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Ceramic Cutting Tools—A Review

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SUMMARY

The use of ceramic inserts for metalcutting, after a long period of slow growth, is increasing more rapidly due to a number of factors. This paper examines some properties of modern ceramic tools, compares them with those of tungsten carbide-based materials, and attempts to relate such properties to the tools' areas of application. Other factors affecting the use of ceramic tools, in particular the nature of the workpiece and the machine tool, are also reviewed as well as some broader considerations involving the overall metalcutting environment.

1 INTRODUCTION

Metalcutting tool materials form a key component of a system (represented in Fig. 1) for manufacturing metal components to final size. The choice of tool material is closely interdependent with the workpiece being machined and the machine tool used for the process, and the system is subject to a variety of environmental influences. Ceramics, after a long period of relatively slow growth, are now being used with increasing frequency as tools in metalcutting operations, and the purpose of this paper is to analyze the fundamental reasons why this growth is taking place. Particular attention is paid to the relationships between physical, mechanical, and chemical properties and metalcutting performance.

2 PROPERTIES REQUIRED FOR METALCUTTING

Figure 2 represents a metalcutting process (turning in this case) and identifies important terms. Figure 3 shows, in simplified form, how major machining

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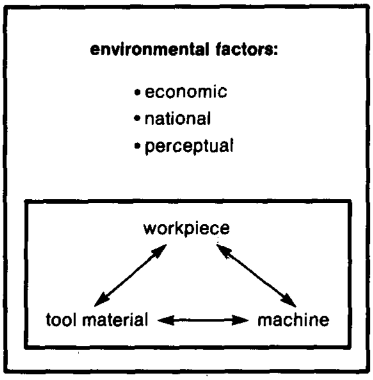

Fig. 1. Overview of metalcutting system.

parameters would be expected to affect the emphasis on different properties of the tool materials. Large depth of cut (DOC), high feeds, and interrupted cuts all demand high strength and toughness from the tool. High speeds will result in lowered cutting forces due to reduced workpiece yield stresses at the higher temperatures being generated. Good performance will generally require that the tool possess good hot hardness and abrasion resistance, and a low level of chemical reactivity with the workpiece. Combinations of high speeds with large depths of cut, feed and/or (in particular) interruptions emphasize thermal shock resistance due to the temperature gradients generated in the tool; the use of coolant also emphasizes this property.

Clearly, the nature of the workpiece material will have a major effect on the relative importance of different properties; for example, low alloy steels

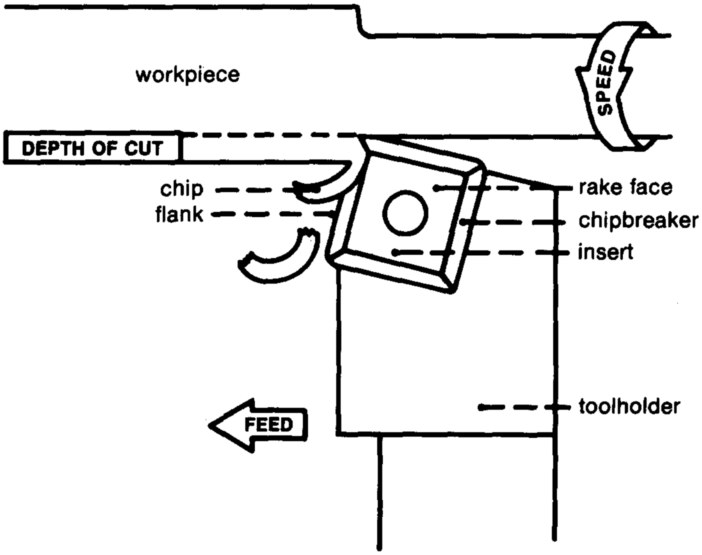

Fig. 2. Metalcutting schematic.

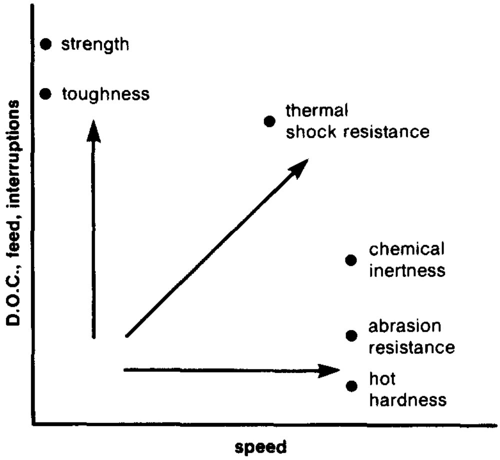

Fig. 3. Key properties.

