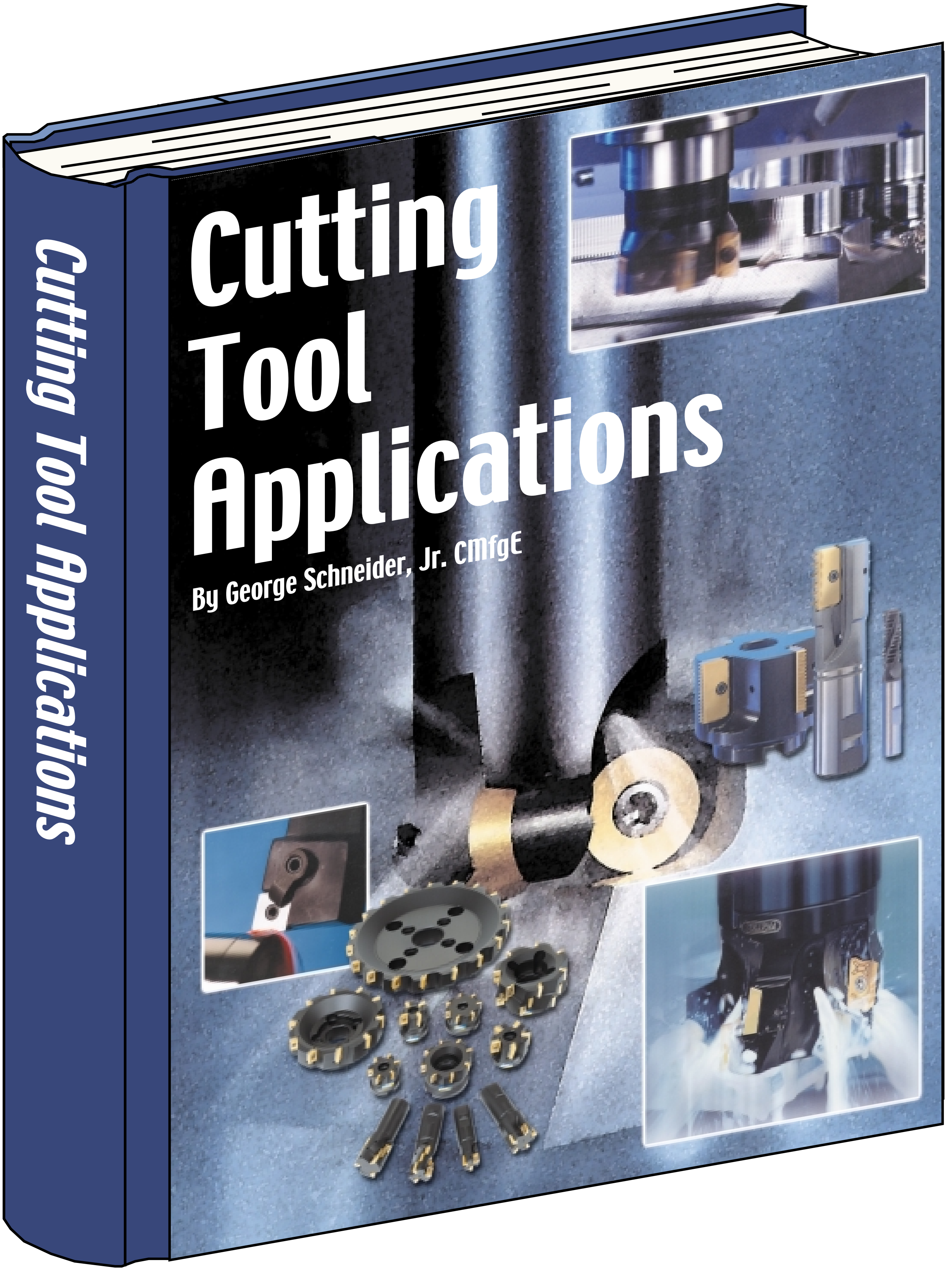
Cutting Tool Applications
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Chapter 3 Machinability of Metals

3.1 Introduction

The condition and physical properties of the work material have a direct influence on the machinability of a work material. The various conditions and characteristics described as 'condition of work material', individually and in combinations, directly influence and determine the machinability. Operating conditions, tool material and geometry, and workpiece requirements exercise indirect effects on machinability and can often be used to overcome difficult conditions presented by the work material. On the other hand, they can create situations that increase machining difficulty if they are ignored. A thorough understanding of all of the factors affecting machinability and machining will help in selecting material and workpiece designs to achieve the optimum machining combinations critical to maximum productivity.

3.2 Condition of Work Material

The following eight factors determine the condition of the work material: microstructure, grain size, heat treatment, chemical composition, fabrication, hardness, yield strength, and tensile strength.

Microstructure: The microstructure of a metal refers to its crystal or grain structure as shown through examination of etched and polished surfaces under a microscope. Metals whose microstructures are similar have like machining properties. But there can be variations in the microstructure of the same workpiece, that will affect machinability.

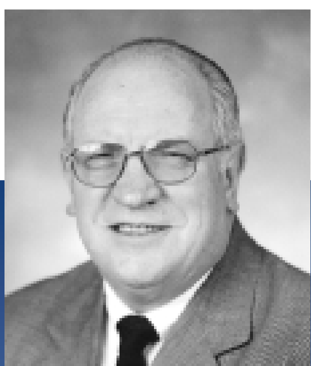
Grain Size: Grain size and structure of a metal serve as general indicators of its machinability. A metal with small undistorted grains tends to cut easily and finish easily. Such a metal is ductile, but it is also 'gummy'. Metals of an intermediate grain size represent a compromise that permits both cutting and finishing machinability. Hardness of a metal must be correlated with grain size and it is generally used as an indicator of machinability.

