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Thermal aspects, material considerations and cooling strategies in cryogenic machining

Shane Y. Hong, Zhibo Zhao

Abstract Conventional machining prolongs tool life by using cutting oils to cool the metal cutting process. Unfortunately, the cutting fluid contaminates the environment, and endangers the health of humans. Cryogenic machining offers an environmentally safe alternative to conventional machining by using liquid nitrogen, which can be naturally recycled. However, for the cryogenic machining process to be effective and economical, manufacturers must select the correct cooling approach. This paper describes our experimental study to investigate the cryogenic properties of some common cutting tool materials and five workpiece materials of industrial interest: low carbon steel, AISI 1010, high carbon steel AISI 1070, bearing steel AISI 52100, titanium alloy Ti-6Al-4V, and cast aluminum alloy A390. The paper addresses the major aspects of heat generated in metal cutting in terms of its effects on chip formation, tool wear, and on the functional integrity of the machined component. The paper then discusses the cooling strategies for cryogenic machining each material based on the thermal effects and material properties. The investigators conclude that the cooling approach must be finely adjusted for different materials to obtain the optimum effectiveness in cryogenic machining. The goal of our study is to provide a basis for designing the cryogenic machining system.

1 Introduction

Metal cutting, or machining, which represents an annual $150 billion output in the United States, is widely used in nearly all manufacturing industries, including the aluminum, steel, automobile, and aerospace industries. Because the high temperatures associated with the cutting process reduce the tool life, the machining industry has been using oil-based or water-based emulsion cutting fluids to cool and lubricate the machining process. Unfortunately, conventional cutting fluids create both health [Beattie and Strohm 1994] and environmental problems, adding to production costs. The National Institute for Occupational Safety and Health estimates that more than 6 million workers are exposed to mineral oil, and that approximately 1.2 million are exposed in the metal cutting fluid application [NIOSH 1977]. Long term exposure to cutting fluid can cause dermatitis, a skin disorder common in the machining industry [Bennett 1992]. Dermatitis can range from an ugly rash to malignant cancer. In Ohio, line operators in a major automobile plant reported to the author that 30% of their machining operators had developed dermatitis of various degrees; two required hospitalized. Inhaling cutting fluid vapor may cause lung disorders as well [Kennedy et al. 1989]. Because conventional cutting fluids are non-biodegradable, manufacturers must comply with environmental regulations to dispose of them. Furthermore, manufacturing materials contaminated with the cutting fluid must be treated before being disposed. The disposal of cutting fluids now costs at least double the purchasing price in the United States and four times its price in Europe. Manufacturers need an environmentally safe new machining process that is energy efficient, yet able to improve tool life, increase productivity, and reduce production cost.

Cryogenic machining offers a potential solution to the environmental and health concerns of conventional machining. This process replaces the cutting fluid coolant with super cold liquid nitrogen. Nitrogen, which is abundant (79% of air), is naturally recycled without damage to the environment. Nitrogen can be compressed to a liquid, and as liquid it cools the cutting process, evaporates and becomes part of the air again. Nitrogen can sufficiently lower the machining temperature to reduce the tool wear and increase the tool life. However, to be effective and economical, cryogenic machining must be done under specific conditions.

The purpose of the machining process is to transform the material into a desirable shape by using a cutting tool. The material properties of the workpiece and of the tool determine the effectiveness in the cutting process. Because heat is a natural byproduct of the cutting process, understanding the effect of temperature on the material properties will help researchers and manufac-

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S.Y. Hong, Z. Zhao
Columbia University, Department of Mechanical Engineering, New York, NY 10027, USA
e-mail: sh295@columbia.edu

Correspondence to: S.Y. Hong

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turers solve ongoing problems with the machining process.

This study investigates the thermal aspects of the metal cutting process, studies the materials' behavior at cryogenic temperatures, and then discusses the cooling strategies for environmentally safe cryogenic machining. The goal is to provide a basis for designing the cryogenic machining system.

2
Temperatures in machining

The power consumed in machining is largely converted into heat near the cutting edge of the tool. This causes the temperature of the tool, chip and workpiece to rise. The heat generated in machining can influence the properties of the work material being machined, as well as the effective life of the cutting tool. As shown in Fig. 1, heat is generated mainly in two plastic deformation zones: the primary zone ahead of the cutting edge, and the secondary zone adjacent to the chip-tool interface. Where additional heat is generated due to the sliding friction along the rake face. The critical temperatures in machining include temperatures at the primary shear zone, and the chip-tool interface, as well as the average body temperature of the chip.

The average temperature in the primary shear zone strongly influences the flow stress and the compressive stress at the cutting edge of the tool, thus influencing the cutting force and tool wear. The temperature at the chip-tool interface greatly affects the rate of tool wear. In general, difficult-to-machine materials generate high cutting temperatures at the chip-tool interface and promote tool wear due to increased adhesion and diffusion. It is unlikely that the stress acting on the tool increases with the cutting speed. The temperatures at the chip-tool interface, however, do increase with the cutting speed; it is this temperature rise which sets the ultimate

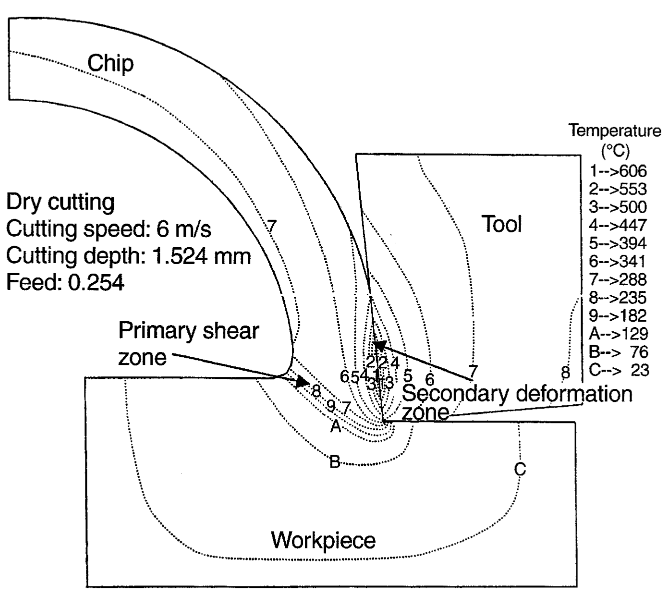

Fig. 1. Heat generation zone and cutting temperature distribution using example in dry cutting low carbon steel

limit on the practical cutting speed for machining metals and alloys with high melting points.

