Chapter 22

Cutting-Tool Materials and Cutting Fluids

QUALITATIVE PROBLEMS

22.16 Explain why so many different types of cutting-tool materials have been developed over the years. Why are they still being developed further?

The reasons for the availability of a large variety of cutting-tool materials is best appreciated by reviewing the top eight parameters in the first column in Table 22.2 on p. 638. Among various factors, the type of workpiece material machined, the type of operation, and the surface finish and dimensional accuracy required all affect the choice of a cutting-tool material. For example, for interrupted cutting operations such as milling, we need toughness and impact strength. For operations where much heat is generated due, for example, to high cutting speeds, hot hardness is important. If very fine surface finish is desired, then materials such as ceramics and diamond would be highly desirable. These materials continue to be investigated further because, as in all other materials, there is much progress to be made for reasons such as to improve properties, extend their applications, develop new tool geometries, and reduce costs. The students are encouraged to comment further.

22.17 Which tool-material properties are suitable for interrupted cutting operations? Why?

In interrupted cutting operations, it is desirable to have tools with a high impact strength and toughness. From Tables 22.1 and 22.2 on pp. 649-650, the tool materials which have the best impact strength are high speed steels, and to a lesser extent, cast alloys and carbides. Therefore, one would prefer to use high-speed steels and carbides in interrupted cutting operations. In addition, in these operations, the tool is constantly being heated and reheated. It is therefore desirable to utilize materials with low coefficients of thermal expansion and high thermal conductivity to minimize thermal stresses in the tool which could lead to tool failure.

22.18 Describe the reasons for coating cutting tools with multiple layers of different materials.

There are several reasons for applying multiple coatings to a cutting tool, as also described in Section 22.5 on p. 656. One of the most obvious is that a given coating material may not bond well directly to the tool surface. A sandwiched layer of coating to which both the metal and the desired coating can bond successfully will increase the life of the tool. Also, one can combine the benefits from different materials. For example, the outermost layer can be a coating which is best from a hardness or low frictional characteristic to minimize tool wear. The next layer can have the benefit of being thermally insulating, and a third layer may be of a material which bonds well to the tool. Using these multiple layers allows a synergistic result in that the weaknesses of one coating can be compensated for with another layer.

22.19 Make a list of the alloying elements used in high-speed steels. Explain why they are so effective in cutting tools.

Typical alloying elements for high-speed steel are chromium, vanadium, tungsten, and cobalt. These elements impart higher strength and higher hardness at elevated temperatures. See Section 5.5.1 on p. 157 for further details on the effects of various alloying elements in steels.

22.20 As we have stated in Section 22.1, tool materials can have conflicting properties in machining operations. Describe your observations regarding this matter.

The brief discussion below should be viewed as illustrative of the type of answers that can be generated by the students. One well-known example of conflicting properties is the competition between hardness and ductility. Hardness is desirable for good wear resistance (see Section 33.5 on p. 1046), and for this reason it is advisable to perform hardening processes such as proper heat treating to high-speed steels. One of the consequences of hardening operations is that the ductility of the tool material may be compromised. If the machining operation is one of interrupted cutting (as in milling), or if chatter occurs, it is better to have good ductility and toughness to prevent premature tool fracture. The students are encouraged to comment further.

22.21 Comment on the purposes of chamfers on inserts and their design features.

As the shown in Fig. 22.5 on p. 655, chamfers serve to increase the edge strength of inserts because, in a sense, they effectively increase the included angle of the insert. Thus, resistance to chipping and fracture also increases. Furthermore, as discussed in Section 17.6 on p. 505, a chamfer is good design practice if the insert is produced by powder metallurgy techniques.

22.22 Explain the economic impact of the trend shown in Fig. 22.6.

The obvious economic impact can be deduced when also considering the axiom "time is money." As the cutting time decreases, the production cost decreases. Notice that the ordinate in Fig. 22.6 on p. 658 is a log scale, which indicates that the reduction in time will be an ever decreasing difference with given time increments. However, the trend is still that parts manufactured by machining are less costly as the years progress.

22.23 Why does temperature have such an important effect on tool life?

Temperature has a large effect on the life of a cutting tool for several reasons. First, all materials become weaker and less hard as they become hotter; therefore, higher temperatures will weaken and soften an otherwise ideal material. Second, chemical reactivity typically increases with increasing temperature, as does diffusion between the workpiece and the cutting tool. Third, the effectiveness of cutting fluids is compromised at excessive temperatures, meaning there is higher friction to overcome, and therefore more tool wear is expected. Finally, in interrupted cutting, there can be excessive thermal shock if the temperatures are high.

