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Cryogenic Properties of Some Cutting Tool Materials

Z. Zhao and S.Y. Hong

Cutting tool materials belong to a group of nonductile materials. Chipping and breaking of the cutting edge and fracturing of the tool are common types of tool failure even under conventional machining conditions. This leads to a concern about whether cutting tool materials are able to maintain their strength and toughness and withstand the low-temperature thermal shock during cryogenic machining. The objective of this investigation was to study the behaviors of these kinds of materials at cryogenic temperatures. The results will also serve as a basis in selecting the suitable cutting tool materials for cryogenic machining and in determining the cryogenic strategy and optimum cutting conditions. Several representative cutting tool materials, such as five grades of commercial carbide-cobalt alloys and M46 high-speed steel, are investigated in terms of microstructural observation, impact testing, transverse rupture strength measurement, and indentation testing. It has been shown that carbide tool materials generally retain their strength and toughness as the temperature decreases to liquid nitrogen temperature. The behaviors of carbide tool materials at cryogenic temperatures can be explained in terms of the temperature effects on the binder phase.

1. Introduction

WITH the rapid development and application of numerical control machine tools, reliability and predictability of cutting tool performance are more significant than before. The increased demand for higher metal removal rates requires more refractory materials. Most refractory materials, however, belong to a category of brittle, nonfragile materials. It is well known that the chipping of cutting edges and the fracturing of carbide cutting tools are the most frequent types of tool failures.[1,2] Generally, most materials become brittle to various degrees as they are exposed to low temperatures. These tendencies of workpiece materials are believed to be beneficial in cryogenic machining, because the brittleness of the material promotes chip formation.[3,4] With regard to cutting tool materials, however, degradation of strength and toughness at low temperatures, if any, would discount any possible gain from cryogenic machining. Therefore, a logical concern is whether cutting tool materials can maintain enough toughness, which would allow them to be applicable in cryogenic machining. Because cutting tools usually are subjected to high-temperature conditions in traditional machining, little is known about the cryogenic properties of cutting tool materials.

This work is an effort both to fill the gap and to establish a basis for cryogenic machining in terms of studying cutting tool materials at cryogenic temperature. Therefore, the objectives of this study in cryogenic machining are to (1) define the properties, applications, and limits of several representative cutting tool materials; (2) select the suitable grade of cutting tool materials for cryogenic machining; and (3) establish the connection between the properties of tool materials and their performance. Generally, an ideal cutting tool material should have the following characteristics:

- High hardness and abrasive wear resistance
- High strength
- Acceptable toughness to resist various kinds of fractures
- Low coefficient of thermal expansion
- High chemical and physical stability

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It is expected that cryogenic temperatures affect not only the mechanical properties of the tool materials, but also their physical/chemical properties. The coefficient of thermal expansion, for example, has been proven to decrease as the temperature decreases.[5,6] It is also believed that the chemical and physical stability of tool materials can be increased by lowering the temperature. Those tool material properties are definitely positive for cryogenic machining. Thus, the scope of this work is restricted to the evaluation of the mechanical properties by the microstructural observation and the testing of impact strength, transverse rupture strength, and hardness at cryogenic temperatures. The tested materials include a high-speed steel, M46, and five grades of carbide-cobalt alloys—K3109, K313, K420, K68, and SP274.

2. Experimental Setup and Procedure

2.1 *Impact Testing of Carbide Tool Materials*

The specimens of carbide-cobalt alloys for use in impact testing are 2.190 by 0.394 by 0.394 in. square bars. Because carbide tool materials generally have low impact strength, a more sensitive instrument rather than the conventional Charpy tester is required. The impact testing of carbide tool materials is performed with an instrument impact tester, Dynatup Model GRC 730-1, which records both the absorbed energy and the maximum applied load simultaneously. Figure 1 is an example curve recorded during impact testing.

2.2 *Transverse Rupture Strength*

Due to extreme hardness and brittleness, carbide tool materials do not respond well to tensile testing. Instead, a test that is widely used to characterize the fracture strength of tungsten carbide tool materials is the three-point bending test on the bar

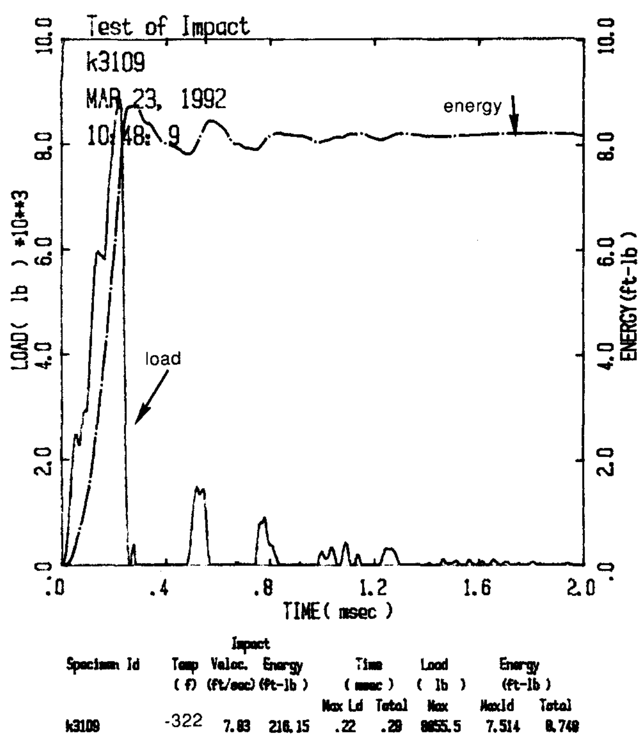


Fig. 1 Load-time and energy-time curves recorded by an instrumented impact tester.

specimen. The transverse rupture strength (TRS) can be defined as:

$$\mathrm{TRS} = \frac{3FL}{2bh^2}$$

where F is the applied load at the fracture, L is the distance between the cylinder axis, h is the thickness of the specimen, and b is its width. All specimens were ground 0.20 by 0.20 by 0.75 in. square bars that were provided by Kennametal Research Laboratory. Figure 2 shows the setup used during the TRS test at low temperatures. To change the temperatures of the specimens, the parts are completely submerged under a cooled chemical liquid whose temperature is adjusted by mixing it with liquid nitrogen or dry ice. A load with a slow, constant rate is applied by a universal tensile machine on all of the specimens. The heat exchange between the specimen and indentation ball may give rise to a temperature gradient near their interface due to their relatively long, tight contact during loading. To avoid the temperature gradient, the indentation ball was kept below the liquid level for a sufficient time before applying the load. The average of five testings at the same temperature was adopted as the transverse rupture strength at this temperature. Specimen preparation, setup, testing procedure, and data analysis were in accordance with ASTM standard, B406-76, of transverse rupture strength testing of the carbide materials.[7]