(which form continuous chips that flow across the rake face of the tool) emphasize the importance of minimizing tool/workpiece chemical interactions, whereas very hard steels (which generate very high temperatures and cutting forces on being machined) also demand high deformation resistance in the tool. In contrast, the machining of low melting point aluminum alloys does not demand good high temperature properties, regardless of machining speed.

3 CARBIDE INSERT TECHNOLOGY

Before turning to ceramics, it is instructive to review the development of tungsten carbide/cobalt-based materials. Figure 4 is a simplified summary of the 'genealogy' of such materials. The main thrust of development after 'straight' WC–Co grades has been to improve steel machining capabilities by improving chemical wear resistance and high temperature mechanical properties by:

(i) Increasing the level of cubic carbides (primarily TiC, TaC and NbC; WC has a hexagonal crystal structural). This line of development has been continued as far as TiC or TiC/TiN-based 'cermets' which contain only low levels of WC, and in which much of the Co is replaced by other metals such as Ni or Mo with improved wetting characteristics.

(ii) Applying thin coatings of hard, chemically stable materials (primarily TiC, Ti(C, N), TiN, and Al_2O_3). Besides steel cutting, this can also give improvements in cast iron machining due to the coatings' abrasion resistance.

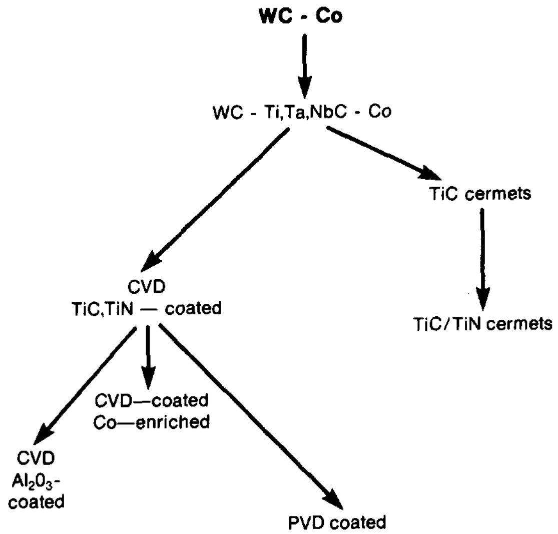

Fig. 4. Summary of carbide metalcutting grade development.

In parallel with these developments have come progressive refinements in molded chipbreakers which are contoured forms on the rake face of inserts, formed during green shaping. Chipbreakers curl the metal chips and hence break them up into short lengths for safe removal.

Clearly, carbide metalcutting tool development has been very successful in its applications over a wide range of machines, metalcutting conditions, and workpiece materials and geometries. Indeed such tools comprise at least 90% of the indexable insert market in not only North America, but also in Western Europe and Japan. However, there are limitations to these lines of development:

(i) High levels of cubic carbide additives reduce thermal shock resistance, which effectively restricts the cermets to low feed and depth of cut conditions.
(ii) Coatings, while they are hard and chemically inert, are necessarily thin and, once penetrated, permit rapid wear of the substrate.
(iii) The metallic binder phase ultimately limits hot hardness and deformation resistance.
(iv) Hardness is limited by the capabilities of bonded transition metal carbides.

4 CERAMIC METALCUTTING TOOLS

The main types of ceramic tool materials are discussed in greater detail subsequently; briefly, however, there are two main families, one based on Al_2O_3, and the other on Si_3N_4.

The simplest Al_2O_3-based tools are white-colored and essentially pure apart from (commonly) a small amount of ZrO_2 added as a grain growth inhibitor. Sometimes, milling pick-up may make such materials appear dark gray or black in color. Most developments have, as their goal, the improvement of hardness and/or toughness and thermal shock resistance, and a variety of dispersed phases have been added to effect these improvements. The most common additives are ZrO_2 (at about the 10 vol% level) or TiC (at about the 30 vol% level), although WC, TiN, TiB_2, Ti(C, N), Zr(C, N) and, most recently, SiC whiskers have also been employed.

Ceramics based on Si_3N_4 have been introduced in the last six years. The materials are called 'sialons' if partial substitution of Si and N atoms by Al and O on the crystal lattice is present. Densification aids, most commonly Y_2O_3, are employed to allow the materials to attain full density. TiC and TiN have been used as dispersed phases in some commercial grades.