22.24 Ceramic and cermet cutting tools have certain advantages over carbide tools. Why, then, are they not completely replacing carbide tools?

Ceramics are preferable to carbides in that they have a lower tendency to adhere to metals being cut, and have a very high abrasion resistance and hot hardness. However, ceramics are generally brittle, and it is not unusual for them to fail prematurely. Carbides are much tougher than ceramics, and are therefore much more likely to perform as expected even when conditions such as chatter occurs. Also, it should be noted that ceramic tools have limits to their geometry; sharp noses are likely to be chipped and high rake angle tools will have suspect strength if made from ceramics. Carbide tools are preferable for these geometries when needed.

22.25 Can cutting fluids have any adverse effects? If so, what are they?

Cutting fluids can have adverse effects on the freshly machined surfaces, as well as various components of the machine tool and the lubricants used on the machines themselves, such as altering their viscosity and lubricating capabilities. If a cutting fluid is very effective as a coolant, it could lead to thermal shock in interrupted cutting operations. Cutting fluids have to be replaced periodically because they degrade, adversely affecting their performance. This degradation can be due to intense shear in the cutting zone, contamination by other materials, or from bacteria attacking the oil (or, more commonly, the emulsifier). If the cutting is no longer effective because of this degradation, workpiece quality will be compromised, but then there is the additional environmental concern associated with fluid disposal. (See also bottom of p. 665.)

22.26 Describe the trends you observe in Table 22.2.

By the student. Table 22.2 on p. 650 lists the cutting-tool materials in the approximate order of their development (from left to right). In terms of mechanical properties of the tool materials, the trend is towards development of harder materials with improved wear resistance. The tradeoff, however, can be a reduction in toughness, impact strength, and chipping resistance. The benefits of the trend is that cutting can take place faster, with greater depths of cut (except for diamond tools) and with better surface finish. Other limitations are the decreasing thermal shock resistance and increasing costs of the tool materials towards the right of the table.

22.27 Why are chemical stability and inertness important in cutting tools?

Chemical stability and inertness are important for cutting tools in order to maintain low friction and wear. One of the causes of friction is the shear stress required to break the microwelds in the interfaces between tool and workpiece materials (see Fig. 33.5 on p. 1043). If the tool material is inert, the microwelds are less likely to occur, and friction and wear will thus be reduced. It is also important that the workpiece and the cutting tool not bond chemically; this can lead to diffusion and adhesive wear.

22.28 How would you go about measuring the effectiveness of cutting fluids? Explain any difficulties that you might encounter.

By the student. The effectiveness of cutting fluids can be measured in a number of ways. The most effective and obvious is to test different cutting fluids under actual cutting operations. Other methods are to heat the fluids to the temperatures typically encountered in machining, and measure the fluid's viscosity and other properties such as lubricity, specific heat, density, etc. The chemical reactivity of the cutting fluid can also be tested against workpiece materials (see Chapter 33 for details). The students are encouraged to develop their own ideas for such tests.

22.29 Titaniumnitride coatings on tools reduce the coefficient of friction at the toolchip interface. What is the significance of this?

The tool-chip interface is the major source of friction in cutting, hence a major source of energy dissipation. Also, reducing friction will increase the shear angle and produce thinner chips and requiring less shear energy (see p. 612). These reductions will, in turn, reduce the cutting forces and hence the total energy required to perform the cutting operation. Reducing friction also reduces the amount of heat generated, which results in lower temperatures, with beneficial effects such as extending tool life and maintaining dimensional accuracy. (See also Problem 21.19.)

22.30 Describe the necessary conditions for optimal utilization of the capabilities of diamond and cubic boron nitride cutting tools.

Because diamond and cBN are brittle, impact due to factors such as cutting-force fluctuations and poor quality of the machine tools used must be minimized. Thus, interrupted cutting (such as milling or turning splines) should be avoided. Machine tools should have sufficient stiffness to avoid chatter and vibrations (see Chapter 25). Tool geometry and setting is also important to minimize stresses and possible chipping. The workpiece material must be suitable for diamond or cBN; for example, carbon is soluble in iron and steels at elevated temperatures as seen in cutting, and diamond would not be suitable for these materials.

22.31 List and comment on the advantages of coating high-speed steel tools.

As stated in Section 22.5.1 on p. 657, tool coatings have several important functions. Although high-speed steels have toughness and shock resistance, their hot hardness decreases with temperature (see Fig. 22.1 on p. 648). Many coatings have been developed with very high hardness. Also, coating materials can be produced from materials with more chemical inertness than high-speed steels. Thus coatings enhance these properties with resistance to temperature and wear.

