Machining of Metals

machining chip formation fundamentals; basic equations; strain rate; strain hardening, residual stresses; surface roughness; surface microstructure

Machining by mechanical chip formation is widely used to remove material from a workpiece in a variety of configurations including: turning, milling, drilling, and tapping. It is a process capable of producing precise geometrical shapes with tight tolerances. Machining has a long history. In the 18th century it was essential to the industrial revolution, as the only process capable of producing cylinder bores to tolerances sufficient for steam engines. Machining today is still widely used to remove large amounts of material, in the order of millimeters per pass, from ductile metals. Machining can also be used to form ductile chips in brittle materials. In production of aircraft parts under 75mm machining tolerances of +/- 5μm are reasonable. The basic process of chip formation is fundamental to all abrasive processes, e.g., grinding, honing, lapping, and abrasive wear. Machining remains economically important.

The chip removal produces technically and scientifically interesting material responses. In single point cutting the process concentrates the mechanical power of a machine tool into small volumes of the workpiece by forcing a hard cutting tool with a small edge radius through an outer layer of the workpiece material. Deformations of the workpiece material during chip formation can exceed 300%, at strain rates that have been estimated to be as high as 10^6 s^{-1}(von Turkovich 1970). The tribological conditions at the tool-chip interface can result in macroscopic welding of the material to the cutting tool and dissolution of tool elements into the chip. The geometry of the deformation zones and the resulting microstructures in the workpiece depend on the geometrical and tribological interaction of the cutting tool with the workpiece material. Further understanding of fundamentals of chip formation is motivated by the desire for higher material removal rates, longer tool life, tighter tolerances and improved quality of machined surfaces.

1. Fundamental Geometrical Relations in Chip Formation

The idealized, fundamental geometry of continuous chip formation for orthogonal cutting is shown in Fig. 1. This idealization is plane strain. It is a reasonable approximation for understanding the kinematics of the formation of a continuous chip and to be representative of the formation of the bulk of the chip in normal machining. Plane strain conditions exist sufficiently far away from the free surface at the edge of the chip, where plane stress conditions exist, and, sufficiently far from the nose of the tool where the flow is complicated by the curvature of the cutting edge.

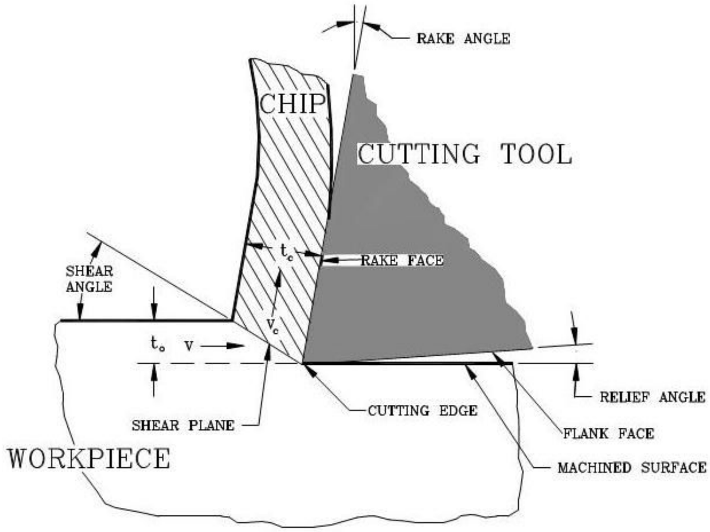

Figure 1. Idealization of orthogonal machining showing the basic geometry of chip formation on the shear plane.

In this idealization (Fig. 1) the workpiece moves with a speed V against hard tool with cutting edge radius of zero. The chip forms by shear on the shear plane, extending from the cutting edge to the free surface. In reality there must be a zone of finite thickness in which the chip is formed, and this zone is referred to as the primary shear zone. The chip contacts the tool along the rake face, until the chip curls away from the tool, forming a natural contact length. The region of deformation in the chip adjacent to the rake face of the tool is called the secondary shear zone. In the idealization the tool only contacts the workpiece along a line approximated by the cutting edge. In reality there is a finite area of contact between the tool and the workpiece, around part of the tool nose and along the tool flank. The region of deformation in the workpiece surface adjacent to the tool nose and flank contact is called the tertiary deformation zone. The newly machined surface forms at the cutting edge. It then passes below the relief, or flank, face of the tool, where it is separated from the tool by a clearance or relief angle. The shear angle is the angle between the shear plane and the free surface, or the cutting direction. The chip flows up the rake face of the tool with a speed, Vc. The rake face of the tool is inclined at an angle, α, to the normal to the cutting direction. The convention is that the rake angle is positive when the angle between the rake face and the cutting direction is obtuse and negative when it is acute.

