Chapter 21

Fundamentals of Cutting

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HOWEWORK ASSIGNMENT

- Solve the following problems at the end of the chapter: 40, 44, 48, 53
- Homework is due Saturday 18/3/2010
Introduction to cutting

- Feed or feed rate is the distance the tool travels per unit rev of the workpiece (mm/rev or in./rev).
Introduction to cutting

- Compare Figs. 20.2 and 20.3, and note that:
  - Feed in turning is equivalent to $t_0$
  - Depth of cut in turning is equivalent to width of cut (dimension perpendicular to the page) in the idealized model.
- These relationships can be visualized by rotating Fig. 20.3 cw by 90°.
Factors Influencing Cutting Processes

- See Table 20-1
- **Independent variables in the cutting process:**
  - Tool material, coatings and tool condition.
  - Tool shape, surface finish, and sharpness.
  - Workpiece material, condition, and temperature.
  - Cutting parameters, such as speed, feed, and depth of cut.
  - Cutting fluids.
  - The characteristics of the machine tool, such as its stiffness and damping.
  - Workholding and fixturing.

- **Dependent variables:**
  - Type of chip produced.
  - Force and energy dissipated in the cutting process.
  - Temperature rise in the workpiece, the chip, and the tool.
  - Wear and failure of the tool.
  - Surface finish produced on the workpiece after machining.
THE MECHANICS OF CHIP FORMATION

Orthogonal cutting

- The tool has a rake angle of $\alpha$, and a relief (clearance) angle.
- The shearing process in chip formation (Fig. 20.4a) is similar to the motion of cards in a deck sliding against each other.
THE MECHANICS OF CHIP FORMATION

Orthogonal cutting

- The ratio of $t_o / t_c$ is known as the cutting ratio, $r$, expressed as:
  \[ r = \frac{t_o}{t_c} = \frac{\sin \phi}{\cos(\phi - \alpha)} < 1 \]  
  (1)

- Chip thickness is always greater than the depth of cut

- Chip compression ratio: reciprocal of $r$. It is a measure of how thick the chip has become compared to the depth of cut.

- The shear strain, $\gamma$, that the material undergoes can be expressed as:
  \[ \gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC} = \cot \phi + \tan(\phi - \alpha) \]  
  (2)
THE MECHANICS OF CHIP FORMATION

Orthogonal cutting

- Large shear strains are associated with low shear angles, or low or negative rake angles.
- Shear strains of 5 or higher in actual cutting operations.
- Deformation in cutting generally takes place within a very narrow deformation zone; that is, $d = OC$ in Fig. 4.20-a is very small.
- Therefore, the rate at which shearing takes place is high.
- Shear angle influences force and power requirements, chip thickness, and temperature.
- Consequently, much attention has been focused on determining the relationships between the shear angle and workpiece material properties and cutting process variables.
Orthogonal cutting

- Assuming that the shear angle adjusts itself to minimize the cutting force, or that the shear plane is a plane of maximum shear stress.
  \[ \phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2} \]  
  \( (3) \)

- \( \beta \) is the friction angle and is related to the coefficient of friction, \( \mu \), at the tool – chip interface (rake face):
  \[ \mu = \tan \beta \]  
  \( (4) \)

- From Eq (20.3), as the rake angle decreases and / or the friction at the tool – chip interface increases, the shear angle decreases and the chip becomes thicker,

- Thicker chips mean more energy dissipation because the shear strain is higher (Eq. (20.2))

- Because work done during cutting is converted into heat, temperature rise is also higher.
Orthogonal cutting

From Fig. 20.3, since chip thickness is greater than the depth of cut, the velocity of the chip, \( V_c \), has to be lower than the cutting speed, \( V \).