Temperature also affects chip-breakability. It is well established that the chip-breakability is characterized by critical fracture strain [Gane 1978, Nakayama 1984, Cook 1963]. The cutting temperature and the chip temperature can affect the critical fracture strain of a chip, in turn affecting chip breaking. The critical fracture strain for various metals increases significantly when the temperature of the chip is above 400 °C [Kluft 1979]. Cook [1963] noted a correlation between the cutting temperature and the critical fracture strain. The cutting temperature at the tool/interface considerably affects the physical state of the machined surface. Surface alterations, such as thermal residual stress, plastic deformation, oxidation, and metallurgical structural transformation, may occur due to the thermal and/or mechanical loads during machining. Surface alterations often impair the functional integrity of the machined component [Neailey 1988, Sadat 1987, Von Turkovich 1981].

Based on this evidence, the objective in machining is to reduce the cutting temperatures. To reduce the negative effects of the high temperatures generated in the machining process, manufacturers have:
- controlled the quantity of heat generated by optimizing operation parameters,
- developed more effective high-temperature resistant tool materials,
- effectively removed heat from the cutting zone,
- changed the metallurgical and mechanical properties of the workpiece and tool materials,
- changed the frictional characteristics at the interfaces.

The development of cutting tool materials, such as tungsten carbides, ceramic tool, diamond, CBN and various tool coatings, has greatly advanced metal machining. Limitations have been reached, however, particularly in the area of high-speed machining of difficult-to-machine materials.

To counteract the destructive effects of high temperature, the machining industry has used a wide variety of cutting fluids in the machining process. However, conventional cutting pollutes the environment. Cryogenic machining, an environmentally safe approach, eliminates many of the detrimental effects of high cutting temperatures.

3
Cryogenic machining and cooling strategies

In cryogenic machining, manufacturers use an extremely cold or sub-zero coolant. Depending on the purpose, cryogenic coolant may be applied to the cutting area, chip, workpiece, or cutting tool [Dillon 1990, Uehara 1968, 1970]. The main functions of cryogenic machining include (1) removing heat effectively from the cutting zone, hence lowering cutting temperatures, (2) modifying the frictional characteristics at the tool/chip interfaces, and (3) changing the properties of the workpiece and the tool material.

Materials respond differently to temperature and machining. Therefore, the strategy for improving machinability must vary depending on the material being machined. For example, machining low carbon steel always causes severe problems in chip breaking; machining heat resistant alloys, such as titanium and nickel alloys, causes tools to wear quickly. Accordingly, in cryogenic machining different cooling strategies are needed for solving problems specific to the individual materials being machined. The authors define cooling strategies as the ways cryogenic coolant is applied in cryogenic machining to improve the machinability of the materials. These strategies, which may serve different purposes, include:

– freezing the workpiece,
– delivering the cryogen to the tool/chip or tool/work interface,
– cooling the cutting tool, or
– cooling the chip.

To choose cooling strategies, the properties of both tool materials and workpiece materials must be considered because they are fundamental in determining machining characteristics. The desirable properties of tool materials generally include high hardness and wear resistance, high toughness and high strength to resist various forms of fractures, and low chemical affinity with the workpiece. Properties of the workpiece materials become problematic when their hardness and strength are abrasive to cutting tools and when these properties cause a high compressive stress to act on the cutting edge raising the cutting temperatures. The materials' ductility and toughness affect the chip formation process. Highly ductile materials, for instance, are likely to produce continuous chips and built-up edges.

These points support the need to understand material behaviors to effectively evaluate cooling strategies for cryogenic machining.

4
Tool materials consideration

Cutting tool materials belong to a group of refractory and non-ductile materials. Chipping and breaking of the cutting edge and fracturing of the tool are common modes of tool failure. To address problems of tool failures requires an understanding of the materials' resistance to chipping and fracturing (i.e., toughness) and the resistance to thermal and mechanical loads. Traditionally, cutting tools have been subjected to high temperature conditions in the machining process, therefore, little is known about the properties of tool materials at the subzero temperatures in cryogenic machining. Low temperatures increase the cutting tool's hardness and wear resistance, while decreasing its chemical affinities to workpiece materials. These characteristics are believed to be beneficial in cryogenic machining; however, when exposed to low temperatures, most materials become brittle. Degradations in tool's strength and toughness at low temperatures, if any, would negate any possible gains from cryogenic machining. To evaluate the potential of cryogenic machining, it is critical to know whether the cutting tool materials can maintain enough toughness.

Table 1. Nominal compositions of the tested carbide tool materials [provided by Kennametal, Inc.]

	Cobalt (wt%)	Ta (wt%)	Ti (wt%)	Other (wt%)	Carbide Size
K3109	12.2	0.3	0	0	Large
K313	6.0	0	0	(Cr:0.4%)	Fine
K420	8.5	10.2	5.9	0	Large
K68	5.7	1.9	0	0	Medium
SP274	5.85	5.2	2.0	0	Medium

To address this issue, several representative grades of carbide-cobalt alloys, K3109, K313, K420, K68 and SP274, were investigated at cryogenic temperatures. A brief description of each material's composition is given in Table 1. The experiments conducted on these materials included microstructural observations, impact tests, three point bending tests, and indentation tests. Due to their extreme hardness and brittleness, carbide tool materials do not respond to tensile testing. Instead, transverse rupture strength was widely used to characterize the fracture strength of tungsten tool materials. The three point bending test was used to study their behavior. The transverse rupture strength (TRS) is defined as $TRS = 3FL/2bh^2$, where F is the applied load, L the distance between the supports, b and h the specimen width and height.