The thickness of the material that will form the chip is frequently referred to as the depth of cut in orthogonal machining, t_o, and the chip thickness is t_c. The cutting ratio, or chip thickness ratio, r, is defined as:

$$r = t_o / t_c \qquad (1).$$

From the geometry of Fig. 1 it can be shown that the cutting ratio is related to the shear angle and the rake angle as follows:

$$r = \sin(\phi)/ \cos(\phi-\alpha) \qquad (2)$$

and:

$$\tan(\phi) = r \cos(\alpha)/(1- r \sin(\alpha)) \qquad (3).$$

The cutting ratio can be determined from the depth of cut in orthogonal machining, and the rake angle, which are generally independent variables and are known, and the chip thickness, which is relatively easy to measure.

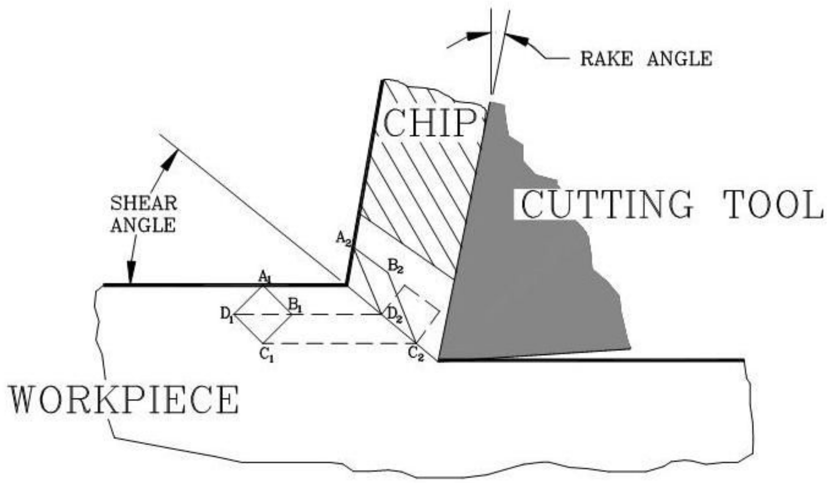

Figure 2. Graphical depiction of the strain of element ABCD as it moves through the shear plane, defined by the shear angle.

The shear strain required to form the chip is derivable from the fundamental geometry of chip formation, as shown in Fig. 2. Consider the unit square in position A_1, B_1, C_1, D_1, which moves to position A_2, B_2, C_2, D_2, such that C_2 and D_2 are on the shear plane. It can be shown from geometry that the shear strain is:

$$\gamma = \cot(\phi) + \tan(\phi-\alpha) \qquad (4).$$

Using equations 3 and 4 the shear strain can be determined experimentally from chip thickness measurements when the chip formation is approximately continuous. The shear strain can also be determined metallographically, for many continuous and discontinuous chips, from the orientation of the axis of maximum grain elongation in the chip, which is not parallel to the shear plane (Brown 1987).

2. Forces

The chip can be considered to be a separate body held in equilibrium by the tool-chip forces and the forces on the shear plane (Merchant 1944). This ignores inertial loading from the chip, which at ordinary machining speeds is significantly lower than the forces of deformation and friction. These forces can be divided into three orthogonal force systems, as shown in Fig.3. The cutting force, Fc, is parallel to the cutting direction and can be used with the cutting speed to determine the total power consumed in chip removal. The thrust force, Ft, is orthogonal to the cutting force, and therefore does not place a demand on the power, although it is important in the deflection of the tool and the workpiece. The shear force, Fs, represented in Fig. 3 as the force exerted by the chip on the shear plane, can be used to determine the flow stress on the shear plane. The normal force exerted by the chip on the shear plane, Fn, acts to suppress fracture on the shear plane. The tangential and normal forces exerted by the rake face of the tool on the chip, F and N respectively, are the third system of orthogonal forces, and determine the coefficient of friction, μ. The vector sum of the forces in each of the systems is equal to the total resultant force, R.

