insert

The applied normal loads and resulting friction forces of the AISI 1018 disk rotated and slid on a coated insert are listed in Table 3. Calculated friction coefficients were plotted versus applied normal loads in Figure 8.

In dry testing, the AISI 1018 sample disk sliding on a coated carbide insert yielded a friction coefficient 0.13–0.18, which is similar to that

**TABLE 3** Experimental Data for AISI 1018 vs. Coated Insert

| Material pair | Cooling conditions | Normal force (N) | Friction force Mean (N) | Friction force Standard deviation | Friction force C.V. (%) | Friction coefficient |
|---|---|---|---|---|---|---|
| AISI 1018 vs. coated insert | Dry | 6.67 | 0.88 | 0.13 | 14.8 | 0.13 |
| | | 13.34 | 1.53 | 0.22 | 14.1 | 0.11 |
| | | 20.02 | 2.77 | 0.26 | 9.2 | 0.14 |
| | | 26.69 | 4.86 | 0.48 | 9.9 | 0.18 |
| | Bath cooling | 6.67 | 1.10 | 0.16 | 14.9 | 0.16 |
| | | 13.34 | 1.99 | 0.21 | 10.4 | 0.15 |
| | | 20.02 | 2.70 | 0.25 | 9.2 | 0.14 |
| | | 26.69 | 3.68 | 0.35 | 9.5 | 0.14 |
| | Disk cooling | 6.67 | 1.47 | 0.23 | 15.5 | 0.22 |
| | | 13.34 | 2.38 | 0.28 | 11.9 | 0.18 |
| | | 20.02 | 3.55 | 0.32 | 8.9 | 0.18 |
| | | 26.69 | 4.11 | 0.38 | 9.3 | 0.15 |
| | Disk and bath cooling | 6.67 | 1.77 | 0.25 | 14.2 | 0.26 |
| | | 13.34 | 3.12 | 0.36 | 11.7 | 0.23 |
| | | 20.02 | 3.62 | 0.33 | 9.1 | 0.20 |
| | | 26.69 | 5.16 | 0.50 | 9.8 | 0.19 |
| | Jet cooling | 6.67 | 0.29 | 0.04 | 14.5 | 0.04 |
| | | 13.34 | 0.67 | 0.07 | 10.7 | 0.05 |
| | | 20.02 | 1.62 | 0.16 | 9.8 | 0.08 |
| | | 26.69 | 2.43 | 0.23 | 9.4 | 0.09 |
| | Jet and bath cooling | 6.67 | 0.38 | 0.06 | 14.8 | 0.06 |
| | | 13.34 | 0.80 | 0.05 | 6.5 | 0.06 |
| | | 20.02 | 1.55 | 0.15 | 9.6 | 0.08 |
| | | 26.69 | 3.21 | 0.31 | 9.6 | 0.12 |

obtained when sliding on the 1018 specimen, but lower than that for an uncoated insert. The friction coefficient increased slightly with increasing normal loads. When the coated carbide insert was cooled in the LN2 bath, the friction coefficients ranged from 0.14 to 0.16, and were almost constant over the range of applied normal loads. However the coefficients of friction were slightly higher than those from the dry test. Cooling the disk yielded a higher friction coefficient, which decreased with load. Even higher friction coefficients were observed when both the disk and the coated insert were cooled by the LN2. It is clear that the coated insert was designed for conventional cutting, and that the LN2 cooling for coated insert pair caused adverse friction results. Higher load tended to decrease the friction coefficient. It is suspected that the heat generation at the sliding interface may have compensated for the temperature reduction at the LN2 cooled disk and insert contact.

