POLITECNICO DI TORINO

Master Degree Thesis

Monitoring of machining processing of CNC machines

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Abstract

With the development of Industry 4.0, great emphasis is placed on intelligent manufacturing, CNC machine is the main tool of product manufacturing, so monitoring the processing of CNC machine plays a decisive role in the realization of intelligent manufacturing. And the cutting tool is an important participant in the machining of CNC machine, so monitoring tool condition is an important part of realizing CNC machine processing automation. This paper designs a tool condition monitoring system to reduce production costs, improve production efficiency and product quality. First, this paper discusses in detail the effects of cutting variables, tool geometric parameters, workpiece materials, cutting fluid etc. on cutting force, cutting heat and tool life to extend the physical database. Then according to the characteristics that the established objective function and the constraint conditions can be linearly transformed, the geometric analysis method is used for optimization. In order to extract the features that can well reflect the change of the tool condition and not be sensitive to the change of the cutting amount, this paper analyzes the cutting force signals in time domain.

Key words：CNC machine; objective function; geometric analysis; time domain analysis

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1. Chapter 1 Introduction of cutting force

1.1. Definition

Cutting force usually refers to the force generated by the tool which has the same magnitude and opposite direction compared to the force generated by the workpiece in the process of processing metal materials. It is an important physical phenomenon that the quality of workpiece, the life of cutting tool, and the loss of power are all directly affected by cutting force.

During the cutting process of metal materials, the cutting force could be affected by the cutting heat, tool wear, the dimensional accuracy of the workpiece itself, and the initial surface roughness of the workpiece. In actual production process, generally we regard cutting force as an important basis for calculating the loss of cutting power, designing machine tool parts, tool holders, and monitoring entire cutting process and working status.

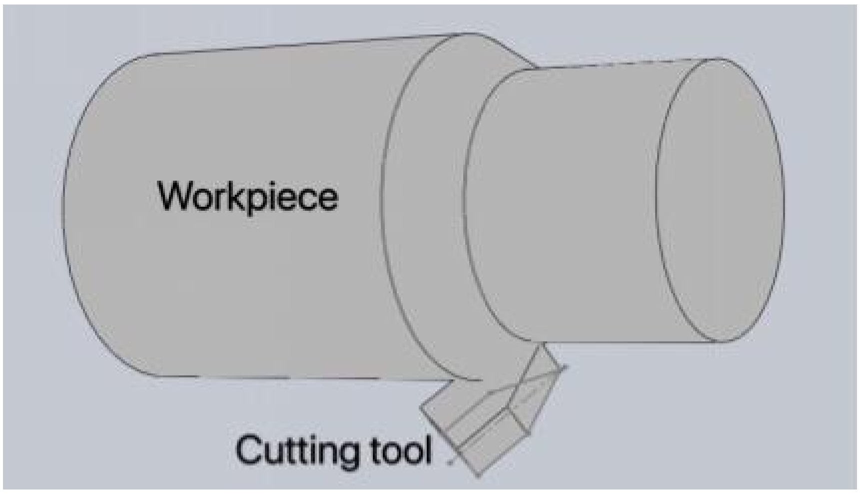

Figure 1-1 Model of cutting tool

1.2. Generation of cutting force

The cutting force mainly comes from three aspects:

Resistance of cutting tool to the elastic deformation of workpiece during processing;

Resistance of cutting tool to the plastic deformation of workpiece during processing;

Friction force between cutting chip and tool on the rake face and flank face respectively.

The generation of cutting force is shown in Figure 1-2.

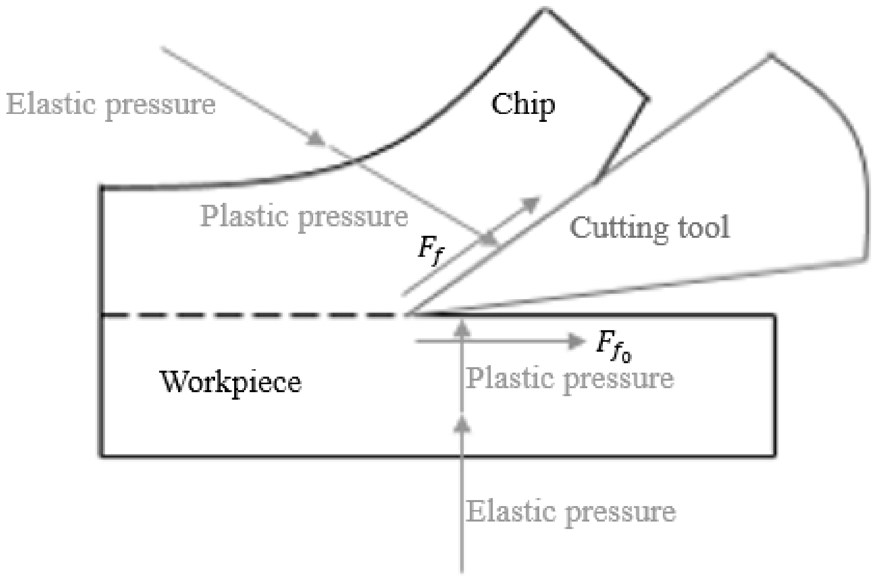

Figure 1-2 The source of cutting force

1.3. Decomposition of cutting force

The cutting force of the machine tool changes in three-dimensional direction in real time during actual machining and cutting process. Usually we decompose the resultant force F into three perpendicular components in the direction of main motion, cutting depth and feed to analyze changes of machine tool geometric errors under the action of different magnitudes and directions of cutting component forces, as shown in the figure 1-3.

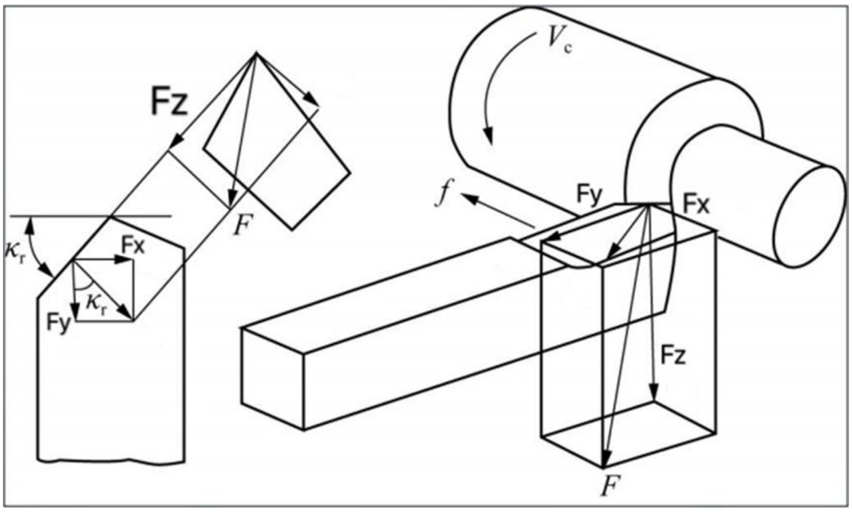

Figure 1-3 Decomposition of cutting force

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \qquad (1-1)$$

Main cutting force F_Z: It is in vertical direction, and it could change the tool pitch angle, influencing geometric error of CNC machine. F_Z is the largest component of force, which accounts for about 95% of the power consumed during cutting process. It is one of the main aspects for designing, manufacturing and using cutting tools.

Radial force F_y: It is the component force in direction of cutting depth, along Y direction. Its magnitude affects the deformation of the workpiece and the tool-guide system, directly related to machining dimensional accuracy and surface quality of the parts, and it is also the main factor that causes the deformation of parts and vibration of machining. During cutting process, F_y does not consume power, but it is one of the main factors that cause chatter during cutting process.

Axial force F_X: It is the component force in feed direction, and its influence on the geometric error of CNC machine is mainly reflected in linear displacement along axial direction and the change of machine tool yaw angle in the XY plane. During cutting process, F_X consumes about 5% of the power. It is the main basis for verifying strength and rigidity of each component part.

1.4. Calculation of cutting force and cutting power

During cutting processing, the magnitude of cutting force changes dynamically in real time with the processing materials, cutting amount, feed rate, cutting speed, etc. In order to make the range of loaded cutting force more scientific, we calculate the cutting force based on current theoretical calculation formula.

At present, we mainly use two methods for force measurement experiments: one is the single-factor method, and the other is the multi-factor method. Normally, the single-factor method is used. First, determine certain fixed experimental procedures, data and conditions, then change the data of back-cutting amount a_p and feed amount f during cutting experiment, and then directly read corresponding value of cutting force from the force measuring instrument, finally we analyze and organize the data, use empirical formula to get the relationship between them.

$$F_z = C_{F_z} a_p^{xF_z} f^{yF_z} v_c^{nF_z} K_{F_z} \quad (1-2)$$

$$F_y = C_{F_y} a_p^{xF_y} f^{yF_y} v_c^{nF_y} K_{F_y} \quad (1-3)$$

$$F_x = C_{F_x} a_p^{xF_x} f^{yF_x} v_c^{nF_x} K_{F_x} \quad (1-4)$$

Table 1-1 Parameters for the formula of forces

$C_{F_z}, C_{F_y}, C_{F_x}$	Their magnitude depends on coefficient of the material used for the workpiece and cutting conditions
$xF_z, yF_z, nF_z, xF_y, yF_y, nF_y, xF_x, yF_x, nF_x$	The index of the amount of back engagement a_p , feed amount f and cutting speed v_c
$K_{F_z}, K_{F_y}, K_{F_x}$	The correction coefficient

Considering cutting common metals, the values of coefficients and index in empirical formula are listed in the table 1-2.

Table 1-2 Parameters for the formula of principal cutting force

Workpiece	Hardness HB	Coefficients and indices in empirical formulas		
		C_{F_z}	X_{F_z}	y_{F_z}
Carbon structural steel 45 Alloy structural steel 40Cr (Normalizing)	187~212	164*9.81	1	0.84
Grey cast iron HT20-40 (annealing)	170	93*9.81	1	0.84
Lead brass H Pb59-1	78	65*9.81	1	0.84

(Hot rolled)				
Tin bronze ZQSn5-5-5	74	58*9.81	1	0.85

Cutting power

The cutting power P_C is used to check processing cost, calculate energy consumption, and select main motor power of CNC machine.

The cutting power consumed by the main movement is P_Z.

$$P_z = \frac{F_z V_c}{60 \times 10^3} KW \qquad (1-5)$$

Where F_z—main cutting force, N; v_c—cutting speed, m/min.

According to the cutting power P_z, the power P_E of main motor of CNC machine can be calculated as following (unit: kW):

$$P_E = \frac{P_z}{\eta_m} \qquad (1-6)$$

η_m is the transmission efficiency of CNC machine, $\eta_m = 0.75 \sim 0.85$.

2. Chapter 2 Establish model of variables influencing cutting force

Maintaining a constant cutting load in high-speed machining is of great significance to reduce vibration, increase the life of cutting tools, and improve quality and efficiency of mold surface processing. The main factors affecting cutting load are as following.

2.1. Chips

2.1.1. Chip formation process

The model shown in Figure 2-1 illustrates deformation of cutting process. Under action of cutting tool, the plastic metal material produces shear slip deformation along direction of 45° with the force. When the deformation reaches a certain limit value, it will produce shear slip failure along the deformation direction. If the tool moves continuously, the material above dotted line will be separated from the material below.