Heat Treatment: To provide desired properties in metals, they are sometimes put through a series of heating and cooling operations when in the solid state. A material may be treated to reduce brittleness, remove stress, to obtain ductility or toughness, to increase strength, to obtain a definite microstructure, to change hardness, or to make other changes that affect machinability.

Chemical Composition: Chemical composition of a metal is a major factor in determining its machinability. The effects of composition though, are not always clear, because the elements that make up an alloy metal, work both singly and collectively. Certain generalizations about chemical composition of steels in relation to machinability can be made, but non-ferrous alloys are too numerous and varied to permit such generalizations.

Fabrication: Whether a metal has been hot rolled, cold rolled, cold drawn, cast, or forged will affect its grain size, ductility, strength, hardness, structure - and therefore - its machinability.

The term 'wrought' refers to the hammering or forming of materials into premanfac-



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tured shapes which are readily altered into components or products using traditional manufacturing techniques. Wrought metals are defined as that group of materials which are mechanically shaped into bars, billets, rolls, sheets, plates or tubing.

Casting involves pouring molten metal into a mold to arrive at a near component shape which requires minimal, or in some cases no machining. Molds for these operations are made from sand, plaster, metals and a variety of other materials.

Hardness: The textbook definition of hardness is the tendency for a material to resist deformation. Hardness is often measured using either the Brinell or Rockwell scale. The method used to measure hardness involves embedding a specific size and shaped indentor into the surface of the test material, using a predetermined load or weight. The distance the indentor penetrates the material surface will correspond to a specific Brinell or Rockwell hardness reading. The greater the indentor surface penetration, the lower the ultimate Brinell or Rockwell number, and thus the lower the corresponding hardness level. Therefore, high Brinell or Rockwell numbers or readings represent a minimal amount of indentor penetration into the workpiece and thus, by definition, are an indication of an extremely hard part. Figure 3.1 shows how hardness is measured.

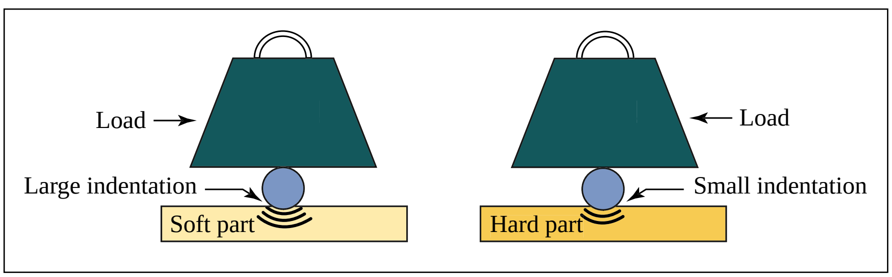


Figure 3.1 Hardness is measured by depth of indentations made.

The Brinell hardness test involves embedding a steel ball of a specific diameter, using a kilogram load, in the surface of a test piece. The Brinell Hardness Number (BHN) is determined by dividing the kilogram load by the area (in square millimeters) of the circle created at the rim of the dimple or impression left in the workpiece surface. This standardized approach provides a consistent method to make comparative tests between a variety of workpiece materials or a single material which has undergone various hardening processes.

The Rockwell test can be performed with various indentor sizes and loads. Several different scales exist for the Rockwell method or hardness testing. The three most popular are outlined below in terms of the actual application the test is designed to address:

Rockwell Scale	Testing Application
A	For tungsten carbide and other extremely hard materials & thin, hard sheets.
B	For medium hardness low and medium carbon steels in the annealed condition.
C	For materials > than Rockwell 'B' 100.

In terms of general machining practice, low material hardness enhances productivity, since cutting speed is often selected based on material hardness (the lower the hardness, the higher the speed). Tool life is adversely affected by an increase in workpiece hardness, since the cutting loads and temperatures rise for a specific cutting speed with part hardness, thereby reducing tool life. In drilling and turning, the added cutting temperature is detrimental to tool life, since it produces excess heat causing accelerated edge wear. In milling, increased material hardness produces higher impact loads as inserts enter the cut, which often leads to a premature breakdown of the cutting edge.

Yield Strength: Tensile test work is used as a means of comparison of metal material conditions. These tests can establish the yield strength, tensile strength and many other conditions of a material based on its heat treatment. In addition, these tests are used to compare different workpiece materials. The tensile test involves taking a cylindrical rod or shaft and pulling it from opposite ends with a progressively larger force in a hydraulic machine. Prior to the start of the test, two marks either two or eight inches apart are made on the rod or shaft. As the rod is systematically subjected to increased loads, the marks begin to move farther apart. A material is in the so-called 'elastic zone' when the load can be removed from the rod and the marks return to their initial distance apart of either two or eight inches. If the test is allowed to progress, a point is reached where, when the load is removed the marks will not return to their initial distance apart. At this point, permanent set or deformation of the test specimen has taken place. Figure 3.2 shows how yield strength is measured.

Yield strength is measured just prior to the point before permanent deformation takes place. Yield strength is stated in pounds per square inch (PSI) and is determined by dividing the load just prior to permanent deformation by the cross sectional area of the test specimen. This material property has been referred to as a condition, since it can be altered during heat treatment. Increased part hardness produces an increase in yield strength and therefore, as a part becomes harder, it takes a larger force to produce permanent deformation of the part. Yield strength should not be confused with fracture strength, cracking or the actual breaking of the material into pieces, since these properties are quite different and unrelated to the current subject.

