Cooling Strategies for Cryogenic Machining from a Materials Viewpoint

Z. Zhao and S.Y. Hong

This article discusses the cooling strategies for cryogenic machining from a materials viewpoint. It is argued that, because different materials respond to temperature and machining processes differently, different cooling strategies are needed to improve the machinabilities of materials by cryogenic machining. In this work, five workpiece materials such as AISI 1010 low-carbon steel, AISI 1070 high-carbon steel, AISI E52100 bearing steel, titanium alloy Ti-6Al-4V, and cast aluminum alloy A390 were studied experimentally at various temperatures. Based on the experimental results of the cryogenic properties of the materials and their known machining characteristics, the cooling strategies for cryogenic machining of these materials were analyzed.

1. Introduction

In the machining process, plastic deformation takes place simultaneously in three distinct regions: the primary shear flow zone ahead of the cutting edge, the secondary shear flow zone adjacent to the tool/work interface, and the rubbing zone adjacent to the tool/work interface. Most of the work done in the machining process is converted into heat, which causes a temperature rise in the workpiece, tool, and chip. This temperature increase greatly affects the chip formation, tool wear, and machined surface finish.

The effects of temperature on chip formation were studied by Trigger and Chao,[1] Zorev,[2] and Williams *et al.*[3] They indicated that the shear plane angle, the contact length between tool/chip, and the average friction stress were all correlated to the temperature at the tool/chip interface.

Various tool wear mechanisms, which are proposed in machining, include abrasion, adhesion, and fusion.[4] Although there is a great dispute as to what extent the proposed wear mechanisms can be applied,[5] it is clear that the cutting temperature is closely related to most of the proposed wear mechanisms. The works of Trent,[6] and Takeyama and Murata,[7] for example, show that, when machining with carbide tools, where cutting temperatures are higher than 800 °C, the primary wear mechanism is expected to be diffusion, which is a temperature-controlled process.

The cutting temperature at the tool/work interface may significantly affect the physical state of the machined surface. Various forms of surface alterations, such as thermal residual stress, plastic deformation, oxidation, and metallurgical structural transformation, may be due to the thermal and/or mechanical loads during the machining process. This often impairs the functional behaviors of the machined component.[8-10]

Generally, the force acting on the cutting edge decreases with increasing cutting speeds, and the compressive stress near the cutting edge changes only slightly as the cutting temperature rises.[11] Studies of high-speed machining[12,13] have shown that the cutting temperature increases consistently as the cutting speed increases. Because the yield stress and the hardness of tool materials decrease rapidly when temperature rises, the practical cutting speed limit is reached when the compressive stress near the tool edge exceeds the yield stress of the tool material.

As discussed above, the temperatures generated at and near the cutting edge of the tool determine the maximum possible rate of metal removal when machining iron, steel, nickel alloys, and other materials with high melting points. Therefore, removing heat from the machining zone is a natural way of controlling the increasing rate and level of the cutting temperature to a certain degree. Cryogenic machining is a potentially effective approach for heat removal. Research[14,15] has demonstrated its advantages.

The machining process is also strongly affected by the temperature of the workpiece. Well-known applications include hot machining and cryogenic machining. Both approaches attempt to improve the machinability of materials by changing their properties. This article concentrates on cryogenic machining.

Generally, the mechanical, physical, and chemical properties of materials are functions of its temperature. A decrease in temperature generally increases the modulus of elasticity, hardness, and strength. The effects of temperature on physical properties, ductility, and toughness, however, vary considerably. As discussed in later sections, the variation of workpiece material properties with temperature and the resulting machining characteristics require different cryogenic cooling strategies when machining these materials.

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Table 1 Chemical Composition of 1010 Plain-Carbon Steel

Composition, wt%								
C	Mn	S	P	Si	Al	Cu	Cr	Ni
0.09	0.39	0.010	0.010	0.006	0.022	0.04	0.04	0.02

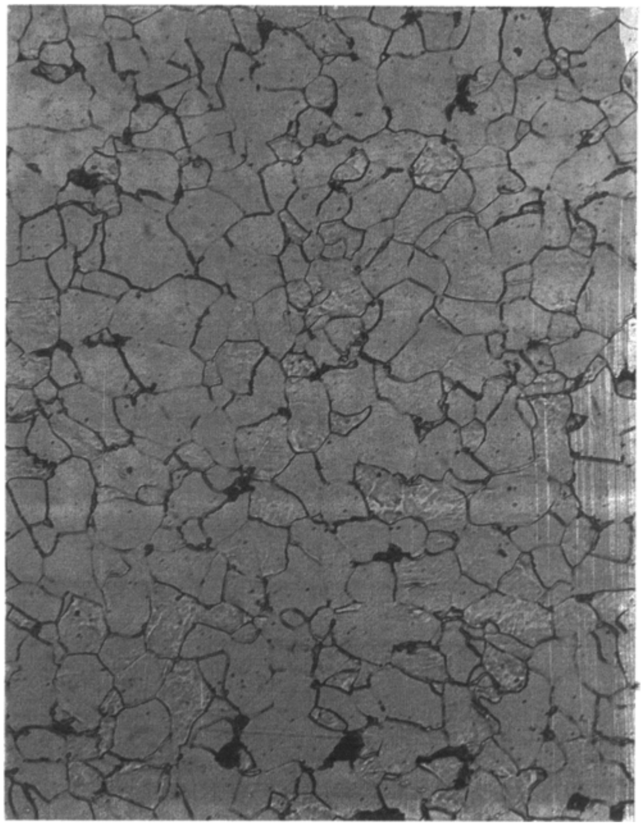


Fig. 1 Microstructure of AISI 1010 steel. 400×.

2. Cryogenic Properties of Materials and Strategies

The mechanical properties of workpiece materials are the major factors influencing their machinabilities. High-hardness and high-strength materials are not only abrasive to cutting tools, but are 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, mechanical properties such as hardness, tensile properties, and impact strength were investigated at low temperatures.