Not strictly ceramics, but deserving mention, are materials based on diamond and cubic boron nitride (CBN). The main characteristic of these materials is their extreme hardness, with CBN being the softer, but more stable chemically.

5 INSERT MATERIAL PROPERTIES

Table 1 lists important physical and mechanical properties of some key ceramic grades, and compares them with two cemented carbides; a low cubic (2 wt%), low Co (6 wt%) grade used primarily for cast iron and nickel-base superalloy machining (C2), and a higher cobalt (8 wt%), higher cubic (20 wt%) grade used for steel (C5).

TABLE 1

Physical and Mechanical Properties

Material	*Three-point bend-strength (MPa)*	*Young's modulus (GPa)*	*Hardness*[b] *(GPa)*	*Toughness*[c] K_{Ic} *($M\,Pam^{1/2}$)*	*Abrasive*[d] *wear*	*Thermal*[e] *exp. coeff.* *($K^{-1} \times 10^6$)*	*Thermal*[f] *cond.* *($Wm^{-1}K^{-1}$)*
Al_2O_3	700	400	17·2	4·3	1·00	8·0	10·5
Al_2O_3–ZrO_2	—	390[a]	16·5	6·5	1·18	8·5[a]	8·0[a]
Al_2O_3–TiC	910	420	20·0	4·5	1·22	8·5	13·0
Al_2O_3–SiC_w	—	420[a]	18·8	6·8	1·37	6·4	15·0[a]
Si_3N_4/Sialon I[g]	760	300	15·6	6·5	1·34	3·1	9·7
Si_3N_4/Sialon II[h]	—	300	14·6	6·5	1·21	3·1	17·2
C2 Carbide	2 080	610	17·6	8·5	1·03	5·1	72·7
C5 Carbide	2 170	510	14·9	10·8	1·06	6·7	45·4

[a] Estimated value.
[b] Vickers, 18 kg load.
[c] Indentation[1] or Short Rod.[2]
[d] $K_{Ic}^{0.5}$, $E^{-0.8}$, $H^{1.43}$ (E = Young's modulus, H = Hardness).[5]
[e] Range 25–870°C.
[f] 500°C value.
[g] α'/β'/Y–Si–Al–O–N glass material.
[h] β'/Y–Si–Al–O–N glass material.

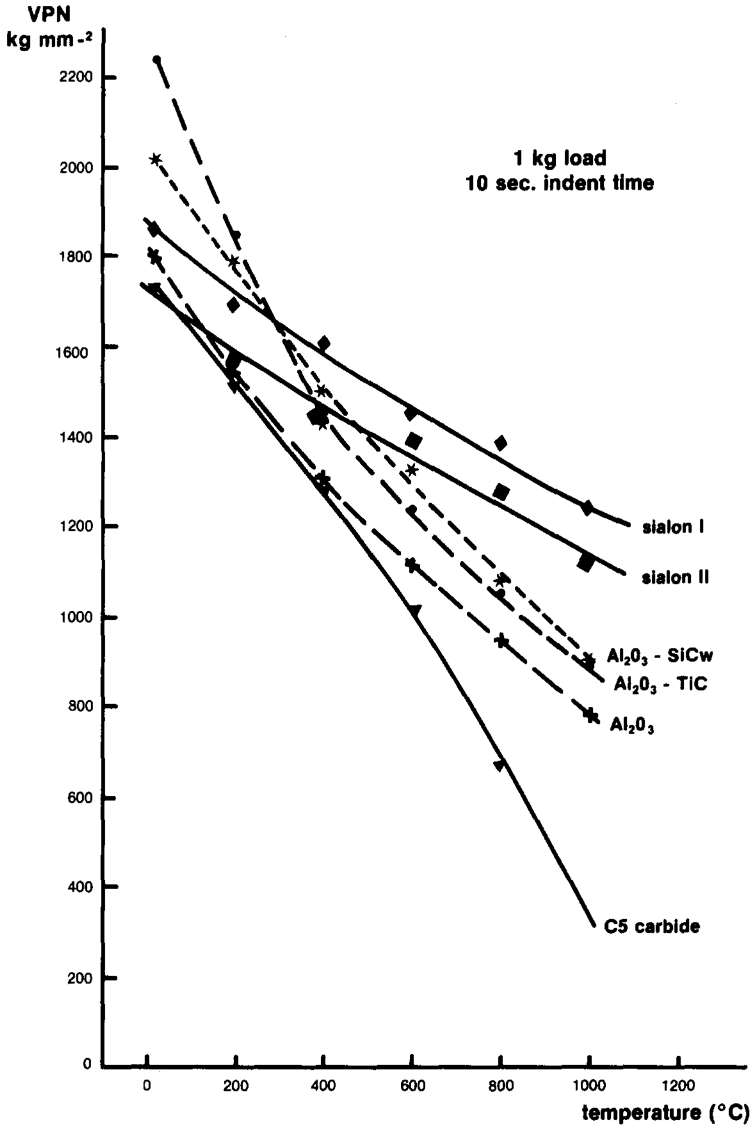

Fig. 5. Vickers hardness vs temperature.