By definition, a material with high yield strength (force required per unit of area to create permanent deformation) requires a high level of force to initiate chip formation in a machining operation. This implies that as a material's yield strength increases, stronger insert shapes as well as less positive cutting geometries are necessary to combat the additional load encountered in the cutting zone. Material hardness and yield strength increase simultaneously during heat treatment. Therefore, materials with relatively high yield strengths will be more difficult to machine and will reduce tool life when compared to mate-

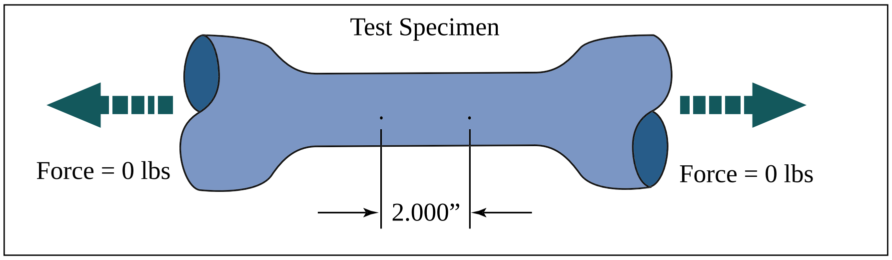


Figure 3.2 Yield strength is measured by pulling a test specimen as shown.

rials with more moderate strengths.

Tensile Strength: The tensile strength of a material increases along with yield strength as it is heat treated to greater hardness levels. This material condition is also established using a tensile test. Tensile strength (or ultimate strength) is defined as the maximum load that results during the tensile test, divided by the cross-sectional area of the test specimen. Therefore, tensile strength, like yield strength, is expressed in PSI. This value is referred to as a material condition rather than a property, since its level just like yield strength and hardness, can be altered by heat treatment. Therefore, based on the material selected, distinct tensile and yield strength levels exist for each hardness reading.

Just as increased yield strength implied higher cutting forces during machining operations, the same could be said for increased tensile strength. Again, as the workpiece tensile strength is elevated, stronger cutting edge geometries are required for productive machining and acceptable tool life.

3.3 Physical Properties of Work Materials

Physical properties will include those characteristics included in the individual material groups, such as the modulus of elasticity, thermal conductivity, thermal expansion and work hardening.

Modulus of Elasticity: The modulus of elasticity can be determined during a tensile test in the same manner as the previously mentioned conditions. However, unlike hardness, yield or tensile strength, the modulus of elasticity is a fixed material property and , therefore, is unaffected by heat treatment. This particular property is an indicator of the rate at which a material will deflect when subjected to an external force. This property is stated in PSI and typical values are several million PSI for metals. A 2” x 4” x 8 ft. wood beam supported on either end, with a 200 pound weight hanging in the middle, will sag 17 times more than a beam of the same dimensions made out of steel and subjected to the same load. The difference is not because steel is harder or stronger, but because steel has a modulus of elasticity which is 17 times greater than wood.

General manufacturing practice dictates that productive machining of a workpiece material with a relatively moderate modulus of elasticity normally requires positive or highly positive raked cutting geometries. Positive cutting geometries produce lower cutting forces and, therefore chip formation is enhanced on elastic material using these types of tools. Sharp positive cutting edges tend to bite and promote shearing of a material, while blunt negative geometries have a tendency to create large cutting forces which impede chip formation by severely pushing or deflecting the part as the tool enters the cut.

Thermal Conductivity: Materials are frequently labeled as being either heat conductors or insulators. Conductors tend to transfer heat from a hot or cold object at a high rate, while insulators impede the flow of heat. Thermal conductivity is a measure of how efficiently a material transfers heat. Therefore, a material which has a relatively high thermal conductivity would be considered a conductor, while one with a relatively low level would be regarded as an insulator.

Metals which exhibit low thermal conductivities will not dissipate heat freely and therefore, during the machining of these materials, the cutting tool and workpiece become extremely hot. This excess heat accelerates wear at the cutting edge and reduces tool life. The proper application of sufficient amounts of coolant directly in the cutting zone (between the cutting edge and workpiece) is essential to improving tool life in metals with low thermal conductivities.

Thermal Expansion: Many materials, especially metals, tend to increase in dimensional size as their temperature rises. This physical property is referred to as thermal expansion. The rate at which metals expand varies, depending on the type or alloy of material under consideration. The rate at which metal expands can be determined using the material’s expansion coefficient. The greater the value of this coefficient, the more a material will expand when subjected to a temperature rise or contract when subjected to a temperature reduction. For example, a 100 inch bar of steel which encounters a 100 degree Fahrenheit rise in temperature would measure 100.065 inches. A bar of aluminum exposed to the same set of test conditions would measure 100.125 inches. In this case, the change in the aluminum bar length was nearly twice that of the steel bar. This is a clear indication of the significant difference in thermal expansion coefficients between these materials.

In terms of general machining practice, those materials with large thermal expansion coefficients will make holding close finish tolerances extremely difficult, since a small rise in workpiece temperature will result in dimensional change. The machining of these types of materials requires adequate coolant supplies for thermal and dimensional stability. In addition, the use of positive cutting geometries on these materials will also reduce machining temperatures.

Work Hardening: Many metals exhibit a physical characteristic which produces dramatic increases in hardness due to cold work. Cold work involves changing the shape of a metal object by bending, shaping, rolling or forming. As the metal is shaped, internal stresses develop which act to harden the part. The rate and magnitude of this internal hardening varies widely from one material to another. Heat also plays an important role in the work hardening of a material. When materials which exhibit work hardening tendencies are subjected to increased temperature, it acts like a catalyst to produce higher hardness levels in the workpiece.