22.32 Explain the limits of application when comparing tungsten-carbide and titanium-carbide cutting tools.

Refer to Section 22.4 on p. 653. Tungsten carbide is generally used for cutting nonferrous metals and alloys because of the chemical similarity of tungsten and iron on the periodic table. Thus, although tough, its wear resistance is not as high with ferrous alloys. Titanium carbide has higher wear resistance in machining steels and cast iron at high speeds.

22.33 Negative rake angles are generally preferred for ceramic, diamond, and cubic boron nitride tools. Why?

Although hard and strong in compression, these materials are brittle and relatively weak in tension. Consequently, negative rake angles (which indicate larger included angle of the tool tip; see, for example, Fig. 21.3 on p. 609) are preferred mainly because of the lower tendency to cause tensile stresses and chipping of the tools.

22.34 Do you think that there is a relationship between the cost of a cutting tool and its hot hardness? Explain.

Generally, as hot hardness increases, the cost of the tool material increases. For example, ceramics have high hot hardness and are generally made of inexpensive raw materials. However, their production into effective and reliable tool materials involves major steps (see Section 18.2 on p. 514) and, hence, expenses (also known as value added; see bottom of p. 2). Likewise, carbides utilize expensive raw materials as well as involving a number of processing steps (see Example 17.4 on p. 504). Diamond and cubic boron nitride are expensive as well.

22.35 Survey the technical literature and give some typical values of cutting speeds for high-speed-steel tools and for a variety of workpiece materials.

By the student. Good sources for such a literature search are periodicals, trade magazines, and cutting-tool vendors whose product specifications will include recommended cutting speeds and various other useful data. See also Table 23.4 starting on pp. 682-684.

22.36 In Table 22.1, the last two properties listed can be important to the life of the cutting tool. Why?

The last two properties in Table 22.1 on p. 649 are thermal conductivity and coefficient of thermal expansion. These properties are important in thermal cracking or shock of the tool material due to internal thermal stresses developed when subjected to thermal cycling, as in interrupted cutting operations. (See Section 3.6 on p. 107 for details.)

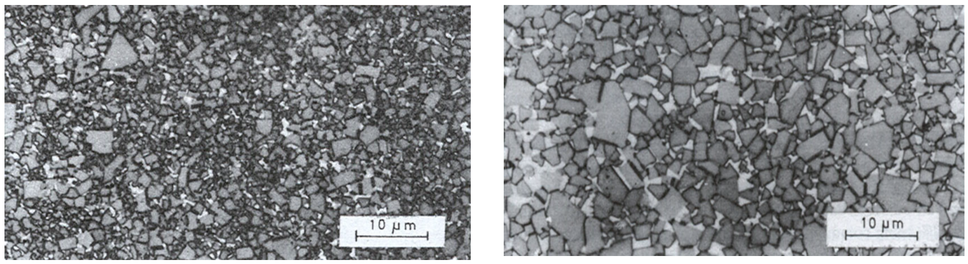
22.37 It has been stated that titanium-nitride coatings allow cutting speeds and feeds to be higher than those for uncoated tools. Survey the technical literature and prepare a table showing the percentage increase of speeds and feeds that would be made possible by coating the tools.

By the student. Good sources for such a literature search are periodicals, trade magazines, and cutting-tool vendors whose product specifications will include data on speeds and feeds. See also Table 23.4 on pp. 682-684.

22.38 You will note in Fig. 22.1 that all tool materials have a wide range of hardnesses for a particular temperature, especially carbides. Describe all the factors that are responsible for this wide range.

By the student. There are many reasons for the range of hardnesses, including:

- All of the materials can have variations in their microstructure, and this can significantly affect the hardness. For example, compare the following two micrographs of tungsten carbide, showing a fine-grained (left) and coarse-grained (right) tungsten carbide. (*Source:* Trent, E.M., and Wright, P.K., *Metal Cutting* 4th ed., Butterworth Heinemann, 2000, pp. 178-185).



- There can be a wide range in the concentration of the carbide compared to the cobalt binder in carbide tools.
- For materials such as carbon tool steels, the carbon content can be different, as can the level of case hardening of the tool.
- 'High speed steels' and 'ceramics' are generic terms with a large range of chemistries.
- Cutting tool materials are available in a wide variety of sizes and geometries, and the hardness will vary accordingly. For example, a large rake angle tool is more susceptible to chipping (see Fig. 22.4 on p. 655), so such tools may be hardened to a lower extent in order to preserve some toughness in the material.