Cemented carbides are a group of hard, wear-resistant, refractory materials in which the hard carbide particles are bonded or cemented together by a ductile metal binder, usually cobalt. The microstructures of the cemented carbides usually consist of two phases: WC grains and the binder phase. The amount of binder and the WC grain size generally determine the properties of the carbide tool materials. Consequently, the tested carbide grades have the following features:

– **K3109**: A large volume of binder phase and coarse WC grains characterize K3109. It is also identified by high impact strength, high strength (TRS), and relatively low hardness. As expected, K3109 is the toughest grade among all the tested carbide tool materials.
– **K313**: K313 is an unalloyed grade that has a low percentage of cobalt binder phase, and has the finest WC grains in its microstructure. Therefore, high hardness, high edge wear-resistance, relatively high strength (TRS), and moderate impact strength characterize K313.
– **K420**: K420 is an alloyed grade of WC/TaC/TiC-Co that has a moderate amount of cobalt binder phase and coarse carbide grains. While the introduction of other carbides such as TaC and TiC contributes to high hardness and high thermal plastic deformation resistance, they also cause a decrease in strength. Consequently, the general features of K420 include moderate hardness, high thermal shock resistance, relatively high impact strength, and relatively high strength (TRS).
– **K68**: K68 is a low cobalt unalloyed grade with intermediate carbide grain sizes. This accounts for its high hardness, moderate impact strength, and moderate strength (TRS). This grade of carbide also exhibits high

edge wear-resistance in machining stainless steels, cast irons, nonferrous metals, nonmetals, and most high temperature alloys.

- **SP274**: SP274 is an alloyed grade with a low binder content. Normally used as a substrate material for coated carbide tool materials, the material is characterized by high hardness and moderate TRS.

The indentation testings at liquid nitrogen temperature indicate an increase in the hardness of all the tested materials compared to the materials' hardness at room temperature. Figures 2 and 3 show impact strength versus temperature, and transverse rupture strength (TRS) versus temperature, respectively. Even though the carbide grades show different tendencies, they generally retain their toughness and transverse rupture strength even as the temperature decreases toward liquid nitrogen temperature. This indicates that the carbide tool materials, within the composition ranges investigated in this study, have the properties needed for cryogenic machining. Therefore, a variety of cooling strategies is available when using these tool materials.