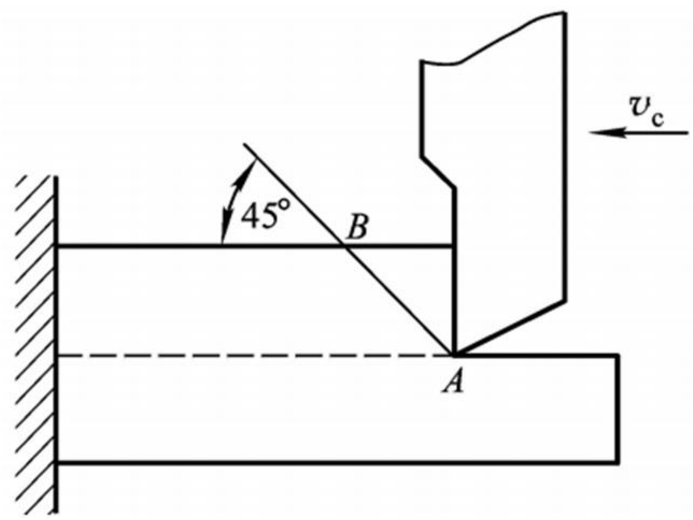

Figure 2-1 Deformation in the cutting process of plastic metal materials

2.1.2. Three deformation zones during cutting process

As shown in Figure 2-2, under the action of cutting tool, the metal of cutting layer is separated from the base material of workpiece after complex deformation process, then forming chips. The deformation generated in this process can be divided into three deformation zones.

The first deformation zone is located in area OAM which is in front of cutting edge, the second deformation zone is near the rake face, and the third deformation zone is near the flank face.

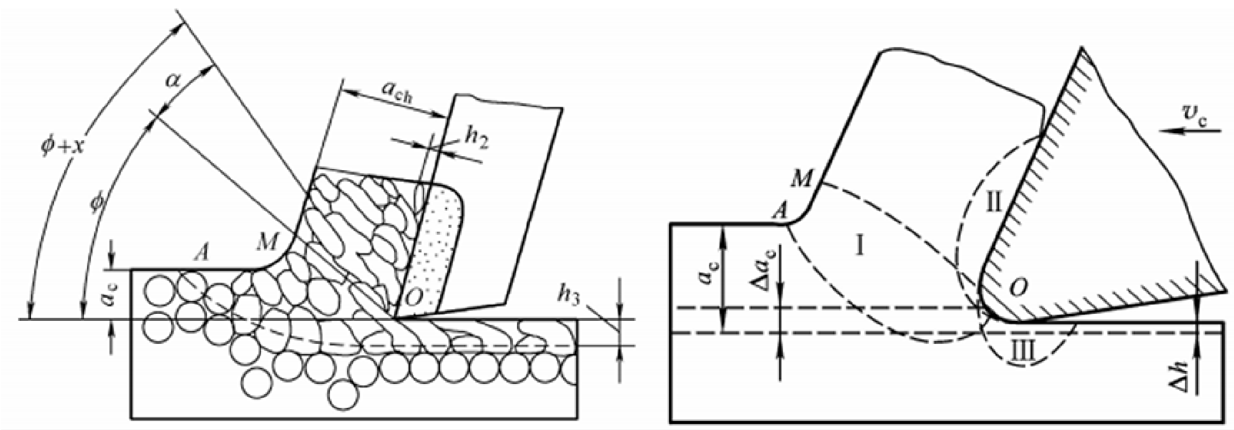

Figure 2-2 Three deformation zones during cutting process

The first deformation zone I

It is the area between OA and OM shown in Figure 2-3, which is from beginning of the plastic deformation of cutting layer metal to completion of the shear slippage.

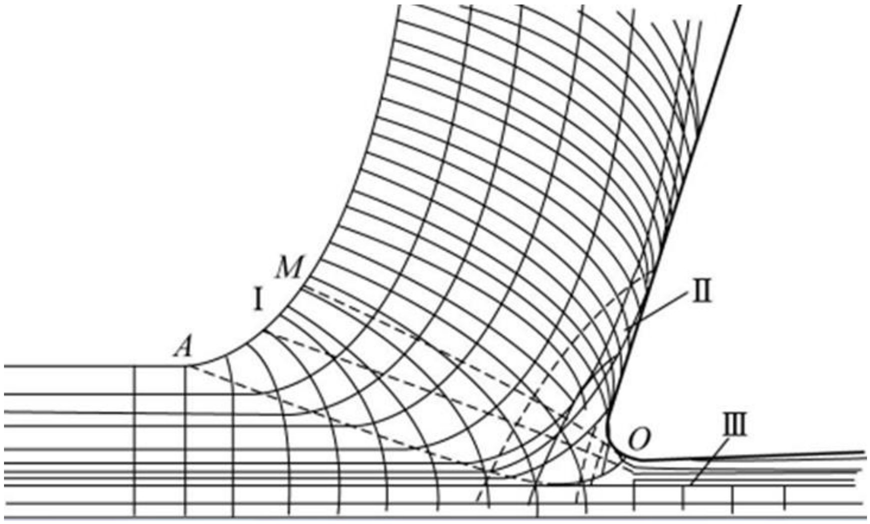

Figure 2-3 Slip and streamlines in the metal cutting process

In the left of OA line, the metal material deforms elastically. On the OA line, shear stress of the material reaches yield strength τ_S, and the material begins plastic deformation, producing slip. Along with continuous movement of cutting tool, the metal which is originally on slip line continues to move closer to cutting tool, and the stress and deformation gradually increase. When it reaches OM line, the stress and deformation reach the maximum. If beyond OM line, the cutting layer metal will flow out along rake face, then form chips and complete cutting process. The area between OA line and OM line is the plastic deformation area.

The first deformation zone is the largest deformation zone during metal cutting deformation process. In this area, the metal will generate a large amount of cutting heat and consume most of the power.

The second deformation zone II

When the chips are discharged along the front of the tool, they will be further hindered by the chips in front. There is strong squeezing and friction between cutting tool and chips at their interface, causing the metal at bottom of the chip which is near the front to have "fibrillated" secondary deformation. This area is called the second deformation zone.

Figure 2-4 Built-up tumor

When cutting plastic metal materials, the flow speed of chips in the bottom is lower than in upper layer, forming a stagnant layer. When the friction between stagnant layer and rake surface exceeds the strength limit of chip metal, the chip metal of stagnant layer will adhere and accumulate near the cutting edge, forming a built-up edge as shown in Figure 2-5.

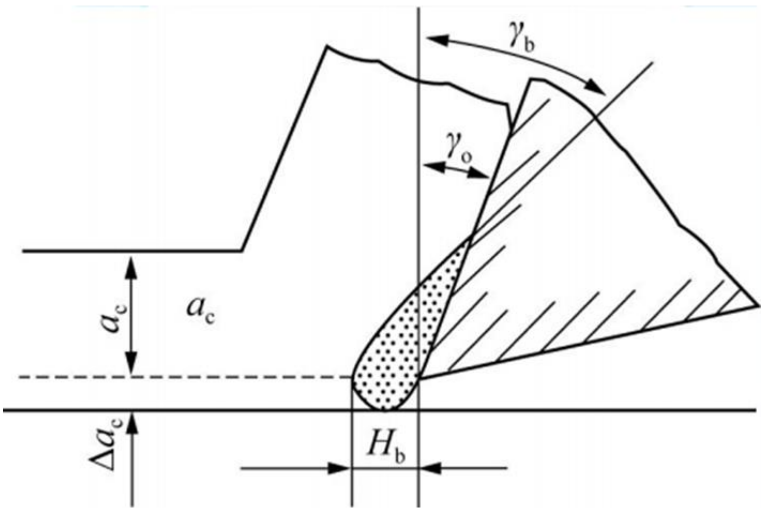

Figure 2-5 Build-up edge

The hardness of built-up edge is much higher than the workpiece, so it can protect the cutting edge and increase rake angle of cutting tool to reduce cutting deformation and cutting force. Therefore, generally generating built-up edge is beneficial for rough machining. But the built-up edge is unstable, it causes continuous changing of cutting depth and cutting thickness, which affects the machining accuracy and fluctuation of cutting force, degrading the surface quality of the workpiece. Therefore, during finishing, the build-up of edge should be avoided.

The third deformation zone III

The deformation zone which is formed by extrusion and friction on machined surface with tool flank is called the third deformation zone Ⅲ. Since the cutting edge of the tool cannot be absolute sharp, existence of the blunt radius makes it impossible to completely remove the nominal cutting thickness. A small part of the cutting layer will be squeezed to the machined surface, generating friction with the tool flank, and further producing elastic and plastic deformation, thereby affecting quality of the processed surface.

2.1.3. Friction in the tool chip contact area

2.1.3.1. Friction characteristics of the tool chip contact area

For dry cutting without cutting fluid, friction between the chip and tool rake face is pure solid friction. Compared with general friction, it has the following characteristics:

Surface of the chip which is rubbing with rake face is a new surface, without any oxide or other pollution, it has strong chemical activity. On the other hand, rake face of the tool also becomes an extremely clean face due to sharp friction with the clean chip. Therefore, the chips and the rake face are easily bonded to each other.

The contact stress is very high, up to 2~3GPa.

The cutting temperature is very high. Average temperature of the contact part between cutting part of cutting tool and processed material can reach 700~1200℃.

Due to these characteristics of the plastic metal cutting process, the bottom of chips can be bonded to rake face. In the case of bonding, there is not general external friction between chips and rake face, but the internal friction between bonding layer of tool-chip and its upper metal.

2.1.3.2. Influence of the friction state of the tool-chip contact area on the cutting process

The friction between rake face of cutting tool and chips has important effects on the metal cutting process:

It has an influence on the degree of chip deformation. As the tool-chip friction coefficient increases, the adhesion between the tool rake face and the chips increases, which hinders the flow of chips, making the chip thickness larger, the deformation coefficient increases, and the degree of chip bending decreases.

It has effects on cutting temperature. As the friction coefficient of the tool-chip contact area increases, the degree of plastic deformation of the chips increases, and the heat which is converted from plastic deformation increases, so the temperature in the cutting zone rises.

It has an impact on tool wear. The more severe the friction of the rake surface, the higher the temperature of the cutting zone, the more severe the adhesion of the rake surface and the chips, which intensifies the wear of the tool.

It has an influence on cutting force and feed resistance. The increase of the friction coefficient of the rake face will reduce the shear angle and increase the cutting force and feed resistance.

The friction of the rake face will also affect the formation of built-up tumors and scales, thereby affecting the quality of the machined surface. Therefore the friction on the rake face has a very important effect on the entire process of metal cutting.

2.1.3.3. Main factors affecting friction coefficient μ of rake face

There are four factors affecting the coefficient of friction on the rake surface: workpiece material, cutting speed, cutting thickness and tool rake angle.

The greater the hardness of the workpiece material, the lower the friction coefficient.

When the cutting speed is low, the tool-chip contact is not close, forming point contact. In point contact, the proportion of external friction is relatively large, and the proportion of internal friction is small, so the friction coefficient is not high. When the cutting speed increases, the plasticity of the metal in the chip bottom layer increases, and the point contact turns into surface contact. The internal friction ratio increases, and the friction coefficient increases with the increase of cutting speed. When the cutting speed exceeds the above value, the friction coefficient decreases with the increase of the cutting speed.

When the cutting thickness increases, the friction coefficient decreases.

In the range of general cutting speed, the larger the rake angle, the greater the friction coefficient value. This is because increasing the rake angle reduces the normal stress and increases the ratio between shear stress and normal stress, so the coefficient of friction increases.

2.1.3.4. Tool-chip contact state

The contact state of metal cutting tools and chips can be divided into three situations:

At low cutting speeds, local adhesion and biting spots are formed on the friction surface, and contact sliding is carried out between the convex peaks on the surface. The sheared mass points are bonded to the harder tool surface, and then become new bonding points, as shown in Figure 2-6(a).

At high cutting speeds, the contact characteristics have changed significantly. The processed material closely fits the surface contour of the tool. Only the separation part between the chip and the rake face remains in point contact, as shown in Figure 2-6(b).