Conservation of mass:

\[
V t_o = V_c t_c, \quad V_c = rV = \frac{V \sin \phi}{\cos(\phi - \alpha)} \quad (5)
\]

From the velocity diagram (Fig. 20.4b), we obtain the equation:

\[
\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos \alpha} = \frac{V_c}{\sin \phi} \quad (6)
\]

\( V_s \) is the velocity at which shearing takes place in the shear plane.
TYPES OF CHIPS PRODUCED IN METAL-CUTTING

1. Continuous
2. Built-up Edge.
3. Serrated or Segmented
4. Discontinuous.

- A chip has two surfaces:
  1. One that is in contact with the tool face (rake face). This surface is shiny, or burnished.
  2. The other from the original surface of the workpiece. This surface does not come into contact with any solid body. This surface has a jagged, rough appearance (Fig. 20.3), which is caused by the shearing mechanism shown in fig. 20.4a.
TYPES OF CHIPS PRODUCED IN METAL-CUTTING: Continuous Chips (CC)

- Formed with ductile materials at high cutting speeds and/or high rake angles (Fig. 20.5a).
- Deformation of the material takes place along a narrow shear zone, primary shear zone.
- CCs may, because of friction, develop a secondary shear zone at tool–chip interface (Fig. 20.5b).
- The secondary zone becomes thicker as tool–chip friction increases.
- In CCs, deformation may also take place along a wide primary shear zone with curved boundaries (Fig. 20.5c).
TYPES OF CHIPS PRODUCED IN METAL-CUTTING: Continuous Chips (CC)

- The lower boundary is below the machined surface, subjecting the machined surface to distortion, as depicted by the distorted vertical lines.
- This situation occurs particularly in machining soft metals at low speeds and low rake angles.
- It can produce poor surface finish and induce residual surface stresses.
- Although they generally produce good surface finish, CCs are not always desirable.
TYPES OF CHIPS PRODUCED IN METAL-CUTTING: Built-up-Edge Chips (BUE)

- BUE, consisting of layers of material from the workpiece that are gradually deposited on the tool, may form at the tip of the tool during cutting (Fig. 20.5d).
- As it becomes larger, BUE becomes unstable and eventually breads up.
- Part of BUE material is carried away by the tool side of the chip; the rest is deposited randomly on the workpiece surface.
- The process of BUE formation and destruction is repeated continuously during the cutting operation, unless measures are taken to eliminate it.
- Because of work hardening and deposition of successive layers of material, BUE hardness increases significantly (Fig. 20.6a).
BUE is generally undesirable.
A thin, stable BUE is sometimes desirable because it reduces wear by protecting the rake face of the tool.
As cutting speed increases the size of BUE decreases.
The tendency for a BUE to form is reduced by any of the following practices:
1. Decreasing depth of cut
2. Increasing the rake angle
3. Using a sharp tool
4. Using an effective cutting fluid
In general, the higher the affinity of the tool and WP materials, the greater the tendency for BUE formation.
A cold-worked metal generally has less tendency to form BUE than one that has been annealed.
TYPES OF CHIPS PRODUCED IN METAL-CUTTING: Serrated Chips

- Serrated chips: semi-continuous chips with zones of low and high shear strain (Fig. 20.5e).
- Metals with low thermal conductivity and strength that decreases sharply with temperature, such as titanium, exhibit this behavior.
- The chips have a saw-tooth-like appearance.
TYPES OF CHIPS PRODUCED IN METAL-CUTTING: Discontinuous Chips (DCs)

- DCs consist of segments that may be firmly or loosely attached to each other (Fig. 20.5f).
- DCs usually form under the following conditions:
  1. Brittle workpiece materials
  2. Workpiece materials that contain hard inclusions and impurities, or have structures such as the graphite flakes in gray cast iron.
  3. Very low or very high cutting speeds.
  4. Large depths of cut.
  5. Low rake angles.
  7. Low stiffness of the machine tool.
- Because of the discontinuous nature of chip formation, forces continually vary during cutting.
- Hence, the stiffness or rigidity of the cutting-tool holder, the Workholding devices, and the machine tool are important in cutting with both DC and serrated-chip formation.
TYPES OF CHIPS PRODUCED IN METAL-CUTTING: Chips Breakers (CBs)

- CBs increase the effective rake angle of the tool and, consequently, increase the shear angle.
- Chips can also be broken by changing the tool geometry, thereby controlling chip flow, as in the turning operations shown in Fig. 20.8.
- Experience has indicated that the ideal chip is in the shape of the letter C or the number 9 and fits within a 25 mm square block.

