Chapter 2

Tool Life and Tool Wear

The cutting tool is one of the most important economic considerations in metal cutting. In roughing operations, the various tool angles, cutting speeds, and feed rates are usually chosen to give an economical tool life. Conditions giving a very short tool life will be uneconomical because tool grinding and tool replacement costs will be high. On the other hand, the use of very low speeds and feeds to give long tool life will be uneconomical because of the low production rate. Clearly any tool or work material improvements that increase tool life will be beneficial. In order to form a basis for such improvements, much effort has been made to understand the nature of tool wear and other forms of tool failure.

The life of a cutting tool can be brought to an end in various ways, but these ways may be separated into two main groups:

1. The gradual or progressive wearing away of certain regions of the face and flank of the cutting tool; and,
2. Failures bringing the tool life to premature end.

2.1 Progressive tool wear

The fundamental nature of the mechanism of wear can be very different under different conditions. In metal cutting, three main forms of wear are known to occur: adhesion, abrasion, and diffusion wear.

In adhesion wear (7), the wear is caused by the fracture of welded asperity junctions between the two metals. In metal cutting, junctions between the chip and tool materials are formed as part of the friction mechanism. When these junctions are fractured, small fragments of tool material can be torn out and carried away on the underside of the chip or on the new work surface.

The form of wear known as abrasion wear occurs when hard particles on the underside of the chip over the tool face and remove tool material by mechanical action. These hard particles may be highly strain hardened fragments of an unstable build-up edge, fragments of the hard tool material removed by adhesion wear, or hard constituents in the work material.

Solid state diffusion occurs when atoms in a metallic crystal lattice move from a region of high atomic concentration to one of low concentration. This process is dependent on the existing temperature, and the rate of diffusion increases exponentially with increases in temperature. In metal cutting, where intimate contact between the work and tool material occurs and high temperatures exist, diffusion can occur where atoms move from the tool material to the work material. This process, which takes place within a very narrow reaction zone at the interface between two materials and causes a weakening of the surface structure of the tool, is known as diffusion wear.

2.2 Forms of wear in metal cutting (8)

The progressive wear of a tool takes place in two distinct ways (Fig. 2.1):

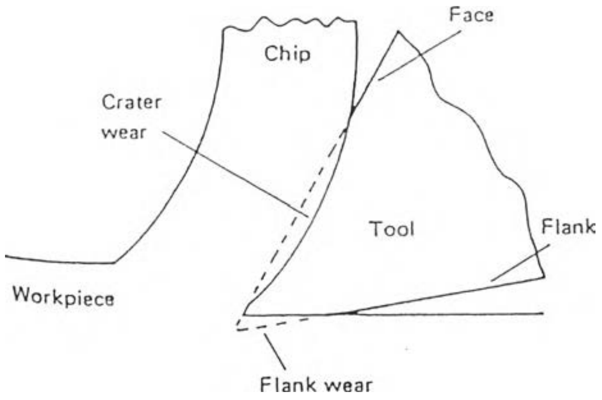

Fig. 2.1 Regions of tool wear in metal cutting (8)

2.2.1 Crater wear

The crate formed on the tool face conforms to the shape of the chip underside and is restricted to the chip tool contact area (Fig. 2.1). In addition, the region adjacent to the cutting edge where sticking friction or a build-up edge occurs is subjected to relatively slight wear.

In metal cutting, the highest temperatures occur some distance along the tool face. At high cutting speeds, these temperatures can easily reach 1000^{0} C. Under these high temperatures, high speed steel tools will wear very rapidly because of thermal softening of the tool material. With carbide tool materials, although they retain their hardness at these high temperatures, solid state diffusion can occur rapid wear.

In experimental work, the maximum depth of crater is usually a measure of the amount of crater wear and can be determined by a surface measuring instrument.