Contrary to the above, LN2 jetting between the disk and the insert performed very well, with a very low friction coefficient 0.04–0.12. It seems that the LN2 jet generated a lubricating film, which was not affected by the

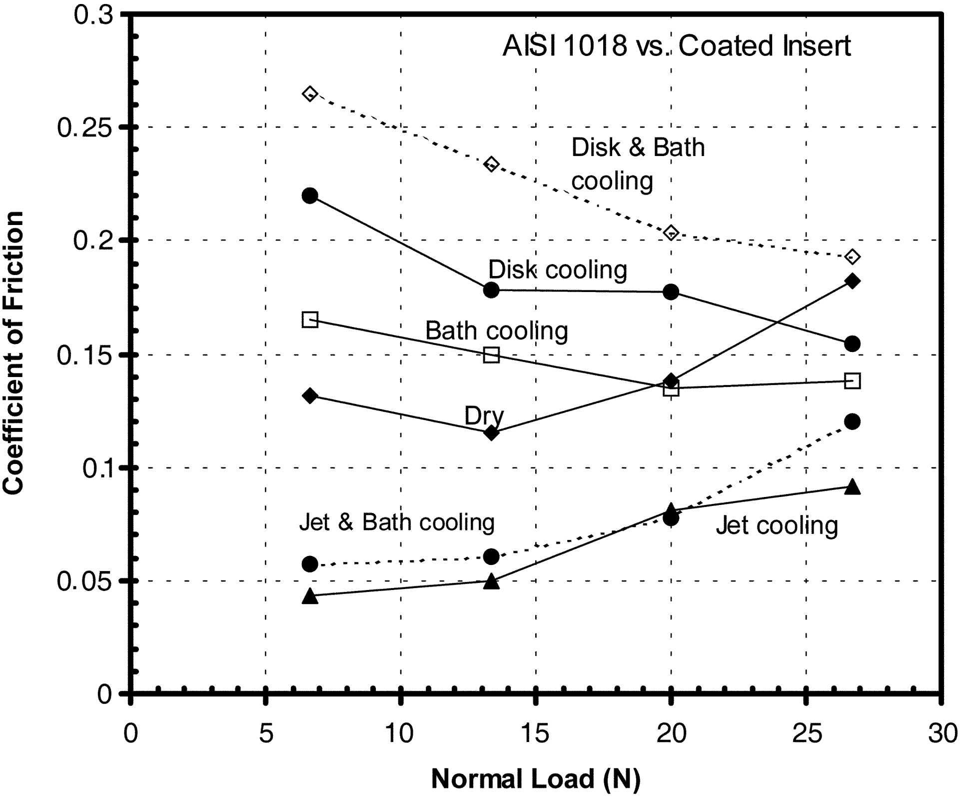


**FIGURE 8** Coefficient of friction for AISI 1018 against coated insert under various LN2 approaches at 0.3 m/s.

material pair. Additional cooling to the tool insert in the LN2 bath did not help in reducing friction.

## Ti-6Al-4V Disk vs. Uncoated Carbide Insert

Based on the same testing conditions as testing with the AISI 1018 sample disk, the Ti-6Al-4V disk was slid against an uncoated insert. The normal force and the measured mean friction are listed in Table 4. The coefficient of friction was calculated and is shown in Figure 9.

From the dry testing result for Ti-6Al-4V, the friction coefficient ranged from 0.3 at normal loads 7 N to 0.24 at 27 N, which decreased with applied normal load. This range is similar to the test results obtained from sliding AISI 1018 against the uncoated insert. All testing results under LN2 cooling showed lower friction coefficients than that obtained under dry conditions, and these friction coefficients decreased with normal loads. When the tool