Essentially, the samples and the procedures for these mechanical testings were in accordance with ASTM standards. The temperature range covered in these investigations was −196 °C to 100 °C. To change the temperature of the samples, a tensile tester and a Rockwell tester were modified so that a liquid container could be attached. Liquid chemicals such as alcohol and isopentane, which were cooled by liquid nitrogen, were used as the cooling media.

Five workpiece materials were specified in this study—AISI 1010 low-carbon steel, AISI 1070 high-carbon steel, E52100 bearing steel, high-silicon aluminum alloy A390, and titanium alloy Ti-6Al-4V. These materials represent a spectrum

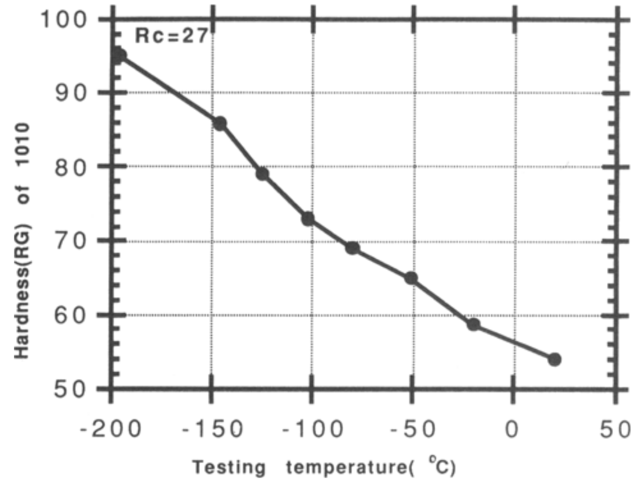


Fig. 2 Hardness of AISI 1010 steel versus temperature.

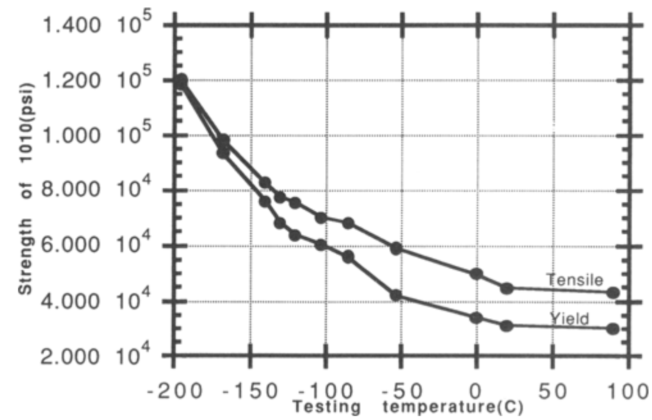


Fig. 3 Tensile and yield strength of AISI 1010 versus temperature.

of typical materials used in automobile and aerospace industries, which are also the interests of our sponsors. The testing results and the cooling strategies for each material are discussed below.

2.1 *AISI-SAE 1010*

AISI-SAE 1010 is a very soft, low-carbon steel of low strength and high ductility. In spite of its low hardness, it has poor machinability due to the difficulty in chip breaking. Adhesive wear of the cutting tool, formation of built-up edges at moderate cutting speeds, and particularly poor chip breakability represent the machining characteristics of this steel and most other low-carbon steels. The chemical composition of this material is given in Table 1.

Figure 1 shows the microstructure of 1010 carbon steel, which consists mainly of the two microconstituents ferrite and pearlite. According to its composition (Table 1) and the iron-carbon phase diagram, the structure can be estimated as 20%

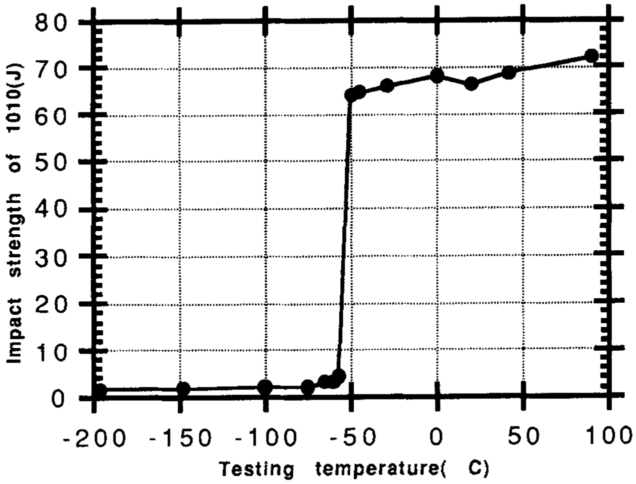


Fig. 4 Impact strength of AISI 1010 steel versus temperature.

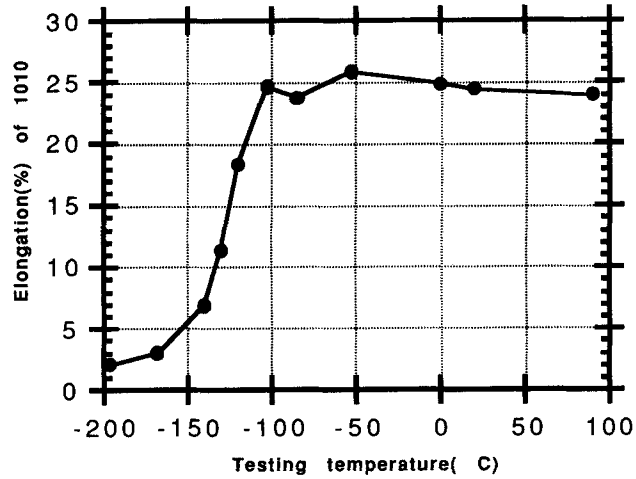


Fig. 5 Tensile elongation of AISI 1010 steel versus temperature.

pearlite and 80% ferrite, which accounts for the soft, ductile, sticky nature of this material.