2.3 *Hardness Measurements*

Hardnesses at room temperature and above were measured with a commercially available Vickers tester. A Rockwell Brale

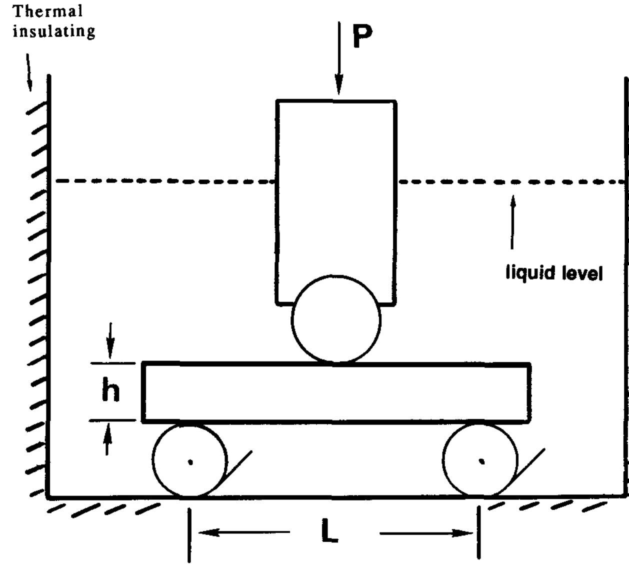


Fig. 2 Schematic setup for low-temperature transverse rupture strength measurement. Both the tested specimen and the three-point bending part were submerged in the cooled chemical liquid, which was in a thermally insulated bath container.

indenter formed a permanent indentation impression under a 60-kg load; this was used as the measure of the hardness at cryogenic temperatures. Similar to Vickers hardness, hardness (H) is defined by:

$$H = \frac{1.103P}{d^2}$$

where P is the applied load in kilograms, and d is the diameter of the indentation impression measured by an optical microscope. Examination of carbide tool materials at room temperature indicates that this method yields similar results as the Vickers hardness test.

2.4 *Impact Testing of High-Speed Steel*

Impact testing of C-notched specimens (for detailed dimensions see Fig. 3) was performed on a Charpy impact tester. The samples were machined from square tool bits manufactured by Cleveland Twist Drill Company. During impact testing, liquid media were also used for cooling or heating the samples.

3. General Features and Cryogenic Properties

3.1 *Cemented Carbides*

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 or nickel).[8] Thus, the microstructure of cemented carbides usually consists of two phases: angular WC grains and a cobalt or nickel binder. The performance of the cemented carbide tool lies between high-speed steel and cermet. Compared with high-speed steel, cemented carbides are not only harder and more wear resistant, but they also exhibit lower toughness and fracture strength. Although high-speed steel allows cutting speeds less than 200 ft/min, carbide tool materials allow cutting speeds as high as 1000 ft/min.[8]

3.1.1 *Microstructures and General Features*

Cemented carbides are available in many different grades, which differ in hardness, wear resistance, toughness, etc. In this investigation, five commercial grades of carbide-cobalt tool materials were selected as the test materials. Their chemical compositions are listed in Table 1. Figures 4 to 8 are the typical microstructures of K3109, K313, K420, K68, and SP274, respectively. As indicated by the microstructures, the typical carbide grain sizes range from submicron to several microns in diameter, depending on the individual grade. Even within the same grade, the grain sizes still have a certain distribution. This is partially due to the fabrication process.

Substantial amounts of WC were dissolved in cobalt during sintering and precipitated during cooling. They appear as the WC grains and as the finely dispersed WC particles in the binder, thus creating a variance in carbide grain sizes. In the alloyed carbide grades, K420 and SP274, the introduction of TaC and TiC produced a considerable amount of round carbide grains from their alloying effect on the WC grains. This gave rise to the significantly different microstructures of the unalloyed grades, K3109, K313, and K68.

The microstructural parameters that usually affect the properties of carbide tool materials are binder volume, binder mean path, carbide chemistry, carbide grain size, grain size distribution, and carbide phase contiguity. The variations of these in the different grades of carbide tool materials account for the different combinations of their properties. Following are brief descriptions of the characteristics of each carbide tool material tested.

K3109 is characterized by a large volume of binder phase and the coarse WC grain size. It is also identified by high impact strength, high transverse rupture strength, and relatively low hardness. As expected, K3109 is the toughest grade among all the tested carbide tool materials.

K313 is an unalloyed grade that has a low percentage of cobalt binder phase and has the finest WC grains in its microstructure. Therefore, it is characterized by high hardness, high edge wear resistance, relatively high transverse rupture strength, and moderate impact strength.

K420 is an alloyed grade of a WC/TaC/TiC-Co that has a moderate amount of cobalt binder phase and coarse carbide grains. Although the introduction of other carbides such as TaC and TiC contributes to high hardness and high thermal deformation resistance, they also cause a decrease in hardness. As a consequence, the general features of K420 include moderate hardness, high thermal shock resistance, relatively high impact strength, and relatively high transverse rupture strength.

K68 is a low-cobalt unalloyed grade with intermediate carbide grain sizes, which accounts for its high hardness, moderate impact strength, and moderate transverse rupture strength. This grade of carbide also exhibits high edge wear resistance in ma-

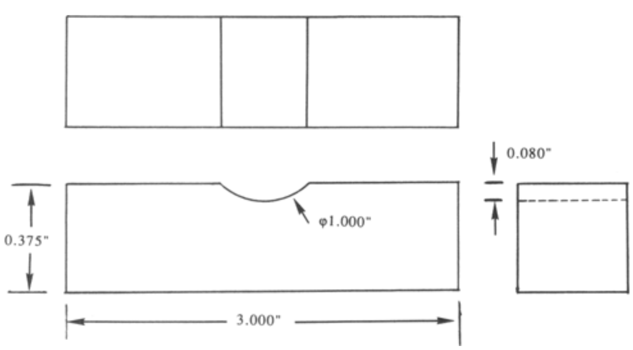


Fig. 3 Dimensions of the M46 high-speed steel specimen used for impact testing.