**TABLE 4** Experimental Data for Ti-6A1-4V vs. Uncoated Insert

| Material pair | Cooling conditions | Normal force (N) | Friction force Mean (N) | Friction force Standard deviation | Friction force C.V. (%) | Friction coefficient |
|---|---|---|---|---|---|---|
| Ti-6Al-4V vs. uncoated insert | Dry | 6.67 | 1.98 | 0.19 | 9.7 | 0.30 |
| | | 13.34 | 3.76 | 0.32 | 8.5 | 0.28 |
| | | 20.02 | 5.06 | 0.52 | 10.2 | 0.25 |
| | | 26.69 | 6.31 | 0.52 | 8.3 | 0.24 |
| | Bath cooling | 6.67 | 1.75 | 0.20 | 11.4 | 0.26 |
| | | 13.34 | 3.15 | 0.40 | 12.6 | 0.24 |
| | | 20.02 | 4.19 | 0.35 | 8.4 | 0.21 |
| | | 26.69 | 4.81 | 0.40 | 8.3 | 0.18 |
| | Disk cooling | 6.67 | 1.90 | 0.20 | 10.4 | 0.29 |
| | | 13.34 | 3.15 | 0.47 | 14.8 | 0.24 |
| | | 20.02 | 4.11 | 0.40 | 9.8 | 0.21 |
| | | 26.69 | 5.34 | 0.49 | 9.1 | 0.20 |
| | Disk and bath cooling | 6.67 | 1.81 | 0.27 | 14.8 | 0.27 |
| | | 13.34 | 3.15 | 0.43 | 13.7 | 0.24 |
| | | 20.02 | 4.03 | 0.40 | 9.8 | 0.20 |
| | | 26.69 | 4.66 | 0.41 | 8.8 | 0.17 |
| | Jet cooling | 6.67 | 0.20 | 0.03 | 12.4 | 0.03 |
| | | 13.34 | 1.07 | 0.14 | 13.2 | 0.08 |
| | | 20.02 | 2.66 | 0.28 | 10.5 | 0.13 |
| | | 26.69 | 4.08 | 0.38 | 9.4 | 0.15 |
| | Jet and bath cooling | 6.67 | 0.97 | 0.14 | 14.8 | 0.07 |
| | | 13.34 | 1.14 | 0.17 | 15.2 | 0.09 |
| | | 20.02 | 2.26 | 0.21 | 9.4 | 0.11 |
| | | 26.69 | 3.25 | 0.24 | 7.5 | 0.12 |

insert was cooled in the LN2 bath, it was effective in reducing the friction coefficient, which ranged from 0.26 to 0.18. Cooling the disk also produced the same results as tool insert cooling. Even combined cooling was very close to LN2 bath and disk, and showed similar friction coefficient ranges (0.17–0.26).

Thus it seems that LN2 cooling is very advantageous in reducting friction for the material pair of uncoated carbide insert and Ti-6Al-4V, regardless of the specifics of the cooling approach.

The test involving LN2 jet application again showed its effectiveness in reducing friction. Similar to the AISI 1018 disk test, the friction coefficient increased with normal loads, ranging 0.03–0.15. Additional bath cooling with jet application showed a slightly lower friction coefficient than that of jet cooling at high loads.

Regardless of whether paired with the AISI 1018 disk or with the Ti-6Al-4V disk, the uncoated insert responded very well to cryogenic cooling in reducting friction.