Clearly, the carbide tools have much higher bend-strength values than any of the ceramics, and it is interesting to note that the Si_3N_4/sialon materials are actually weaker than Al_2O_3–TiC ceramics.

The carbide tools have very high Young's modulus values (although reduced substantially by high Co and cubic levels), while the Si_3N_4/sialon grades have particularly low values. This parameter is important in both abrasion and thermal shock resistance.

The values for hardness demonstrate that Al_2O_3 hardness is further

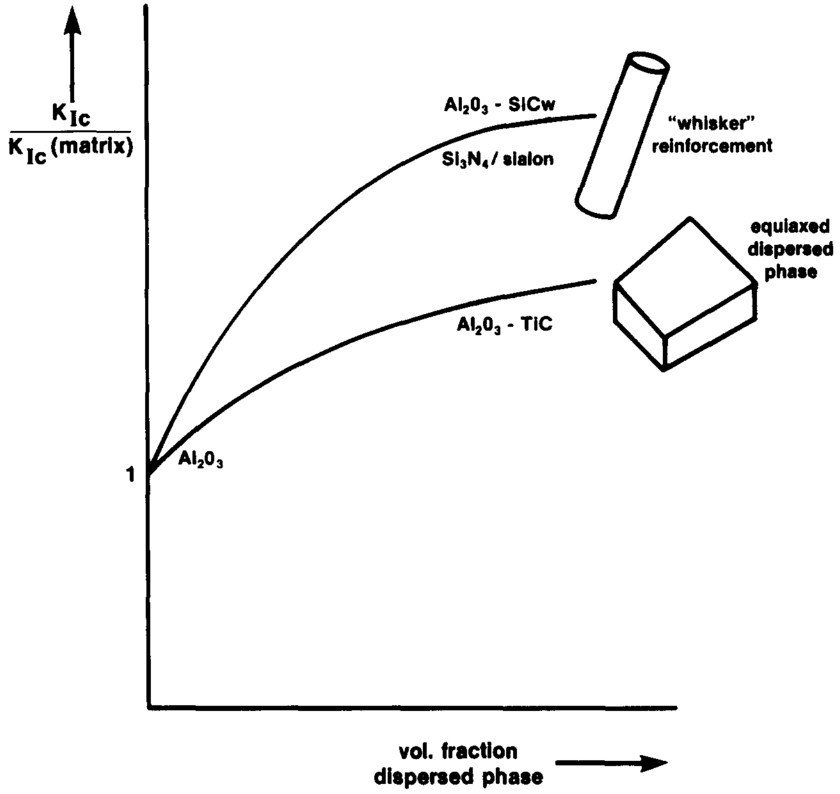

Fig. 6. Toughening by crack deflection.

increased by SiC whisker or TiC additions. It is also noteworthy that the Si_3N_4/sialon materials are not particularly hard at room temperature; their values are similar to those for carbides. However, Fig. 5 demonstrates that at the elevated temperatures characteristic of the tool/chip interface, the Si_3N_4/sialon materials retain their hardness particularly well, while the cemented carbides lose hardness rapidly (especially above about 600°C) due largely to their metallic intergranular phase.

Fracture toughness (K_{Ic}) values[1,2] demonstrate the superiority, in this respect, of cemented carbides (especially at higher Co levels). Indeed, together with a high Young's modulus and freedom from large flaws, this property is responsible for their high strength. Al_2O_3 ceramics are low in toughness; TiC additions increase this property somewhat but greater improvements may be realized by adding ZrO_2 (making use of the strain energy associated with the monoclinic to tetragonal phase transformation,[3] or alternatively by maximizing crack deflection and pull-out mechanisms[4] by dispersing SiC whiskers in an Al_2O_3 matrix (see Fig. 6). The relatively high toughness values of the Si_3N_4/sialon materials derives from a similar