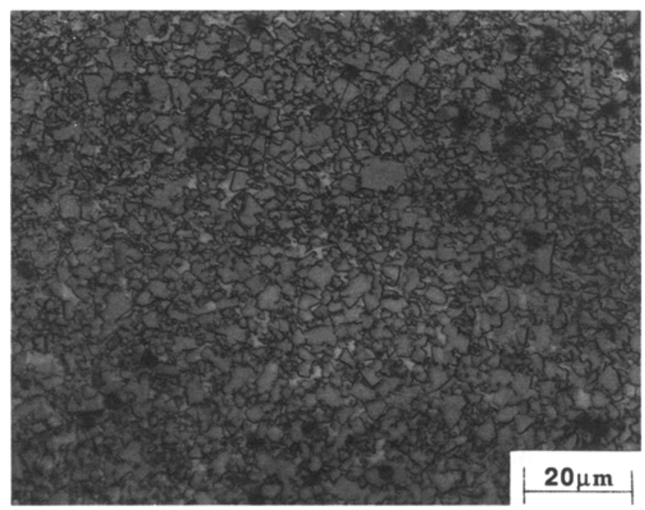


Fig. 4 Microstructure of K3109, which consists of the coarse WC grains and the large volume fraction of the binder phase.

Table 1 Nominal Compositions of Carbide Tool Materials

	Composition, wt%				
	Cobalt	Tantalum	Titanium	Other	Carbide size
K3109	12.2	0.3	0	0	Large
K313	6.0	0	0	0.4% Cr	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

Note: Provided by Kennametal, Inc.

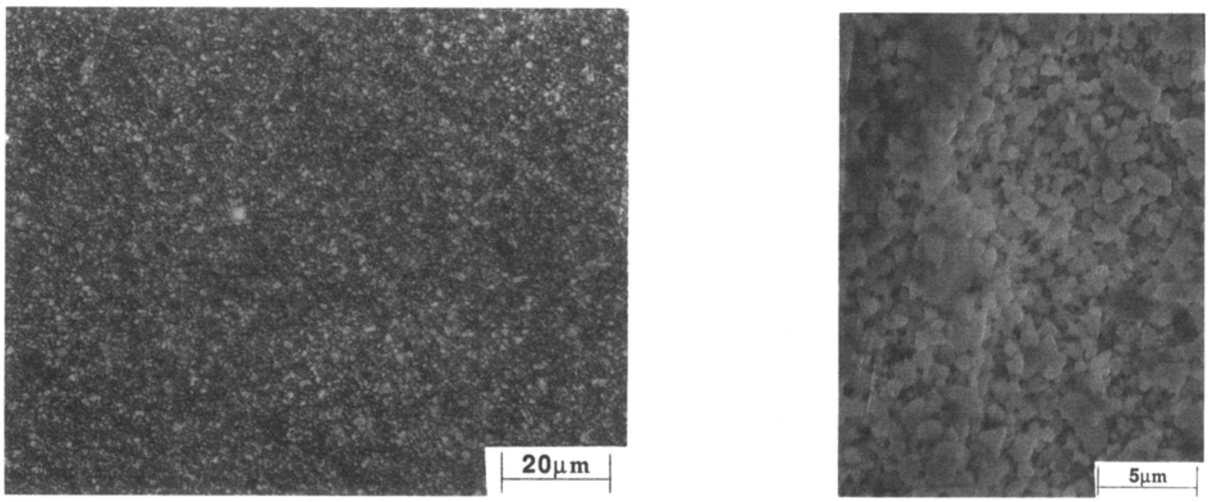
chining stainless steels, cast irons, nonferrous metals, nonmetals, and most high-temperature alloys.

SP274 is an alloyed grade with low binder content. It is normally used as a substrate material for coated carbide tool materials. The material is characterized by high hardness and moderate transverse rupture strength.

3.1.2 *Impact Strength*

There are two approaches (techniques) used in defining toughness of carbide tool materials, namely, fracture toughness and fracture energy. Fracture toughness has been proven to be an effective measure of carbide material toughness, in which the onset of unstable crack growth dominates the fracture event. No direct measurement of fracture toughness was made in this work. As will be discussed later, indentation testing performed at both room temperature and liquid nitrogen temperature presented some evidence about the variation in crack resistance with temperature.

An alternate technique for measuring the toughness of carbide materials is evaluating the energy absorbed during the fracturing. This is actually the total energy required to initiate and propagate the fracture through the specimen. The load/time curve and the absorbed energy/time curve (see Fig. 1), recorded by an instrumented impact tester, indicate that the fractures of carbide-cobalt alloys are characteristic of brittle fractures. Figures 9 to 12 present the plots of the absorbed energy and maximum load versus testing temperatures for the carbide tool materials tested. As expected, each carbide tool material exhibits scattered impact strength values to different degrees. This is



(a) (b)

Fig. 5 (**a**) Optical micrograph of the microstructure of K313. (**b**) SEM micrograph of K313 at higher magnification reveals fine carbide grains.

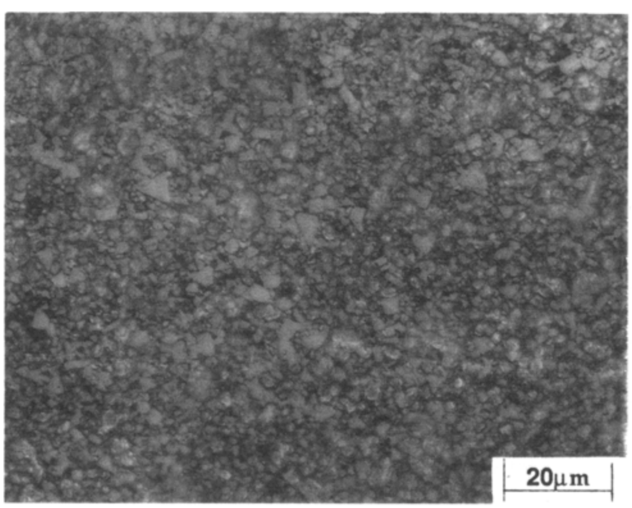


Fig. 6 Microstructure of K420.