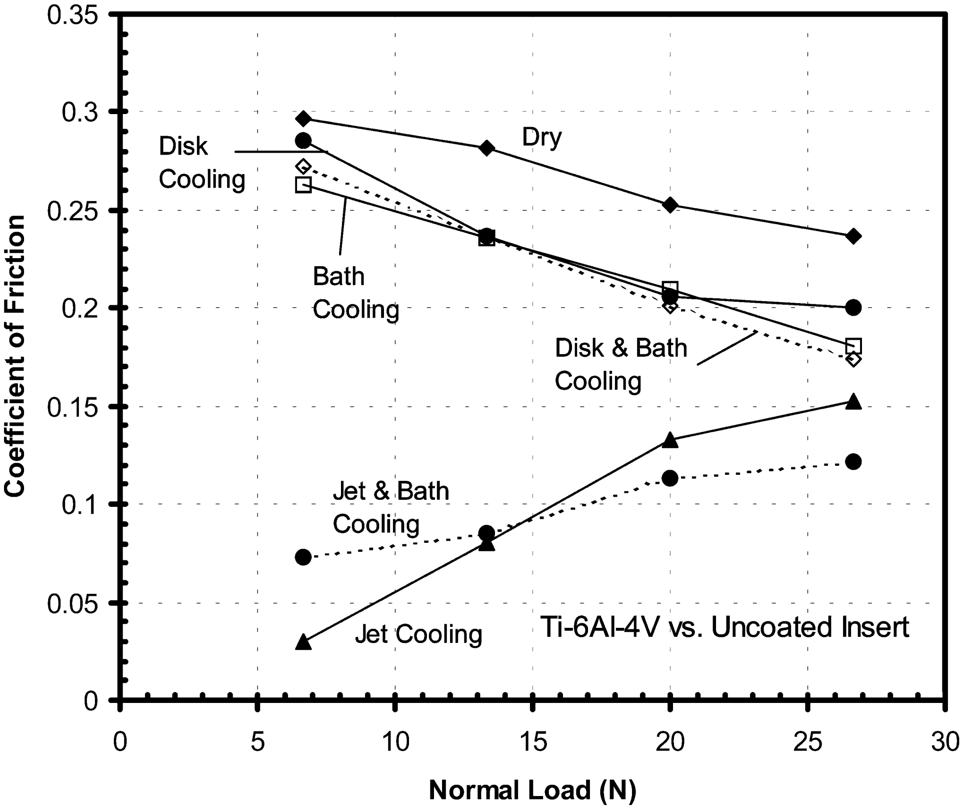


**FIGURE 9** Coefficient of friction for Ti-6A1-4V against uncoated insert under various LN2 approaches at 0.3 m/s.

## Ti-6Al-4V Disk vs. Coated Carbide Insert

For the case of the Ti-6Al-4V disk sliding on the coated carbide insert, the variation in the resultant friction forces with applied normal force under various LN2 cooling conditions is listed in Table 5. Changes in the friction coefficient under these various LN2 cooling conditions are presented in Figure 10.

In the dry test, the Ti-6Al-4V disk sliding on the coated insert resulted in friction coefficients ranging from 0.2 at normal loads of 7 N to 0.23 at loads of 27 N, showing the effectiveness of the low friction coating. This result is slightly higher than that obtained when testing with the AISI 1018 sample disk. The general trends of the friction coefficient under LN2 cooling were similar to those of the AISI 1018 sample disk, however the friction coefficient was higher. LN2 bath cooling resulted in a friction coefficient ranging from 0.28 to 0.25, i.e., cooling the coated insert unfavorably increased the friction compared to that of dry. Cooling the disk showed