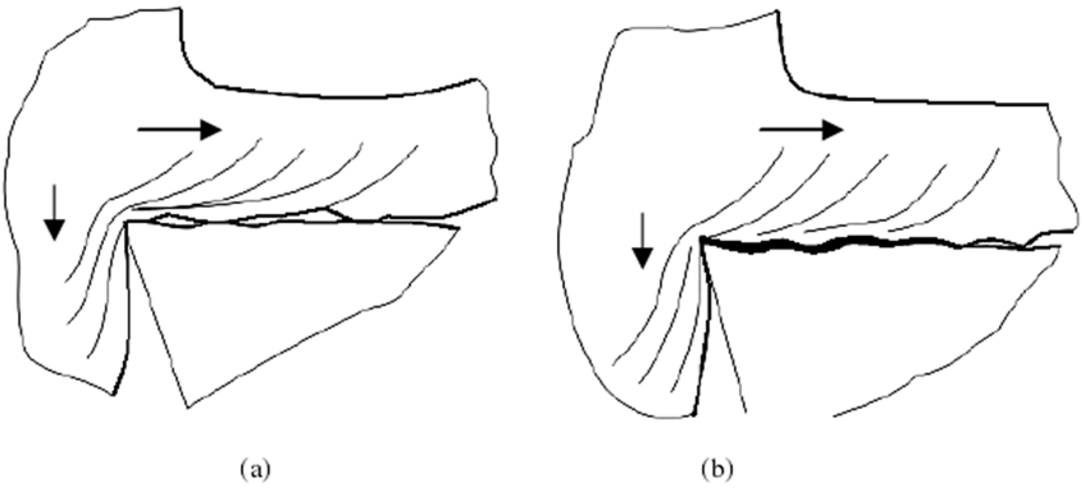

Figure 2-6 The tool-chip contact state

In most cases, the contact state is between the above two situations. The change of contact state mainly depends on the cutting temperature. If the temperature of the contact zone is between 800°C and 1000°C, the yield limit of the steel is 10-20 times smaller than that at room temperature, which is equivalent to the surface pressure being 10-20 times larger than that at room temperature. In this way, it is completely possible for cutting chips to fill the surface of tissue skin of any shapes, then obtain a close fit of the entity.

2.1.3.5. Tool-chip contact friction model

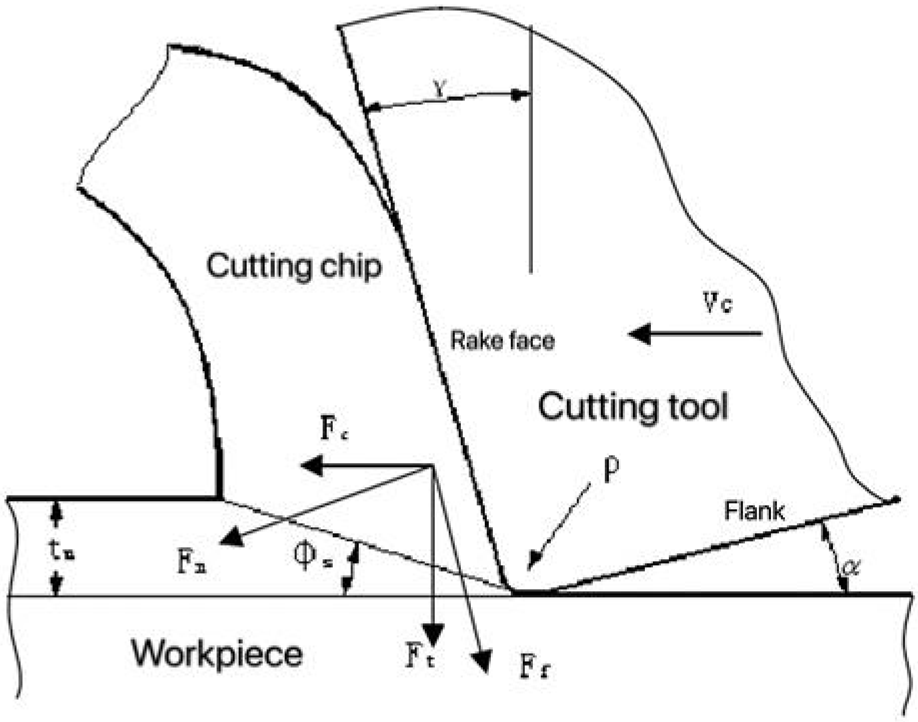

Figure 2-7 Forces generated during orthogonal cutting process

In the early physical simulation analysis, the Coulomb friction model is commonly used to define the tool-chip friction. The tool-chip friction was considered as sliding friction, and the friction coefficient is a fixed value, which can be described by Coulomb's law as

$$\tau = \mu\sigma_n \qquad (2-1)$$

In the formula, τ is the shear stress generated by friction, μ is the tool-chip friction coefficient, and σ_n is the normal stress.

This model can simulate the metal cutting process well in the case of low-speed cutting, but in the case of high-speed cutting, the tool-chip contact area will produce high temperature and high plastic deformation. In this case, the rake face of the tool and the root of the chip are prone to sticking. Therefore, the friction in the tool-chip contact area should be composed of two parts: bonding friction and sliding friction.

When the tool-chip is under sliding friction, we choose the Coulomb model to define the friction; When the value of friction stress is equal to the ultimate shear stress, the tool-chip is under bonding friction, and its value gradually increases as the normal stress decreases. The expression of the modified Coulomb friction model is

$$\tau_f = min\{\mu\sigma_n, \tau_s^*\}$$
$$when\ \mu\sigma_n < \tau_s^* (sliding\ friction\ area)$$
$$when\ \mu\sigma_n \geq \tau_s^* (bonding\ friction\ area) \qquad (2-2)$$

In the formula, τ_f is the friction stress of the contact surface, μ is the friction coefficient of the sliding zone, σ_n is the normal stress of the contact surface, and τ_s^* is the critical shear flow stress of the material.

2.2. The influence of three elements of cutting amount

2.2.1. Impact of back engagement/cutting depth a_p on cutting force

As the depth of cutting increases, the cutting force increases proportionally, and the back force and feed force increase approximately proportionally.

2.2.2. The influence of feed amount f on cutting force

As the feed amount increases, the cutting force also increases, but the increase of cutting force is not proportional to the feed amount.

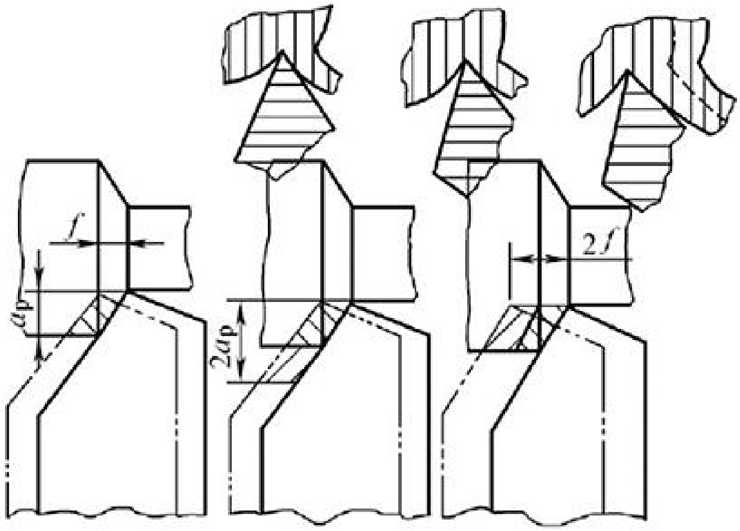

Figure 2-8 Influence of cutting depth and feed amount

When the back engagement a_p or the feed amount f gradually increases, the cutting force will continue to increase, but they have different effects on the cutting force. When the amount of back engagement a_p doubles, the cutting thickness h_D remains unchanged, while the cutting width b_D doubles, and the cutting load on the cutting edge also doubles, the exponentially increase of deformation force and friction leading to the cutting force increase exponentially. When the feed amount f doubles, the cutting width b_D remains unchanged, but the cutting thickness h_D doubles, the average deformation of the chip decreases, and the deformation coefficient decreases, so the cutting force increases less than double.

$$F_z = C_{F_z} a_p^{xF_z} f^{yF_z} v_c^{nF_z} K_{F_z}$$
$$F_y = C_{F_y} a_p^{xF_y} f^{yF_y} v_c^{nF_y} K_{F_y}$$
$$F_x = C_{F_x} a_p^{xF_x} f^{yF_x} v_c^{nF_x} K_{F_x} \qquad (2-3)$$

During processing, the index xF_z of the plastic material is about 1, and the index of the feed amount yF_z=0.75～0.9, when we double the amount of the back engagement, cutting force is also doubled. When the feed amount is doubled, the cutting force will only increase by 68% to 86%.

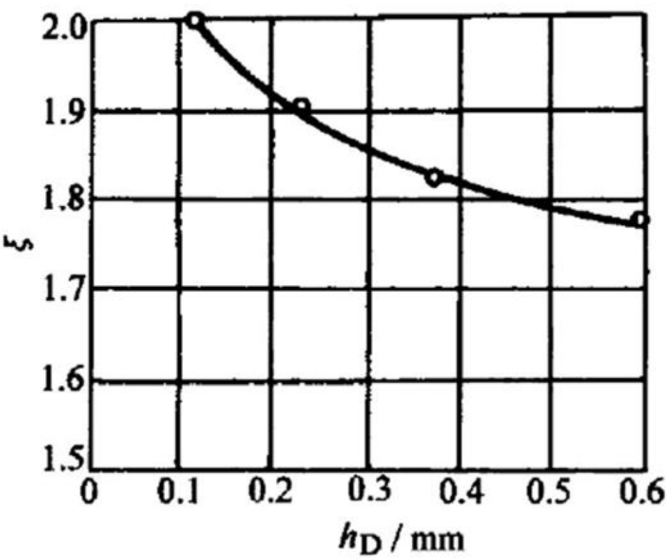

Figure 2-9 Relationship between cutting thickness and deformation coefficient

2.2.3. The influence of cutting speed V_c on cutting force

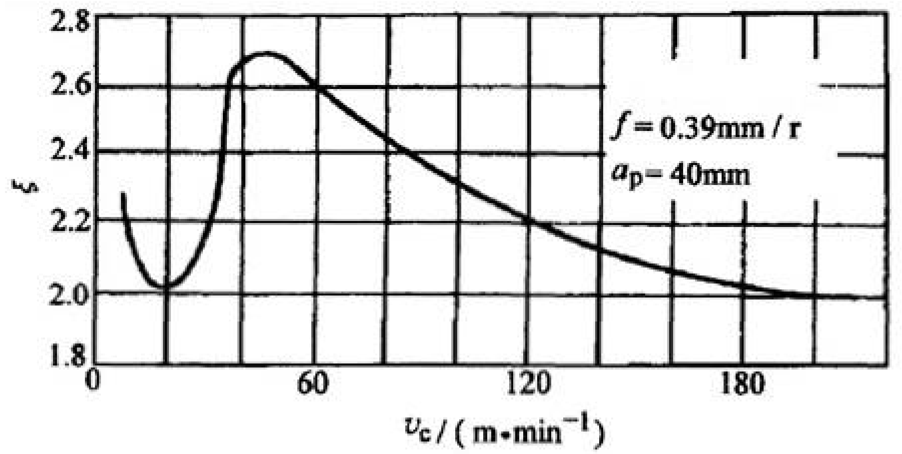

Figure 2-10 Influence of cutting speed on deformation coefficient

Influence of cutting speed on deformation coefficient

Cutting speed affects the degree of cutting deformation through the growth-disappearing process of built-up edge. During the growing process of built-up edge, the actual working rake angle increases, the shear angle φ increases, and the deformation coefficient decreases. Within the speed range where the built-up edge disappears, the actual working rake angle continues to decrease, and the deformation coefficient ξ continues to rise to the maximum value. Then, the built-up edge completely disappears. In the cutting speed range without built-up edge, the higher the cutting speed, the smaller the deformation coefficient. When cutting brittle metals such as cast iron, chip build-up edge is not generated. As the cutting speed increases, the deformation coefficient gradually decreases.

The influence of cutting speed on cutting force

During the growing process of the built-up edge, as the cutting speed increases, the height of the built-up edge increases, the degree of chip deformation decreases, the cutting force per unit area of the cutting layer decreases, and the cutting force decreases. On the contrary, the cutting force gradually increases during the reduction stage of the built-up edge.

In the stage of no built-up edge, as the cutting speed increases, the cutting temperature increases, the friction coefficient of the rake face decreases, the degree of deformation decreases, and the cutting force decreases.