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TYPES OF CHIPS PRODUCED IN METAL-CUTTING: Chips Breakers (CBs)

- With soft workpiece materials such as pure aluminum or copper, chip breaking by such means is generally not effective.
- Common techniques used with such materials, include machining at small increments and then pausing (so that a chip is not generated) or reversing the feed by small increments.
- In interrupted cutting operations, such as milling, chip breakers are generally not necessary, since the chips already have finite lengths because of the intermittent nature of the operation.
THE MECHANICS OF OBlique CUTTING

- Chip in Fig. 20.9a flows up the rake face of the tool at angle $\alpha_c$ (chip flow angle), which is measured in the plane of the tool face.
- Angle $\alpha_n$, the normal rake angle, is a basic geometric property of the tool. This is the angle between the normal oz to the workpiece surface and the line oa on the tool face.
- The workpiece material approaches the tool at a velocity $V$ and leaves the surface (as a chip) with a velocity $V_c$
THE MECHANICS OF OBLIQUE CUTTING

- Effective rake angle $\alpha_e$ is calculated in the plane of these two velocities.
- Assuming that the chip flow angle $\alpha_c$ is equal to the inclination angle $i$, the effective rake angle $\alpha_e$ is
  $$\alpha_e = \sin^{-1}(\sin^2 i + \cos^2 i \sin \alpha_n).$$
- As $i$ increases, the effective rake angle increases and the chip becomes thinner and longer.
THE MECHANICS OF OBLIQUE CUTTING

Right-Hand Cutting Tool

(a) 

End-cutting edge angle (ECEA)
Side rake angle, (SR)
Face
Nose radius
Shank
Axis

(b) 

Clamp screw
Clamp
Insert
Seat or shim
Toolholder

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CUTTING FORCES AND POWER

- Cutting force, \( F_c \), acts in the direction of cutting speed, \( V \), and supplies energy required for cutting.
- Thrust force, \( F_t \), acts in a direction normal to cutting velocity, perpendicular to WP.
- The resultant force, \( R \) can be resolved into two components:
  1. friction force, \( F \), along the tool-chip interface
  2. normal force, \( N \), perpendicular to it.

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CUTTING FORCES AND POWER

\[ F = R \sin \beta, \quad (20.8) \]
\[ N = R \cos \beta. \quad (20.9) \]

- \( R \) is balanced by an equal and opposite force along the shear plane and is resolved into a shear force, \( F_s \), and a normal force, \( F_n \).

\[ F_s = F_c \cos \Phi - F_t \sin \Phi \quad (10) \]
\[ F_n = F_c \sin \Phi + F_t \cos \Phi \quad (11) \]

- The ratio of \( F \) to \( N \) is the coefficient of friction, \( \mu \), at the tool-chip interface, and the angle \( \beta \) is the friction angle.

\[ \mu = \frac{F}{N} = \frac{F_t + F_c \tan \alpha}{F_c - F_t \tan \alpha} \quad (20.12) \]

- The coefficient of friction in metal cutting generally ranges from about 0.5 to 2.