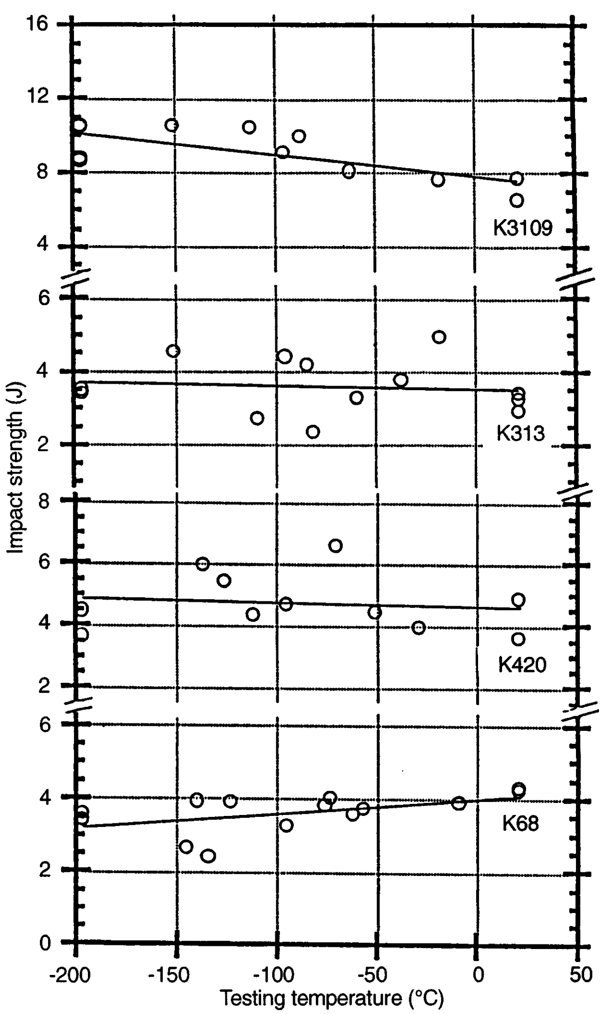

Fig. 2. The impact strength of the carbide tool materials versus temperature

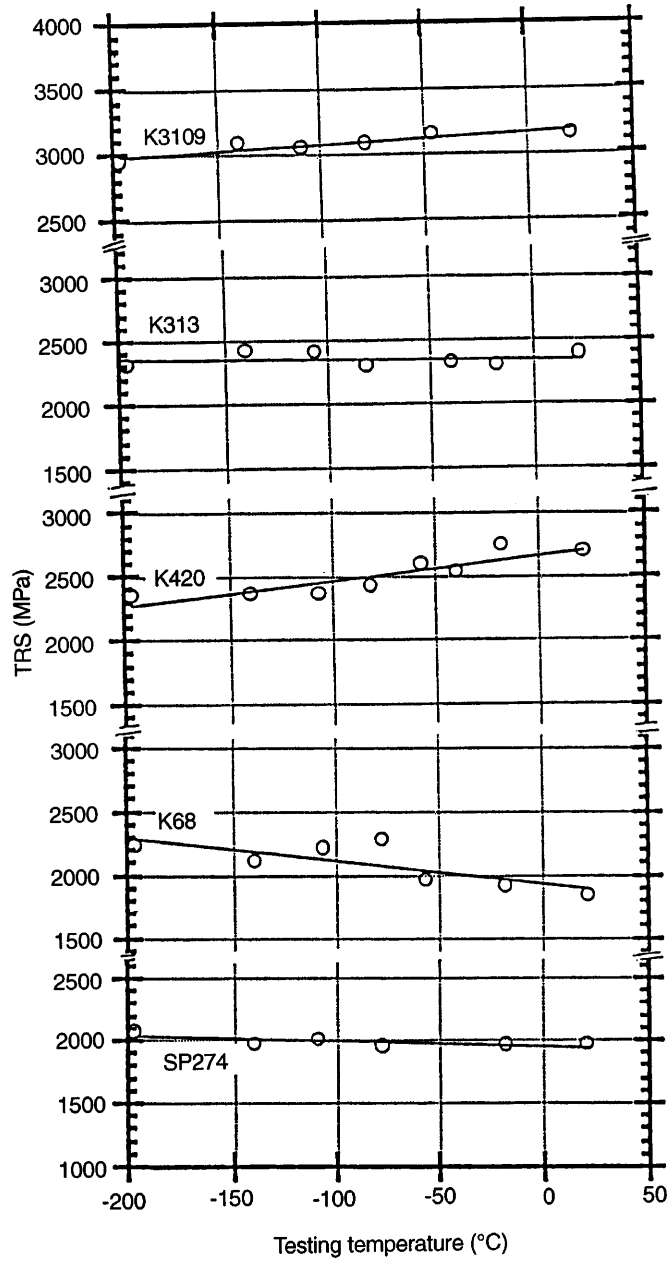

Fig. 3. Transverse rupture strength of the carbide tool materials versus temperature

5
Properties of workpiece materials: case studies of cooling strategies

The mechanical properties of the workpiece materials are the major factors influencing their machinabilities. High hardness and high strength materials are not only abrasive to cutting tools, but also responsible for the high compressive stress acting on the cutting edge and high cutting temperatures. Ductility and toughness of materials affect the chip formation process; highly ductile materials, for instance, are likely to produce continuous chips and built-up edges. In an effort to determine the best machining temperature or cooling strategy for cryogenic machining, the mechanical properties such as hardness, tensile properties and impact strength were investigated at low temperatures.

5.1 Materials and experiments

Five workpiece materials were utilized in this study: low carbon steel 1010, high carbon steel 1070, bearing steel E52100, high silicon aluminum alloy A390, and titanium alloy Ti-6Al-4V. These materials represent a spectrum of the typical materials used in automobile and aerospace industries of special interests to our sponsors. Their compositions are given in Table 2. Essentially, the specimen preparation and the procedures for these mechanical testing meet ASTM standards. For low temperature experiments, a tensile tester, a Rockwell tester and an impact tester were modified so that a liquid container could be attached. Liquid chemicals, such as alcohol and isopentane, that were cooled by liquid nitrogen were employed as the cooling media.

Machining tests on some of the workpiece materials were conducted using a CNC turning machine. The evaluated machining characteristics included cutting force, rate of tool wear, chip breakability, and surface finish of the machined surface.

5.2 AISI-SAE 1010

AISI-SAE 1010 is a very soft, mild steel of low strength and high ductility. In spite of its low hardness, it has a poor machinability due to its difficulty in chip breaking. The adhesive wear of the cutting tool, the formation of built-up edges at moderate cutting speeds, and its particularly poor chip breakability represent the machining characteristics of this steel and most other low carbon steels.

The microstructure of 1010 steel consists of two micro-constituents, ferrite and pearlite, which accounts for the soft, ductile, sticky nature of this material. Figures 4 and 5 show the mechanical properties of 1010 steel at cryogenic temperatures. Hardness and strength increase as the temperature decreases. The average room temperature hardness is only $R_g = 54$, (corresponding to $R_b = 83$). Even at liquid nitrogen temperature, the hardness of 1010 only reaches a level of $R_c = 27$. Due to the existence of the BCC (body center cubic) structure of ferrite, the impact strength of 1010 exhibits a sharp transition from ductility to brittleness when the temperature is decreased to about –50 °C. While elongation and reduction in area also indicate the transition, they occur at a lower temperature. This means that the same material responds differently to temperature according to the loading modes.

Table 2. The materials and their compositions

Alloys	Compositions
1010	0.09% C, 0.39% Mn, 0.01% S, 0.01%P, 0.006% Si, 0.022% Al
1070	0.65–0.76% C, 0.60–0.90% Mn
E52100	0.98–1.1% C, 0.25–0.45% Mn, 0.025% S, 0.025% P, 0.15–0.30% Si, 1.30–1.60% Cr
A390	4.0–5.0% Cu, 0.45–0.65% Mg, 0.10% Mn, 16.0–18.0% Si, 0.5% Fe, 0.1% Zn, 0.2% Ti
Ti-6Al-4V	6% Al, 4% V