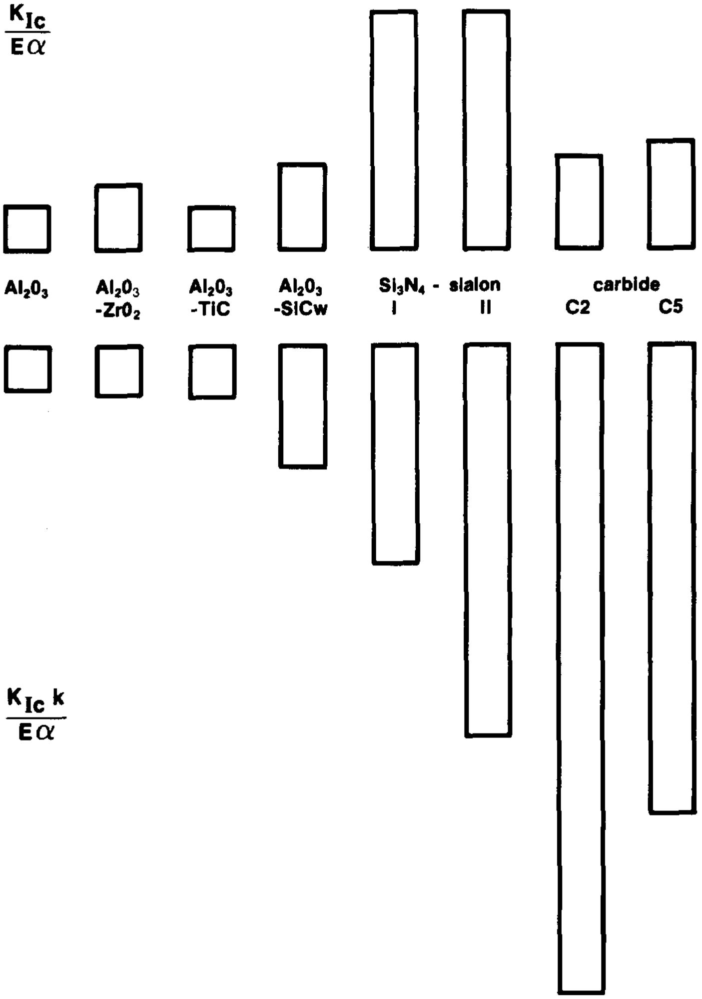

Fig. 7. Thermal shock figures-of-merit. K, Thermal conductivity at 500°C; α, expansion coefficient, 25–870°C range.

mechanism due to the highly elongated nature of the βSi_3N_4 or β'sialon grains. The high toughness of Al_2O_3–SiC whisker composites is obtained at the expense of both raw material and fabrication costs.

Resistance to abrasion is a function of several physical and mechanical properties. The particular parameter in Table 1 is derived from considerations of indentation of surfaces by hard particles.[5] Broadly, a low value for Young's modulus is desirable because, for a given applied strain, a lower stress is developed, while high fracture toughness is desirable to resist fracture under this stress. High hardness is clearly preferred for abrasion resistance. The values in Table 1 are applicable at room temperature, and demonstrate some advantage for the Al_2O_3-based composite tools and the

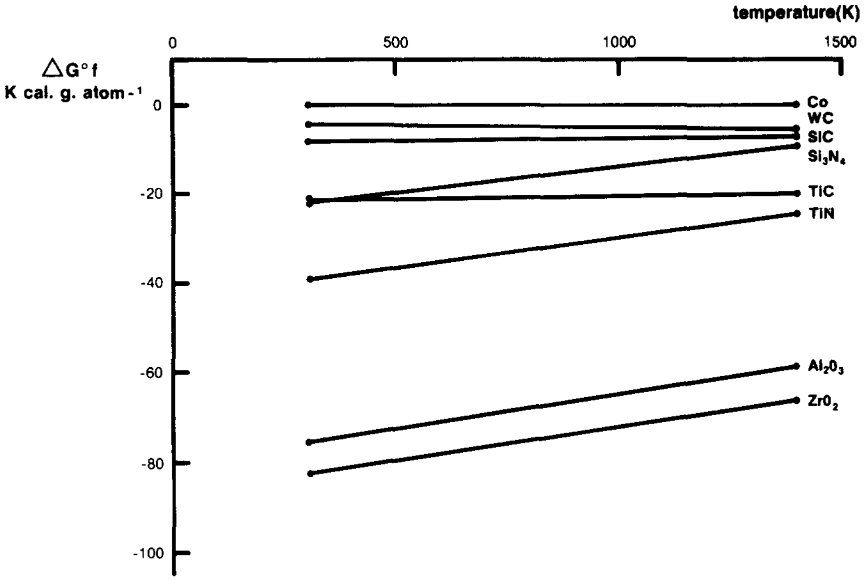

Fig. 8. Free energies of formation vs temperature.