22.39 List and explain the considerations involved in the decision to recondition, recycle, or discard a cutting tool.

By the student. The main considerations are structural, economic, and environmental. For example, a tool can only be reconditioned so many times before it is structurally unsound and could fracture prematurely. If the cost of reconditioning exceeds the cost of a new tool, then clearly reconditioning is wasteful. If the cutting tool is an expensive material or where discarding it introduces environmental hazards, it should be recycled instead of discarded.

22.40 Referring to Table 22.1, state which tool materials would be suitable for interrupted cutting operations. Explain.

By the student. Interrupted cutting operations basically require cutting-tool materials that have high impact strength (toughness) as well as thermal-shock resistance. Note in Table 22.1 on p. 649 that high-speed steels are by far the toughest; however, their resistance to high temperatures is rather low and have limited tool life in such operations. Consequently, although not as tough, carbides, cermets, and polycrystalline cubic boron nitride and diamond are used widely in interrupted cutting various workpiece materials, as shown in Table 24.2 on p. 736. These tool materials are continuously being developed for increasing toughness and resistance to edge chipping.

22.41 Which of the properties listed in Table 22.1 is, in your opinion, the least important in cutting tools? Explain.

By the student. It would appear that modulus of elasticity and density are not particularly important in cutting. However, as a very low order effect, elastic modulus may have some influence in very high precision machining operations because of the deflections involved. As for density, although the cutting tool itself has a rather small mass compared to other components, in high-speed operations where tool reversals may be involved, inertia effects can be important.

22.42 If a drill bit is intended for woodworking applications, what material is it most likely to be made from? (Hint: Temperatures rarely rise to 400 °C in woodworking.) Are there any reasons why such a drill bit cannot be used to drill a few holes in a metal? Explain.

Because of economic considerations, woodworking tools are typically made of carbon steels, with some degree of hardening by heat treatment. Note from Fig. 22.1 on p. 648 that carbon steels maintain a reasonably high hardness for temperatures less than 400F. For drilling metals, however, the temperatures are high enough to soften the carbon steel (unless drilling at very low rotational speeds), thus quickly dulling the drill bit.

22.43 What are the consequences of a coating having a different coefficient of thermal expansion than the substrate?

Consider the situation where a cutting tool and the coating are stress-free at room temperature when the tool is inserted. Then consider the situation when the tool is used in cutting and the temperatures are very high. A mismatch in thermal expansion coefficients will cause high thermal strains at the temperatures developed during machining. This can result in a separation (delamination) of the coating from the substrate.

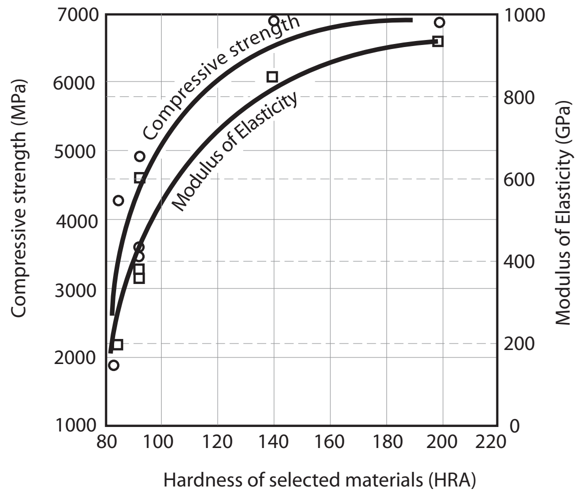
22.44 Discuss the relative advantages and limitations of near-dry machining. Consider all relevant technical and economic aspects.

Refer to Section 22.12.1 on p. 669. The advantages are mostly environmental as there is no cutting fluid which would add to the manufacturing cost, or to dispose of or treat before disposal. This has other implications in that the workpiece doesn't have to be cleaned, so no additional cleaning fluids, such as solvents, have to be used. Also, lubricants are expensive and difficult to control. However, cutting-fluid residue provides a protective oil film on the machined part from the environment, especially with freshly machined metals that begin to rapidly oxidize.

QUANTITATIVE PROBLEMS

22.45 Review the contents of Table 22.1. Plot several curves to show range relationships, if any, among parameters such as hardness, transverse rupture strength, and impact strength. Comment on your observations.

By the student. There are many variables that can be selected for study; some will give no apparent relationship but others will give some correlation. For example, below is a plot of hardness compared to compressive strength and elastic modulus. Note that the hardness of cubic boron nitride and diamond have been extrapolated from Fig. 2.14 on p. 84 and are only estimates for illustrative purposes. It should be noted that the plot is restricted to the materials in Table 22.1. In general, there is no trend between hardness and elastic modulus, but Table 22.1 has a small selection of materials suitable for cutting tools.