The machining of workpiece materi-

als with work hardening properties should be undertaken with a generous amount of coolant. In addition, cutting speeds should correlate specifically to the material machined and should not be recklessly altered to meet a production rate. The excess heat created by unusually high cutting speeds could be extremely detrimental to the machining process by promoting work hardening of the workpiece. Low chip thicknesses should be avoided on these materials, since this type of inefficient machining practice creates heat due to friction, which produces the same type of effect mentioned earlier. Positive low force cutting geometries at moderate speeds and feeds are normally very effective on these materials.

3.4 Metal Machining

The term 'machinability' is a relative measure of how easily a material can be machined when compared to 160 Brinell AISI B1112 free machining low carbon steel. The American Iron and Steel Institute (AISI) ran turning tests of this material at 180 surface feet and compared their results for B1112 against several other materials. If B1112 represents a 100% rating, then materials with a rating less than this level would be decidedly more difficult to machine, while those that exceed 100% would be easier to machine.

The machinability rating of a metal takes the normal cutting speed, surface finish and tool life attained into consideration. These factors are weighted and combined to arrive at a final machinability rating. The following chart shows a variety of materials and their specific machinability ratings:

Material	Hardness	Machinability Rating
6061-T Aluminum	—	190%
7075-T Aluminum	—	120%
B1112 Steel	160 BHN	100%
416 Stainless Steel	200 BHN	90%
1120 Steel	160 BHN	80%
1020 Steel	148 BHN	

3.4.1 Cast Iron

All metals which contain iron (Fe) are known as ferrous materials. The word 'ferrous' is by definition, 'relating to or containing iron'. Ferrous materials include cast iron, pig iron, wrought iron, and low carbon and alloy steels. The extensive use of cast iron and steel workpiece materials, can be attributed to the fact that iron is one of the most frequently occurring elements in nature.

When iron ore and carbon are metallurgically mixed, a wide variety of workpiece materials result with a fairly unique set of physical properties. Carbon contents are altered in cast irons and steels to provide changes in hardness, yield and tensile strengths. The physical properties of cast irons and steels can be modified by changing the amount of the iron-carbon mixtures in these materials as well as their manufacturing process.

Pig iron is created after iron ore is mixed with carbon in a series of furnaces. This material can be changed further into cast iron, steel or wrought iron depending on the selected manufacturing process.

Cast iron is an iron carbon mixture which is generally used to pour sand castings, as opposed to making billets or bar stock. It has excellent flow properties and therefore, when it is heated to extreme temperatures, is an ideal material for complex cast shapes and intricate molds. This material is often used for automotive engine blocks, cylinder heads, valve bodies, manifolds, heavy equipment oil pans and machine bases.

Gray Cast Iron: Gray cast iron is an extremely versatile, very machinable relatively low strength cast iron used for pipe, automotive engine blocks, farm implements and fittings. This material receives its dark gray color from the excess carbon in the form of graphite flakes which give it its name.

Gray cast iron workpieces have relatively low hardness and strength levels. However, double negative or negative (axial) positive (radial) rake angle geometries are used to machine these materials because of their tendency to produce short discontinuous chips. When this type of chip is produced during the machining of these workpieces, the entire cutting force is concentrated on a very narrow area of the cutting edge and therefore, double positive rake tools normally chip prematurely on these types of materials due to their lower edge strength.

White Cast Iron: White cast iron occurs when all of the carbon in the casting is combined with iron to form cementite. This is an extremely hard substance which results from the rapid cooling of the casting after it is poured. Since the carbon in this material is transformed into cementite, the resulting color of the material when chipped or fractured is a silvery white. Thus the name white cast iron. However, white cast iron has almost no ductility, and therefore when it is subjected to any type of bending or twisting loads, it fractures. The hard brittle white cast iron surface is desirable in those instances where a material with extreme abrasion resistance is required. Applications of this material would include plate rolls in a mill or rock crushers.

Due to the extreme hardness of white cast iron, it is very difficult to machine. Double negative insert geometries are almost exclusively required for these materials, since their normal hardness is 450 - 600 Brinell. As stated earlier with gray iron, this class of cast material subjects the cutting edge to extremely concentrated loads, thus requiring added edge strength.

Malleable Cast Iron: When white cast iron castings are annealed (softened by heating to a controlled temperature for a specific length of time), malleable iron castings are formed. Malleable iron castings result when hard, brittle cementite in white iron castings is transformed into tempered carbon or graphite in the form of rounded nodules or aggregate. The resulting material is a strong, ductile, tough and very machinable product which is used on a broad scope of applications.

Malleable cast irons are relatively easy to machine when compared to white iron castings. However, double negative or negative (axial) positive(radial) rake angle geometries are also used to machine these materials as with gray iron, because of their tendency to produce short discontinuous chips.

Nodular Cast Iron: Nodular or 'ductile' iron is used to manufacture a wide range of automotive engine components including cam shafts, crank shafts, bearing caps and cylinder heads. This materials is also frequently used for heavy equipment cast parts as well as heavy machinery face plates and guides. Nodular iron is strong, ductile, tough and extremely shock resistant.

Although nodular iron castings are very machinable when compared with gray iron castings of the same hardness, high strength nodular iron castings can have relatively low machinability ratings. The cutting geometry selected for nodular iron castings is also dependent on the grade to be machined. However, double negative or positive (radial) and negative (axial) rake angles are normally used.

3.4.2 Steel

Steel materials are comprised mainly of iron and carbon, often with a modest mixture of alloying elements. The biggest difference between cast iron materials and steel is the carbon content. Cast iron materials are compositions of iron and carbon, with a minimum of 1.7 percent carbon to 4.5 percent carbon. Steel has a typical carbon content of .05 percent to 1.5 percent.