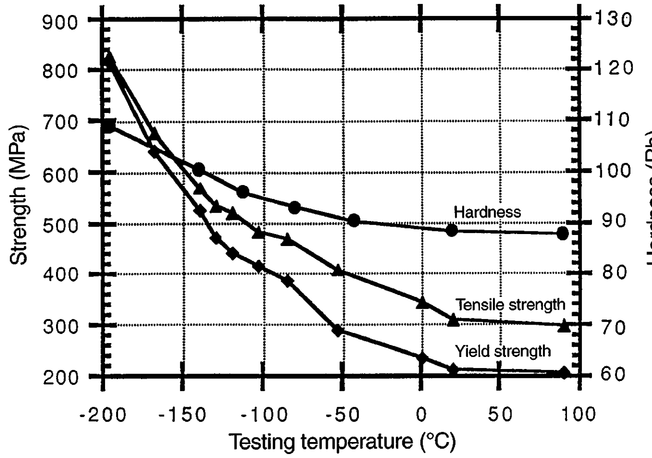

Fig. 4. Strength and hardness of 1010 versus temperature

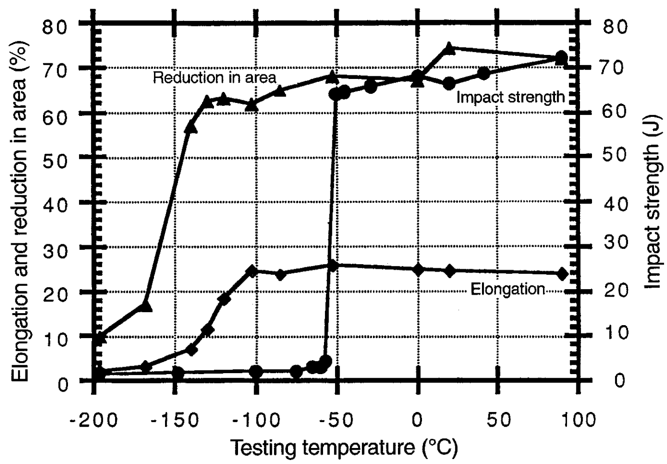

Fig. 5. Elongation or reduction in area and impact strength of 1010 steel versus temperature

The main effects of low temperature on the low carbon steel 1010 include:
- increased strength and hardness,
- reduced toughness, and
- reduced elongation and reduction in area.

The effects of these variations on the machining process can be evaluated by observing their influence on chip formation. The decrease in toughness and ductility promotes chip formation, reduces contact length between the tool and chip, and increases the shear plane angle, which results in a decrease in cutting force. Enhancing brittleness is favorable for increasing the curvature of the chip curl and increasing chip breakability. For steels of low hardness, the dominant factor determining their poor machinability is their soft, ductile (plastic), sticky nature rather than their hardness and strength. This corresponds with the observation that hard steels often require a lower cutting resistance than soft steels, especially at high cutting speeds [Araki 1985]. Previous studies also show a decrease in cutting force in spite of an increase in hardness and strength by freezing a workpiece of mild carbon steels [Uehara 1970, Rice 1966].

Based on this evidence, cooling the workpiece to the temperature range at which the workpiece becomes brittle is a better machining condition for low carbon steels. Cryogenic machining tests were conducted in our laboratory. Pre-cooling the workpiece improved chip breaking as demonstrated in our separate paper [Ding and Hong 1998]. Yet, cooling the chip produced even better chip breaking [Hong 1999].

5.3
AISI 1070 and AISI E52100 steels

The high carbon content of these steels has a significant influence on their mechanical properties and machinability. It increases their tensile strength, shear strength, and hardness; this often causes a high temperature rise during machining. The effects of the carbon content on machinability are also directly related to the formation of hard, abrasive carbides.

Large amounts of eutectoid pearlite are found in the microstructures of the 1070 steel and the annealed E52100 steel. The highly abrasive and sharp lamellae of cementite within the pearlite accelerates tool wear. Extra carbide particles are also present in the microstructure of E52100 because of its hypereutectoid composition. This can create severe abrasive wear. Therefore, tool life in machining steels depends largely on the amount of carbon. Up to 0.24% carbon in steels can favorably affect the machinability because it generates the desired brittleness for chip formation. A higher content of carbon usually adversely affects machinability because of the high strength of steel and the large amount of carbides.

Through our own material tests at cryogenic temperatures, the mechanical properties of 1070 and E52100 steels are displayed as Fig. 6, Fig. 7, Fig. 8 and Fig. 9. Both steels exhibit similar temperature dependencies. As temperature decreases, their hardness and strength increase rapidly. According to the results of impact strength, percent of elongation, and area reduction tests, toughness and ductility decrease with lowering temperatures. Unlike the 1010 steel, 1070 and E52100 alloys have no distinctive ductility to brittleness transition. Instead, impact strength, elongation and reduction in area change gradually.

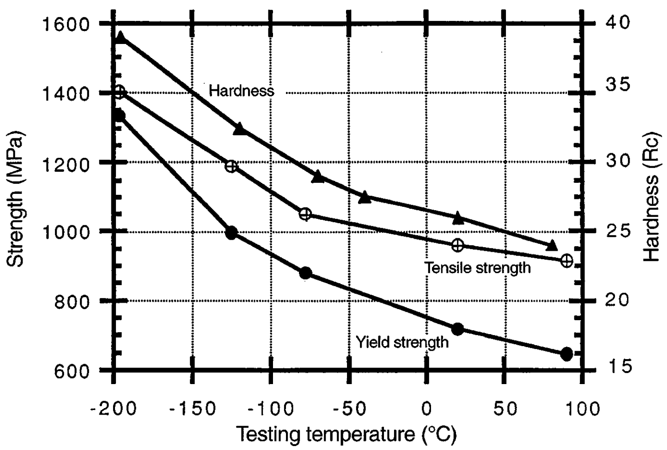

Fig. 6. Strength and hardness of 1070 versus temperature

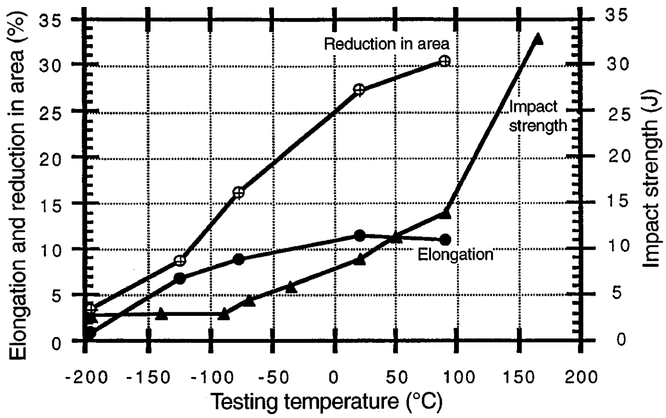

Fig. 7. Elongation, reduction in area and impact strength of 1070 versus temperature