Figures 2 to 6 show the mechanical properties of 1010 steel at cryogenic temperatures. The hardness and strength increase as the temperature decreases. The average room-temperature hardness is only 54 HRG (corresponding approximately to 83 HRB). Even at liquid nitrogen temperature, the hardness of 1010 reaches only 27 HRC. Because of the body-centered cubic (bcc) structure of ferrite, the impact strength exhibits a sharp transition from ductility to brittleness when the testing temperature is decreased to about –50 °C. Although the elongation and reduction in area also indicate the ductility-to-brittleness transition, they occur at a lower temperature. This implies that the response of the same material to temperature varies with loading modes.

The main effects of low temperature on 1010 low-carbon steel are:

- Strength and hardness increase
- Toughness decreases
- Elongation and reduction in area decrease

The effects of these variations on the machining process can be considered through their influence on chip formation. The decrease in toughness and ductility promote chip formation; this leads to a reduction in contact length between tool and chip and an increase in shear plane angle, resulting in a decrease in cutting force. Enhancing brittleness is also favorable for 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 lower cutting resistance than soft steels, especially at high cutting speeds.[16] Compared to the occurrence of brittleness, the increase in hardness (strength) at low temperatures is expected to play a secondary role in cryogenic machining.

Based on the above consideration, cooling the workpiece to the temperature range where the workpiece becomes brittle is a more suitable machining condition for low-carbon steels. Cryogenic machining of mild steels demonstrates the technical advantages of cooling the workpiece, such as reduction in cutting force and power consumption, decrease in tool wear rate, improvement in surface finish, and improved chip formation.[17-20]

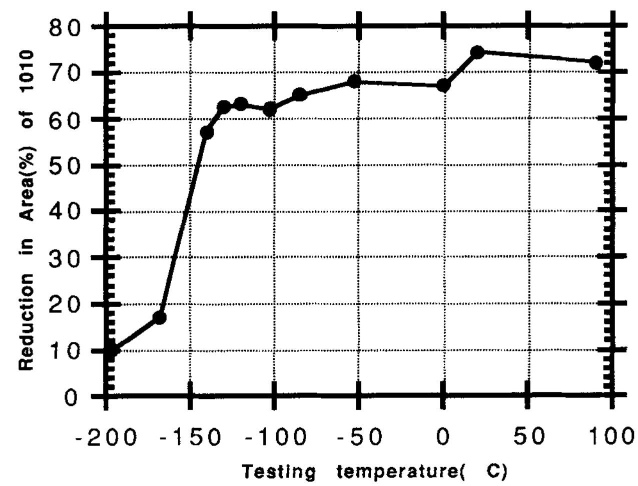
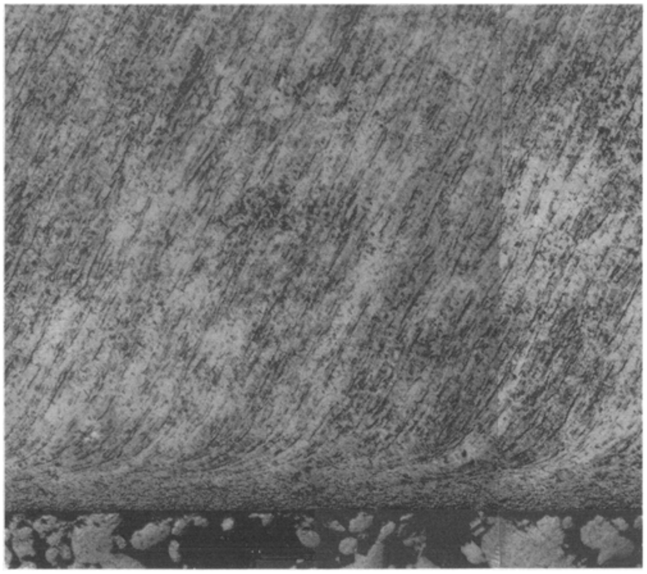
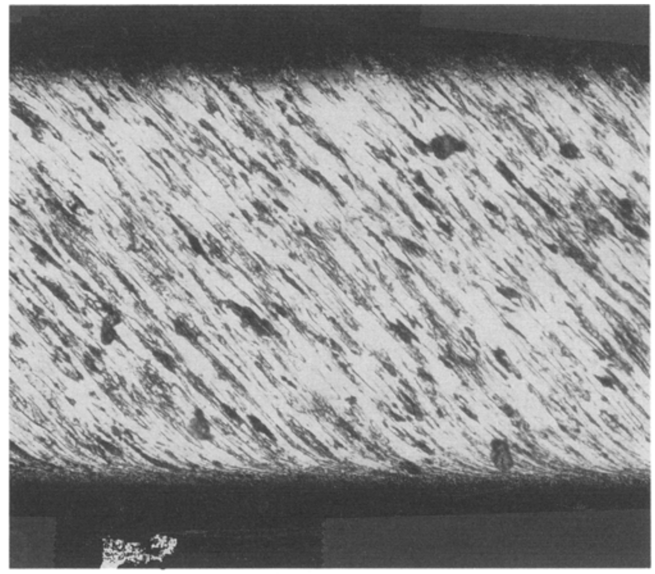


Fig. 6 Reduction in area of AISI 1010 steel versus temperature.

Chip disposability often plays a primary role in machining low-carbon steels with automated machine tools. The improvement in machinability of low-carbon steels is usually referred to as chip breakability. Studies on chip fracturing[21,22] suggest that the inherent factors in controlling chip breaking are fracture strain and the secondary flow zone. In practical machining, breaking of the chip occurs at a maximum bending moment, which is accompanied by tension on the rough side of the chip due to the decrease in the curvature of the chip curl.[23] When a chip curl of radius (R_o) is bent to one of radius (R_b), the maximum tensile strain of the rough side of the chip can be estimated by:



(a)



(b)

Fig. 7 Microstructure of 1010 chip machined at (**a**) room temperature and (**b**) −196 °C. 200×.