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Thrust Force

- If the thrust force is too high or if the machine tool is not sufficiently stiff, the tool will be pushed away from the surface being machined.
- This movement will, in turn, reduce the depth of cut, resulting in lack of dimensional accuracy in the machined part.
- As the rake angle increases and/or friction at the rake face decreases, this force can act upward.
- This situation can be visualized by noting that when $\mu = 0$ (that is, $\beta = 0$), the resultant force, $R$, coincides with the normal force, $N$.
- In this case, $R$ will have a thrust-force component that is upward. Also note that when $\mu = 0$ and $\beta = 0$, the thrust force is zero.
CUTTING FORCES AND POWER

Power

- The power input in cutting = \( F_c \ V \)  \( (13) \)
- **Power for shearing** = \( F_s \ V_s \)  \( (14) \)
- Let \( \omega \) be the width of cut

\[
\text{specific energy for shearing} = u_s = \frac{F_s V_s}{\omega t_o V} \quad (15)
\]

- **Power for friction** = \( FV_c \)  \( (16) \)

\[
\text{specific energy for friction} = u_f = \frac{FV_c}{\omega t_o V} = \frac{Fr}{\omega t_o} \quad (17)
\]

- **Total specific energy** = \( u_t = u_s + u_f \)  \( (18) \)
- Table 20-2
TEMPERATURE IN CUTTING

- The main sources of heat generation are the primary shear zone and the tool-chip interface.
- If the tool is dull or worn, heat is also generated when the tool tip rubs against the machined surface.
- Cutting temperatures increase with:
  1. strength of the workpiece material
  2. cutting speed
  3. depth of cut
- Cutting temperatures decrease with increasing specific heat and thermal conductivity of workpiece material.
TEMPEATURE IN CUTTING

- The mean temperature in turning on a lathe is proportional to the cutting speed and feed:
  \[ \text{Mean temperature} \propto V^a f^b \]  
- \(a\) and \(b\) are constants that depend on tool and workpiece materials, \(V\) is the cutting speed, and \(f\) is the feed of the tool.

<table>
<thead>
<tr>
<th>Tool material</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbide</td>
<td>0.2</td>
<td>0.125</td>
</tr>
<tr>
<td>High-speed steel</td>
<td>0.5</td>
<td>0.375</td>
</tr>
</tbody>
</table>

- Max temperature is about halfway up the face of the tool.
- As speed increases, the time for heat dissipation decreases and temperature rises.
TEMPERATURE IN CUTTING

Chip

Temperature (°C)

360
400
450
500
550
600
700
80
30

Tool

Workpiece

Energy (%)

Cutting speed

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TEMPERATURE IN CUTTING

Figure 20.13: Temperatures developed in turning 52100 steel: (a) flank temperature distribution; and (b) tool-chip interface temperature distribution.

(a) Flank surface temperature (°F)

- Work material: AISI 52100
- Annealed, 188 HB
- Tool material: K3H carbide
- Tool shape: 0-7-7-7-0-10-0.02 in.
- Feed: 0.14 mm/rev (0.0055 in./rev)
- V = 170 m/min

(b) Temperature at tool-chip interface (°F)

- Fraction of tool-chip contact length measured in the direction of chip flow

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TOOL LIFE: WEAR AND FAILURE

Conditions that would cause tool wear:
1. high localized stresses
2. high temperature
3. sliding of chip along the rack face
4. sliding of the tool along the machined surface

The rate of wear depends on:
1. tool and work-piece materials
2. tool shape
3. cutting fluids
4. process parameters
5. machine tool characteristics
TOOL LIFE: WEAR AND FAILURE

Flank and crater wear
TOOL LIFE: WEAR AND FAILURE

\[ VT^n = C \] (20)

- \( T \) = time required to develop certain flank wear land (fig 15c)
- \( n \) = exponent that depends on tool and workpiece materials and cutting conditions
- see table 20.3 for \( n \) values
- to take into account feed rate and depth of cut effects on wear, eq (20) is modified:

\[ VT^n d^x f^y = C \] (21)
TOOL LIFE: WEAR AND FAILURE

Tool life curves

- Curves in fig 17 are generally linear over a limited range of cutting speeds
- Exponent $n$ can become $-ve$ at low cutting speeds
- Thus tool life curves may reach a max and then curve down
- As temp increases, flank wear rapidly increases
TOOL LIFE: WEAR AND FAILURE