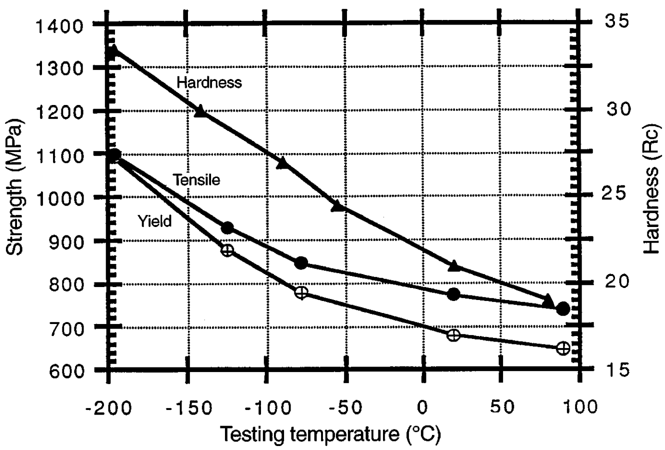

Fig. 8. Tensile strength, yield strength and hardness of 52100 steel versus temperature

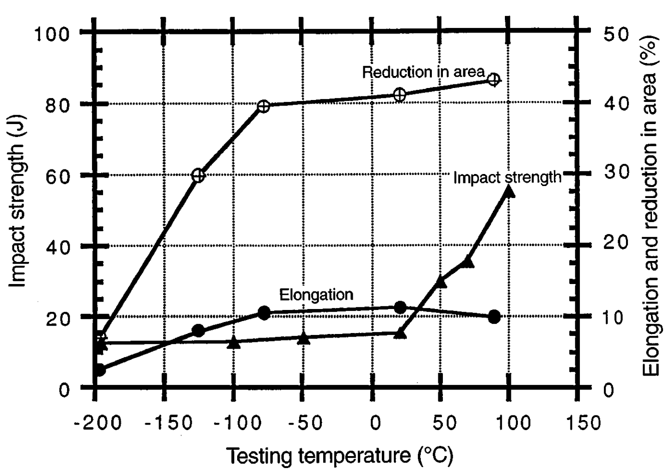

Fig. 9. Elongation, reduction in area and impact strength of 52100 versus temperature

Considering the cryogenic properties of 1070 and E52100 and their conventional machining characteristics, cooling the workpiece may not be an ideal approach. First, 1070 and E52100 have high strength levels even at room temperature. Their rapid increases in strength with decreasing temperatures lead to higher cutting resistances. Second, the hard carbides would become more abrasive at low temperatures. Because abrasive wear and adhesive wear at operating cutting temperatures are the major concerns in machining 1070 and E52100, an effective cryogenic approach is applying the cryogen to the cutting zone adjacent to the chip tool interface. This targets lower cutting temperatures, enhances the hardness of the cutting tool, and reduces the friction at the chip/tool interface. Our test results on cryogenic machining of high strength materials showed that applying the cryogenic coolant to the cutting zone produces better results than freezing the workpiece. Cryogenic machining of 1070 and 52100 by injecting liquid nitrogen to the tool face and chip yielded significant tool life improvement [Markus 1993].

5.4
Cast aluminum alloy A390

The microstructure of A390 consists mainly of two constituents: a soft aluminum matrix and a primary silicon phase. The high nominal Si content in the alloy provides sufficient quantities of the hard primary silicon phase to ensure the strength and the high degree of wear resistance of these cast alloys. However, this large amount of primary silicon phase also causes the machining problem of this alloy.

Almost all aluminum alloys belong to a group of materials with high toughness, but A390 does not follow this trend because of its high content of silicon. A390 is extremely brittle; the impact strength of a standard V-notch A390 specimen is only about 0.5 J, and its elongation is less than 0.5% at any temperature from 20 °C to −196 °C. These characteristics are responsible for the desirable chip forms in the machining of this alloy.

The A390 alloy contains 16–18% silicon, which makes it a hyper-eutectic casting alloy. This alloy has a large amount of primary silicon phase in the microstructure. This phase has a Knoop hardness number (KHN) of 1000–1300, compared to a maximum aluminum matrix hardness of 180KHN [Jorstad 1980]. The presence of the primary silicon phase in the alloy provides its strength and superior wear resistance. However, because of its hardness, it is extremely abrasive to any cutting tools. Tool life is strongly dependent on the size of the primary silicon phase; tool life decreases as the size of the primary silicon phase increases. The ductile and sticky nature of the aluminum matrix phase makes it likely to adhere to the cutting tools and form built-up edges, which often cause a poor surface finish.

The evaluation of AA and ASM indicate that the A390 alloy has the poorest machinability among the cast aluminum alloys, mainly due to the abrasive nature of its primary silicon phase. Increasing tool life by reducing the abrasive wear of the cutting tool is particularly important in machining the A390 alloy. The variation of the hardness of A390 with temperature is given in Fig. 10. The increase in bulk hardness by cooling the workpiece may not be a concern for cryogenic machining, but the increase in the micro-hardness of the primary silicon phase would make the workpiece more abrasive. Therefore, a possible solution is cooling the cutting tool with a cryogenic to enhance its hardness and resistance to abrasive wear. Keeping the cutting tool cool may also decrease the tool's tendencies to adhere to the soft aluminum matrix phase, which may reduce build-up edges and improve surface finish.