Si_3N_4/sialon materials. Elevated temperature values are not given here due to the absence of sufficient high temperature property data, but it is probable that the Si_3N_4/sialon materials would be favored due to their better hardness retention.

Thermal shock resistance depends on toughness and Young's modulus as well as the thermal expansion coefficient and conductivity. Figure 7 shows relative values of two 'figures-of-merit' derived by considering the onset of crack propagation in flat plates.[6] The first is most relevant to a sudden thermal shock while the second is appropriate to a steady state thermal gradient situation. Clearly, Al_2O_3 is poor in thermal shock, although some improvements are gained from the addition of ZrO_2, TiC and (in particular) SiC whiskers whose high thermal conductivity, low expansion coefficient, and contribution to fracture toughness give a major improvement. However, thermal shock resistance is a property which particularly favors the Si_3N_4/sialon materials due primarily to their combination of low Young's modulus and very low thermal expansion coefficient.

Finally, chemical properties are very important due to workpiece material/tool interactions. A simple way of ranking materials is to consider their free energies of formation, and Fig. 8 does this over a large temperature range, normalized to a gram atom basis. Broadly, the more negative the value, the greater the chemical stability, and the less the degree of reaction which might be expected with the workpiece. Clearly, Co and WC fare poorly in this respect and this represents the prime reason for the addition of cubic carbides such as TiC, or coating by TiC, Ti (C, N), TiN or Al_2O_3 to improve metalcutting performance. Al_2O_3 and Al_2O_3–ZrO_2 ceramic tools are very stable chemically while TiC and, in particular, SiC additions will degrade their chemical properties. Si_3N_4 is, especially at high temperatures, not very inert chemically, although alloying with Al and O to form a sialon does increase stability somewhat.

6 TOOL GEOMETRIES

The fabrication techniques and the properties of tool materials have a major effect on tool geometries, both in terms of the styles that can be made economically, and because the inserts' mechanical properties determine whether certain geometries can be used in practice. Tungsten carbide-based materials can be pressed to shape readily in the green state, are pressureless sintered, and are quite tough. This permits a particularly wide range of styles, and a range of edge preparations and molded-in chipbreakers. Ceramics are far less versatile in these respects for a number of reasons: the starting powders are generally finer and are often partially non-equiaxed which makes pressing behavior more difficult, and the plastic Co powder in cemented carbide mixes may assist pressing. The more refractory nature of ceramics determines that sintering is difficult, and so hot unaxial or isostatic pressing techniques are frequently needed to assure full densification, and grinding is generally more difficult because of the materials' relative brittleness. Molded chipbreakers are thus difficult to form, and furthermore act as stress-raisers which would, in any case, limit their practical use.

For the above reasons, ceramics have historically been primarily used with chamfered edges in negative rake styles (i.e. with the rake and flank faces normal), with relatively large thicknesses without molded chipbreakers, and without a central hole for a locking pin or screw. However, improvements in fabrication techniques, mechanical properties, and machine tool rigidity are permitting the increasing use of inserts with positive rake geometries (i.e. with an acute angle between the rake and flank faces), central holes, and honed (or even sharp) edges. Simple chipbreaker styles have also been demonstrated, although in many cases the higher speed capabilities of ceramics, especially if combined with high feeds, may give adequate chip control alone.

7 MACHINE TOOLS

New machine tools tend to be more powerful and capable of higher speeds than earlier models. They are also 'stiffer' which reduces the magnitude and fluctuation of stress levels experienced by the inserts. Higher speeds reduce cutting forces and also increase cutting temperatures. In general, these machine developments emphasize the properties of hot hardness, abrasion resistance, chemical wear resistance and, in some cases, thermal shock resistance (especially if high feeds and/or depths of cut are employed as well).

8 WORKPIECE

Important issues with respect to the workpiece are its geometry, composition, and properties.

With regard to geometry, the trend to near-net shape is very important in tool choice because this technology tends to reduce depths of cut. For a given machine power level this will allow higher machining speeds which, in general, will favor ceramics, although on steels, because of chip control problems, cermet or coated carbide tools may be favored.