Under very high speed cutting conditions, crater wear is often the factor which determines the life of the cutting tool: the cratering becomes so severe that the tool edge is weakened and eventually fractures. However, when tools are used under economical conditions, the wear of the tool on its flank, known as flank wear, is usually the controlling factor.

2.2.2 Flank wear

Wear on the flank of a cutting tool is caused by friction between the newly machined workpiece surface and the contact area on the tool flank. Because of the rigidity of the workpiece, the worn area, referred to as the flank wear, must be parallel to the resulting cutting direction. The width of flank wear is usually taken as a measure of the amount of wear and can be readily determined by means of a toolmaker's microscope.

Figure 2.2 shows a typical graph of the progress of flank wear (VB) with a time or a distance cut. The curve can be divided into three regions:

1. The region AB where the sharp cutting edge is quickly broken down;

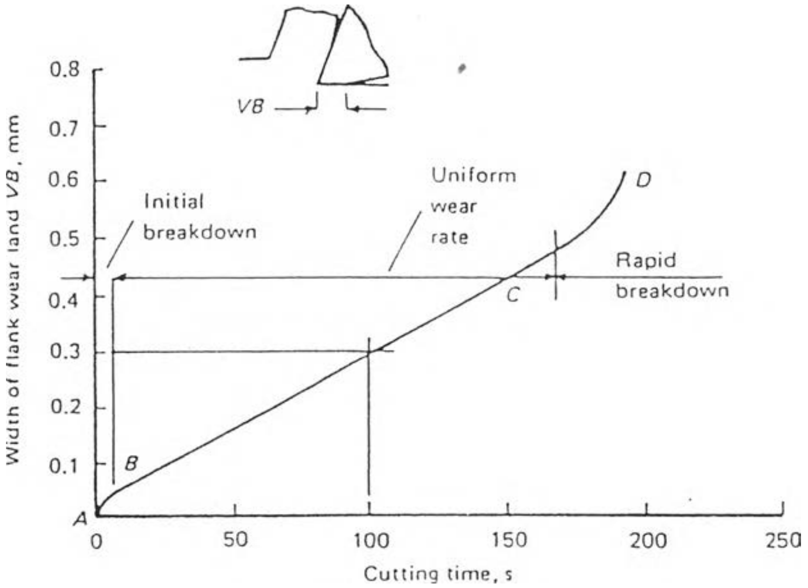

Fig. 2.2 Development of flank wear with time at a cutting speed of 1 m/s (8)

2. The region BC where wear progresses at a uniform rate; and,

3. The region CD where wear occurs at a gradually increasing rate.

Region CD is thought to indicate the region where wear of the cutting tool has become sensitive to the increased tool temperatures caused by the presence of a flank wear of such large proportions. Clearly, in practice, it would be advisable to regrind or change the tool before the flank wear enters the last region (region CD in Fig. 2.2) where rapid breakdown occurs.

2.3 Tool life criteria

A tool life criteria is defined as a predetermined threshold value of a tool wear measure, or the occurrence of a phenomenon. In practical machining operations, the wear of the face and flank of the cutting tool is not uniform along the active cutting edge. Therefore, it is necessary to specify the locations and degree of the wear when deciding on the amount of wear allowable before regrinding or changing the tool. Figure 2.3 shows a typical worn single point tool. As shown in the figure, the amount of cratering varies along the active cutting edge, and the crater depth KT is measured at the deepest point of the crater (section A-A). It can be seen that the crater wear is usually greatest at the extremities of the active cutting edge. Conditions at the tool corner tend to be more severe than those in the central part of the active cutting edge because of the complicated flow of chip material in that region. The width of the flank wear at the tool corner (zone C) is designated VC. At the opposite end of the active cutting edge (zone N) a groove or