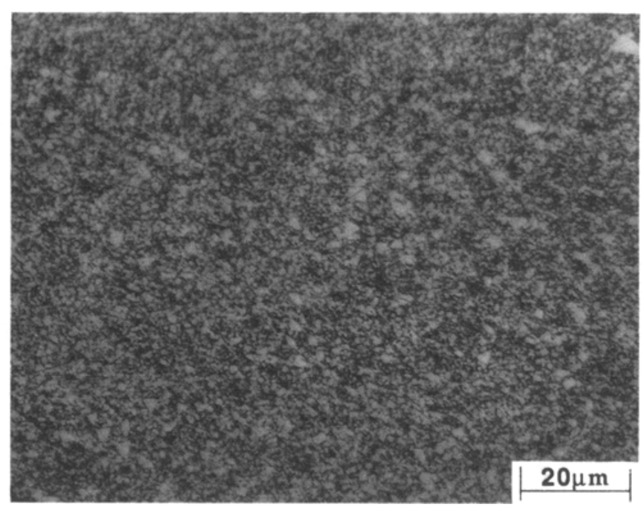


Fig. 7 Microstructure of K68.

primarily due to the variations in internal stress concentrators, such as pores and inclusions in the samples. Among all the tested grades, the toughest grade, K3109, with evenly distributed data, exhibits a remarkable increase in impact strength as temperature decreases. For the grades K313 and K420, it is difficult to derive a quantitative temperature dependence of their impact strengths due to the inherent nonductile nature of carbide tool materials. There is no evidence that indicates that these carbide tool materials become more brittle and weaker at cryogenic temperatures. K68, with the lowest binder content among the materials tested, shows a decreasing tendency in impact strength as the temperature decreases.

3.1.3 *Transverse Rupture Strength*

The transverse rupture strengths of carbide tool materials depend on temperature, as shown in Fig.13 to 17. K313, K68, and SP274, which have relatively low transverse rupture strength at room temperature, tend to experience an increase in transverse rupture strength as the temperature decreases. On the other hand, K3109 and K420 possess higher room-temperature transverse rupture strength and exhibit the opposite tendencies. Their strength levels decrease insignificantly at liquid nitrogen temperature, and they still maintain higher levels than those of K313, K68, and SP274.

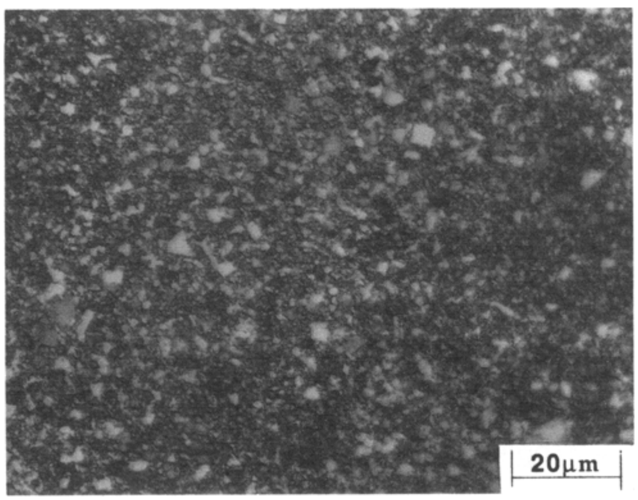


Fig. 8 Microstructure of SP274.

3.1.4 *Indentation Testing, Hardness, and Crack Resistance*

By combining the high-temperature data provided by Kennametal, Inc. and the test results at cryogenic temperature, Table 2 summarizes the hardness of carbide tool materials at various temperatures. The low-temperature hardnesses were obtained by using the Rockwell Brale indenter. The effect of temperature on hardness is obvious. At liquid nitrogen temperature, the indentations from the load produce smaller permanent impressions than at room temperature. This displays an increase in hardness as the temperature decreases.

For hard, brittle materials, a sharp indentation may result in cracking. This phenomenon has received considerable attention because of its potential in evaluating the toughness of WC-Co materials. For the toughest grade, K3109, no cracks were observed from the indentation made under 60 kg at both room temperature and liquid nitrogen temperature. This is consistent with its relatively low hardness and high toughness.

For K313, K420, K68, and SP274, cracks of various lengths were induced by indentations. As an example, Fig. 18 shows the permanent impressions of K68 at room temperature and at liquid nitrogen temperature. The parameter, P/l, where P is the indentation load, and l is the average length of the cracks, was used to evaluate the crack resistance of the brittle materials.[9] Comparison of crack lengths at cryogenic and room temperatures indicates crack resistance to cryogenic temperatures. Cracks at liquid nitrogen temperature are of comparable or even shorter lengths than those at room temperature for all the carbide-cobalt alloys. This may be indicative of the comparable

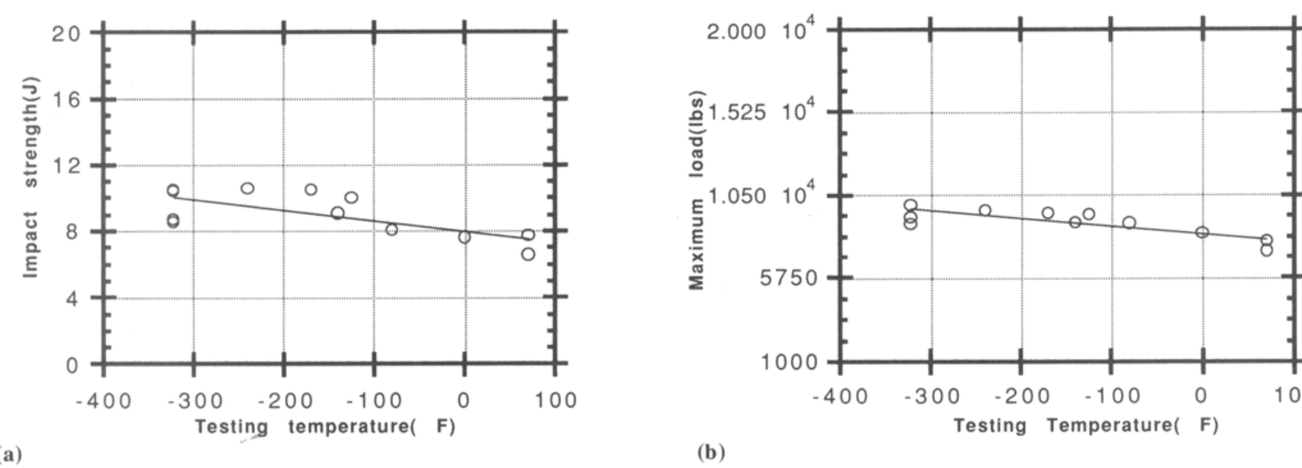


Fig. 9 **(a)** Impact strength of K3109 versus temperature. **(b)** Maximum load on K3109 during impact testing versus temperature.