A separate issue is that of interrupted cutting, of which milling is the most common form. Interruptions in the cut result in both mechanical and thermal shocking which effectively precludes Al_2O_3, Al_2O_3–ZrO_2 and Al_2O_3–TiC ceramics except at light feeds, and particularly suits the Si_3N_4/sialon materials and carbides.

Workpiece composition has a major effect on tool material choice because of chemical interaction, the presence of abrasive inclusions, workpiece yield strength (which affects the cutting forces on the tool), and chip flow. Figure 9 summarizes (very broadly) typical speed/feed regimes of different tool materials for three major classes of workpiece—cast iron, alloy steels, and nickel-base superalloys. It is instructive to review Fig. 3 at this point and examine parallels between application ranges and the properties of different tools. The vertical axis in Fig. 9, while specifically representing feed, can also be viewed in a more general sense as being related to depth of cut and degree of interruption since these also raise mechanical and thermal loadings on the tool. Figure 9 demonstrates the versatility of cemented carbide tools at moderate speeds, with a useful speed advantage being gained on cast iron and steels by the application of coatings. Al_2O_3 and, in particular, Al_2O_3–TiC ceramics are also very versatile in the high speed range, although on softer steels chip control can be a problem. The high speed/feed combinations possible with Si_3N_4/sialon materials are apparent, with the noticeable absence of application on steel, where the chemical wear problem discussed earlier precludes their effective use except on very hard steels.[7] The prime application area of the new Al_2O_3–SiC whisker ceramics to date has been on nickel-base superalloys at high speed/feed combinations.