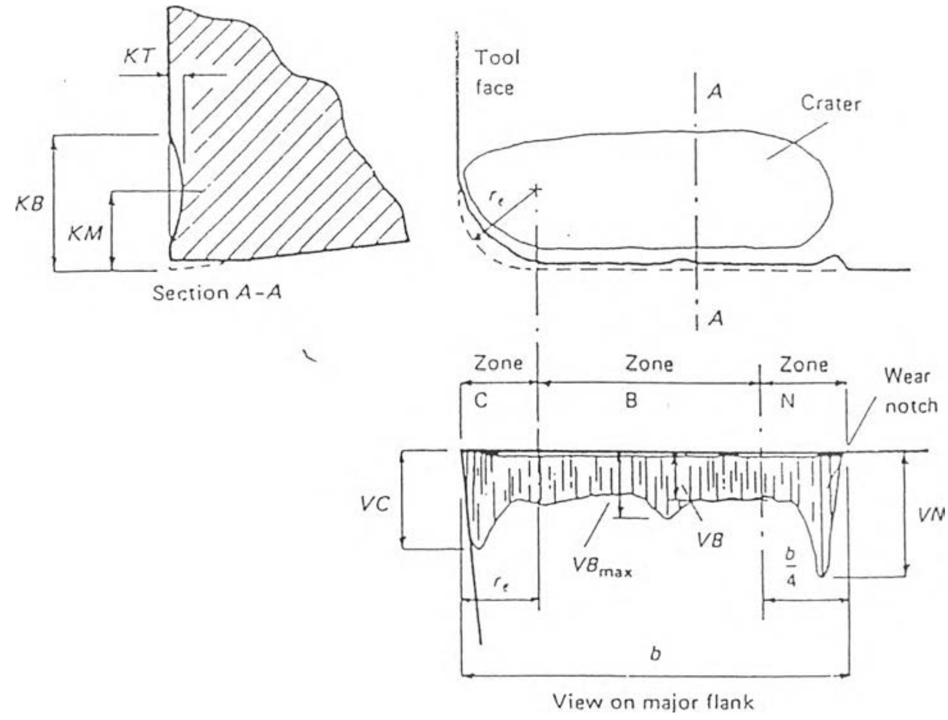

Fig. 2.3 Some features of single point tool wear in turning operations (8)

wear notch often forms because, in this region, the work material tends to be work-hardened from the previous processing operation. The width of the flank wear at the wear notch is designated VN.

In the central of the active cutting edge (zone B), the flank wear is usually fairly uniform. However, to allow for variations that may occur, the average flank wear width in this region is designated VB, and the maximum flank wear width is designated VB_{max} .

Tool life can be specified by one of several variables. The TOOL ENGINEERS HANDBOOK (9) lists the following methods of specifying the life of a cutting tool:

1. Machine time; elapsed time of operation of machine tool. (Tools may be cutting intermittently during this time.)

2. Actual cutting time; elapsed time during which tools were actually cutting (common definition of tool life)

3. Volume of metal removed

4. Number of workpieces machined

5. Equivalent cutting speed (often referred to as "Taylor speed"); e.g., V_{60}, cutting speed at which a standard value of machine time or actual cutting time, such as 60 min., is obtained under a given set of cutting conditions.

6. Relative cutting speed; a modification of item 5, above, for general practice use. It is the cutting speed at which the same machine time or actual cutting time is obtained for the test material (or tool) as for standard material (or tool), when cutting under given conditions. This quantity is also often called "relative machinability" or "percent machinability". In the latter case, the standard material is assigned a value of 100 (9).

7. Length of work cut to failure

Number 7 above is a method of specifying tool life which has been used by some researchers since the printing of the TOOL ENGINEERS HANDBOOK. By far the most common method of specifying tool life is by using actual cutting time (number 2 above) because of its adaptability to machining economics.

In order to determine tool life, some criteria must be picked to define the endpoint of the tool life. These criteria can be divided into three groups: those having to do with some process variables; those having to do with some product variables; and, those having to do with some tool variables.

The common criteria having to do with process variables are:

1. Thrust Force Failure. The thrust force on the cutting tool increases over a specified amount of thrust force. This usually indicates a large amount of wear on the flank of the tool nose.