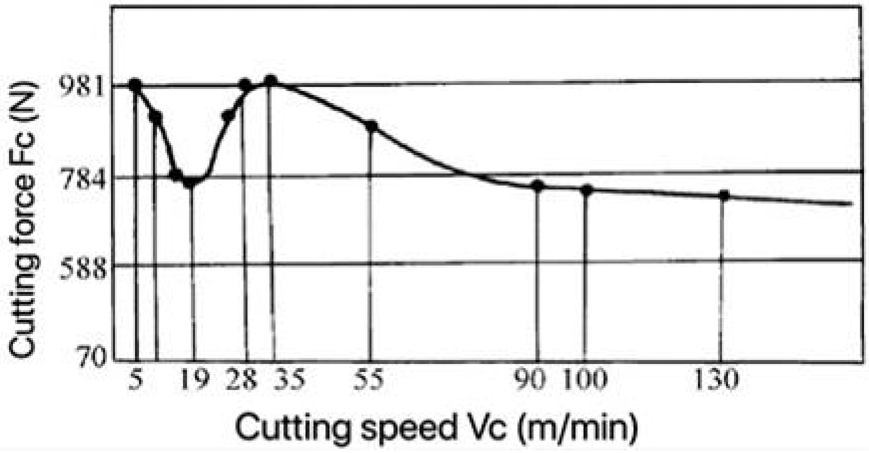

Figure 2-11 The influence of cutting speed on cutting force

Experiments are carried out under the conditions shown in Figure 2-11. When we are processing plastic metal materials, if cutting speed is greater than 27m/min, the built-up edge of the tool generated on the rake face, that is, the tip of the tool, will quickly disappear. At this time, the cutting force will gradually decrease with the continuous increase of the cutting speed. When the cutting speed is less than 27m/min, the cutting force will be affected by the built-up edge. When the cutting speed is 5m/min, built-up edge will quickly appear at the tool tip. At the same time, as the cutting speed continues to increase, the built-up edge will continue to grow, and the rake angle of the tool will actually increase, resulting in a slow reduction in cutting force. When the cutting speed is 17m/min, the built-up edge at the tool tip will show the maximum value, and the cutting force will be the minimum. When the cutting speed rapidly exceeds 16m/min and finally reaches about 27m/min, the built-up edge will continue to decrease, the cutting force will gradually increase.

When processing brittle metal materials, such as gray cast iron, due to small possibility of plastic deformation of the metal material, the friction force generated by the iron filings on the rake face is very small, then the cutting speed has a relatively small effect on the cutting force.

2.3. The influence of cutting tool material

Nowadays, the tool materials used for high-speed turning of ultra-high-strength steel mainly include cemented carbide, coated cemented carbide, ceramics, and cubic boron nitride. The affinity between the tool material and the workpiece material affects the friction therebetween, therefore, it directly affects the cutting force.

There are several basic requirements for tool materials:
High hardness, the hardness at room temperature should be above 60HRC.
Sufficient strength and toughness to withstand cutting forces, shock and vibration.
High wear resistance to resist wear during cutting process and maintain a certain cutting time.
Higher heat resistance, that is, the performance of maintaining higher hardness at high temperature.
Better manufacturability to facilitate the manufacture of various tools.

Nowadays, commonly used tool materials include carbon tool steel, alloy tool steel, high-speed steel, cemented carbide, ceramics, diamond, cubic boron nitride, etc. Carbon tool steel and alloy tool steel are only used for tools with low cutting speeds due to their poor heat resistance. Ceramics, diamonds and cubic boron nitride are only used for special occasions, and the most used materials are high-speed steel and cemented carbide.

High speed steel
High-speed steel is a high-alloy tool steel formed by adding more alloying elements such as tungsten, chromium, and vanadium to carbon tool steel.
Its strength and impact toughness are good, with certain hardness and wear resistance.

According to different uses, high-speed steel can be divided into general high-speed steel and high-performance high-speed steel.

Table 2-1 Performance comparison of different tool materials

Material characteristics	Cemented carbide materials	Ceramic material	Cubic boron nitride material
Hardness	HRA89-94	HRA91-95	HV8000-9000
Bending strength (MPa)	1050-2940	345-1176	700
Compressive strength (MPa)	3100-5900	2750-5000	3800
Impact toughness (KJ/m^2)	25-60	5-12	25-60
Elastic Modulus (GPa)	310-690	310-420	587-680
Young's modulus (GPa)	620	370	720
Thermal conductivity (W/mK)	17-125	20-29	40-100
Thermal expansion coefficient	4-9	6.3-9	2.1-4.8
Heat resistance	800-1000	>1200	1400-1500

Hard alloy

Cemented carbide is made of high-hardness, high-melting metal carbide powder and metal binder after high-pressure forming, and then sintered at high temperature to form a powder metallurgy material. Its hardness, wear resistance and heat resistance are all high, the allowable cutting speed far exceeds that of high-speed steel, its processing efficiency is high, and it can cut hard materials such as hardened steel, so it is widely used as a tool material.

When using carbide tools for high-speed turning of ultra-high-strength steel, the use of K-type alloys with better toughness and thermal conductivity and S-type alloys with better high-temperature performance can effectively alleviate the occurrence of chipping and reduce plastic deformation. Because cemented carbide tools can be adapted to cutting process of most metal materials, they are also the most common materials.

Ceramic tools

Ceramic tools are typical super-hard tools with high hardness, good wear resistance, heat resistance and chemical stability. They can process parts with high precision for a long time at high cutting speeds. When processing high-hardness metal materials, its tool life and cutting efficiency are far from comparable to cemented carbide tools. It is very suitable for CNC machine tools and processing equipment to be with a high degree of automation, and can make the equipment's high efficiency fully utilized.

Cubic boron nitride

Compared with ceramics, cubic boron nitride has higher hardness and wear resistance, better thermal stability and chemical inertness, and has a lower coefficient of friction and good thermal conductivity. Its excellent comprehensiveness makes it even more dazzling in the high-speed turning direction. When using cubic boron nitride to make metal cutting tools, there is a "cleavage surface" that is easy to be split. Therefore, we often use polycrystalline cubic boron nitride tools in cutting, that is, PCBN tools.

The choice of PCBN tool material has a huge impact on the performance of the tool. The main factors affecting the performance of PCBN tool materials are the content of CBN, the particle size of CBN and the type of binder. The higher the CBN content, the higher the hardness; the binder is mainly divided into two types: metal binder and ceramic binder, which are related to the toughness and temperature resistance of PCBN tools; If the particle size of CBN increases, then the wear resistance is improved and toughness decreases.

Table 2-2 shows the main uses of PCBN tools with different CBN content and different types of binders.

Table 2-2 Reference about selection of PCBN tool material

CBN content %	Binder type	The main purpose
~60	TiN	Processing hardened steel
~70	TiC	Machining cast iron
~70	Al_2O_3	Machining cast iron
~90	AlN	Machining high-strength cast iron
~80	Co	Processing heat-resistant alloys, cast iron

2.4. Influence of cutting fluid

The first function of water-soluble cutting fluid is cooling, and the second is to take away the chips dropped from processing. Its influence on cutting force is very limited. If we use the cutting oil with lubricating effect during cutting process, the lubrication of the cutting oil can effectively reduce the friction between the tool flank surface and the surface of the workpiece, and the friction between the tool rake surface and the chip, At the same time, it can effectively reduce the plastic deformation ability of the metal material itself, thereby greatly reducing the influence of cutting force on the cutting process. For example, in the turning process, we use extreme pressure emulsion, compared to dry cutting without any cutting fluid, its cutting force will be reduced by at least 10% to 20%.

Main function of cutting fluid

1. Lubrication: Improve the surface accuracy of the workpiece and prolong the service life of cutting tool

In the cutting process, friction occurs between the tool-chips and the tool-workpiece surface, and the cutting fluid is the lubricant to reduce this friction. On the flank surface, due to the relief angle of the tool, the contact area where it contacts with the processing material is less than that of the rake surface, and the contact pressure is also lower. Therefore, the frictional lubrication state of the rear tool is close to the boundary lubrication state. Generally, a substance with strong adsorption is used (such as Oily agents) and substances that reduce the shear strength of metal contact parts (extreme pressure agents) can effectively reduce friction.

The condition of the rake face is different from that of the flank face. The deformed chips in the shear zone are squeezed out by the feed force of the tool. The contact pressure is high, and the chips also reach high temperatures due to plastic deformation. After the cutting fluid is supplied, the chips shrink due to the sudden cooling, which reduces the contact length between the tool and the chip on the rake face , the metal contact area between the chip and the tool, and at the same time reduces the average shear stress, this leads to an increase in the shear angle and a decrease in the cutting force, thereby improving the cutting performance of the workpiece material..

Generally, oil-based cutting fluids have better lubrication effects than water-based cutting fluids, their oil-containing and extreme pressure additives have better cutting effects.

Oily additives are generally long-chain organic compounds with polar groups (-COOH, -OH, -CO-NH2, etc.), such as higher fatty acids, higher alcohols, animal and vegetable oils, etc. The oily agent is adsorbed on the metal surface by polar groups to form a lubricating film.

This lubricating film has a low friction coefficient, which can reduce the friction between the tool-workpiece and the tool-chips to reduce cutting resistance and extend life of cutting tools and reducing the surface roughness of the workpiece.

The role of oil additives is limited to the condition of low cutting temperature. When the temperature exceeds 200°C, the adsorption layer of the oily agent is destroyed and loses its lubricating effect. Therefore, cutting fluids containing oily agents are generally used for low speed cutting with high precision. In high-speed, heavy-duty cutting situations, cutting fluids containing extreme pressure additives should be used.

The so-called extreme pressure additives are compounds containing sulfur, phosphorus, and chlorine. These compounds chemically react with metals at high temperatures to produce iron sulfide, iron phosphate, iron chloride and other substances with low shear strength, thereby reducing cutting resistance and the friction of tool-workpiece contact surface and tool-chips contact surface, making the cutting process easier. The cutting fluid containing extreme pressure additives can also inhibit the formation of tool buildup and improve the surface roughness of the workpiece.

The lubricity of cutting fluid is related to its permeability. With good permeability, the lubricant can penetrate through the chip-tool interface and the tool-workpiece interface in time, to form a lubricating film on the surface of the chip, tool, and workpiece, reducing the friction factor and cutting force. The cutting fluid directly penetrates through the tiny cracks on the metal surface, changing the physical properties of the material being processed, thereby reducing the cutting resistance and making the cutting process easier.

2.Cooling: Take the cutting heat away from the tool, workpiece and chips, reduce the temperature in the cutting zone, reduce the deformation of the workpiece, and maintain the hardness and size of the tool

The cooling effect relies on the convection heat exchange and vaporization of the cutting (grinding) cutting fluid to remove the cutting heat from the tool, workpiece and chips, reduce the temperature in the cutting zone, reduce the deformation of the workpiece, and maintain the hardness and size of the tool.

The cooling effect of cutting fluid depends on its thermal parameter values, especially specific heat capacity and thermal conductivity. Here, the flow conditions of the liquid and the heat exchange coefficient also play an important role. The heat exchange coefficient can be improved by changing the surface material and the heat of vaporization. Water has high specific heat capacity and large thermal conductivity, so water-based cutting fluid has better cooling performance than oil-based cutting fluid.

Table 2-3 Thermal parameter value

Category	Thermal conductivity [W/(m·K)]	Specific heat capacity [J/kg·K]	Heat of vaporization (J/g)
Water	0.63	4.18×10^3	2260
Oil	0.125-0.21	$1.67\text{-}2.09\times 10^3$	167-314
Steel	36-53.2	460.5	--

Changing the flow conditions of fluid, high flow speed and increasing flow rate can effectively improve the cooling effect of the cutting fluid, especially for oil-based cutting fluids with poor cooling effect, the effect is more obvious. In gun drilling, deep hole drilling and high-speed gear hob, large flow and high pressure oil supply is used. Spray cooling is used to make it easy for the liquid to vaporize, and the cooling rate can also be significantly increased. For machining process with a large amount of cutting, the temperature of the cutting fluid rises quickly, and the volume of the storage tank of the cutting fluid is required to be larger, and the cycle period of the cutting fluid is prolonged to avoid excessively high temperature of the cutting fluid.