The commercial production of a significant number of steel grades is further evidence of the demand for this versatile material. Very soft steels are used in drawing applications for automobile fenders, hoods and oil pans, while premium grade high strength steels are used for cutting tools. Steels are often selected for their electrical properties or resistance to corrosion. In other applications, non magnetic steels are selected for wrist watches and minesweepers.

Plain Carbon Steel: This category of steels includes those materials which are a combination of iron and carbon with no alloying elements. As the carbon content in these materials is increased, the ductility (ability to stretch or elongate without breaking) of the material is reduced. Plain carbon steels are numbered in a four digit code according to the AISI or SAE system (i.e. 10XX). The last two digits of the code indicate the carbon content of the material in hundredths of a percentage point. For example, a 1018 steel has a .18% carbon content.

The machinability of plain carbon steels is primarily dependent on the carbon content of the material and its heat treatment. Those materials in the low carbon category are extremely ductile, which creates problems in chip breaking on turning and drilling operations. As the carbon content of the material rises above .30%, reliable chip control is often attainable. These materials should be milled with a positive (radial) and negative (axial) rake angle geometry. In turning and drilling operations on these materials, negative or neutral geometries should be used whenever possible. The plain carbon steels as a group are relatively easy to machine; they only present machining problems when their carbon content is very low (chip breaking or built up edge), or when they have been heat treated to an extreme (wear, insert breakage or depth of cut notching).

Alloy Steels: Plain carbon steels are made up primarily of iron and carbon, while alloy steels include these same elements with many other elemental additions. The purpose of alloying steel is either to enhance the material's physical properties or its ultimate manufacturability. The physical property enhancements include improved toughness, tensile strength, hardenability, (the relative ease with which a higher hardness level can be attained), ductility and wear resistance. The use of alloying elements can alter the final grain size of a heat treated steel, which often results in a lower machinability rating of the final product. The primary types of alloyed steel are: nickel, chromium, manganese, vanadium, molybdenum, chrome-nickel, chrome-vanadium, chrome-molybdenum, and nickel-molybdenum. The following summaries detail some of the differences in these alloys in terms of their physical as well as mechanical properties for alloyed carbon steels:

- **Nickel -** This element is used to increase the hardness and ultimate strength of the steel without sacrificing ductility.
- **Chromium -** Chromium will extend the hardness and strength gains which can be realized with nickel. However, these gains are offset by a reduction in ductility.
- **Manganese -** This category of alloyed steels possesses a greater strength level than nickel alloyed steels and improved toughness when compared to chromium alloyed steels.
- **Vanadium -** Vanadium alloyed steels are stronger, harder and tougher than their manganese counterparts. This group of materials however, loses a significant amount of its ductility when compared to the manganese group to benefit from these other physical properties.
- **Molybdenum -** This group of alloyed steels benefit from increased strength and hardness without adversely affecting ductility. These steels are often considered very tough, with an impact strength which approaches the vanadium steels.
- **Chrome-Nickel -** The alloying elements present in the chrome nickel steels produce a very ductile, tough, fine grain, wear resistant material. However, they are relatively unstable when heat treated and tend to distort, especially as their chromium and nickel content is increased.
- **Chrome-Vanadium -** This combination of alloying elements produces hardness, impact strength and toughness properties which exceed those of the chrome-nickel steels. This alloyed steel has a very fine grain structure and, therefore, improved wear resistance.
- **Chrome-Molybdenum -** This alloyed steel has slightly different properties than a straight molybdenum alloy due to the chromium content of the alloy. The final hardness and wear resistance of this alloy exceeds that of a normal molybdenum alloy steel.
- **Nickel-Molybdenum -** The properties of this material are similar to chrome-molydenum alloyed steels except for one, its increased toughness.

The machinability of alloy steels varies widely, depending on their hardness and chemical compositions. The correct geometry selection for these materials is often totally dependent on the hardness of the part. Double positive milling or turning geometries should be selected for these materials only when either the workpiece, machine or fixturing lacks the necessary rigidity to use stronger higher force generating geometries. In milling, positive (radial) negative (axial) geometries are preferred on alloyed steels due to their strength and toughness. In turning operations, double negative or neutral geometries should be used on softer alloy steels. Lead angled tools should be used on these *materials whenever possible to minimize the shock associated with cutter entry into the cut.*

Tool Steels: This group of high strength steels is often used in the manufacture of cutting tools for metals, wood and other workpiece materials. In addition, these high strength materials are used as die and punch materials due to their extreme hardness and wear resistance after heat treatment. The key to achieving the hardness, strength and wear resistance desired for any tool steel is normally through careful heat treatment. These materials are available in a wide variety of grades with a substantial number of chemical compositions designed to satisfy specific as well as general application criteria.

Tool steels are highly alloyed and therefore, quite tough; However, they can often be readily machined prior to heat treatment. Negative cutting geometries will extend tool life when machining these materials, provided the system (machine, part and fixturing) is able to withstand the additional tool force.

Stainless Steels: As the name implies, this group of materials is designed to resist oxidation and other forms of corrosion, in addition to heat in some instances. These materials tend to have significantly greater corrosion resistance than their plain or alloy steel counterparts due to the substantial additions of chromium as an alloying element. Stainless steels are used extensively in the food processing, chemical and petroleum industries to transfer corrosive liquids between processing and storage facilities. Stainless steels can be cold formed, forged, machined, welded or extruded. This group of materials can attain relatively high strength levels when compared to plain carbon and alloy steels. Stainless steels are available in up to 150 different chemical compositions. The wide selection of these materials is designed to satisfy the broad range of physical properties required by potential customers and industries.