Allowable Wear Land

- VB in fig 15c for various machining conditions is given in table 20.4
- The recommended cutting speed for a HSS tool is the one that yields a tool life of 60 to 120 min, for carbide tools, (30-60 min)
- Optimum cutting speed
- See example on p554
Crater Wear

- Occurs on the rack face (fig 20.15a, b, and d and fig 20.18)
- Factors influencing crater wear:
  1. temp at tool-chip interface
  2. chemical Affinity between tool and workpiece materials
  3. + factors for flank wear
- Diffusion mechanism, movement of atoms across tool-chip interface.
- Diffusion rate increases with temp, so increasing crater wear (fig 20.19)
TOOL LIFE: WEAR AND FAILURE

Crater Wear

![Graph showing the relationship between average tool-chip interface temperature and crater wear rate and mm^3/min.](image)
TOOL LIFE: WEAR AND FAILURE

Examples of Wear and Tool Failures

(a) 
- Chamfer
- Thermal cracks in interrupted cutting

1. Flank wear (wear land)
2. Crater wear
3. Primary groove or depth-of-cut line

(b) 
- Chamfer
- High-speed steel, thermal softening and plastic flow

1. Flank wear
2. Crater wear
3. Failure face

- High-speed steel tool, thermal softening and plastic flow

4. Secondary groove (oxidation wear)
5. Outer metal chip notch
6. Inner chip notch

- Ceramic tool, chipping and fracture

4. Primary groove or depth-of-cut line
5. Outer metal chip notch
6. Plastic flow around failure face

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TOOL LIFE: WEAR AND FAILURE

Chipping

- Two main causes:
  1. Mechanical shock
  2. Thermal fatigue

- Thermal crackes normal to the cutting edge of the tool (fig 20.18a)

- Chipping may occur in a region in the tool where a small crack or defect already exists

- High +ve rack angles can contribute to chipping

- It’s possible for crater wear region to progress toward the tool tip, weakening the tip and causing chipping
General observations on tool wear

- Due to dec in yield strength from high temp during cutting, tools may soften and undergo plastic deform.
- This type of deformation generally occurs when machining high-strength metals and alloys.
- Therefore, tools must be able to maintain their strength and hardness at elevated temperature.
- Wear groove or notch on cutting tools is due to:
  1. This region is the boundary where chip is no longer in contact with the tool.
  2. This boundary known as DOC line, oscillates because of inherent variations in the cutting operation and accelerates the wear process.
  3. This region is in contact with the machined surface from the previous cut.
  4. Since a machined surface may develop a thin work-hardened layer, this contact could contribute to the formation of the wear groove.
- Light cuts should not be taken on rusted work-pieces.
TOOL LIFE: WEAR AND FAILURE

Tool Condition Monitoring

1. Direct techniques
   - optical measurement of wear
   - done using toolmaker microscope

2. Indirect methods
   - correlation of tool condition with process variables:
     forces, power, temp rise, surface finish, and vibration
TOOL LIFE: WEAR AND FAILURE

Tool Condition Monitoring

a. Acoustic emission tech (AE)
   - Utilizes a piezo-electric transducer attached to tool holder
   - The transducer picks up acoustic emissions that result from the stress waves generated during cutting.
   - By analyzing the signals, tool wear and chipping can be monitored

b. Transducers are installed in original machine tools
   - Continually monitor torque and forces during cutting
   - Signals are pre-amplified and microprocessor analyses and interprets their content
   - The system is capable of differentiating the signals that come from tool breakage, tool wear, a missing tool, overloading of the machine, or colliding machine comp
   - The system also auto compensate for tool wear and thus improve dim accuracy

c. Monitoring by tool-cycle time

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SURFACE FINISH AND SURFACE INTEGRITY

- SF: geometric Features of surfaces
- SI: refers to properties such as fatigue life and corrosion resistance.
- Factors influencing SI:
  1. temp
  2. residual stresses
  3. metallurgical transformations
  4. surface plastic deform, tearing and cracking
- BUE has greatest influence on SF
SURFACE FINISH AND SURFACE INTEGRITY

- At small DOC, rack angle can effectively become negative, the tool may simply ride over the workpiece surface and not remove chips.
- Rubbing generates heat and induce residual stresses causing surface damage.
- DOC should be greater than the radius on the cutting edge.