Table 2 Nominal Compositions of AISI 1070 and AISI E52100

	Composition, wt%					
Alloy	**C**	**Mn**	**S**	**P**	**Si**	**Cr**
AISI 1070	0.65-0.76	0.60-0.90	...	...	...	...
AISI E52100	0.98-1.10	0.25-0.45	0.025	0.025	0.15-0.30	1.30-1.6

Source: Ref 24.

$$\varepsilon = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_b}\right) \quad [1]$$

where t is the chip thickness, R_o is the radius of the free chip curl (before touching any obstacle), and R_b is the radius of the chip after it is straightened. The chip breaking criterion is:

$$\frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_b}\right) \geq \varepsilon_c \quad [2]$$

where ε_c, the critical fracture strain, is the inherent property of the materials of the chip. Due to the high plasticity (hence the high ε_c) and the occurrence of the thick secondary flow zone, AISI 1010 steels, particularly hot rolled types, represent the most challenging material for chip controllability. Therefore, reducing the plasticity of the chip (*i.e.*, reducing ε_c) and the size of the secondary flow zone by cryogenic machining is expected to promote the ease of chip breaking. Figure 7 shows the microstructures of chips that were produced by dry machining and cryogenic machining with flat inserts. The inhomogeneity in deformation and the significant decrease in the secondary flow zone induced by cryogenic machining can be observed.

2.2 *AISI 1070 and AISI E52100 Steels*

Table 2 lists the nominal compositions of 1070 high-carbon steel and E52100 high-alloy steel. The high carbon content of these alloys has a significant influence on their mechanical properties and machinabilities. The high carbon content increases their tensile strength, shear strength, and hardness; this often results in a significant temperature increase during machining. The effects of carbon content on machinability are also directly related to the formation of hard and abrasive carbides.

Figures 8 and 9 present the microstructures of hot rolled 1070 steel and annealed E52100, respectively. In both microstructures, a large amount of eutectoid pearlite exists, in which the highly abrasive and sharp lamellae of the cementite accelerates tool wear. In the E52100 microstructure, extra carbide particles are also present because of its hypereutectoid composition, and this creates more severe abrasive wear. Therefore, tool life in machining steels depends largely on the carbon content. Generally, up to 0.24% carbon in steels can favorably affect the machinability, because it generates the desired brittleness for chip formation. A higher carbon content usually adversely affects machinability because of both the high strength of steel and the large amount of carbides.

AISI-SAE 1070

Fig. 8 Microstructure of hot rolled AISI-SAE 1070 steel. 400×.

AISI-SAE 52100

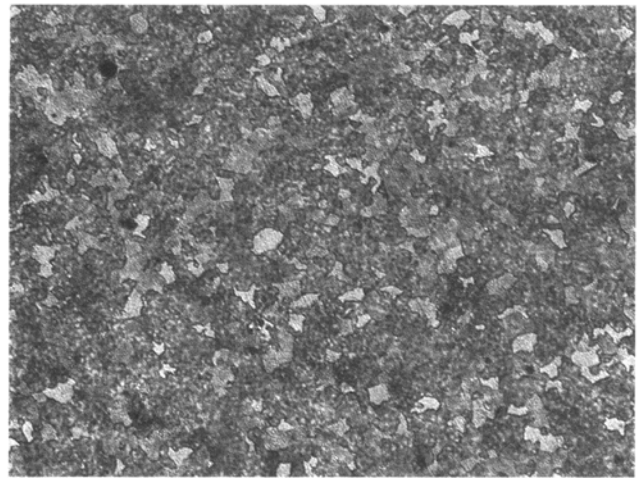


Fig. 9 Microstructure of annealed AISI-SAE E52100. 200×.

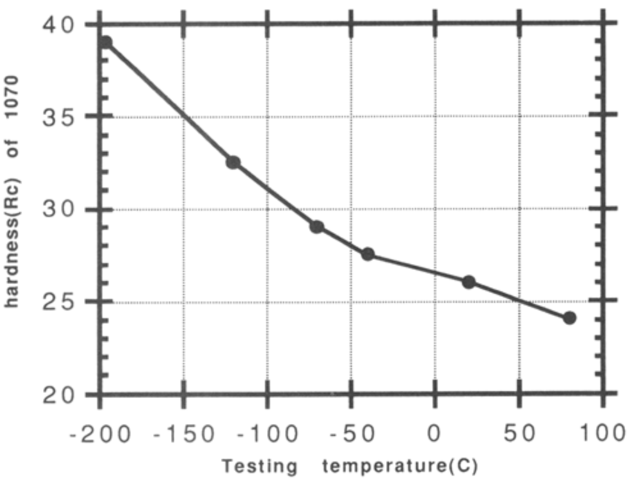


Fig. 10(a) Hardness of 1070 steel versus temperature.

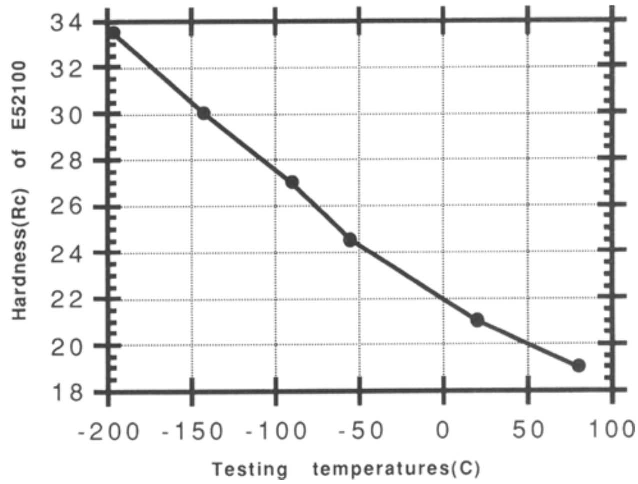


Fig. 10(b) Hardness of E52100 versus temperature.