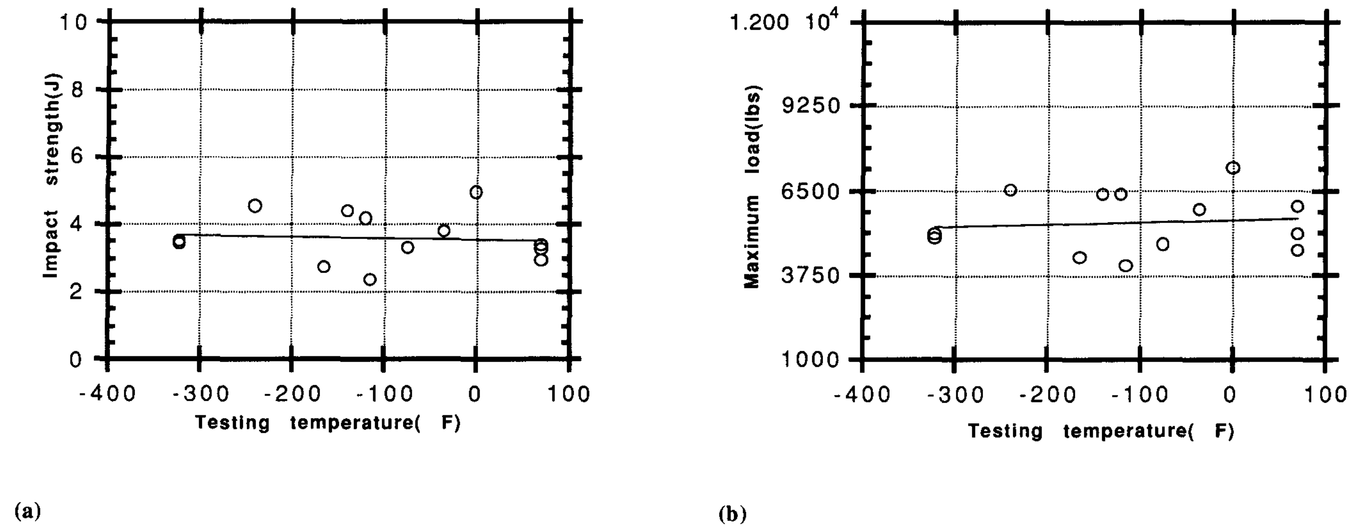


Fig. 10 (**a**) Impact strength of K313 versus temperature. (**b**) Maximum load on K313 during impact testing versus temperature.

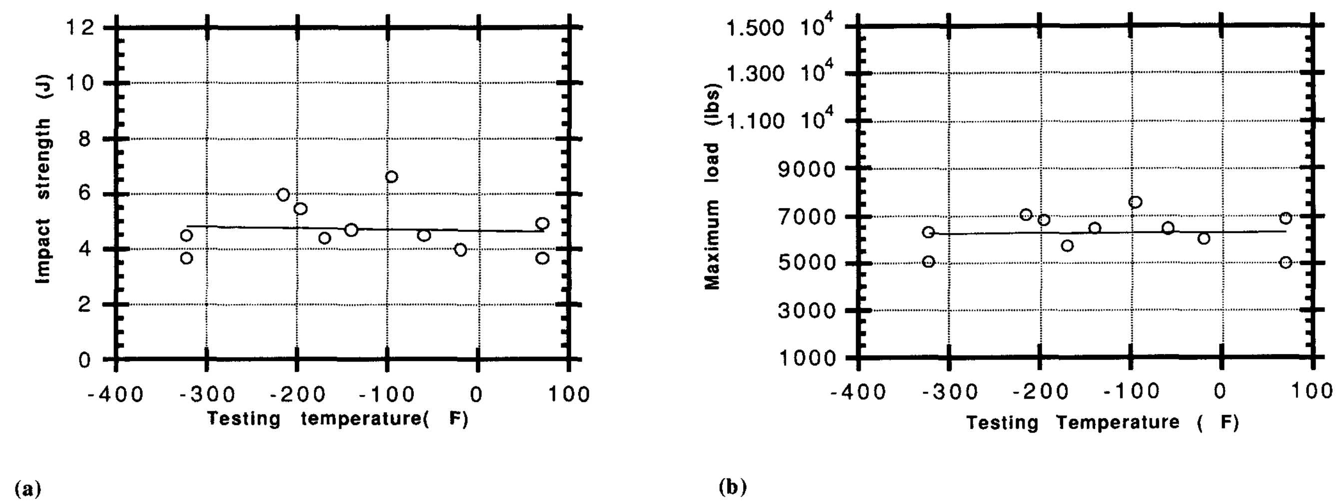


Fig. 11 (**a**) Impact strength of K420 versus temperature. (**b**) Maximum load on K420 during impact testing versus temperature.

or higher crack resistance of the tested carbide tool materials at cryogenic temperature.

3.1.5 *Discussion*

The behaviors of carbide tool materials at cryogenic temperatures indicate their applicability in cryogenic machining. The characteristics of carbide-cobalt alloys and their cryogenic properties indicate their potential not only in cryogenic machining, but also in other applications in the cryogenic industry where an extremely high Young's modulus, high compressive strength, transverse rupture strength, and exceptional wear resistance are required. Carbide-cobalt alloys have already been used successfully as seal materials.[6]

In considering the temperature effects on mechanical properties, one of the most important factors is the crystalline structure of the material. Carbide-cobalt alloys possess heterogeneous structures that have composite natures. Both the hard, brittle carbides and the ductile binder phases in the microstructure account for the unique combinations of the properties of carbide-cobalt alloys. Among mechanical properties, hardness may be due to the composite nature of the microstructure. A number of correlations have been proposed to explain the effects of the microstructure on hardness. The one that seems to have a firm physical basis is proposed by Lee and Gurland,[10] which states that Vickers hardness of WC-Co alloys are related by:

$$H_v = H_{WC} f_{WC} + H_{Co}(1 - f_{WC} C) \qquad [1]$$

where H_{WC} and H_{Co} are the hardnesses of WC and Co, respectively; f_{WC} represents the volume fraction of the carbide grains;