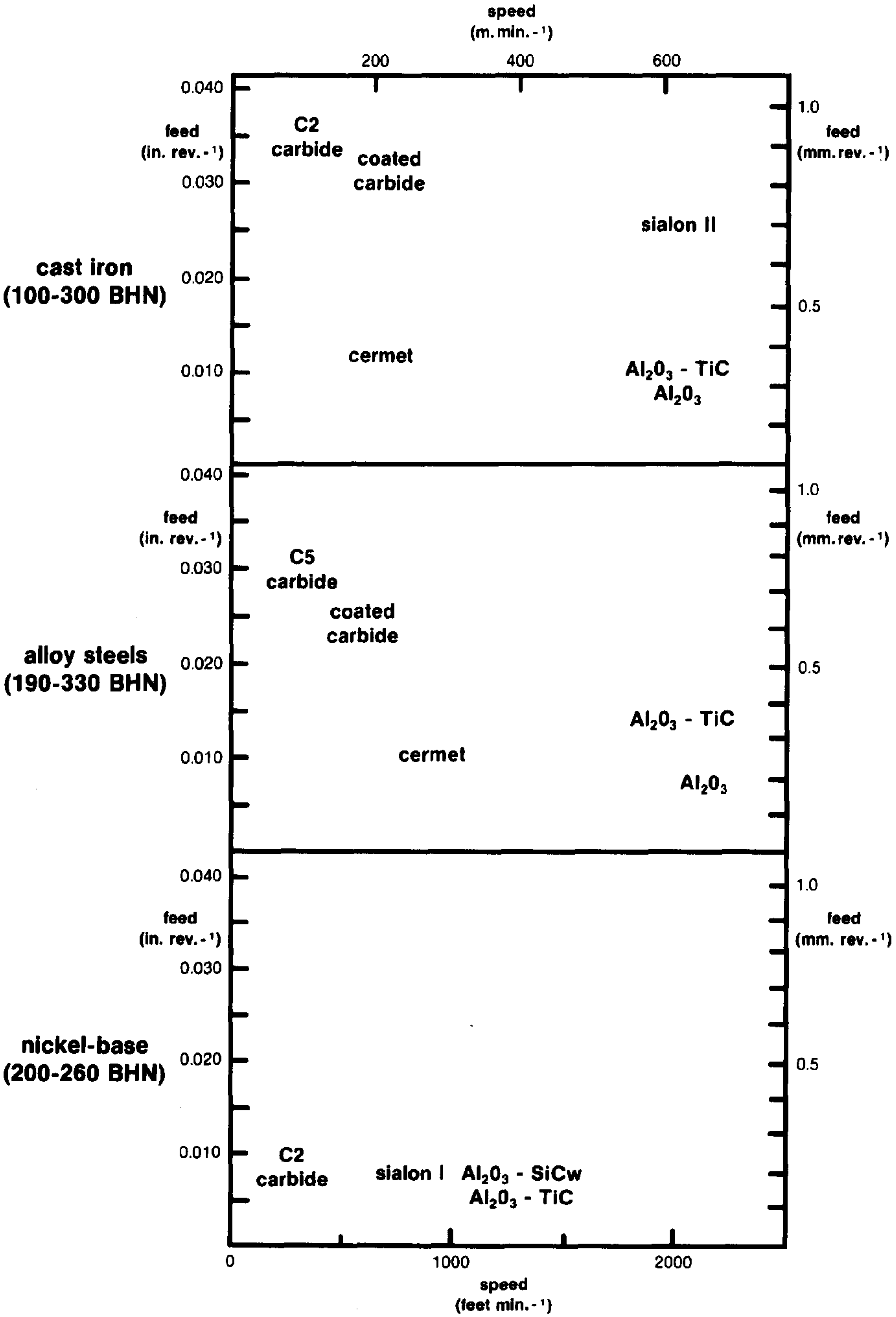

Fig. 9. Approximate application ranges (actual conditions depend on workpiece, cut geometry, machine, and surface requirements).

Certain important workpieces are not amenable to machining with ceramics. In particular, soft non-ferrous metals and non-metals can be satisfactorily machined with uncoated carbides or, at very high speeds or if abrasive inclusions are present, with diamond tooling. The prime reason is that such workpieces do not generate very high temperatures on being machined. On particularly hard cast iron and steels, cubic boron nitride tools may give the best tool lives. Stainless steels and titanium based alloys are best machined with carbide tools, probably because these workpieces work-harden very rapidly and so generate particularly high cutting forces.

9 ENVIRONMENTAL FACTORS

The economic, national and social environment within which the metalcutting industry exists has a major impact on the nature of tools being used.

Increasing international trade, and the resulting competition, places strenuous demands on the metalworking industry to be very productive, of which a simple manifestation is the need to produce more parts per machine per operator per unit time. This translates to high speeds and feeds (and sometimes high depths of cut to avoid multi-pass operations), together with low wear rates and high reliability to minimize the frequency of indexing. Such developments favor the use of high quality, high performance tooling in general, with ceramics being favored in certain applications.

There are substantial national differences which affect individual countries' use of ceramics. In Japan, the ceramic share of indexable inserts is about 8–10%,[8] whereas in the USA the proportion is now estimated at about 3–4%.[9] Western European countries generally lie in the 3–8% range, with West Germany perhaps having the highest level. There are several reasons for these material differences. Countries with relatively young machine tool populations can make better use of ceramics, and the existence of (large in proportion to these countries' economies) major automotive industries (which machine a lot of cast iron) also encourages their use. Alumina tool manufacturing also became well established during World War II in countries which needed to conserve tungsten for ordnance purposes. However, the USA is the leader in development and commercialization of the most advanced ceramics, particularly the Si_3N_4/sialon and Al_2O_3/SiC whisker materials. Reasons for this include high temperature engine-driven ceramics research (much of which took place in the USA, and from which such tooling materials 'spun-off'), the high power levels of many modern US machine tools (which allow high speed to be combined with high feeds and/or depths of cut), and the presence of strong automotive and aerospace industries which machine a lot of cast iron and nickel-base superalloys respectively.

Customer perception of ceramics, and the aggressiveness with which they are marketed, has a major impact on the extent of application. In the USA, memories persist of early sintered 'white' Al_2O_3 which, for reasons of (probably) both application and properties, gained a poor reputation. Subsequent dark-colored Al_2O_3 (obtained by sintering in a reducing atmosphere with metallic impurities) and hot-pressed Al_2O_3–TiC composites performed better, and white ceramics are still not widely accepted in the USA (in contrast to, in particular, West Germany and Japan, where they are widely used on cast iron). Confidence in ceramic tools is increasing as the number of machines able to take advantage of them increases, and the toughness and thermal shock resistance of the materials themselves improve. As the major tool manufacturers market broader ranges of ceramics (in terms of grades and insert styles) the resulting availability and familiarity will also tend to enhance ceramic usage.

Current worldwide usage of ceramic cutting inserts is estimated at about US$ 75 million with growth to about US$ 150 million in 1995.[10]

10 CONCLUSIONS

This paper has discussed the major factors affecting the use of ceramic tooling. Given a reasonable continuation of current trends, it seems certain that ceramics will grow in use, but they do have shortcomings with respect to carbide tooling in many situations. It is not clear that future developments in materials, workpieces and machine tools will necessarily eradicate these shortcomings. For the foreseeable future, it is expected that carbide and ceramic tools will complement one another, with the relative balance being difficult to predict because of the large number of variables involved.

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