Figures 10 to 14 illustrate the mechanical properties of 1070 and E52100 steels at low temperatures. Both steels exhibit similar temperature dependencies. As temperature decreases, their hardnesses and strengths increase rapidly. According to the results of impact strength, percent elongation, and area reduction tests, toughness and ductility decrease with decreasing temperature. 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.

Considering the cryogenic properties of 1070 and E52100 and their conventional machining characteristics, cooling the workpiece may not be a favorable 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 operating at high cutting temperatures are major concerns in machining 1070 and E52100, an effective cryogenic approach involves applying the cryogen to the cutting zone adjacent to the chip/tool interface. This targets lower cutting temperatures and enhances the hardness of the cutting tool. Prior research on cryogenic machining of high-strength materials shows that applying the cryogenic coolant to the cutting zone produces better results than freezing the workpiece.[14] The manner in which the coolant is applied is also expected to influence the cooling effects. A study on the effects of conventional coolants indicates that delivering a jet of coolant to the end clearance face is more effective than applying the coolant over the rake face.[25]

2.3 *Cast Aluminum Alloy A390*

The hypereutectic aluminum-silicon cast alloy, A390, has wear characteristics superior to any of the more common aluminum cast alloys. These excellent wear characteristics, combined with good mechanical properties, high hardness, and low coefficients of thermal expansion, have created a rapid growth in their use.[26] The designated nominal composition of the A390 alloy is given in Table 3.

As shown in Fig. 15, the microstructure of A390 consists primarily of two constituents—a soft aluminum matrix and a primary silicon phase. The high nominal silicon content in the alloy provides sufficient quantities of hard primary silicon phase to ensure the strength and high degree of wear resistance of these cast alloys. However, the existence of a large amount of primary silicon phase also causes machining problems in this alloy.

Almost all aluminum alloys belong to a group of materials with high toughness, but A390 does not follow this trend due to its high silicon content. The impact strength of a standard V-notch A390 specimen is only about 0.5 J. A390 is extremely brittle, and according to current tensile testing, its 2 in. length elongates under 0.5% from 20 to –196 °C. This is responsible for the desirable chip formation during machining.

A390 alloy contains 16 to 18% silicon, which makes it a hypereutectic casting alloy. As indicated by the aluminum-silicon phase diagram, the alloy with this composition has a large amount of primary silicon phase in the microstructure. This phase has a Knoop hardness of 1000 to 1300 HK, compared to a maximum aluminum matrix hardness of 180 HK.[27] The presence of the primary silicon phase in the alloy provides its strength and superior wear resistance. However, because of its hardness, it also causes machining problems. Tool life is strongly dependent on the size of the primary silicon phase; tool life decreases as the size of the primary silicon phase in-

Table 3 Composition of A390 Cast Alloy

Composition, wt%							
Cu	Mg	Mn	Si	Fe	Zn	Ti	Al
4.0-5.0	0.45-0.65	0.10	16.0-18.0	0.5	0.1	0.2	bal

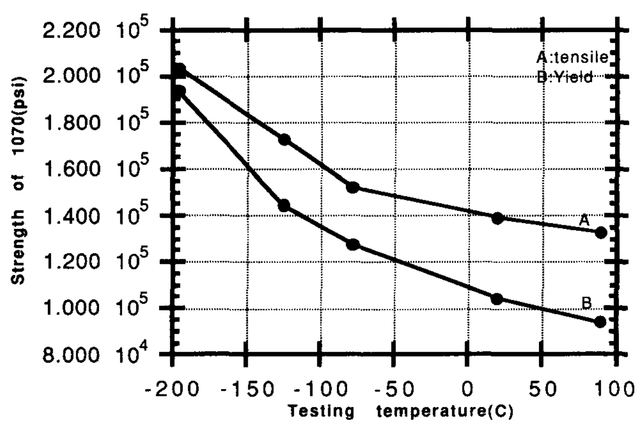


Fig. 11(a) Strengths of 1070 steel versus temperature.

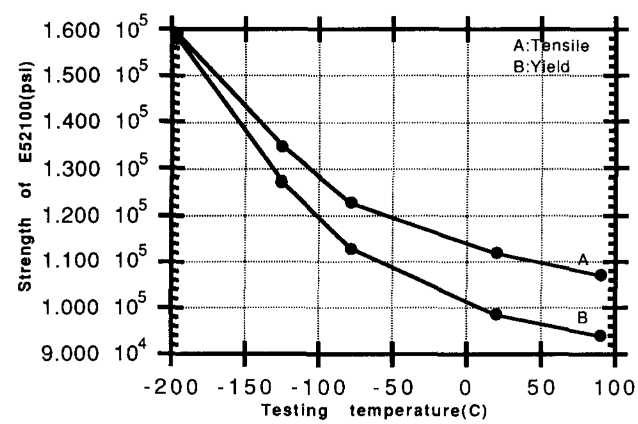


Fig. 11(b) Strengths of E52100 versus temperature.

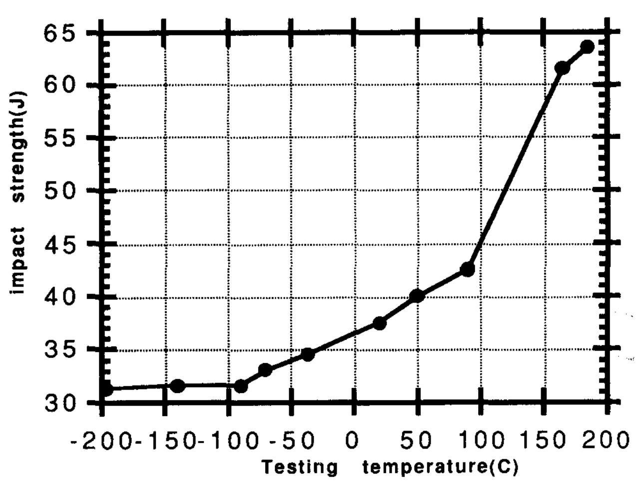


Fig. 12(a) Impact strength of 1070 steel versus temperature.