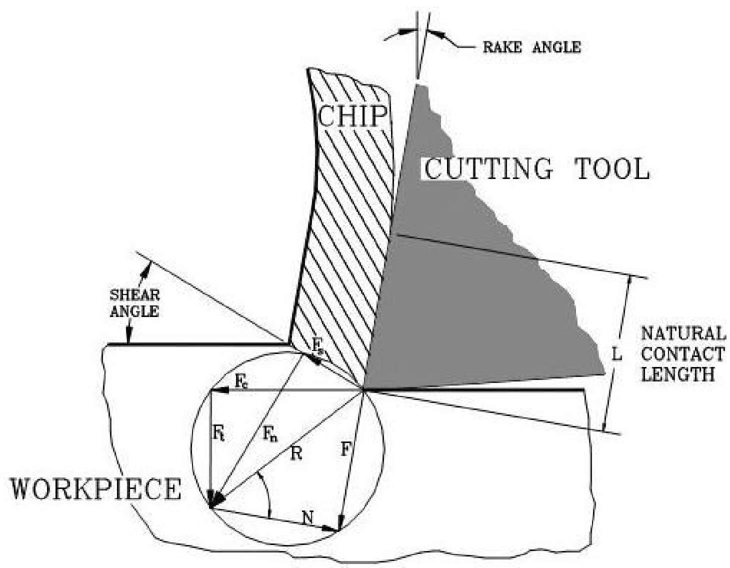

Figure 3. Graphical depiction of three systems of orthogonal forces in chip formation.

The circle diagram in Fig. 3 is a convenient and traditional means of representing systems of orthogonal forces in machining. R is a diameter of the circle. The other force systems consist of two cords that sum to the diameter and are therefore orthogonal to each other. The circle is positioned for clarity in understanding the orientation of the forces. The center of force between the chip and tool is somewhere nearer the center of the natural contact length.

The relations between the forces can be found by multiplying the force vectors by the appropriate rotation matrix, for example:

$$F = Fc \sin(\alpha) + Ft \cos(\alpha) \qquad (5),$$

$$N = Fc \cos(\alpha) - Ft \sin(\alpha) \qquad (6),$$

$$Fn = Fc \sin(\phi) + Ft \cos(\phi) \qquad (7),$$

$$Fs = Fc \cos(\phi) - Ft \sin(\phi) \qquad (8).$$

3. Shear angle

The shear angle is of fundamental importance in chip formation. The smaller the shear angle the larger the strain, the machining forces, and the power requirements. There is nothing in the geometry of the tool that dictates what the shear angle should be. The shear angle can be determined a priori from the chip thickness (Eq. 3), although the chip is not constrained to any particular thickness. The determination of the shear angle is fundamental for understanding chip formation.

The shear angle can be estimated by assuming that it is oriented such that the work to form the chip is a minimum (Merchant 1945). To do this the cutting force is written in terms of the stress on the shear plane, the tool-chip friction, the shear angle and the parameters of the cutting geometry. Assuming that the tool-chip friction and stress on the shear plane do not vary with the shear angle, the shear angle for minimum cutting force is determined:

$$\phi = \pi/4 - \beta/2 + \alpha/2 \qquad (10)$$

where β is the friction angle, such that:

$$\mu = F/N = \tan\beta \qquad (11)$$

where μ is the average friction coefficient of tool-chip contact. The expression for the shear angle in equation (10) works reasonably well, despite ignoring strain hardening or the ability of the chip to transmit the deformation forces from the tool to the shear plane.

A slip line field can be used to determine the shear angle (Lee and Shaffer 1951). This approach assumes that the material in the chip that transmits the stress to the shear plane is at the same state of stress as the shear plane:

$$\phi = \pi/4 - \beta + \alpha \qquad (12).$$

The Lee and Shaffer solution for the shear angle (12) results in a lower shear plane and therefore more strain in forming the chip than Merchant's solution (10), whenever the rake angle is less than the friction angle, which is usual. Therefore, in most cutting situations, for a material that does not strain-harden, a larger chip than that predicted by equation (10) would be necessary to transmit the loads for chip formation.