The cooling effect of the cutting fluid is affected by the permeability of the cutting fluid. The cutting fluid with good permeability can cool the cutting edge fast. The permeability of cutting fluid is related to the viscosity and wettability of cutting fluid. The permeability of low-viscosity oil is better than that of high-viscosity oil, the permeability of oil-based cutting fluid is better than that of water-based cutting fluid, and the permeability of water-based cutting fluid containing surfactants is greatly improved.

The wettability of the cutting fluid is related to the surface tension of the cutting fluid. When the surface tension of the liquid is high, the liquid shrinks on the solid surface to form droplets. This liquid has poor permeability; when the surface tension of the liquid is low, the liquid is expanding to surroundings on the solid surface, the contact angle of solid-liquid-gas is very small or even zero which means the permeability of the liquid is good. The liquid can quickly expand the gap between cutting tool and the workpiece, and between cutting tool and the cutting surface, which can enhance cooling effect.

3.Rust prevention: ensure that the workpiece, machine tool, and mold are not corroded

During the cutting process, if the cutting fluid does not have certain anti-rust ability, the workpiece will be corroded by moisture in the air and corrosive media after processing or during storage processes, resulting in chemical corrosion or electrochemical corrosion, causing rust ,then the CNC machine will also rust. Therefore, the cutting fluid must have good anti-rust performance.

Oil-based cutting fluids generally have a certain anti-rust ability. If the storage period between processes is not long, rust inhibitors can be omitted, because the addition of additives such as barium petroleum sulfonate to the cutting oil will reduce the anti-wear performance of the cutting fluid. If cutting oil with good rust resistance is required, 0.1~0.2% of T746 rust inhibitor can be added. The small amount of addition has little effect on the lubricity of cutting fluid. Non-ferrous metals such as copper and aluminum can have a good anti-corrosion effect by adding a small amount of metal deactivator. For water-based cutting fluids, the control of pH value has a great influence on its anti-rust performance. It has the best anti-rust effect for ferrous metals such as steel and iron in the range of pH 9~9.5, and it is more suitable for non-ferrous metals such as copper and aluminum in the range of 7~8.

The cleaning and anti-rust process of the workpiece processed with water-based cutting fluid before packaging and sealing is very important. Generally, it must be dehydrated and anti-rust cleaned before applying anti-rust oil. If water and impurity particles of the workpiece are not cleaned, even the best anti-rust oil will quickly rust. Accidents of rusting parts and products due to improper cleaning and rust prevention processes often occur.

4.Cleaning: reduce surface residue

During the metal cutting process, it is easy for chips, iron powder, grinding chips, oil stains, etc. to be adhere to the surface of the workpiece and the tool, affecting the cutting effect, and at the same time, making the CNC machine and the workpiece dirty and difficult to be clean. Therefore, the cutting fluid must have cleaning performance.

For oil-based cutting fluids, the lower the viscosity, the stronger the cleaning ability. Especially cutting oils containing light components such as kerosene and diesel have better cleaning and penetration performance. Water-based cutting fluids containing surfactants have better cleaning effects. On the one hand, surfactants can adsorb various particles and sludge, and form an adsorption film on the surface of the workpiece to prevent particles and sludge from being adsorbed on the workpiece, tools and grinding wheels; on the other hand, surfactants can penetrate into the interface where the particles and oil are adhered to separate particles and oil from the interface and they are carried away by the cutting fluid.

The cleaning effect of the cutting fluid should also be manifested in the good separation and sedimentation function of cutting chips, wear debris, iron powder, oil stains, etc. After the circulating, cutting fluid is returned to the coolant tank, it can quickly make the cutting chips, abrasive chips, iron powder, particles, etc. settle at the bottom, and oil dirt and other substances can be suspended on the liquid surface, so as to ensure that even the cutting fluid is used repeatedly, it can still keep clean, ensure processing quality and extend service life.

The oil drainage of fully synthetic water-based cutting fluid and semi-synthetic microemulsion is very important. If the synthetic cutting fluid and semi-synthetic microemulsion have poor oil drainage, they will soon be mixed with the oil leaking from the CNC machine or the oil brought in by the workpiece to become an emulsion, losing the characteristics of the original cutting fluid, and after becoming an emulsion. It is easy to be corroded by microorganisms, be decayed and deteriorated, affecting the processing effect and service life.

5.Debris sedimentation and filterability: Debris can settle right there when reaching the tank or central system instead of in the pipeline, and can be easily filtered out by filter cloth etc.

The ability of the metal cutting fluid to settle metal particles or chips is an important performance of the cutting fluid, and it is essential to maintain the excellent processing performance of the cutting fluid. The metal cutting fluid carries debris from the processing area to the tank or central system tank area, where the debris settles and is removed. If the metal cutting fluid suspends the debris, the debris will circulate, scratch the metal surface and affect the roughness. Another possibility is that the metal working fluid causes the metal powder to settle too fast. The metal powder is deposited in the CNC machine or deposited in the return pipe filling the liquid return groove or pipe.

The sedimentation of debris is generally determined by adding a certain weight of metal powder to a shaker bottle containing a half of the measuring foam, shaking the bottle, and then recording the time when the metal powder is separated from the metal cutting fluid. At the same time, observe whether the debris settles or floats to the liquid.

The filtration experiment is done by the selected filter medium, vacuum filter the mixture of liquid or metal scraps, the time to pass the filter medium, whether the flow is continuous or blocked due to filter clogging, and can be used to evaluate metalworking fluid products.

In addition to the above basic functions, metalworking fluids must have the following properties: corrosion resistance, corruption inhibition, water quality adaptability, paint adaptability, stability, defoaming, safe and non-toxic, low odor and non-irritating, and easy post-processing.

6.Stability: Long service life and stable performance

7.Environmental protection: human body and environment friendly

2.5. Influence of workpiece material

①Many factors existing in the workpiece material itself, such as mechanical properties, heat treatment process, various chemical components, degree of hardening treatment, etc., are the main factors affecting the cutting force. Under the same heat treatment state, the cutting force of cutting alloy steel is greater than that of carbon steel.

②The workpiece material will be interfered by many factors during processing, such as hardness, strength, impact, elastoplastic deformation, hardening, etc., which are all factors that affect the cutting force. The higher the strength and hardness of the workpiece material to be processed, the greater the T_S. Although the deformation coefficient ξ has been reduced, the overall cutting force is still increased.

③The physical mechanical properties of the workpiece material are also the factors that affect the cutting force.

Studies have shown that a workpiece material with high strength and hardness values has a greater shear strength value. If the cutting thickness is too large, the coefficient of friction related to each processing surface of the tool will be large, so the cutting force will continue to increase.

During cutting process, if it is a brittle material such as gray cast iron, a lot of crushing iron filings will be generated during cutting process. When the iron filings flow through the rake face of the tool at high speed, the contact time between them and length of the iron filings will affect the friction. If the contact time is too short during this process, the cutting force will be smaller. In addition, the high temperature generated by the workpiece material itself during cutting process will also affect the cutting force.

2.6. The influence of tool geometry parameters

Tool geometry parameters include tool geometry angle, cutting edge form, cutting edge shape and face form, etc. Reasonable tool geometry parameters can ensure the quality of processed workpiece, extend tool life, increase production efficiency, and reduce production costs.

2.6.1. Rake angle γ_0

The rake angle has a greater influence on the cutting force. When cutting plastic materials, the cutting force decreases as the rake angle increases. Because as the rake angle increases, the deformation coefficient decreases and the resistance of chip flow decreases. The influence of the rake angle on the cutting force decreases with the increase of cutting speed. When cutting brittle materials, due to the small cutting deformation, the rake angle has no significant effect on the cutting force.

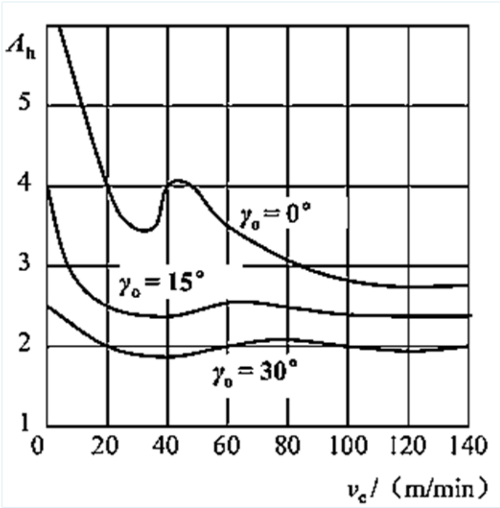

Figure 2-12 Relationship between rake angle and cutting speed

The relationship between deformation coefficient and rake angle is shown in the figure 2-13

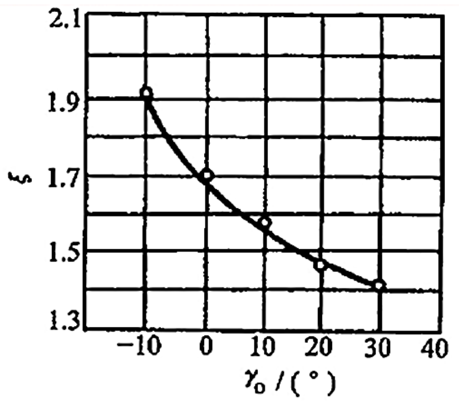

Figure 2-13 Relationship between deformation coefficient and rake angle

2.6.1.1. Selection of rake angle

1. The function of the rake angle

The rake angle affects cutting deformation and friction, thereby affecting cutting force, cutting heat and cutting power. It also affects the sharpness of the tool, and at the same time affects the strength of the cutting edge and the cutter head and the heat dissipation conditions of the cutter head.

2. The effect of increasing the rake angle

①Reduce chip deformation, cutting force, cutting temperature and power consumption

②It can improve the friction of chips on the rake face, reduce tool wear, and improve tool durability.

③It can improve the quality of the machined surface, suppress the generation of built-up edge, and reduce cutting vibration.

If the rake angle is too large, it will weaken the strength of the cutting edge, reduce the heat dissipation volume, and cause the heat effect to be concentrated, and the local temperature of the cutting area will increase, which will easily cause tool damage and wear.

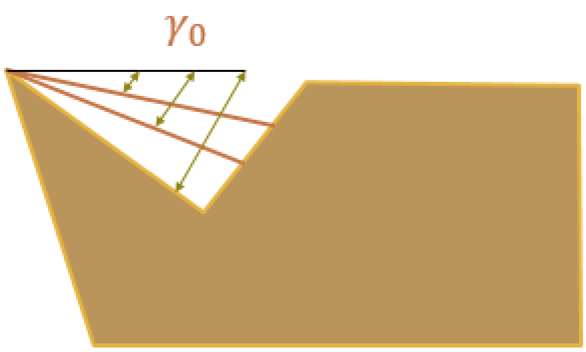

Figure 2-14 Different size of rake angle

When the value of the rake angle of the tool is increasing, the degree of deformation of the metal material being machined will be reduced, and the possibility of changes in the compression ratio of the cutting thickness itself will be reduced. The friction between tool and chips will also decrease. Therefore, the cutting force will be reduced.

However, the increase in the rake angle of the tool itself will also have a significant impact on materials with large plastic deformation (such as aluminum, copper, etc.), that is, the degree of plastic deformation of the metal material itself and the degree of hardening during processing will be significantly reduced, causing the cutting force to drop a lot; and when cutting brittle metal materials such as gray cast iron or brittle copper, the possibility of plastic deformation is very small, so the cutting force is not affected by the rake angle.

3. Selection principle of rake angle

According to the material of the workpiece

For workpieces of different materials, the rake angles used in cutting process are different.

Large rake angle for processing plastic materials

Smaller rake angle for brittle materials

The reasonable rake angle of cutting steel is larger than that of cutting cast iron

The reasonable rake angle for cutting medium-hard steel is smaller than cutting soft steel

When processing high-strength steel, hardened steel, and high-speed steel, a small rake angle should be selected

According to the tool material

For different tool materials, the rake angle used in cutting is different.