Stainless steels fall into four distinct metallurgical categories. These categories include: austenitic, ferritic, martensitic, and precipitation hardening. Austenitic (300 series) steels are generally difficult to machine. Chatter could be a problem, thus requiring machine tools with high stiffness. However, ferritic stainless steels (also 300 series) have good machinability. Martensitic (400 series) steels are abrasive and tend to form built-up edge, and require tool materials with high hot hardness and crater-wear resistance. Precipitation-hardening stainless steels are strong and abrasive, requiring hard and abrasion-resistant tool materials.

3.4.3 Nonferrous Metals and Alloys

Nonferrous metals and alloys cover a wide range of materials from the more common metals such as aluminum, copper, and magnesium, to high-strength high-temperature alloys such as tungsten, tantalum, and molybdenum. Although more expensive than ferrous metals, nonferrous metals and alloys have important applications because of their numerous properties, such as corrosion resistance, high thermal and electrical conductivity, low density, and ease of fabrication.

Aluminum: The relatively extensive use of aluminum as an industrial as well as consumer based material revolves around its many unique properties. For example, aluminum is a very lightweight metal (1/3 the density when compared to steel), yet it possesses great strength for its weight. Therefore, aluminum has been an excellent material for framing structures in military and commercial aircraft. The corrosive resistance of aluminum has made it a popular material selection for the soft drink industry (cans) and the residential building industry (windows and siding). In addition, most grades of aluminum are easily machined and yield greater tool life and productivity than many other metals.

Aluminum is a soft, machinable metal and the limitations on speeds are governed by the capacity of the machine and good safe practices. Chips are of the continuous type and frequently they are a limiting safety factor because they tend to bunch up. Aluminum has been machined at such high speeds that the chip becomes an oxide powder. To increase its strength and hardness, aluminum is alloyed with silicon, iron, manganese, nickel, chromium, and other metals. These materials should be machined with positive cutting geometries.

Copper: Copper is a very popular material which is widely used for its superior electrical conductivity, corrosion resistance and ease in formability. In addition, when alloyed properly, copper alloys can exhibit a vast array of strength levels and unique mechanical properties.

Several copper alloys are now in widespread commercial use including: copper nickels, brasses. bronzes, copper-nickel-zinc alloys, leaded copper and many special alloys. Brass and bronze are the most popular copper alloys in use.

The machinability of copper and its alloys varies widely. Pure copper and high copper alloys are very tough, abrasive, and prone to tearing. To limit and prevent tearing, these materials should be machined with positive cutting geometries. Positive geometries should also be used on bronze and bronze alloys due to their toughness and ductility. Negative axial and positive radial rake angle geometries should be used on brass alloys, since they have greater levels of machinability and in a cast state their chip formation is similar to cast iron.

Nickel: Nickel is often used as an alloying element to improve corrosion and heat resistance and the strength of many materials. When nickel is alloyed or combined with copper (Monels), chromium (Inconels and Hastelloys) or chromium and cobalt (Waspalloys), it provides a vast array of alloys which exhibit a wide range of physical properties. Other important alloys belonging to this group of materials include: Rene, Astroloy, Udimet, Incoloys, and several Haynes alloys. The machinability of nickel based alloys is generally quite low.

Most nickel based alloys should be machined using positive cutting geometries. Since these materials are machined with carbide at 120 SFPM or less, positive rake angle geometries are required to minimize cutting forces and heat generation. In the machining of most materials, increased temperature enhances chip flow and reduces the physical force on the cutting edge. Adequate clearance angles must be utilized on these materials, since many of them are very ductile and prone to work hardening. When a tool is stopped and left to rub on the workpiece, hardening of the workpiece surface will often occur. To avoid this condition, care should be taken to insure that as long as the cutting edge and part are touching, *the tool is always feeding.*

Titanium and Titanium alloys: Titanium is one of the earth's most abundant metals. Thus, its application is fairly widespread from a cutting tool material to the struts and framing members on jet aircraft. Titanium and its alloys are often selected to be used in aerospace applications due to their high strength to weight ratio and ductility.

The machining of titanium and its alloys involves the careful selection of cutting geometry and speed. Positive rake tools are often preferred on these materials to minimize part deflection and to reduce cutting temperatures in the cutting zone. The generous use of coolants on titanium and its alloys is strongly advised to maintain thermal stability and thus avoid the disastrous effects of accelerated heat and temperature buildup which leads to workpiece galling or tool breakage (drilling) and rapid edge wear. Type machinability rating for titanium and its alloys is approximately 30% or less.

Refractory Alloys: The group of materials designated as refractory alloys includes those metals which contain high concentrations of either tungsten (W), tantalum (Ta), molybdenum (Mo) or columbium (Co). This group of materials is known for its heat resistance properties which allows them to operate in extreme thermal environments without permanent damage. In addition, these materials are known for their extremely high melting points and abrasiveness. Most of these materials are quite brittle, thus, they possess very low machinability ratings when also considering their heat resistance and extreme melting properties. The machining of this group of materials is characterized by extremely low cutting speeds and feed rates when utilizing carbide cutting tools.

Cast molybdenum has a machinability rating of approximately 30 percent while pure tungsten has a rating of only 5 percent. The machinability of tantalum and columbium is at a more moderate level and thus falls between these two figures. Generally speaking, these materials should be machined at moderate to low speeds at light depths of cut using positive rake tools.

3.5 Judging Machinability

The factors affecting machinability have been explained; four methods used to judge machinability are discussed below:

Tool Life: Metals which can be cut without rapid tool wear are generally thought of as being quite machinable, and vice versa. A workpiece material with many small hard inclusions may appear to have the same mechanical properties as a less abrasive metal. It may require no greater power consumption during cutting. Yet, the machinability of this material would be lower because its abrasive properties are responsible for rapid wear on the tool, resulting in higher machining costs.