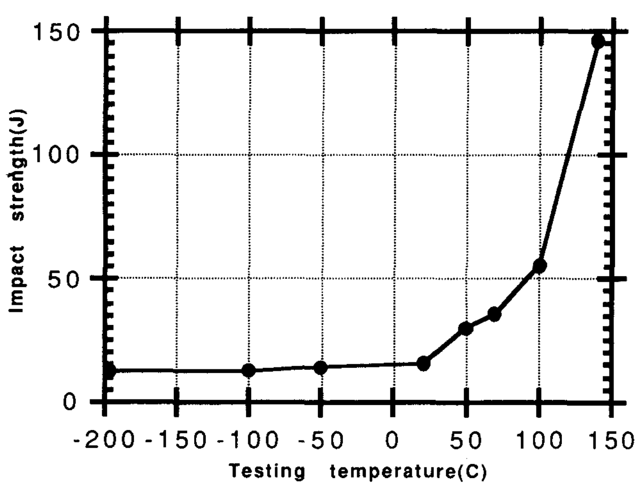


Fig. 12(b) Impact strength of E52100 versus temperature.

creases. Evaluations of The Aluminum Association and The American Society for Metals indicate that 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 A390. Figure 16 illustrates the variation of the hardness with temperature for A390. The increase in bulk hardness by cooling the workpiece may not be a concern for cryogenic machining, but the increase in the microhardness of primary silicon phase would make it more abrasive. Therefore, a possible solution is cooling the cutting tool with a cryogenic to enhance its hardness and resistance to abrasive wear. The successful application of the polycrystalline diamond tool in machining A390 may suggest the feasibility of this approach.

2.4 *Titanium Alloy Ti-6Al-4V*

2.4.1 *Properties*

Figure 17 shows the microstructure of annealed α-β Ti-6Al-4V. It consists of a coarse, plate-like α phase and a grain-boundary β phase. Variation in hardness with temperature is shown in Fig. 18. At room temperature, the hardness of annealed Ti-6Al-4V is 33.5 HRC. Between room temperature and –50 °C, hardness increases rapidly. When the temperature drops below –50 °C, the hardness increases gradually. At liquid nitrogen temperature, the hardness of Ti-6Al-4V is about 42 HRC. The results of impact strength, percent elongation, and reduction in area indicate that Ti-6Al-4V can maintain, to a large extent, its toughness and ductility at low temperatures, even at liquid nitrogen temperature.[28]

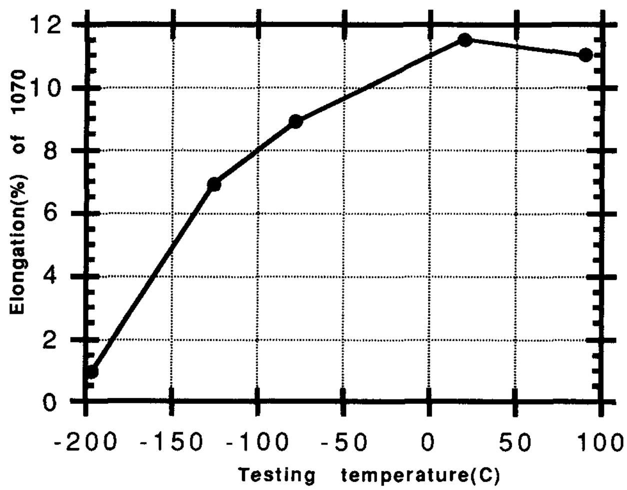


Fig. 13(a) Tensile elongation of 1070 versus temperature.

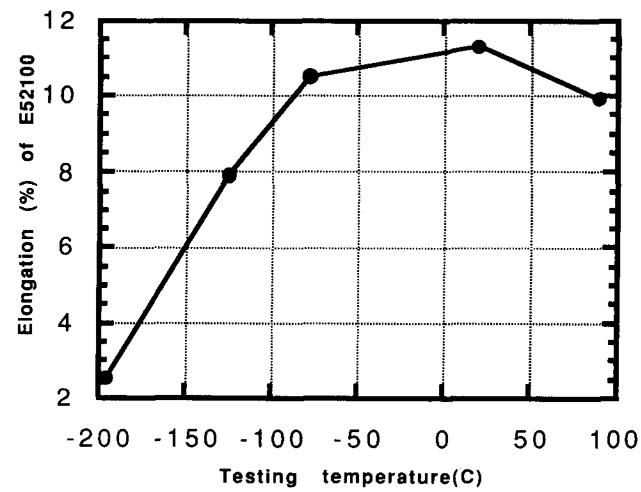


Fig. 13(b) Elongation of E52100 versus temperature.

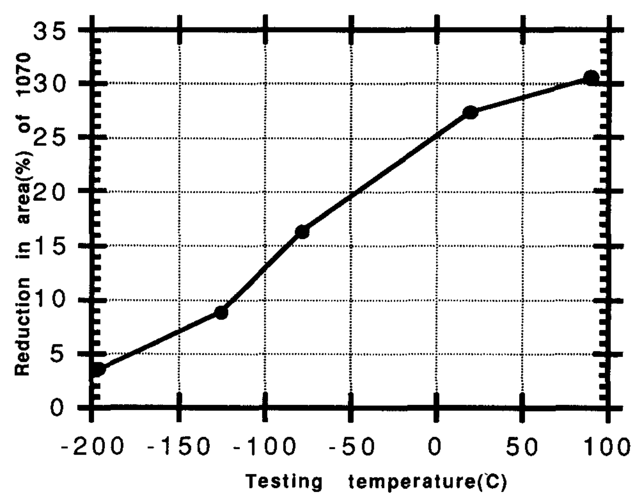


Fig. 14(a) Reduction in area of 1070 steel versus temperature.