Cemented carbide has low bending strength and poor impact toughness, so the reasonable rake angle should be smaller.

High-speed steel tools have higher bending strength, so the reasonable rake angle should be larger.

According to processing requirements

When roughing, interrupted cutting or cutting extra-hard materials, in order to ensure the strength of the cutting edge, a smaller rake angle or even a negative rake angle should be used.

When finishing, choose large rake angle.

When the process system is not rigid enough, easy to cause vibration, a smaller rake angle should be selected.

2.6.1.2. The form and selection of rake face

1. Chamfer

Chamfering refers to a small edge surface with a negative rake angle that is ground along the cutting edge on the rake face. Chamfering can increase the strength of the blade and enhance the heat dissipation capacity, thereby improving the durability of the tool.

There are two parameters for chamfering: chamfering front angle and chamfering width.

Chamfered front angle

Its value is related to the tool material. The angle of high-speed steel tools generally equals to 0°, and the angle of cemented carbide tools generally equals to -15°~-5°.

Chamfer width

It is related to processing properties and feed rate. When the process is rough machining and feed rate is large, we take the larger value; When the process is finishing machining and feed rate are small, generally $b_{\gamma 1} = 0.2 \sim 1mm$.

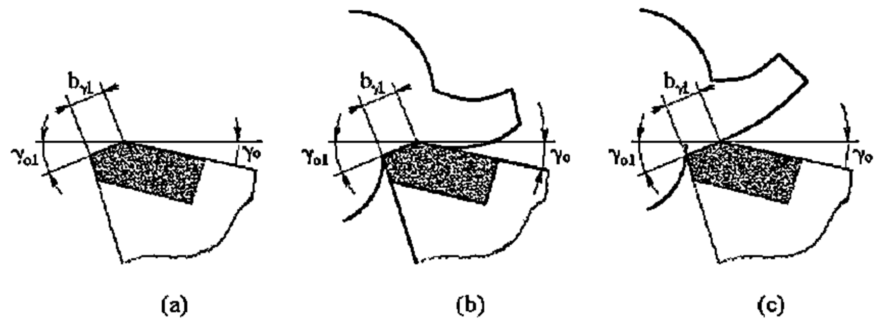

Figure 2-15 Rake angle and chamfer width

2. The form of rake face

①Positive rake angle flat type

Features: Simple manufacturing can obtain a sharper edge, but it has low strength and poor heat transfer ability. Generally it is used for finishing tools, forming tools, milling cutters and brittle materials.

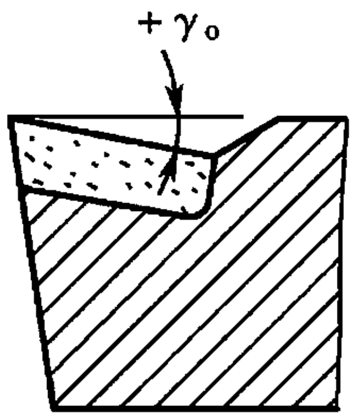

Figure 2-16 Positive rake angle

②Positive rake angle plane with chamfered

At this time, the chips still flow out along the rake face and not along the chamfer. When cutting plastic materials, we select the value according to $b_{\gamma1} = (0.5 \sim 1.0)f$、$\gamma_{01} = -15^{\circ} \sim -5^{\circ}$. This type of rake face is used for rough cut castings and forgings or intermittent surface processing.

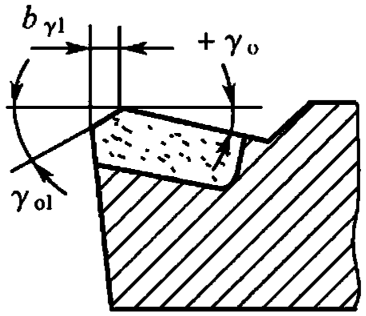

Figure 2-17 Positive rake angle plane with chamfered

③Rake angle surface with chamfer

This type is formed by grinding a certain curved surface on the rake face, on the basis of the chamfering of the positive rake angle plane, in order to curl up the chip and increase the rake angle. It is often the same as tools for roughing or finishing plastic materials.

The parameter of the chip flute is approximately $lB_n = (6\sim8)f, rB_n = (0.7\sim0.8)lB_n$.

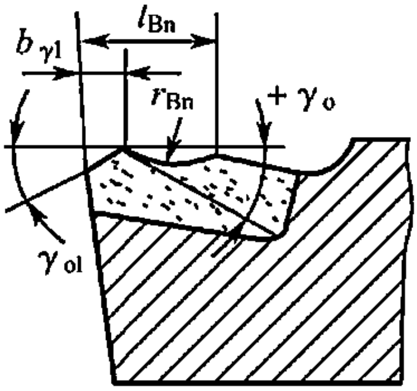

Figure 2-18 Rake angle surface with chamfer

④Negative rake angle single side

When the wear mainly occurs on the flank face, it can be made into a negative rake angle single-sided type. At this time, the blade bears the compressive stress and has good blade strength. Therefore, it is often used for cutting materials with high hardness and hardened steel materials, but a negative rake angle will increase the cutting force.

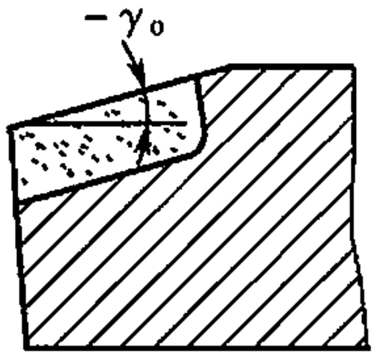

Figure 2-19 Negative rake angle single side

⑤Negative rake angle double-sided type

When the wear occurs on both the front and rear blade faces at the same time, a negative rake angle double-sided type is made, which can increase the number of regrinding of the blade. At this time, the edge face of the negative rake angle should have sufficient width to ensure that the chips flow out along the edge.

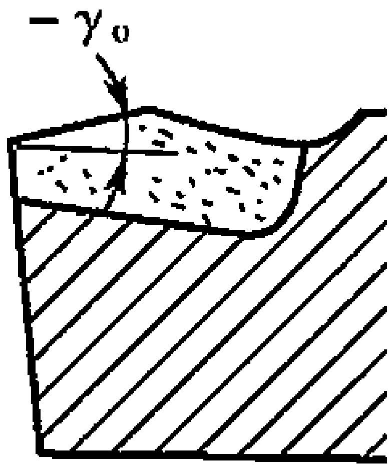

Figure 2-20 Negative rake angle double-sided type

2.6.2. Back angle α_0

2.6.2.1. selection of back angle

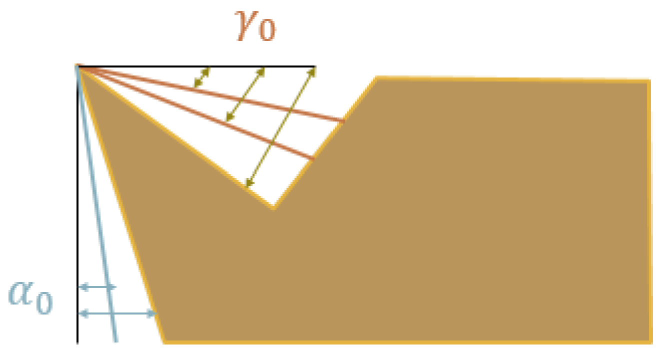

Figure 2-21 Back angle

1. The function of the back angle

①The main function of the relief angle is to reduce the friction between the flank face and the machined surface, reduce tool wear, and improve the surface quality of the workpiece.

②Working with the rake angle, the larger the relief angle, the smaller the blunt radius of the cutting edge and the sharper the cutting edge.

③Affect the strength and heat dissipation volume of the cutting edge and cutter head

2. The effect of increasing the clearance angle

It can reduce the friction between the flank face and the machining surface of the workpiece, thereby reducing tool wear and improving the quality of the machining surface and tool durability. The blunt radius r_n of the cutting edge can be reduced to make the cutting edge sharp, so that the friction is further reduced, the wear is reduced, and the tool durability can be improved, quality of the processed surface is also improved.

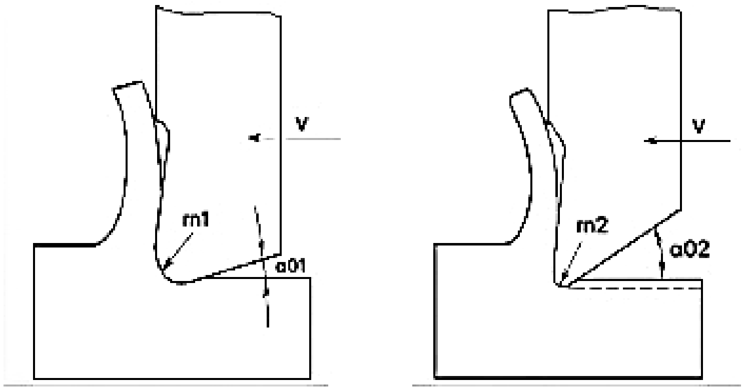

Figure 2-22 Effect of increasing the clearance angle

$$\alpha_{01} < \alpha_{02}$$
$$r_{n1} > r_{n2} \qquad (2-4)$$

Increasing the clearance angle, under the same blunt standard VB condition, the tool is used from new sharpening to blunt, allowing a larger volume of metal to be removed, which is beneficial to improve the durability of the tool. But the larger the clearance angle is, the radial wear value NB of the tool will increase under the same blunt standard condition. Therefore, for some finishing tools, when the requirements of dimensional accuracy is high, it is not advisable to use a large clearance angle according to the general principle.

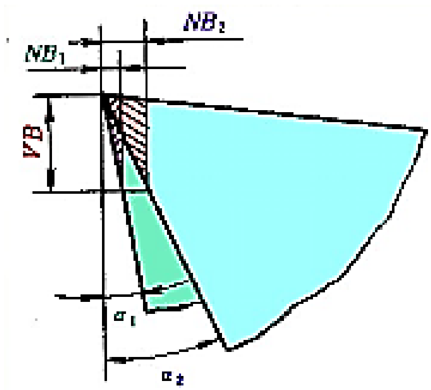

Figure 2-23 Increasing the clearance angle

3. The principle of rear angle selection

During rough machining process, for cutting tools with strong cutting force and impact load, in order to increase the tool strength, the clearance angle should be smaller.

During finishing, increasing the relief angle can improve the tool durability and the quality of the machined surface.

When the hardness and strength of the workpiece material are high, a smaller relief angle is used to ensure the strength of the cutter head.

When the hardness and strength of the workpiece material is low, and the plasticity is large, the relief angle should be appropriately increased.

When processing brittle materials, the cutting force is concentrated near the cutting edge, and a smaller relief angle is better.

When using a negative rake angle, take a larger relief angle to ensure that the cutting edge is relatively sharp.

The fixed-size tool has a smaller relief angle to prevent the tool size from changing after regrinding.

In order to reduce the cost of regrinding, it is advisable to appropriately reduce the clearance angle for regrinding tools.

2.6.2.2. Flank selection

①Double flank

In order to ensure the strength of the cutting edge and reduce the workload of sharpening the flank, a double relief angle is often ground on the flank of the turning tool.

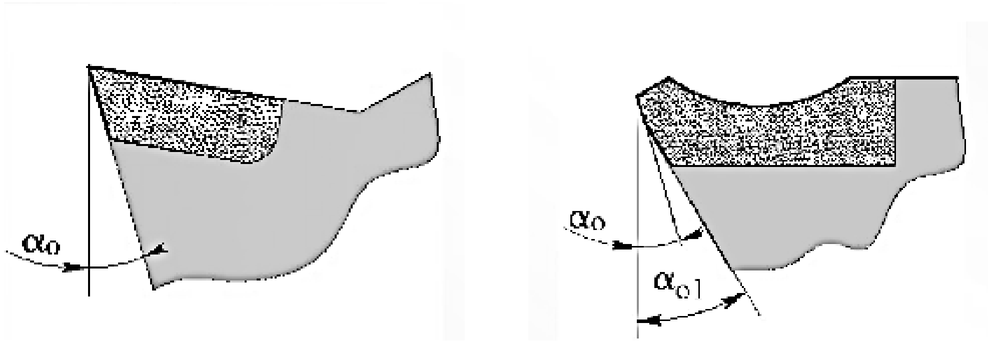

Figure 2-24 Double flank

②Cutting edge

A small edge surface with a clearance angle of zero degree is ground on the flank surface to stabilize, guide, absorb vibration and strengthen the cutting edge. The width of the cutting edge should not be too wide, otherwise it will increase the friction.