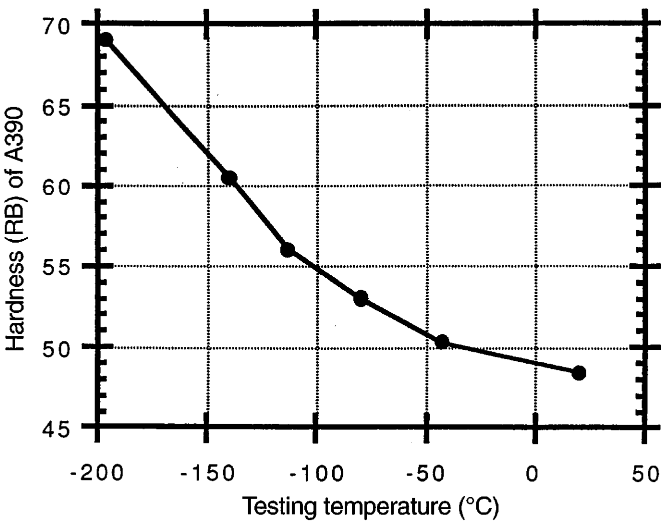

Fig. 10. Hardness of A390 versus temperature

5.5
Titanium Alloy Ti-6A1-4V

5.5.1
Properties of the Ti-6A1-4V alloy

The tested material in this study is the Ti-6Al-4V annealed alloy. Its microstructure consists of a coarse, plate-like alpha phase and a grain boundary beta phase. The variation of its hardness with temperature is shown in Fig. 11. At room temperature, the hardness of the annealed Ti-6A1-4V alloy is $R_c = 33.5$. Between room temperature and −50 °C, the hardness exhibits a rapid increase. When the temperature further drops below −50 °C, the hardness increases gradually. At liquid nitrogen temperature, the hardness of Ti-6Al-4V is about $R_c = 42$. The results of the impact strength, percent elongation, and reduction in area indicate that the alloy Ti-6Al-4V can maintain, to a large extent, its toughness and ductility at low temperatures, even at liquid nitrogen temperature [Collings 1983].

5.5.2
Characteristics of machining Titanium alloy

Titanium and its alloys are classified as difficult-to-machine materials. The main problems in machining titanium and their alloys are the high cutting temperatures and the rapid tool wear. Most tool materials wear rapidly even at moderate cutting speeds when machining

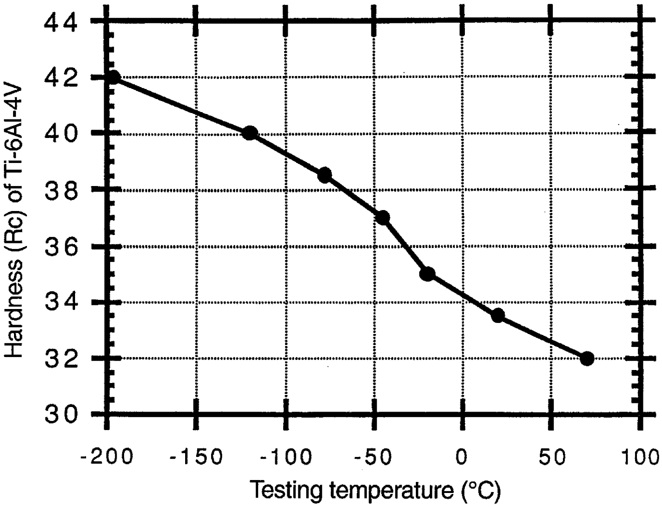

Fig. 11. Hardness of Ti-6Al-4V versus temperature

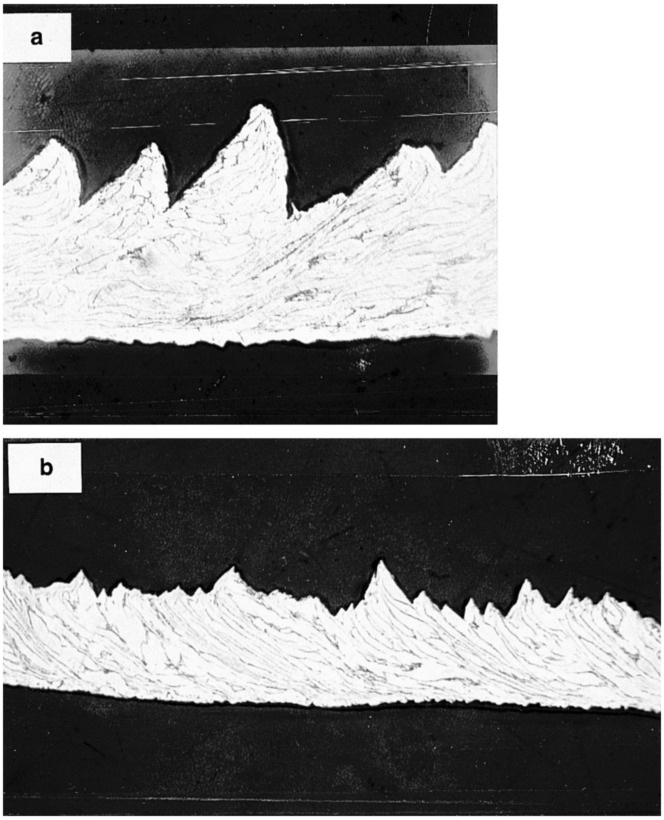

Fig. 12a,b. The microstructures of Ti-6Al-4V chips (200×) cut at (**a**) dry machining condition and (**b**) cryogenic temperature (−196 °C). Low temperature has a remarkable effect on the chip formation process of Ti-6Al-4V alloy

titanium and its alloys. Therefore, current machining practice limits the cutting speed to less than 1 m/s to minimize tool wear. The machining characteristics for titanium and its alloys are summarized below [Machado 1990, Komanduri 1981; Donachie 1982].