One problem arising from the use of tool life as a machinability index is its sensitivity to the other machining variables. Of particular importance is the effect of tool material. Machinability ratings based on tool life cannot be compared if a high speed steel tool is used in one case and a sintered carbide tool in another. The superior life of the carbide tool would cause the machinability of the metal cut with the steel tool to appear unfavorable. Even if identical types of tool materials are used in evaluating the workpiece materials, meaningless ratings may still result. For example, cast iron cutting grades of carbide will not hold up when cutting steel because of excessive cratering, and steel cutting grades of carbide are not hard enough to give sufficient abrasion resistance when cutting cast iron.

Tool life may be defined as the period of time that the cutting tool performs efficiently. Many variables such as material to be machined, cutting tool material, cutting tool geometry, machine condition, cutting tool clamping, cutting speed, feed, and depth of cut, make cutting tool life determination very difficult.

The first comprehensive tool life data were reported by F.W. Taylor in 1907, and his work has been the basis for later studies. Taylor showed that the relationship between cutting speed and tool life can be expressed empirically by:

$$VT^n = C$$

where: V = cutting speed, in feet per minute
T = tool life, in minutes
C = a constant depending on work material, tool material, and other machine variables. Numerically it is the cutting speed which would give 1 minute of tool life.
n = a constant depending on work and tool material.

This equation predicts that when plotted on log-log scales, there is a linear relationship between tool life and cutting speed. The exponent n has values ranging from 0.125 for high speed steel (HSS) tools, to 0.70 for ceramic tools.

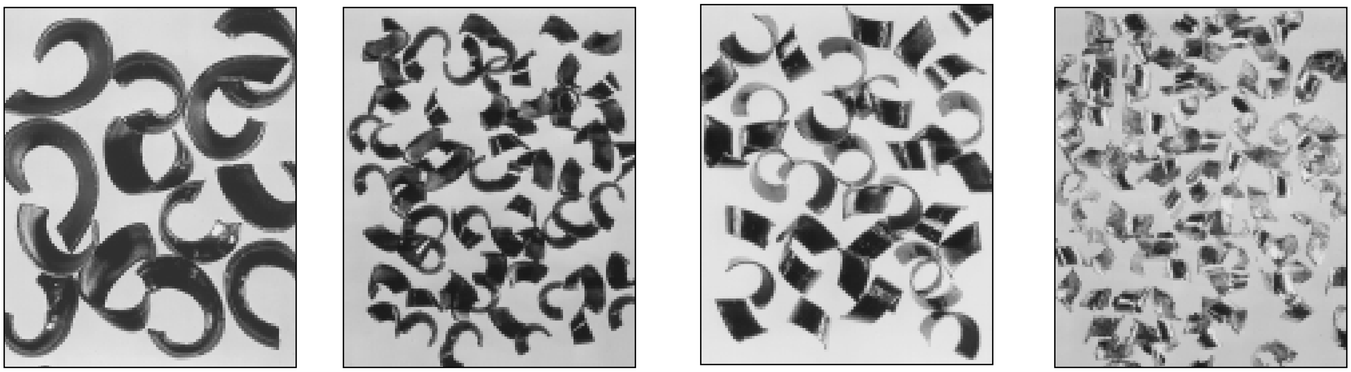
Tool Forces and Power Consumption: The use of tool forces or power consumption as a criterion of machinability of the workpiece material comes about for two reasons. First, the concept of machinability as the ease with which a metal is cut, implies that a metal through which a tool is easily pushed should have a good machinability rating. Second, the more practical concept of machinability in terms of minimum cost per part machined, relates to forces and power consumption, and the overhead cost of a machine of proper capacity.

When using tool forces as a machinability rating, either the cutting force or the thrust force (feeding force) may be used. The cutting force is the more popular of the two since it is the force that pushes the tool through the workpiece and determines the power consumed. Although machinability ratings could be listed according to the cutting forces under a set of standard machining conditions, the data are usually presented in terms of specific energy. Workpiece materials having a high specific energy of metal removal are said to be less machinable than those with a lower specific energy.

The use of net power consumption during machining as an index of the machinability of the workpiece is similar to the use of cutting force. Again, the data are most useful in terms of specific energy. One advantage of using specific energy of metal removal as an indication of machinability, is that it is mainly a property of the workpiece material itself and is quite insensitive to tool material. By contrast, tool life is strongly dependent on tool material.

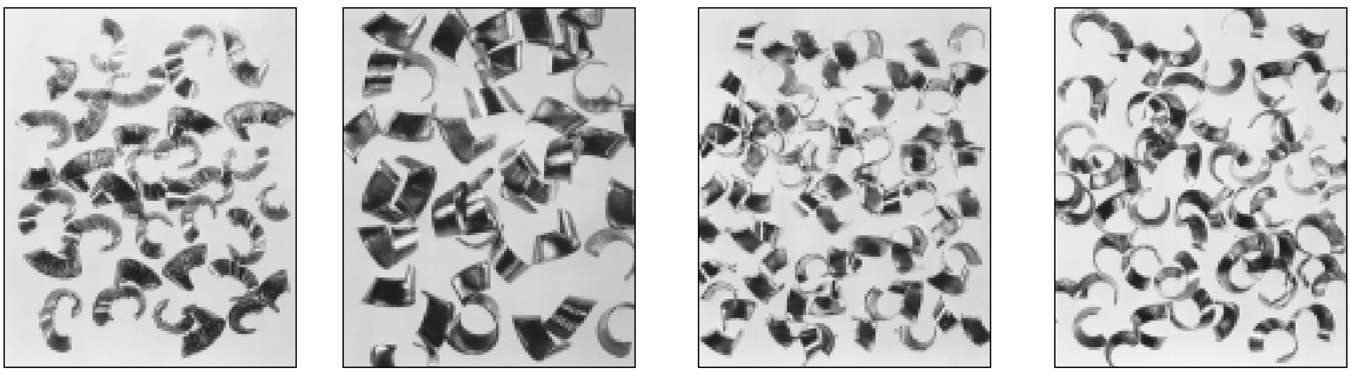
The metal removal factor is the reciprocal of the specific energy and can be used directly as a machinability rating if forces or power consumption are used to define machinability. That is, metals