The orientation of shear plane has also been attributed to the strain-hardening properties of the workpiece in the primary deformation zone, at least to the extent that hardening is not off-set by thermal softening. Strain-hardening tends to rotate the shear plane down into the softer, undeformed material in front of it until the lower flow stresses in the softer material are balanced, energetically, by the increased length of the shear plane (Wright 1982, Stevenson 1992). This approach assumes that the chip formation system will work at the lowest work rate for initiating shear instability in severely strain-hardened material, k_1, and that it will operate at this work rate while shearing the softer material, k_0, along a longer shear plane. The longer shear plane will form at an angle ϕ_0 such that:

$$\cos(\phi_0 - \alpha)\sin\phi_0 = k_0/k_1[\cos(45 - \alpha/2)\sin(45 + \alpha/2)] \qquad (13).$$

Eq. 13 is an upper bound solution for the shear angle, as it ignores tool-chip friction. Interestingly, for many materials it does appear to be a good approximation of the shear angle and or an upper bound, for others it is less than measured shear angles (Wright 1982). In Wright's work the k_0/k_1 ratio was estimated from published tensile test data, where k_0 is the yield stress and k_1 is the ultimate stress divided by the square root of 3. Wright noted that these tests achieve neither the strain level nor the strain rates seen in machining. Nevertheless the strain-hardening properties should be expected to influence any system in which some component achieves such high strains.

4. Tool-chip friction

The friction at the tool-chip interface is an essential element for understanding the system that forms the chip. Work is required to overcome the friction, and increasing the friction has the additional influence of reducing the shear angle, according to both the

Merchant (Eq. 10) and Lee and Shaffer (Eq. 12) solutions. Reducing the shear angle also increases the work required to form the chip by increasing the area of the primary shear zone (which is proportional to $t_o/\sin\phi$, Fig. 1) and the chip strain (Eq. 4). Both these classic solutions for the shear angle pre-suppose that the tool-chip friction and the rake angle are the only parameters that can influence the shear angle. Therefore the friction angle in equations 10 and 12 might be better assumed to be a kind of machining constant (Chao and Trigger 1951).

The tool-chip friction in machining occurs under unusual conditions. The chip material is separated from the workpiece and, free from contamination and oxides, is immediately in intimate contact with the tool. Under these conditions the chip material frequently adheres strongly to the tool. Unless there is an independent means of measuring the friction, as it would be under the unusual conditions on the rake face of the tool, equations 10 and 12 lose their predictive value in an absolute sense. However the value of the sense of the equations is born out by the chip formation system's dramatic response to changes in tool-chip friction. The shear stress at the tool-chip can approximate the shear stresses on the shear plane when the tool rake face geometry is modified so as to restrict the tool-chip contact the length below what it would be naturally, i.e., a controlled or restricted contact tool (Brown 1983). The more restricted the contact length, until the point where the chip flows around the restricted contact and remains in contact with the tool, despite the contact restriction, the lower the machining forces (Chow and Trigger 1959). At extremely high machining speeds, 50000 m/min, steel has been observed to melt and the tool chip friction coefficient drops from above 0.25 to 0.01, with melt layer lubrication (Recht 1985).

5. Discontinuous or Segmented Chips

Large deformations at high rates can lead to strain localization, and this is seen in machining chips. Rather than the quasi-continuous deformations, as in Figures 1-3, a segmented or discontinuous chip can form, where narrow regions of large deformation separate larger regions with less strain. There are several kinds of discontinuous chips that may form for different reasons (Komanduri and Brown 1981). High speed deformation tends to concentrate in regions where it begins when the heat from deformation remains in the region of deformation to raise the temperature and lower the yield stress so that more deformation is favored in the same region. The point at which this kind of catastrophic thermoplastic shear is reached depends on the change in shear stress with respect to temperature and strain, and on the thermal conductivity, density and specific heat of the material. A ratio of these properties can be used to estimate the relative tendency of materials to form discontinuous chips at lower machining speeds (Recht 1964). Other discontinuities in chip thickness, observed in brass, have been postulated to result from the strain hardening behavior of the workpiece leading to systematic rotations of the shear plane in both directions (Stevenson 1992).

6. Energy partition

The energy dissipation in machining can be divided into the three deformation regions: primary, in the shear zone; secondary, in the chip adjacent to the tool rake face; and tertiary, in the workpiece adjacent to the tool flank face (Williams 1978). Most of the energy is dissipated in the primary shear zone and most of this goes with the chip in the form of heat. Of the three, the least energy is dissipated in the tertiary shear zone and heats the work piece. Tools with higher thermal conductivity have been shown to have longer natural contact lengths, and have a thicker secondary shear zone (Balaji et al. 1999).