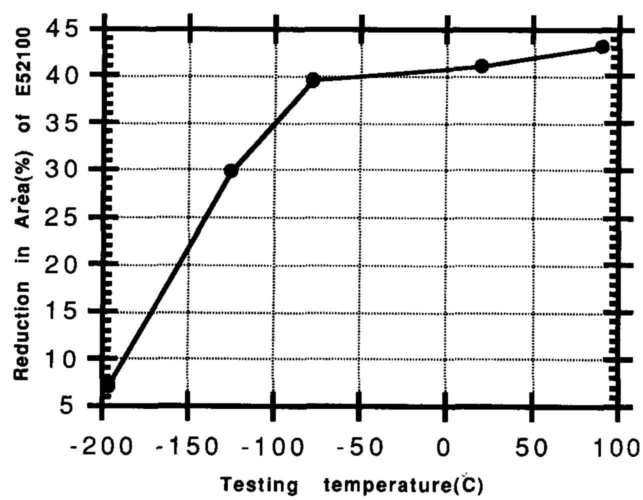


Fig. 14(b) Reduction in area of E52100 versus temperature.

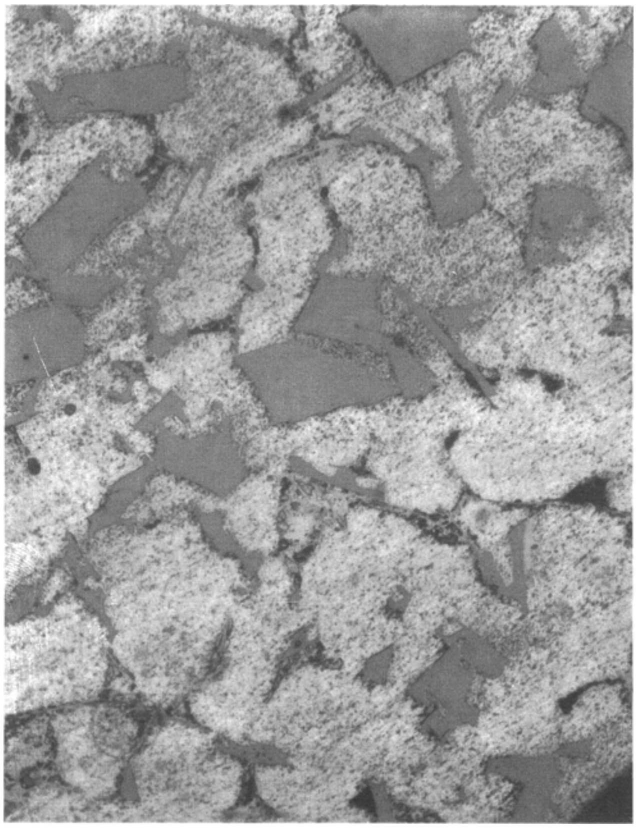


Fig. 15 Microstructure of cast aluminum A390 alloy. 500×.

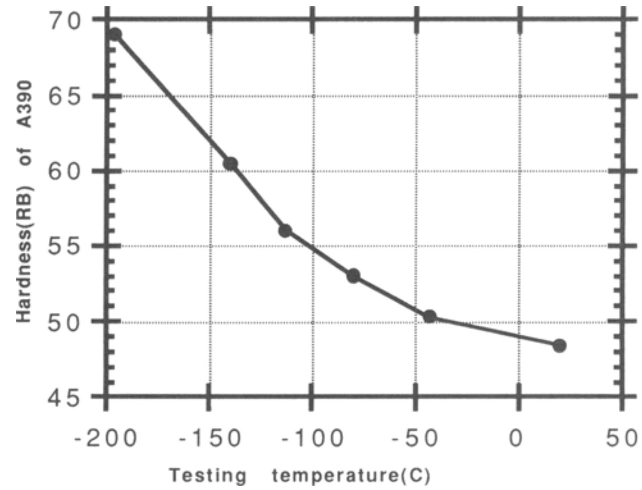


Fig. 16 Hardness of A390 versus temperature.

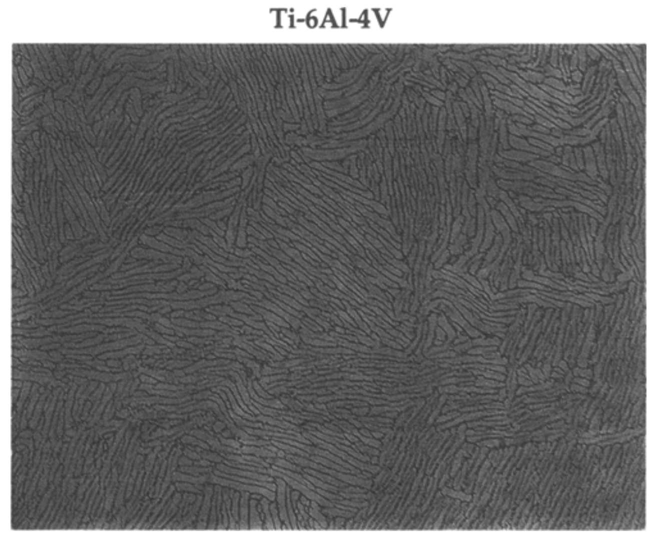


Fig. 17 Microstructure of annealed Ti-6Al-4V. 200×

2.4.2 *Machining Characteristics*

Titanium and its alloys are classified as difficult-to-machine materials. Although these alloys have about the same strain-hardening tendencies as ordinary structural steels, the cutting forces required to machine titanium alloys are slightly higher than those needed to machine steel. However, their physical, chemical, metallurgical, and mechanical properties cause other problems that are responsible for their poor machinability. The basic problems are the high cutting temperature and the rapid tool wear. Most tool materials wear rapidly even at moderate cutting speeds when machining titanium and its alloys. Therefore, current machining practice limits the cutting speed to less than 1 m/sec to minimize tool wear. A summarization of machining characteristics for titanium and its alloys is discussed below.[29-31]

Titanium and its alloys are poor thermal conductors, and their thermal conductivities are equivalent to steel. As a result, the heat generated during machining cannot dissipate quickly; most of the heat is concentrated on the cutting edge and tool face. 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.