**TABLE 5** Experimental Data for Ti-6A1-4V vs. Coated Insert

| | | | Friction force | | | |
|---|---|---|---|---|---|---|
| Material pair | Cooling conditions | Normal force (N) | Mean (N) | Standard deviation | C.V. (%) | Friction coefficient |
| Ti-6Al-4V vs. coated insert | Dry | 6.67 | 1.36 | 0.14 | 10.3 | 0.20 |
| | | 13.34 | 3.01 | 0.40 | 13.3 | 0.23 |
| | | 20.02 | 4.14 | 0.46 | 11.1 | 0.21 |
| | | 26.69 | 6.07 | 0.57 | 9.4 | 0.23 |
| | Bath cooling | 6.67 | 1.87 | 0.23 | 12.3 | 0.28 |
| | | 13.34 | 3.50 | 0.53 | 15.1 | 0.26 |
| | | 20.02 | 4.62 | 0.46 | 10.0 | 0.23 |
| | | 26.69 | 6.55 | 0.61 | 9.3 | 0.25 |
| | Disk cooling | 6.67 | 1.99 | 0.22 | 11.0 | 0.30 |
| | | 13.34 | 3.53 | 0.65 | 18.4 | 0.26 |
| | | 20.02 | 4.99 | 0.40 | 8.0 | 0.25 |
| | | 26.69 | 6.95 | 0.67 | 9.6 | 0.26 |
| | Disk and bath cooling | 6.67 | 2.11 | 0.23 | 10.9 | 0.32 |
| | | 13.34 | 4.28 | 0.15 | 3.5 | 0.32 |
| | | 20.02 | 5.77 | 0.48 | 8.3 | 0.29 |
| | | 26.69 | 7.03 | 0.63 | 9.0 | 0.26 |
| | Jet Cooling | 6.67 | 0.30 | 0.05 | 16.6 | 0.05 |
| | | 13.34 | 0.98 | 0.05 | 5.1 | 0.07 |
| | | 20.02 | 2.71 | 0.30 | 11.1 | 0.14 |
| | | 26.69 | 3.98 | 0.38 | 9.5 | 0.15 |
| | Jet and bath cooling | 6.67 | 0.47 | 0.04 | 8.5 | 0.07 |
| | | 13.34 | 1.07 | 0.10 | 9.3 | 0.08 |
| | | 20.02 | 2.61 | 0.27 | 10.3 | 0.13 |
| | | 26.69 | 4.32 | 0.44 | 10.2 | 0.16 |

results similar to those when cooling the tool insert, but generated even slightly higher coefficients of friction. Combined disk and bath cooling resulted in still higher friction coefficients (0.26–0.32). These results on both the SAE 1018 steel and the Ti-6Al-4V disks showed that the coated carbide insert did not respond positively to LN2 cooling.

LN2 jet cooling was superior in reducting friction among all the LN2 application approaches investigated, with friction coefficients ranging from 0.04 to 0.15. The coefficients of friction measured when tool insert cooling combined with LN2 jet cooling were very close to jet cooling and thus this additional application of LN2 had no advantage in terms of reducting friction. This may have been because the hydrodynamic lubrication film effect overwhelmed additional LN2 cooling, making the additional cooling insignificant.

## DISCUSSION

As observed from the tests, workpiece materials AISI 1018 and Ti-6Al-4V did not behave much differently as regards the trend of the