2. Feed Force Failure. The feed force on the cutting tool increases over a specified amount of feed force. This usually indicates a large amount of wear on the tool side flank.

3. Cutting Force Failure. The cutting force on the tool increases over a specified amount of cutting force. This usually indicates wear on either the tool flank or tool face.

4. Power Failure. The horsepower required by the tool increases over a specified level of horsepower. This criteria is very similar to the cutting force failure criteria since the horsepower required is a product of the cutting force times the cutting speed.

5. Temperature Failure. The temperature at the tip of the cutting tool increases above some specified level of temperature.

The common criteria having to do with product variables are:

1. Surface Finish Failure. The tool is no longer able to meet a specified surface roughness level. This roughness level is usually specified as an arithmetic average.

2. Size Failure. The tool is no longer able to produce parts within a specified tolerance interval.

The common criteria having to do with some tool variables are:

1. Total Failure. The cutting tool is completly unable to cut metal. Taylor (3) was responsible for this definition.

2. Crater Wear Failure. The crater formed on the rake face of the cutting tool increases over some specified amount of depth, width, area or volume.

3. Volume or Weight Failure. The weight or volume of the cutting tool decreases by some specified amount.

4. Flank Wear Failure. The flank wear of the cutting tool increases above a specified amount.

The most frequently used criteria is that of flank wear. N. Hallberg (10) has suggested that two measurements, an average value and a maximum value, of the flank wear be taken, and that the position of the measurements along the side flank of the tool should be recorded. Hallberg also suggests that crater depth and position should be recorded.

H. Opitz (11) suggests that pictures of the side flank wear be made thus, providing a permanent record of the amount and position of the flank wear. Opitz further suggests that tool wear tests should be standardized by following a set experimental procedure. It is important to note here that, presently, flank wear is only measured on the side flank and not on the tool end flank.

Although flank wear is usually time dependent, numerous experiments have revealed that flank wear can be linearized with regaed to time by introducing the concept of initial wear. The value of initial wear is usually 0.05 mm approximated by Takeyama et al. (2) and the wear criterion is to set a limit on the width of the flank wear in the uniform wear region.

2.4 Tool material

One of the greatest steps forward in the machining of metals was made when Taylor (3) discovered the heat-treatment process used in producing high speed steel cutting tools. Use of these cutting tools made higher metal removal rates possible owing to the improved tool wear behavior. Since Taylor's heat-treatment discovery, developments in metallurgical science and technology have led to other new tool materials such as cast alloys, cemented carbides, and, more recently, sintered oxides or ceramics.

Practical experience has shown which tool materials are most suited to particular operations; with single point tools, where the manufacturing problems are not serious, the desirable property appears to be a high hardness value that is maintained at high temperatures. Unfortunately, an increase in hardness is usually accompanied by a decrease in the impact strength of the material; an increase in hardness also increases the tool manufacturing problems. Consequently, the materials found most suitable for continuous cutting with single point cutting tool can rarely be used for multipoint cutting tools. Since single point tools form only a small proportion of the total number of cutting tools used in practice, most metal cutting is still performed with tool manufacturing from high speed steels.

High speed steels are alloy steels with the alloying elements consisting mainly of tungsten (about 18%) and chromium (about 4%); they may also contain cobolt, vanadium, or molybdenum.

Cast alloy tools contain no iron and are cast into their final shape. They consist of cobolt, chromium, tungsten, and carbon; the carbide phase being about 25-30%, by volume, of the matrix. These tools can usually be used at slightly higher speeds than high speed steels and have less tendency to form a built-up edge during machining. They find the widest applications in the machining of cast iron, malleable iron, and the hard bronzes.