FIGURE 20.21 Surfaces produced on steel by cutting, as observed with a scanning electron microscope: (a) turned surface and (b) surface produced by shaping. Source: J. T. Black and S. Ramalingam.

FIGURE 20.22 Schematic illustration of a dull tool in orthogonal cutting (exaggerated). Note that at small depths of cut, the positive rake angle can effectively become negative, and the tool may simply ride over and burnish the workpiece surface.
Dull Tool in Orthogonal Cutting and Feed Marks

Figure 20.23: Schematic illustration of feed marks in turning (highly exaggerated). See also Fig. 20.2.
MACHINABILITY

- Machinability of a material is defined in terms of 4 factors:
  1. SF and SI of the machined part
  2. tool life
  3. force and power req
  4. chip control
- Tool life and SF: most important factors in machinability
- Machinability ratings
  - based on a tool life, $T = 60\text{min}$
  - standard material is AISI 1112 steel (resulfurized), given a rating of 100
  - for a tool life of 60 min, this steel should be machined at speed of 100 ft/min
MACHINABILITY
machinability of steels

• Improved by adding lead and sulfur (free machining steels)

• Resulfurized & Rephosphorized Steels
  • S forms manganese sulfide inclusions (2\textsuperscript{nd} phase particles)
  • Act as stress raisers in the primary shear zone
  • So chips break up easily and are small

• P has 2 major effects:
  1. It strengthens ferrite, causing increased hardness, resulting in better chip formation and SF
  2. Increased hardness causes the formation of short chips
MACHINABLILITY

leaded steels

- High % of lead in steels solidifies at the tip of manganese sulfide inclusions in non-resulfurized steels, lead takes the form of dispersed fine particles
- Pb acts as solid lubricant because of low shear strength
- When temp is high, Pb melts in front of the tool, acting as a liquid lubricant
- Bismuth and tin are possible substitutes for lead in steel

Calcium-Deoxidized steels

- Oxide flakes of Calcium silicates (CaSO) are formed
- These flakes reduce strength of secondary shear zone, decreasing tool-chip interface friction and wear
- Temp is reduced, better crater wear
MACHINABILITY

Stainless steels

- Austentitic steels are generally difficult to machine
- Chatter can be a problem, need machine tools with high stiffness
- Ferrite steels have good mach
- Martensitic steels are abrasive, tend to form BUE, and req tool mat with high hot hardness and crater wear resistance
- Precipitation-hardeing steels are strong and abrasive, require hard and abrasion resistance tool material
MACHINABLITY

Effects of other elements in steel

- Al and Si is always harmful because they combine with O to form aluminium oxide and silicates, which are hard and abrasive.
- C and Mn have various effects on mach, depending on their comp...
- Plain low carbon steels (< 0.15% C) can produce poor SF by forming BUE.
- Tool and die steels are very difficult to machine and usually require annealing prior to machining.
- Mach of most steels is improved by cold working, which hardens the material and reduces the tendency to form BUE.
- Ni, Cr, Molybdenum, Vn generally reduce mach...
MACHINABLITY
Thermally Assisted Machining

- Source of heat is focused to an area just ahead of the cutting tool
- Advantages are:
  1. lower cutting forces
  2. increased tool life
  3. use of inexpensive cutting tool materials
  4. higher material removal rates
  5. reduced tendency for vibration and chatter