Steel



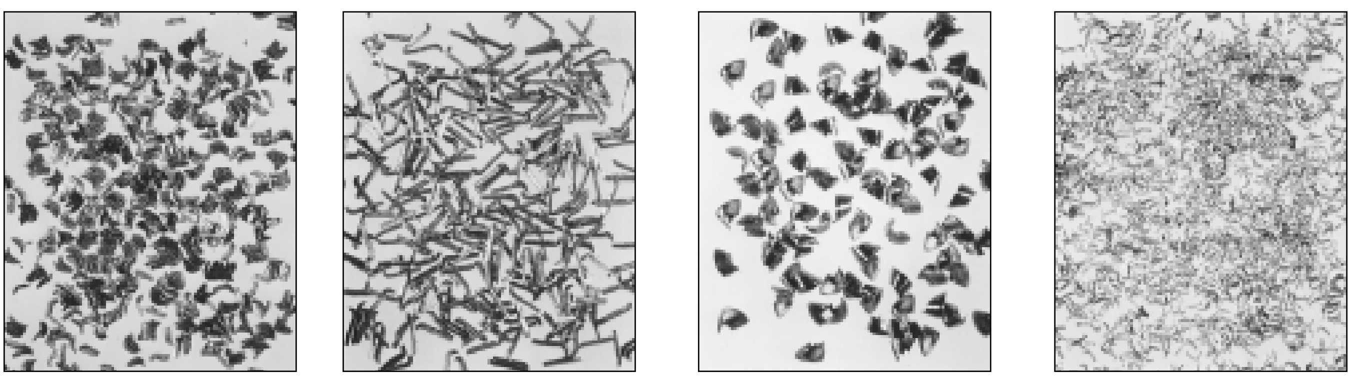
1018 Steel | *1045 Steel* | *4340 Steel* | *Tool Steel*

Stainless Steel



316 Stainless | *17-4 PH Stainles* | *Inconel 718* | *Ti-6AI-4V*

Cast Iron



Gray Iron | *80-55-06 Nodular Iron* | *A356 Aluminium* | *Brass*

Figure 3.3 Ideal chips developed from a variety of common materials. (Courtesy Valenite Inc.)

with a high metal removal factor could be said to have high machinability.

Cutting tool forces were discussed in Chapter 2. Tool force and power consumption formulas and calculations are beyond the scope of this article; they are discussed in books which are more theoretical in their approach to discussing machinability of metals.

Surface Finish: The quality of the surface finish left on the workpiece during a cutting operation is sometimes useful in determining the machinability rating of a metal. Some workpieces will not ‘take a good finish’ as well as others. The fundamental reason for surface roughness is the formation and sloughing off of parts of the built-up edge on the tool. Soft, ductile materials tend to form a built-up edge rather easily. Stainless steels, gas turbine alloy, and other metals with high strain hardening ability, also tend to machine with built-up edges. Materials which machine with high shear zone angles tend to minimize built-up edge effects. These include the aluminum alloys, cold worked steels, free-machining steels, brass, and titanium alloys. If surface finish alone is the chosen index of machinability, these latter metals would rate higher than those in the first group.

In many cases, surface finish is a meaningless criterion of workpiece machinability. In roughing cuts, for example, no attention to finish is required. In many finishing cuts, the conditions producing the desired dimension on the part will inherently provide a good finish within the engineering specification.

Machinability figures based on surface finish measurements do not always agree with figures obtained by force or tool life determinations. Stainless steels would have a low rating by any of these standards, while aluminum alloys would be rated high. Titanium alloys would have a high rating by finish measurements, low by tool life tests, and intermediate by force readings.

The machinability rating of various materials by surface finish are easily determined. Surface finish readings are taken with an appropriate instrument after standard workpieces of various materials are machined under controlled cutting conditions. The machinability rating varies inversely with the instrument reading. A low reading means good finish, and thus high machinability. Relative ratings may be obtained by comparing the observed value of surface finish with that of a material chosen as the reference.

Chip Form: There have been machinability ratings based on the type of chip that is formed during the machining operation. The machinability might be judged by the ease of handling and disposing of chips. A material that produces long stringy chips would receive a low rating, as would one which produces fine powdery chips. Materials which inherently form nicely broken chips, a half or full turn of the normal chip helix, would receive top rating. Chip handling and disposal can be quite expensive. Stringy chips are a menace to the operator and to the finish on the freshly machined surface. However, chip formation is a function of the machine variables as well as the workpiece material, and the ratings obtained by this method could be changed by provision of a suitable chip breaker.

Ratings based on the ease of chip disposal are basically qualitative, and would be judged by an individual who might assign letter gradings of some kind. Wide use is not made of this method of interpreting machinability. It finds some application in drilling, where good chip formation action is necessary to keep the chips running up the flutes. However, the whipping action of long coils once they are clear of the hole is undesirable. Chip formation and tool wear were discussed in Chapter 2; Figure 3.3 shows ideal chips developed from a variety of common materials.