Cemented carbides are usually made by mixing tungsten powder and carbon at high temperatures in the ratio of 94% and 6% respectively, by weight. This compound is then combined with cobalt, and the resulting mixture is compacted and sintered in a furnace at about 1400° C. This tungsten-carbon-cobalt material can maintain high hardness values at temperatures as high as 1200° C and can therefore be used at much higher cutting speeds than high speed steel or cast alloy tool materials. However, as mentioned earlier, cemented carbides are not as tough and cannot be shaped after sintering. For this reason, they usually take the form of inserts, either brazed on or clamped on as shown in Fig. 2.4. The clamped on inserts are thrown away

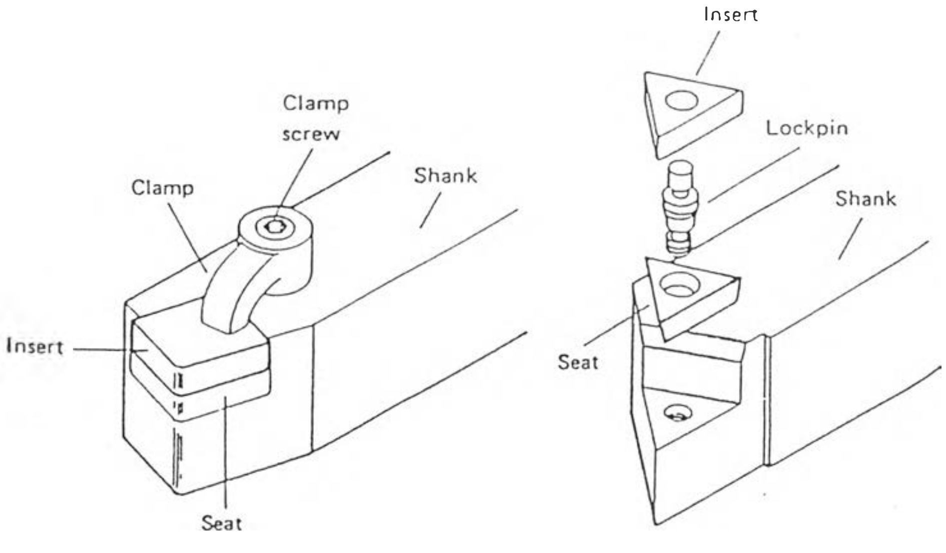

Fig. 2.4 Typical styles of clamped on inserts tools (8)

after all the cutting edges have been worn. Straight tungsten carbides are the strongest and most wear resistant but are subject to rapid cratering when machining steels. To improve resistance to cratering, tantalum carbide and titanium carbide are added to the basis composition, resulting in tungsten-tantalum carbide or tungsten-titanium carbide.

More recently, a cemented titanium carbide tool has been available in the form of disposable inserts. This material is more wear resistant than straight tungsten carbide but has the disadvantage of lower strength. However, developments in the manufacturing of this material have led to the production of superior grades that allow cutting speeds approaching those of ceramics; these superior grades can be used in the semi-rough cutting of steels and certain cast irons. Some believe that by the end of this decade at least one-half of all steel machining will be carried out using cemented titanium carbide (12).

The basis requirement for the efficient rough machining of steel is a tool material that exhibits the toughness of tungsten carbide while giving the superior wear resistance of titanium carbide. For this reason much interest is being shown in the coating of cemented tungsten carbides with a thin layer of harder material. Successes have been reported with coating of titanium carbide (13), titanium dioxide (14), and titanium nitride (15). These coatings are between 5 and 8 μm thick and are found to practically eliminate interdiffusion between the chip and the tool.

Sintered oxides, or ceramics, are made from sintered aluminum oxide and various boron-nitride powders; these powders are mixed together and sintered at temperatures of 1700° C.

Sintered oxides can be used at cutting speeds of two or three times those employed with tungsten carbides, are very hard, and have a high compressive strength and low thermal conductivity. They are, however, extremely brittle and can only be used where shock and vibrations do not occur. They are only available in the form of throw-away inserts, and their widest applications are in high speed finish turning.