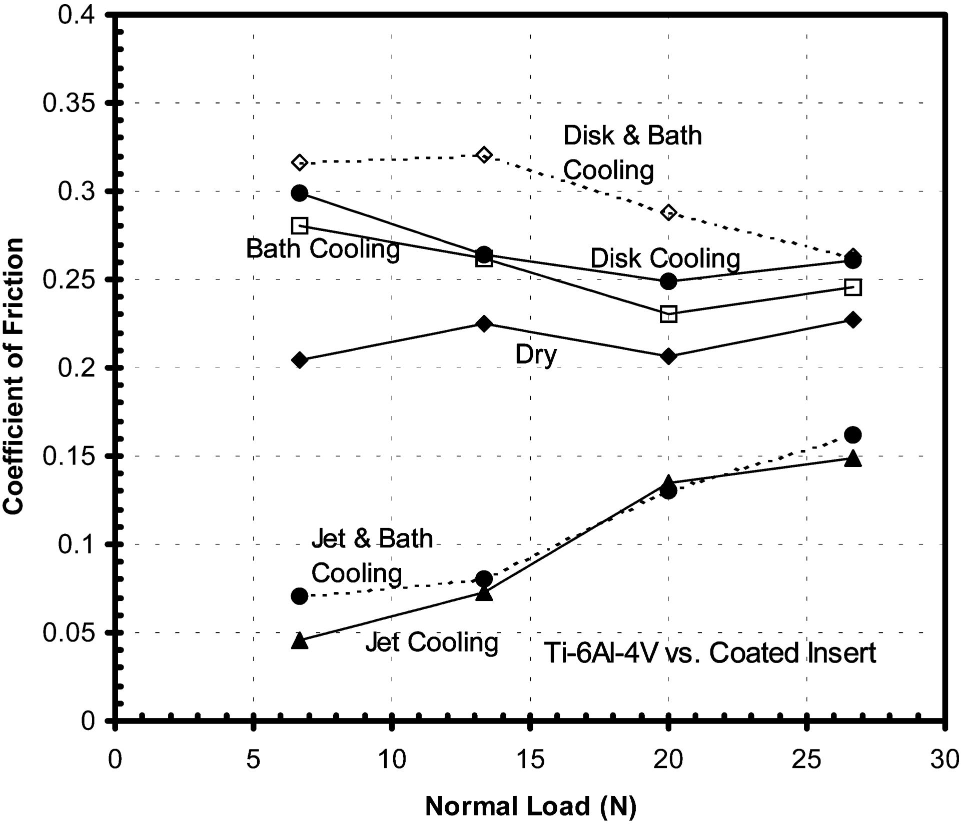


**FIGURE 10** Coefficient of friction for Ti-6A1-4V against coated insert under various LN2 approaches at 0.3 m/s.

friction coefficient when tested as disks, sliding on different tool material specimens. However, the tool inserts, coated or not coated, showed significant differences in the friction behavior when cooled by LN2. Generally coated inserts have a lower coefficient of friction than uncoated inserts in dry cutting or emulsion cooling. But, in our case, the coated insert reacted negatively when under LN2 cooling. Except in the case of jet cooling, the friction force increased when either mist cooling the disk or bath cooling the tool by LN2. On the other hand, the uncoated insert showed a very favorable reaction to LN2 cooling; friction was reduced under LN2 cooling when compared with dry and LN2 jet application was always very effective in reducing the coefficient of friction, regardless of friction pairs. Combining other LN2 cooling approaches with the jet cooling did not show any additional effectiveness in reducing the friction.

## Regarding Temperature Effect

In this study, the bath cooling was designed to lower the tool sample's temperature, but to avoid introducing any LN2 between the rotating disk and the tool flat. The friction change under this kind of cooling is purely due to tool material property changes resulting from the low temperature. When the AISI 1018 disk slid on the uncoated insert which was cooled in the LN2 bath, the friction coefficient ranged from 0.24 to 0.20, which is much lower than the values of 0.35–0.23 observed in dry testing as shown in Figure 7. When the disk was Ti-6Al-4V, a similar trend was also observed; the friction coefficient was reduced from 0.3–0.24 in dry testing to 0.26 to 0.18 in LN2 bath cooling of uncoated insert (Figure 9). Lowering the temperature of uncoated carbide was effective in reducing the friction coefficient. However, the coated carbide insert reacted to the LN2 bath cooling differently. The friction coefficients ranged from 0.14 to 0.16, slightly higher than 0.12–0.18 of dry test for 1018 disk, and for the Ti-6Al-4V disk from 0.28 to 0.25 which is higher than the 0.2 to 0.23 range observed during dry testing. Lowering the temperature of the coated insert resulted in higher friction.

The disk cooling test setup was designed to reduce the temperature of the workpiece material without introducing any LN2 at the point of contact so that any change in the friction coefficient reflects only the surface property changes of the workpiece material. When LN2 cooled, the AISI 1018 disk slid on the uncoated insert, and the friction coefficient ranged from 0.29 to 0.23, lower than the 0.34–0.22 range of dry testing. However, in the AISI 1018 disk in the LN2 enclosure against the coated carbide insert test, the friction coefficient (0.22 to 0.16) increased from that of dry (0.12–0.18). A similar pattern was observed for Ti-6Al-4V disk cooling. Against an uncoated tool insert, the friction coefficient was reduced relatively from 0.3–0.23 dry to 0.29–0.20 (disk cooling). However, when sliding on the coated insert, a higher friction coefficient (0.30 to 0.26) was observed than the range of 0.20–0.23 measured in the dry test. Lowering the temperature of the AISI 1018 disk or Ti-6Al-4V disk resulted in lower friction with the uncoated insert and higher friction with the coated insert i.e. the response was dependent on tool insert material.