22.46 Obtain data on the thermal properties of various cutting fluids. Identify those that are basically effective coolants (such a water-based fluids) and those that are basically good lubricants (such as oils).

By the student. Most cutting fluids are emulsions (water-based fluids), but they may be provided as a base oil, and the supplier will report data for the base oil only. The actual emulsion produced from this base oil will have higher specific heat and superior thermal properties. Properties such as thermal conductivity and specific heat can be linearly interpolated from the water concentration according to rules of mixtures. This is a challenging problem because thermal properties are usually not readily available. The most common practice for applying the lubricant is flooding (see p. 667), so that most heat is removed by convection. Predicting convection coefficients using well-characterized fluids is extremely difficult.

22.47 The first column in Table 22.2 shows seven properties that are important to cutting tools. For each of the tool materials listed in the table, add numerical data for each of these properties. Describe your observations, including any data that overlaps.

There are many acceptable answers since all of the tool materials in the table have a wide range of values. Also, some of the measures are qualitative, such as chipping resistance and thermal-shock resistance. Cutting speeds depend on the workpiece material and its condition, as well as the quality of surface desired. However, examples of acceptable answers are:

Property	**Material**			
	HSS	**Cast-cobalt alloys**	**Cubic boron nitride**	**Diamond**
Hot hardness	60 HRA	75 HRA	4000 HK	7000 HK
Impact strength, J	4	1	< 0.5	< 0.2
Cutting speed, m/min	90	300	400	760
Thermal conductivity, W/m-K (shock resistance)	40	-	13	500

SYNTHESIS, DESIGN, AND PROJECTS

22.48 Describe in detail your thoughts regarding the technical and economic factors involved in tool material selection.

By the student. The technical and economic factors are constantly in competition. Among the technical factors are (see pp. 647-648):

- A tool material with sufficiently high hot hardness for strength and wear resistance.
- Chemical stability and inertness for adhesive wear resistance.
- Toughness for fracture prevention.
- High thermal conductivity to minimize severe temperature gradients.

Among the economic factors are:

- Tool cost should be minimized.
- The material should be readily available.

22.49 One of the principal concerns with coolants is degradation due to biological attack by bacteria. To prolong life, chemical biocides are often added, but these biocides greatly complicate the disposal of coolants. Conduct a literature search regarding the latest developments in the use of environmentally benign biocides in cutting fluids.

By the student. There are a few approaches, such as: (a) Increase the pH to an extent to where no microorganisms can survive. (b) Develop chemical agents which directly kill microorganisms (biocides). (c) Use a chemical which the microorganism ingests and which, in turn, poisons the microbe.

22.50 Contact several different suppliers of cutting tools or search their web sites. Make a list of the costs of typical cutting tools of various sizes, shapes, and features.

By the student. Very useful websites are those for major suppliers such as Kennametal, Iscar, Sandvik, Carboloy, and Valenite; general product catalogues are also helpful. In comparing costs from older and newer cost data, it will be noted that, as in many other products, costs vary (up or down) by time. (See also Section 40.9 on p. 1261.)

22.51 As you can see, there are several types of cutting-tool materials available today for machining operations. Yet, there is much research and development that is being carried out on these materials. Make a list of the reasons why you think such studies are being conducted. Comment on each with a specific application or example.

By the student. This is a challenging and rich topic for literature studies. For example, students could examine this question based on requirements for cutting-tool materials for machining of new materials such as nanophase materials and composites. The students can also consider this question as an issue of the continued trend in increasing cutting speeds and tool life.

22.52 Assume that you are in charge of a laboratory for developing new or improved cutting fluids. On the basis of the topics presented in this and in Chapter 21, suggest a list of topics for your staff to investigate. Explain why you have chosen those topics.

By the student. For example, one approach would be to direct the students to current conference programs, so that they can examine the technical papers currently being presented. Appropriate sources would be the Society of Tribologists and Lubrication Engineers (www.stle.org) and the American Society of Mechanical Engineers (www.asme.org). Among the major research topics of current interest are:

- The use of environmentally benign cutting fluids, such as vegetable oil-based fluids.
- The use of ionic fluids.
- Elimination of cutting fluids (dry or near-dry machining; see p. 669).
- Formulation of additives, such as detergents, lubricity additives, and alkalinity modifiers.

22.53 Survey the technical literature and describe the trends in new cutting-tool materials and coatings. Which of these are becoming available to industry?

By the student. As discussed throughout this chapter, there is much ongoing research on cutting-tool materials. Currently, major research interests are focused on nanophase materials (see Section 6.16 on p. 186) and coatings, as well as the development of improved tool coatings.