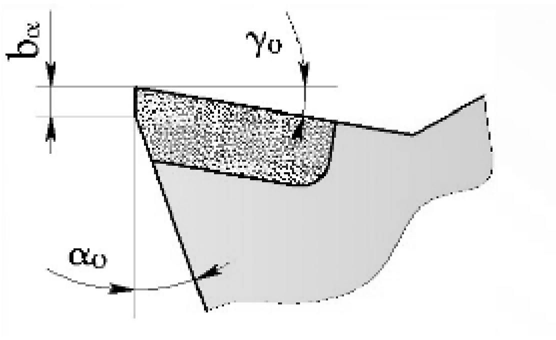

Figure 2-25 Cutting edge

③Damping edge

It refers to a small edge surface with a negative clearance angle ground along the cutting edge on the flank surface, which has the effect of strengthening the cutting edge, reducing tool wear and absorbing vibration.

It has two parameters: the back angle of the damping edge and the width of the damping edge.

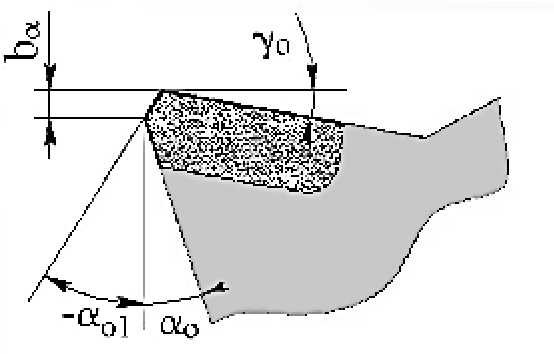

Figure 2-26 Damping edge

2.6.3. Tool cutting edge angle k_r and tool minor cutting edge angle k_r'

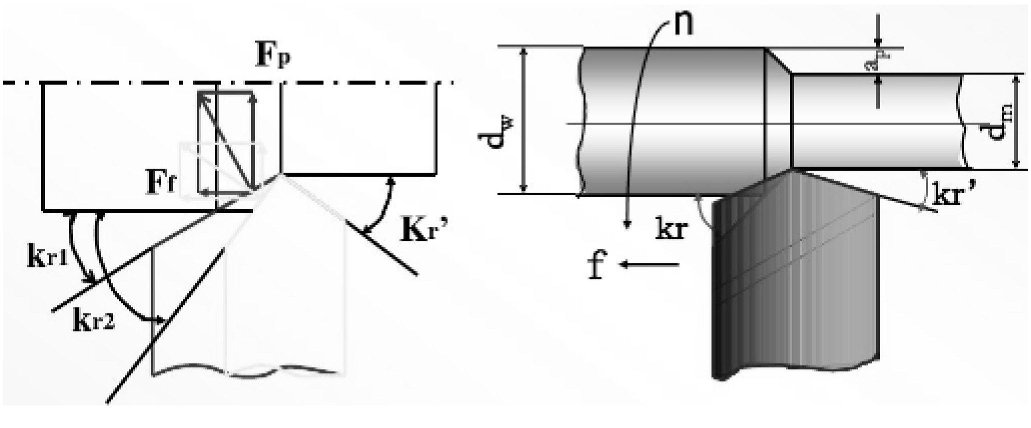

Figure 2-27 Tool cutting edge angle and tool minor cutting edge angle

2.6.3.1. Choice of tool cutting edge angle

The tool cutting edge angle has little effect on the main cutting force. When the angle is 60°~75°, Fc is the smallest. Therefore, in actual production, the value of the angle k_r is often equal to 75°. The back force F_p and the feed force F_f have a greater impact. If the angle k_r

increases, then the back force F_p decreases, and the feed force F_f increases.

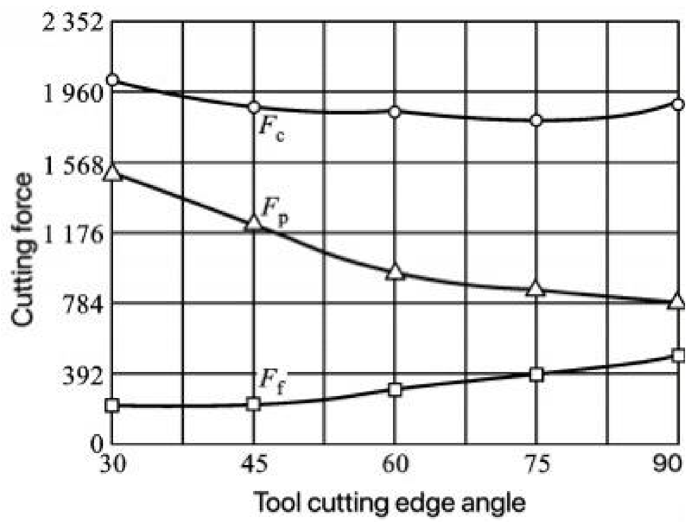

Figure 2-28 Influence of tool cutting edge angle on the cutting force

1. The effect of tool cutting edge angle on the cutting process

①The change of the angle k_r affects the ratio of each cutting component force and the possibility of vibration.

Decrease the angle k_r, the back force F_p will increase, and the feed force F_f will decrease. When the rigidity of the process system is poor, if k_r is reduced too much, causing significant increase of F_p, it may cause vibration, damage the tool, top bend the workpiece.

②The change of k_r affects the shape of the cutting section.

In the case of a certain cutting depth and feed rate, as the k_r angle decreases, the cutting thickness will decrease, the cutting width increases, the length of the cutting edge participating in the work increases, the load per unit length of the cutting edge will decrease, and the tool included angle increases , then this will increase the strength of the tool tip, improve the heat dissipation conditions, and thus increase the durability of the cutting tool.

③k_r affects the surface shape of the workpiece.

When turning a stepped shaft, $k_r = 90^{\circ}$ should be selected, and when turning the outer end face and chamfering, you can select$k_r = 45^{\circ}$.

④The size of the k_r also affect the effect of chip breaking.

The larger the k_r, the larger the cutting thickness and the smaller the cutting width, the easier it is to break chips.

④The size of the k_r may also affect the height of the residual area.

When the straight part of the main cutting edge participates in the formation of the residual area, reducing k_r can improve the surface finish of the processing.

Residual area refers to the cross-sectional area of the uneven part remaining on the machined surface after the tool was cut, when the tool minor cutting edge angle is not zero.

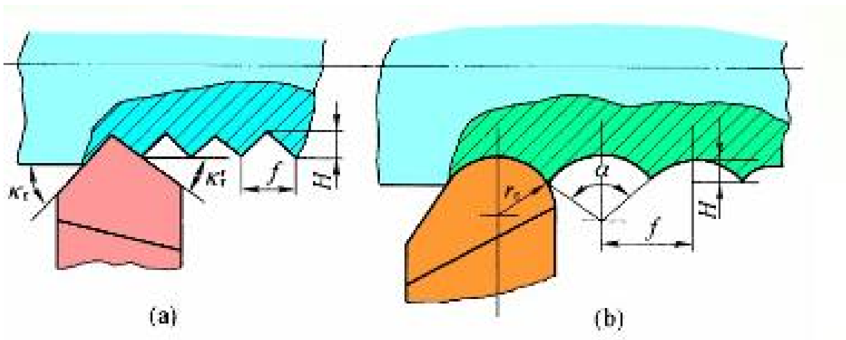

Figure 2-29 The residual area of the workpiece surface during turning

⑤The size of k_r affects the cutting conditions and thus affects the cutting impact.

2.The selection principle of tool cutting edge angle

We should make a reasonable choice according to the workpiece shape or process requirements.

①When the rigidity of the process system is insufficient, a larger angle should be selected.

②When the workpiece material has high strength and hardness, in order to reduce the load on the unit cutting edge, increase the strength of the tool tip, improve the heat-receiving conditions, and improve the durability of the tool , we should take the smaller angle $k_r = 10^{\circ} - 30^{\circ}$.

③In order to prevent vibrations during high-speed and powerful cutting process, a large angle should be selected, generally $k_r > 15^{\circ}$.

2.6.3.2. The choice of tool minor cutting edge angle

1.The influence of tool minor cutting edge angle on the cutting process

①Reducing the angle k_r' can enhance the strength of the tool tip and improve the heat dissipation conditions.

②Reducing the angle k_r' can significantly reduce the residual area after cutting and improve the surface finish.

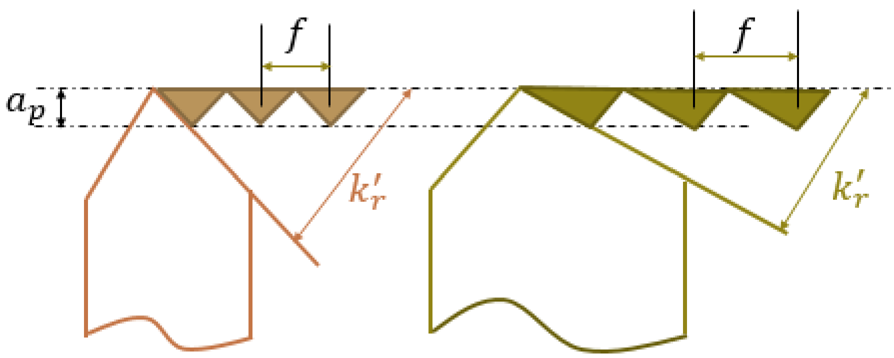

Figure 2-30 Influence of k_r' on the residual area

③But if k_r' is too small, it will increase the working length of the negative cutting edge and increase the friction between the secondary flank face and the machined surface, which will easily cause vibration and increase the surface roughness value.

2. The selection principle of tool minor cutting edge angle

It depends on the surface finish of the workpiece and the specific processing conditions.

Under the premise of not causing vibration, the tool minor cutting edge angle is usually a small value. In general, choose $k_r' = 10^{\circ} - 15^{\circ}$; For special cases, such as a cutting knife, in order to ensure the strength of the cutter head, you can choose $k_r' = 1^{\circ} = 2^{\circ}$.

2.6.4. Tool cutting edge inclination angle λ_S

1.The function of λ_S

①Affect the direction of chip removal.

When the value of λ_S is negative, the chips flow out to the machined surface; When it is a positive value, the chips flow out to the surface to be machined; when $\lambda_S = 0^{\circ}$, the chips flow out perpendicular to the cutting edge.