1. Titanium and its alloys are poor thermal conductors; their thermal conductivity is only about one sixth that of steel. As a result, the heat generated when machining titanium cannot dissipate quickly; rather most of the heat is concentrated on the cutting edge and tool face.
2. Titanium has a strong alloying tendency or chemical reactivity with the cutting tool material at tool operation temperatures. This causes galling, welding, and smearing, along with rapid wear or cutting tool failure.
3. During machining, titanium alloys exhibit thermal plastic instability which leads to unique characteristics of chip formation. The shear strains in the chip are not uniform; rather, they are localized in a narrow band that forms serrated chips.
4. The contact length between the chip and the tool is extremely short (less than one-third the contact length of steel with the same feedrate and depth of cut). This implies that the high cutting temperature and the high stress are simultaneously concentrated near the cutting edge (within 0.5 mm).
5. Serrated chips create fluctuations in the cutting force; this situation is further promoted when alpha-beta alloys are machined. The vibration force, together with the high temperature, exerts a micro-fatigue loading on the cutting tool, which is believed to be partially responsible for severe flank wear.

Regarding mechanical properties, titanium alloys experience rapid increases in their strength and hardness while their toughness and ductility show little variation as temperature decreases. Therefore, it is difficult to discuss a cryogenic strategy based on their mechanical properties at a cryogenic temperature. However, considering the main machining characteristics of titanium which arise from a high cutting temperature and its high chemical affinity for tool materials at operating temperatures, an effective cryogenic strategy is to cool the workpiece and cutting tool simultaneously. This is expected to:

- lower the cutting temperature,
- enhance the chemical stability of the workpiece,
- enhance the hardness and chemical stability of the tool, and
- reduce the friction at the work/tool interface and tool/chip interface.

Titanium and its alloys have been a major subject of cryogenic machining studies. Most of the work indicates an improvement in their machinabilities by either freezing the workpiece or cooling the tool using a cryogenic coolant. [Uehara 1968, 1970, Dillon 1990, Holis 1961, Reed 1965, Christopher 1990]. Freezing the workpiece was suggested as the ideal cutting condition for machining titanium and its alloys from a technical perspective [Dillon 1990, Rennhack 1974, Xuan 1991]. However, due to its increased strength and hardness, frozen titanium negatively affects the machining process. Therefore, if an effective coolant were available for lowering the tool temperature, it would be more appropriate to use than to cool the workpiece.

Titanium and its alloys represent the most challenging materials in machining. With the advancement in cutting tool materials, many difficult-to-machine materials can

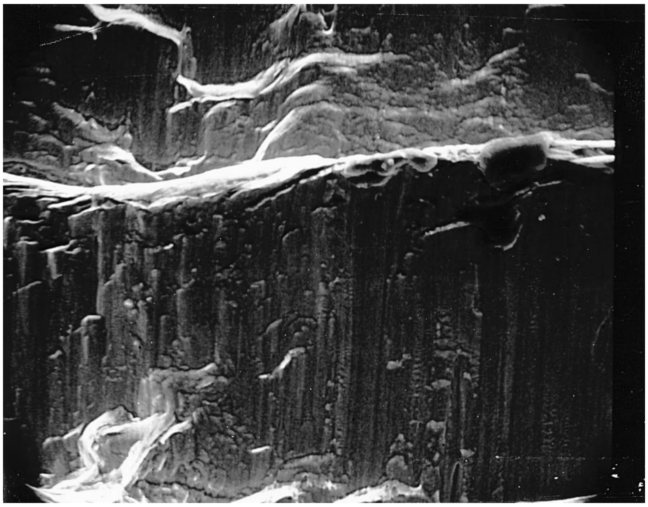

Fig. 13. The SEM photograph of the rough side of Ti-6Al-4V chip cut under dry machining conditions

Fig. 14. The SEM Photograph of the rough side of Ti-6Al-4V chip cut under cryogenic machining conditions

now be machined at higher metal removal rates. None of these tool materials, however, seem to be effective in machining titanium because of their chemical affinities with titanium. The calculation of Hartung, et. al. [1982], indicates that no potential materials are suitable for machining titanium. Thus, cryogenic machining, which is able to both lower the cutting temperature and enhance chemical stability of both the workpiece and the tool, is expected to have a great potential in high productivity machining of titanium and its alloys. This can be achieved by injecting a focused liquid nitrogen jet to the cutting point.

Based on the understanding of titanium alloy property, we have developed an economical cryogenic process that focuses micro liquid nitrogen jets to the chip-tool interface and tool-workpiece interface. This process improves tool life up to five times that of the state-of-art emulsion cooling method. Because the nitrogen consumption is so small (less than 0.2 gallon per minute, 0.01 kg/s), this process improves the productivity and reduces the production cost significantly [Hong 1995].

6 Summary

In cryogenic machining, the liquid gas is used to lower the cutting temperature, alter the material properties, and maximize the effectiveness of the cutting tool. As the temperature decreases, the tool material increases its hardness, and physical and chemical stability – tendencies that we anticipate will be beneficial for cryogenic machining. Our studies on carbide-cobalt alloys at cryogenic temperature revealed desirable mechanical properties, such as high transverse rupture strength and high impact strength. The properties of these carbide tool materials will allow the machining industry to flexibly select cooling strategies for cryogenic machining.

We studied five workpiece materials. This paper discussed the cooling strategies for cryogenic machining of these materials based on their mechanical properties at cryogenic temperatures and their characteristics during conventional machining. Low temperatures appear to be an ideal machining conditions for low carbon steel 1010 because it exhibits a distinctive ductility-brittleness transition. For high carbon steel 1070 and high alloy steel E52100, applying cryogens to the cutting zone is expected to impede the rise in temperature and rate of tool wear. When machining A390, we propose cooling the cutting tool with cryogens, which may enhance its hardness and resistance to the abrasive wear of the Si phase in A390. Cooling the workpiece and cutting tool for the Ti-6Al-4V alloy may effectively lower the cutting temperature and reduce the chemical affinity. This can most effectively be achieved by injecting cryogen to the tool-chip and tool-workpiece interfaces.

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