In grinding, where an abrasive grain in an agglomeration act as individual cutting tools, long wear flats can develop, increasing the energy dissipation into the work piece. In especially abusive grinding conditions a white etching, martensitic layer can form on the machined surface. The specific energy for material removal in grinding can increase to the specific heat of fusion (Malkin 1989). The energy partition can be calculated from the grinding parameters and thermal properties of the abrasive grain, coolant and workpiece (Guo et al. 1999).

7. Deformation mechanics

Even for the so-called continuous chips the slip process in the primary shear zone may not be homogeneous, but involve cyclic variations in material behavior between predomination by work hardening and predomination by sufficient recovery for constant stress deformation or work softening (von Turkovich 1970). This is consistent with the rippled appearance of the free surface of the chip (Kobayashi and Thomsen 1959). The strain rate in the primary deformation zone can be expressed as a function of the burgers vector, dislocation density and dislocation velocity. It has been shown that, making the allowance for dislocation parameters such as density, climb rate and loop length, the width of the primary deformation zone should be about 25 nm and the strain rate is therefore about 8×10^6 s^{-1}. Assuming a chip velocity of 1m/s the total strain should be a reasonable 2, giving support to this dislocation mechanics approach (von Turkovich 1970). Whatever the mechanism the deformation conditions in machining are severe enough so that there appears to be significant strain gradients and exhaustion of strain hardening during chip formation (Stevenson 1992).

8. Machined surfaces.

The topography of the machined surface can be complex. In turning the movement of a round tool nose with a radius r through the workpiece with a feed of s from purely geometric considerations results in a series of cusps with a peak-to-valley roughness of:

$$Rt = r - (r^2 - s^2/4)^{1/2} \approx s^2/8r \qquad (14).$$

There is a finite minimum thickness of material that can be removed along the tool nose where the depth of cut thickness diminishes towards zero in many cutting situations, and this can alter the peak-to-valley roughness (Shaw and Crowell 1965). Other deviations from the perfect cusp geometry can be the result of multiple factors including: re-deposition of material adhered to the tool, cracks and tears resulting from the chip removal and tertiary deformation, vibrations, micro-constituents in the workpiece being dragged along with the tool (Brown et al. 1989). Deviations from the cusp geometry, may not alter the peak-to-valley roughness, as topographic characterization parameters cannot give a complete description of the geometry. The topography of machined and ground surfaces can be highly complex at fine scales and have been shown to have fractal components (Brown et al. 1996).

The process of separating the chip from the workpiece and the subsequent deformation of the freshly created surface in the tertiary deformation zone can have a profound influence on the microstructure and can also influence the composition of the near surface layers. Hard turning of tool steels can result in a superficial white layer (Chou and Evans 1997). Conventional turning of commercial aluminum alloys can form a nano-crystalline layer, remarkably low in dislocations, for about the first 0.1 to 0.3μm, which is followed by another layer, an order of magnitude thicker, which contains localized deformation bands with high dislocation densities (Dupont et al. 1988). Machining of pure aluminum can produce a layer of fully re-crystallized grains relatively low in dislocations, below which there is a heavily deformed layer. In both cases the large, high-speed deformations and accompanying heat resulted in a dramatic re-organization of the crystal structure in the superficial layer, which appears to be consistent with the kind of strain saturation hypothesized in chip formation (von Turkovich 1970, Stevenson 1992). Damage-depth profiles have been generated below machined single crystals as a function of CdS crystal orientation using ion beam channeling to show damage depths of a few hundred nanometers depending on machining direction (Lucca et al. 1996).

Machining and grinding introduce residual stresses into the near surface layers Brinksmeier et al. 1982, Lucca et al. 1998). There can be high gradients in these residual stresses, making them difficult to measure. In turning, where the tool passes each location once, tensile stresses dominate superficially. With the passage of the tool and the high temperatures resulting from the large high-speed deformations the superficial material expands, while constrained by cooler underlying material, and yields. Tensile stresses remain after cooling. In milling, where the machined surface is subsequently subjected to re-passage of the tool, plastically deforming the surface, but with significantly less temperature rise, superficial compressive stresses can be introduced. Grinding with sharp, CBN abrasive wheels can also produce superficial compressive stresses (Brinksmeier et al. 1982).

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