Titanium and its alloys have relatively low moduli of elasticity. Workpieces have a tendency to move away from the cutting tool unless heavy cuts are maintained, or proper backup is used. Slender parts also tend to deflect under tool pressure, causing chatter, tool rubbing, and tolerance problems. Titanium alloys exhibit thermal plastic instability during machining, which leads to unique chip formation characteristics. The shear strain in chips is not uniform, rather it is localized in a narrow band that forms serrated chips. The second flow zone is unusually thin.

The contact length between the chip and the tool is extremely short (less than one third of the contact length of steel with the same feed rate and depth of cut). This implies that the high cutting temperature and high stress are simultaneously concentrated near the cutting edge (within 0.5 mm). Serrated chips create fluctuations in the cutting force; this situation is further promoted when α-β alloys are machined. The vibrational force plus the high temperature exert a microfatigue 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

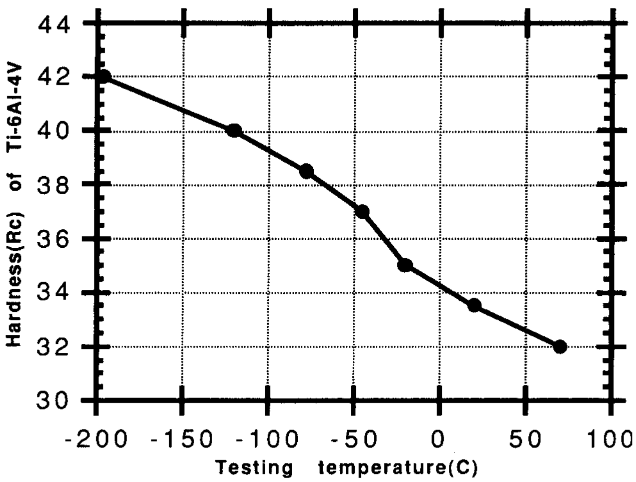


Fig. 18 Hardness of annealed Ti-6Al-4V versus temperature.

toughness and ductility show little variation as temperature decreases. Therefore, it is difficult to discuss a cryogenic strategy based on cryogenic properties. However, considering the main machining characteristics of titanium, which arise from high cutting temperatures and its chemical affinity for tool materials at the operating temperatures encountered in machining, an effective cryogenic strategy involves cooling the workpiece and cutting tool simultaneously. This is expected to lower the high cutting temperature, enhance the chemical stability of the workpiece, and enhance the chemical stability of the cutting tool.

Titanium and its alloys have been a major subject of cryogenic machining. Most of the work supports an improvement in their machinabilities by either freezing the workpiece or by applying a cryogenic coolant.[15,19,20,32-36] Freezing the workpiece has been suggested as the ideal cutting condition for machining titanium and its alloys from a technical point of view.[15,34,36]

Titanium and its alloys represent the most challenging materials in machining. With the advancement of cutting tool materials, many difficult-to-machine materials can now be machined at higher metal removal rates. None of these materials, however, seem to be effective in machining titanium because of their chemical affinities with titanium. The calculation of Hartung *et al.*[37] 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, is expected to have great potential in high productivity machining of titanium and its alloys.

3. Cryogenic Properties of Carbide Tool Materials

Cemented carbide tool materials are a group of hard, wear-resistant, and refractory materials in which the hard carbide particles are bonded or cemented together by the ductile metal binders. Low temperature decreases their thermal expansion properties and chemical affinities with workpiece materials. This is expected to be beneficial for cryogenic machining. Generally, however, carbide tool materials belong to the category of nonductile materials. A major concern in cryogenic machining is whether the tool materials can maintain enough toughness to resist various forms of fracturing at low temperatures. By means of microstructural observations, impact tests, three-point bending tests, and indentation tests, several representative grades of carbide-cobalt alloys (K3109, K313, K420, K68, and SP274) were investigated extensively at cryogenic temperatures. The detailed experimental results will be published separately, and only a brief summary is given here.

The amount of binder phase determines, to a large extent, the properties of carbide tool materials. Therefore, the behaviors of carbide tool materials at cryogenic temperatures can be explained in terms of the temperature effects on the binder phase. A decrease in temperature increases the hardness of the carbide tool materials and their wear resistance. Regarding their toughness and transverse rupture strength, different grades of carbide tool materials vary with temperature. As the temperature decreases to liquid nitrogen temperature, the carbide tool materials generally retain their transverse rupture strength and impact strength. From these characteristics of their mechanical properties plus the inevitable decrease in their chemical affinities from lower temperatures, better performances of carbide tool materials in cryogenic machining can be expected.

4. Summary

The cryogenic properties of five kinds of engineering materials were investigated. Based on the experimental results and the characteristics of their conventional machining, the cryogenic machining strategies for these materials were discussed. Low temperatures seem to provide the ideal machining conditions for 1010 low-carbon steel because it exhibits a distinctive ductility-to-brittleness transition. For 1070 high-carbon steel and E52100 high-alloy steel, applying cryogens to the cutting zone is expected to impair the high temperature increase and the rate of tool wear. In the case of A390, a possible approach is cooling the cutting tool with cryogens, which tends to enhance the hardness and resistance to abrasive wear of the silicon phase. Cooling the workpiece and cutting tool for Ti-6Al-4V may effectively lower the cutting temperature and reduce the chemical affinity between titanium and the tool material.

From the tool material sites, low temperature increases the hardness and wear resistance of the carbide-cobalt tool materials. They generally retain their toughness and transverse rupture strength at cryogenic temperatures. These features not only allow for the flexible cryogenic strategies, but also imply better performances of the tool materials in cryogenic machining.

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