Combined tool insert and disk cooling reduced the temperature for both materials, which provided additional cooling to the friction pairs. However when LN2 was excluded from the sliding zone between the sample disk and specimen. the friction coefficients obtained from the tests showed no real improvement over the workpiece disk cooling or tool piece bath cooling. They were lower still for the uncoated carbide and even higher for the coated insert than dry friction. Lowering the temperature of both the disk and tool insert showed similar trends of friction coefficient to that of disk cooling or tool insert cooling, and it is hard to say the performance was any better than just bath cooling the tool insert.

The testing results indicated that the low temperature properties of tool insert material are more critical than the workpiece material in determining the LN2 lubrication effect. The uncoated insert was effective in reducing friction under LN2 cooling. This may indicate the reduction of friction force by changes of tool material properties. Carbide tools at low temperatures tend to show enhanced hardness and increased wear resistance (17). A coated insert under LN2 cooling did not show a reduction in friction. The insert was a multiple coated insert composed of very thin coating layers in which each layer had different thermal expansions. When exposed to low temperatures, these coatings may have begun to contract the different extents leading to compatibility stresses which buckled the layers and resulted in a change in surface texture. This may be the origin of the increased friction force for the coated insert in LN2 bath cooling (18).

Lowering the workpiece material temperature by disk cooling consistently performed worse than lowering the tool insert temperature by bath cooling. Whether there was an advantageous lubrication effect for LN2 by lowering the temperature of the tool insert, disk, or both, still depended mainly on the material properties of tool insert.

### Regarding Hydrodynamic Effect

The application of LN2 to the surface by jet cooling was designed to generate a hydrodynamic lubrication film between the disk and the specimen. The observed change of the friction coefficient under LN2 jet cooling was mainly due to the hydrodynamic effect, although obviously surface cooling also occurred. All the LN2 jet applications testing results shown in Figure 6 through Figure10, show that the LN2 jet application was very effective in friction force reduction, as compared to dry test or even other non-hydraulic LN2 applications. Very low friction coefficients ranging (0.05–0.15) were almost the same regardless of material pairs. The reason is that the LN2 jet provided an effective lubrication film between the disk and sample, which may separate the contacting bodies. In addition, it cools the disk and sample together, a more effective method in improving material surface properties. The friction coefficient increased as the load was increased, indicating that the lubrication film was decreased with the normal load.

## CONCLUSION

As indicated previously, it was originally assumed that the LN2 lubrication mechanism was ascribed to a reduction in friction due to a change in material properties on cooling. The test results showed, however, that is not always the case and that the effect is highly dependent on material pairs. Another assumption of the LN2 lubrication mechanism was that the injection of LN2 into contact zone created a lubricating film. The test results showed that the LN2 jet was very effective in reducing friction.

In this study, five different friction pairs were tested under various LN2 cooling conditions and the friction coefficients determined were compared to the friction coefficients measured under dry conditions. It can be concluded:

LN2 lubrication capacity by low temperature effect depends on material pairs; it can enhance the lubrication effect or aggravate it.

LN2 lubrication by generating hydrodynamic film yields very low friction coefficients. This hydrodynamic film generates the same lubricating effect regardless of material pair.

1. Coating layer as a solid lubricant is effective in reducing friction under dry conditions, but it may cause adverse lubrication effects at low temperatures.
2. LN2 cooling provides effective lubrication with uncoated inserts.
3. Flood LN2 cooling may not have advantages in enhancing the lubrication effect.

## ACKNOWLEDGMENTS

Special thanks to my graduate student Woo-Cheol Jeong, and to visiting scholar Dr. Y. Ding for their help in conducting the tests during my service in Columbia University.

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