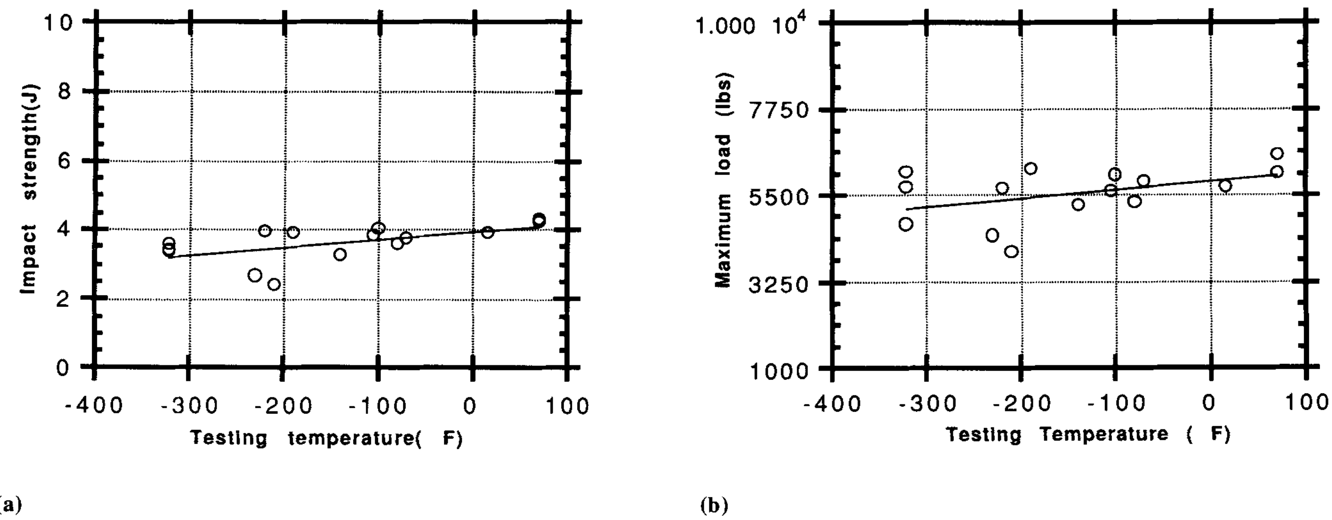


Fig. 12 (**a**) Impact strength of K68 versus temperature. (**b**) Maximum load on K68 during impact testing versus temperature.

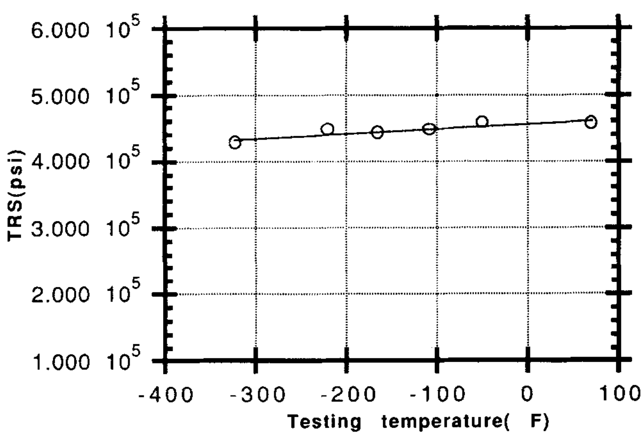


Fig. 13 Transverse rupture strength of K3109 versus temperature.

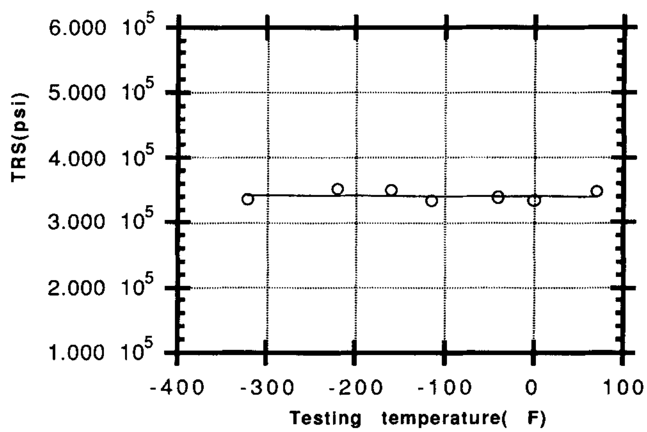


Fig. 14 Transverse rupture strength of K313 versus temperature.

Table 2 Vickers Hardness of Tested Materials at Various Temperatures

	Vickers hardness at test temperature, °F:				
	–322	80	390	750	1830
High-speed steel, M46	1054	914	...	...	...
K3109	1489	1204	1051	901	...
K313	2123	1831	1649	1497	486
K420	1848	1546	1341	1147	365
K68	2092	1703	1413	1454	397
SP274	2034	1695	...	...	...

and *C* is their contiguity. The microhardness of each individual constituent of WC, TaC, TiC, and cobalt increases as temperature decreases.[11] Thus, the increase in hardness of the carbide-alloys at cryogenic temperatures can be regarded as a common element of both the carbides and the cobalt binder phase.

The composite nature of the microstructure also affects the fracturing of carbide-cobalt alloys. Observing the fracture mechanism reveals that the fracturing process is dualistic. It is a macroscopic, quasibrittle phenomenon, and evidence of extensive plastic deformation in the binder phase indicates a mi-

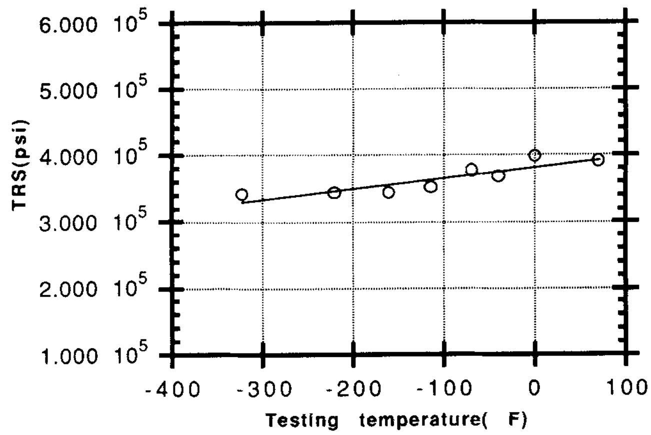


Fig. 15 Transverse rupture strength of K420 versus temperature.

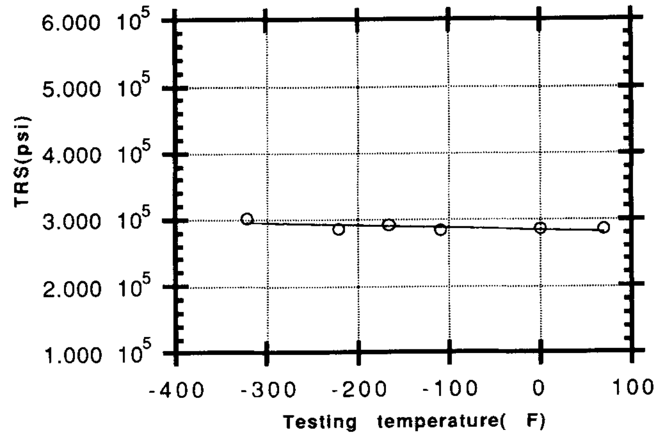


Fig. 17 Transverse rupture strength of SP274 versus temperature.

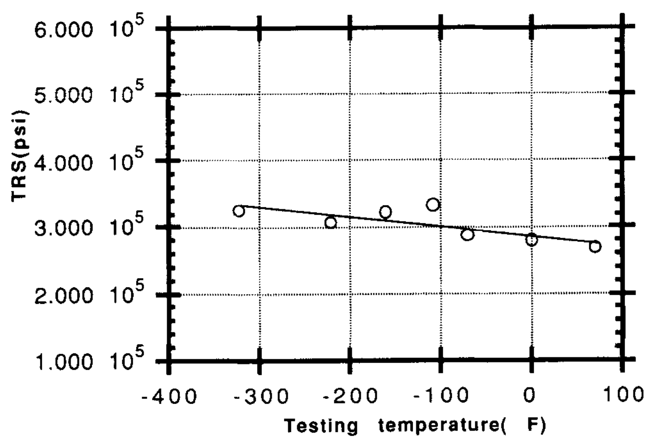


Fig. 16 Transverse rupture strength of K68 versus temperature.

croscopic ductile process.[12] The energy consumed in plastic deformation contributes a majority of the total absorbed energy in impact testing.

Despite the composite nature of the microstructure, it has been well established that the amount of binder phase greatly affects the mechanical properties and other properties of the carbide-cobalt alloys.[13] The binder phase may also play a predominant role in determining cryogenic properties. Understanding the temperature variations in fracture-related properties, such as impact strength and transverse rupture strength, allows one to consider the temperature effects on the binder phase cobalt. This is particularly important for carbide-cobalt alloys with large amounts of binder, in which the carbide grains are highly contiguous. The binder cobalt phase consists of α-cobalt with the hcp structure and retained γ-cobalt with the fcc structure. Close-packed hexagonal metals usually become brittle at low temperatures, whereas metals with the fcc structure are generally ductile at room temperature and below. However, α-cobalt, like titanium, may be an exception. Some cobalt-base alloys are considerably tough at cryogenic temperatures.[14,15] The high toughness of the binder phase may explain why carbide-cobalt alloys generally retain their impact strength at cryogenic temperatures. This also implies that the carbide-cobalt alloys with lower binder content may lose their impact strength at cryogenic temperatures due to the significant decrease in the mean free path of the binder phase. Decreasing impact strengths are actually observed in K68, which has the lowest cobalt content among the tested carbide-cobalt alloys.

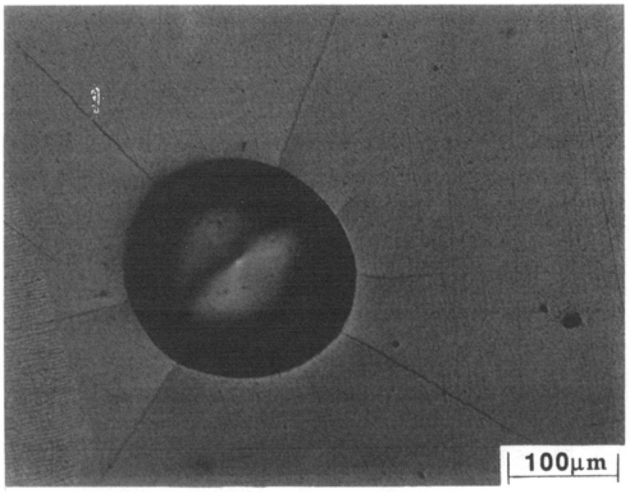
Similarly, the effects of temperature on the binder phase are also expected to influence the strengths of the carbide-cobalt alloys. The strength of cobalt increases as the temperature decreases; therefore, the strength of the carbide-cobalt alloys would be expected to show the same tendencies. The test results of the K313, K68, and SP274 grades, which have low binder contents, are consistent with this prediction. K313 and K420, which have high cobalt contents, however, exhibit the opposite effect. To interpret this discrepancy, another temperature effect, thermal stress, needs to be taken into account.

The strength of the brittle material is highly dependent on the variation of internal stress in the material. Due to the large difference between the coefficients of thermal expansion of the cobalt and tungsten carbides, cooling from the sintering temperature during fabrication leads to a substantially different thermal residual stress. X-ray and neuron diffraction studies[16,17] show that the binder phase is typically tensile, and the carbides are compressed. The results also indicate that the carbide-cobalt alloys with higher binder contents have higher residual stress levels. As the samples are cooled from room temperature to cryogenic temperatures, new thermal stress can be introduced besides the residual stress. According to Turner's formulation,[18] thermal stress can be expressed as:

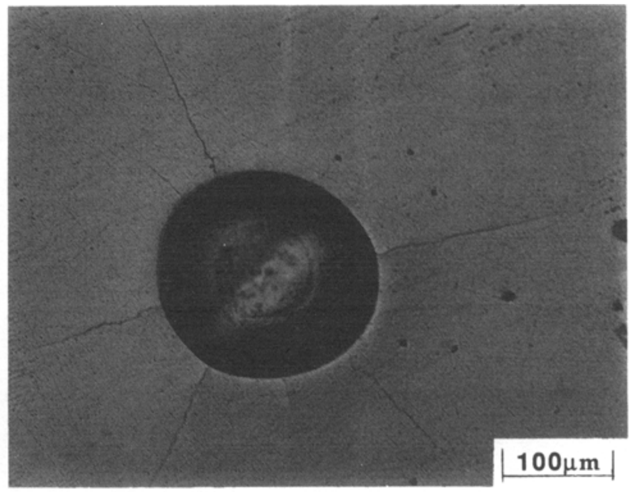
$$\sigma_{WC} = K(\alpha - \alpha_{WC})\,\Delta T \qquad [2]$$

where K is the bulk modulus of the carbide, α is the volume coefficient of the carbide-cobalt alloy, α_{WC} is the volume coefficient of the carbide, and ΔT is the difference between the tested and room temperatures. If σ_{Co} represents the stress in the binder phase, then the mechanical equilibrium requires:

$$f_{WC}\sigma_{WC} + f_{Co}\sigma_{Co} = 0 \qquad [3]$$



(a)



(b)

Fig. 18 Permanent impressions of indentation on K68: (**a**) at room temperature and (**b**) at liquid nitrogen temperature.

Table 3 Chemical Composition of M46 High-Speed Steel

Element	wt%
Carbon	1.25
Tungsten	2.00
Molybdenum	8.25
Chromium	4.00
Vanadium	3.00
Cobalt	8.25

where f_{WC} and f_{Co} are volume fractions of the WC and the binder phase, respectively. It has been shown that carbide-cobalt alloys with higher binder content have larger coefficients of thermal expansion.[13] This implies that the temperature effect in terms of thermal stress is significant in carbide-cobalt alloys with higher binder contents.This effect, resulting from the lower temperature and the existing higher residual stress, may counterbalance or exceed the increased strength of cobalt. This may also be the main reason that, as the temperature decreases, K3109 and K420 exhibit decreasing transverse rupture strength tendencies, whereas K313, K68, and SP274 show the opposite tendency.

3.2 *M46 High-Speed Steel*

High-speed tool steels are highly alloyed steels that are used for high cutting rates of hard metals. In spite of the rapid development of advanced cutting tool materials like cemented carbides, cermet, sintered diamond, cubic boron nitride (CBN), etc., high-speed steels are still widely used in the machining industry. High-speed steel can be classified into two main groups: T and M types. In the present study, a widely used grade, M46, was selected as the testing material. Table 3 gives the chemical composition of AISI M46 high-speed steel.[19]

The microstructure of M46 high-speed steel is shown in Fig. 19. The undissolved carbide particles (white color) are dispersed throughout the matrix of tempered martensite (dark gray). The coexistence of these two phases accounts for the high hardness and high abrasive wear resistance of the material. Indentation testing indicated that the permanent impression at liquid nitrogen temperature was obviously smaller than that at room temperature, which is evident by the increase in hardness of the high-speed steel at low temperature. The low-temperature data are listed in Table 2. Because high-speed steel suffers a rapid decrease in hardness at high temperature, which is a severe disadvantage in machining, this tool material provides better performance when used in cryogenic machining.

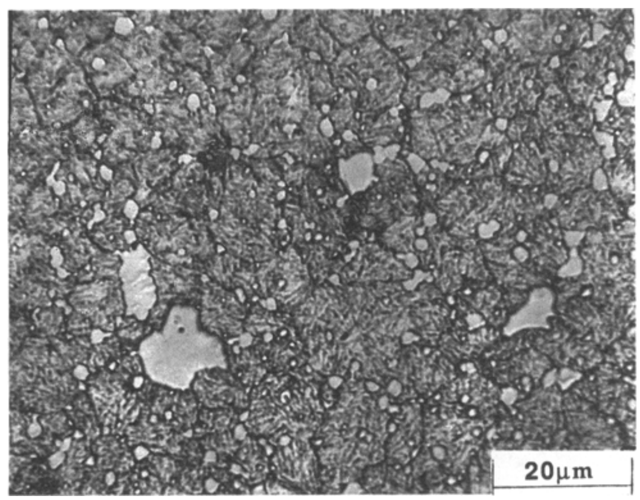


Fig. 19 Microstructure of high-speed steel, which consists of tempered martensite as the matrix and dispersed undissolved carbides.

Figure 20 shows the impact strength of a C-notched M46 specimen at various temperatures. The impact strength exhibits a strong dependence on temperature because the matrix phase is tempered martensite of distorted bcc structure. Similar vari-

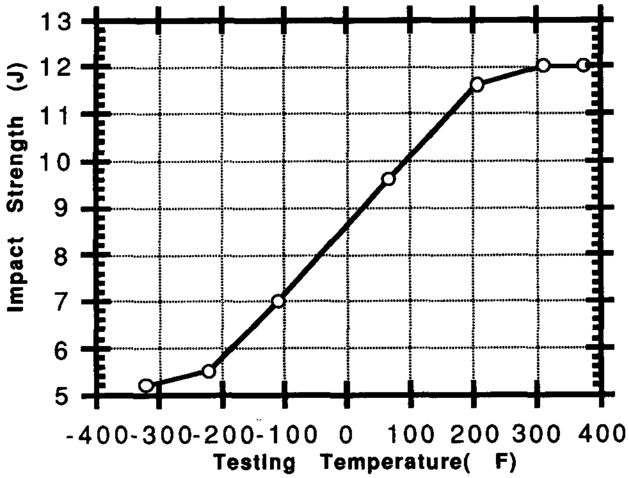


Fig. 20 Impact strength of M46 high-speed steel versus temperature.

ations of impact strength with temperature are expected to occur with other kinds of high-speed steels due to the comparable structures of their matrix phases. This tendency is less for high-speed steel. However, the toughness decreases gradually, and even at –322 °F, M46 high-speed steel is still notably tougher than carbide and ceramic tool materials. This indicates that they may still be applicable in cryogenic machining.

4. Conclusions

Carbide tool materials generally retain their transverse rupture strength and impact strength, and their hardness also increases as the testing temperature decreases toward liquid nitrogen temperature. Therefore, carbide tool materials possess good cryogenic properties. The quantity of binder phase determines not only the room-temperature properties, but also the cryogenic properties of the carbide tool materials. As the temperature decreases, the impact strength and transverse rupture strength exhibit opposite tendencies for certain grades of carbide-cobalt alloys. This suggests that a proper amount of binder phase may offer the advantage of both reasonable toughness and high transverse rupture strength at cryogenic temperatures. With regard to high-speed steel, low temperature increases its hardness and decreases its impact strength.

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