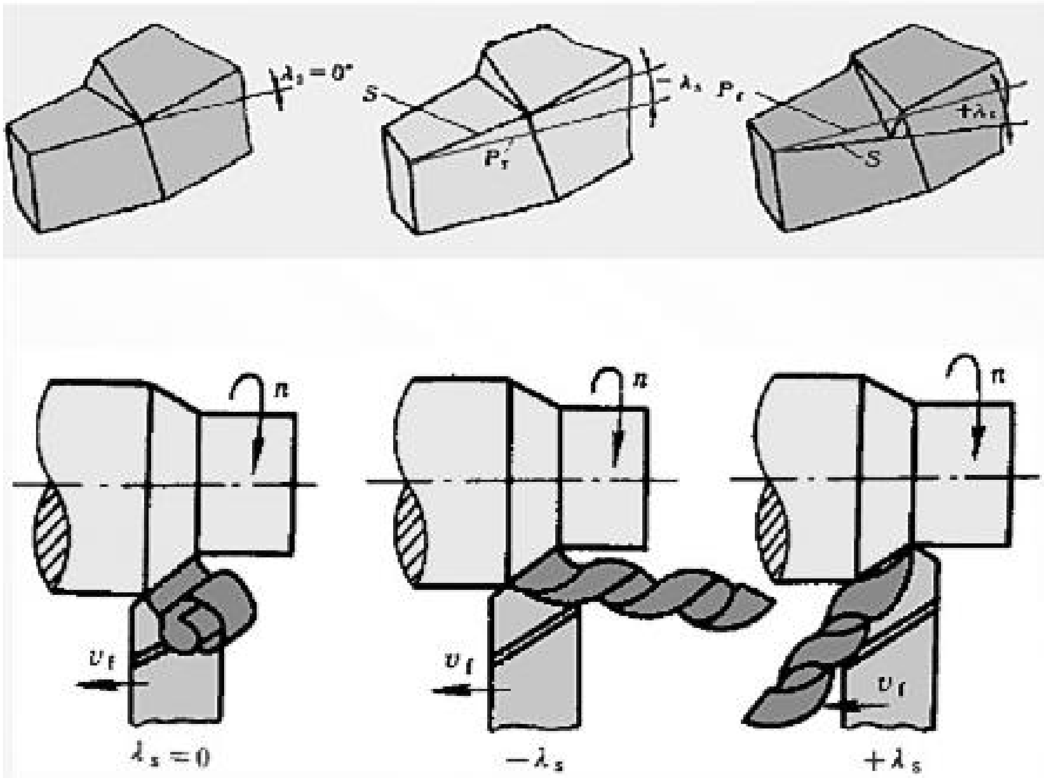

Figure 2-31 The influence of λ_S on the direction of chip removal

②Affecting the strength of the cutter head and heat dissipation conditions

The negative tool cutting edge inclination angle can enhance the strength of the cutter tip. When cutting in, the cutting edge of the far part of the tool tip first contacts the workpiece, instead of starting from the tool tip, it improves the heat dissipation condition and improves the durability of the tool.

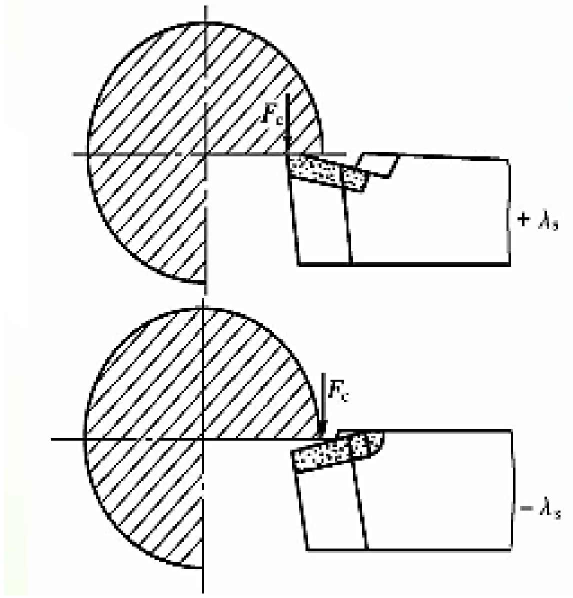

Figure 2-32 negative tool cutting edge inclination angle

③Control the smoothness of the cutting edge when cutting in and cutting out.

If the tool cutting edge inclination angle λ_S is not equal to zero, the points on the cutting edge will gradually cut into the workpiece and gradually cut away from the workpiece, so the cutting process is stable.

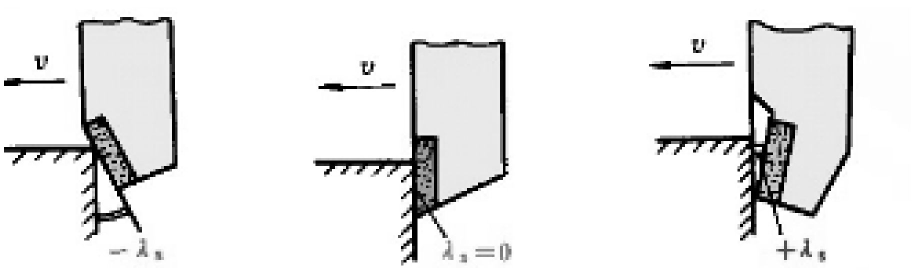

Figure 2-33 Different tool cutting edge inclination angle

2. The selection principle

The principle of selecting the tool cutting edge inclination angle is mainly determined by the tool strength, chip removal direction and processing conditions.

①In order to ensure the strength of the tool during rough machining, usually select a smaller value for the tool cutting edge inclination angle. $\lambda_S = -5^{\circ} \sim 0^{\circ}$.

②During finish machining, in order to improve the surface quality of the workpiece and prevent the chips from flowing to the machined surface, generally the value of the tool cutting edge inclination angle should be larger. $\lambda_S = 0^{\circ} \sim 5^{\circ}$.

③When there is an impact load, $\lambda_S = -15^{\circ} \sim -5^{\circ}$.

④When turning hardened steel, $\lambda_S = -12^{\circ} \sim -5^{\circ}$.

⑤When fine turning the outer circle and fine turning the hole , $\lambda_S = 45^{\circ} \sim 75^{\circ}$.

⑥If the system has poor rigidity, it is not suitable to choose negative tool cutting edge inclination angle during cutting process.

3. Chapter 3 Tool wear and life of tool

3.1. Effects of tool wear

Tool wear directly leads to the increase of cutting force, which results in the increase of the vibration of workpiece-tool system and the noise. At the same time, there will be strong relative vibration between the workpiece and the tool, which makes the machining in an unstable state. These factors greatly reduce the service life of cutting tool, and directly damage the accuracy of CNC machine.

Tool wear will also affect the roughness of the workpiece and the size of the workpiece, resulting in poor dimensional accuracy of the workpiece. In order to ensure the dimensional accuracy, it is necessary to frequently stop cutting process to do measurement and determine the compensation amount of tool or the time to change the tool, which will inevitably cause the increase of the processing auxiliary time and reduce productivity, in the meanwhile, greatly reduce the degree of automation of the processing.

As the tool wear is a process quantity, if we change the tool in advance before it is scrapped, that will increase the processing cost and cause unnecessary losses. If the tool is not changed in time, it will affect the quality of the workpiece, limit the cutting efficiency, increase the probability of machine failure, and cause serious consequences.

In summary, the identification and monitoring of tool wear status becomes more and more important in actual production.

3.2. Tool wear process

The tool wear process can be roughly divided into three stages as shown in the figure 3-1. The graph uses cutting time and flank wear as the abscissa and ordinate respectively.

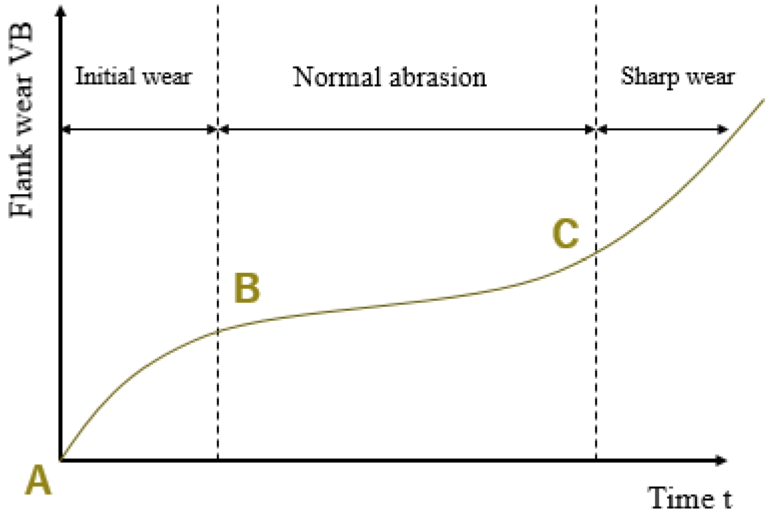

Figure 3-1 Tool wear process

The first stage is the initial wear stage, in this stage, the speed of wear is fast. This is because the newly sharpened tool, blade and the surface of cutting tool are not flat enough, so they are quickly smoothed.

The second stage is the normal wear stage, in this stage, the speed of tool wear is relatively slow, the cutting process is relatively stable, and the amount of flank wear increases approximately proportionally with the extension of cutting time.

The third stage is the sharp wear stage, after the wear value of the tool reaches a certain value, due to the increase in friction, the cutting heat will increase significantly, and the cutting force and cutting temperature will rise sharply, which will cause the cutting performance of the tool material to drop sharply, resulting in substantial wear or burning of tool, losing its cutting ability.

In general, the wear process of high-speed steel tools and cemented carbide tools mostly conform to the above-mentioned laws. For some tool materials with good heat resistance and wear resistance but poor bending strength and impact toughness, such as ceramics, cubic boron nitride and some cemented carbides, they tend to collapse due to increased cutting force and vibration before the rapid wear stage.

3.3. Main methods of monitoring tool condition

Currently the general way of tool wear monitoring is measuring and comparing some signals such as cutting force, cutting heat, acoustic emission, vibration, motor current and power to distinguish the tool wear. If these signals are detected being changing, it means that the state of the tool may have changed.

There are two methods of tool condition monitoring: direct method and indirect method. The direct monitoring method measures the wear of the cutting edge of the tool and the damage on the front and flank surfaces by analyzing optical and image processing technology. The indirect method refers to measure the signals related to the tool wear and breakage status and then extracting characteristic values that characterize the tool condition through signal processing.

Table 3-1 Two methods of tool condition monitoring

Monitoring method	Sensor	Working principle	Application and features
	Optical fiber, camera	Observe the light reflected from the worn surface or take a video with a camera	It could be used for various types of processing, but it is expensive.
Direct method	Probe, magnetic gap sensor	Monitoring the position of cutting	Used for turning, drilling, milling,

		edge	but it is easily affected by temperature and cutting process.
	Radioactive elements	Inject isotope into cutting tool to measure the radioactivity in the chips	It is Used for various cutting processes, which are harmful to the human body
	Thermocouple	Measure the amount of sudden increase of cutting temperature between workpiece and tool	Used for turning, but it has low sensitivity, therefore, it cannot be used in the presence of coolant
Indirect method	Laser sensor, infrared sensor	Measure the change of surface roughness	Used for turning, milling, but it is non-real-time monitoring, its application range is small.
	Ultrasonic Heater and Receiver	Receive the reflected wave of the active ultrasonic wave	Used for turning and milling, it could be affected by cutting vibration
	Accelerometer,	Monitoring vibration	Used for turning,

	vibration sensor	signal	milling, drilling, the effect of being used independently is poor, and it is easily affected by the environment
	Force sensor	Monitoring cutting force	It is used for turning, milling, drilling, and has high sensitivity

3.4. The life of cutting tool

Tool life is the net cutting time between the beginning of cutting and reaching the blunt standard. It is represented by T. Tool life is used as the standard to measure the material machinability, cutting performance, and rationality of geometric parameters in metal cutting process.

Considering the influence of cutting speed, feed amount and back engagement amount, we obtain the relationship between cutting amount and tool life:

$$T = \frac{C_V}{{V_C}^{\frac{1}{m}} f^{\frac{1}{n}} {a_P}^{\frac{1}{p}}} \qquad (3-1)$$

Table 3-2 Parameters in formula 3-1

C_V	Service life factor, which is related to workpiece material, tool material and processing conditions
m	It shows the degree of influence of cutting speed on tool life
n	The influence index of feed amount on tool life
p	The influence index of back engagement on tool life

4. Chapter 4 Cutting heat and cutting temperature

In the metal cutting process, most of the power consumed by the tool for cutting is converted into heat, which we call the cutting heat. During the metal cutting process, the generated cutting heat will gradually increase the temperature of the entire cutting area, which in turn affects the wear of the entire tool and the dimensional accuracy of the workpiece, resulting in the appearance of scrap parts.

4.1. Generation and conduction of cutting heat

During the cutting process, the generation and transmission of cutting heat is shown in the figure. Cutting heat comes from three aspects:

The shear deformation heat of the cutting layer, the friction extrusion deformation heat between the bottom layer of chips and the tool, and the friction extrusion deformation heat of the tool and the machined surface. Therefore, the temperature field in the cutting zone can be divided in: shear zone temperature field, tool-chip contact zone temperature field and tool-workpiece contact zone temperature field.

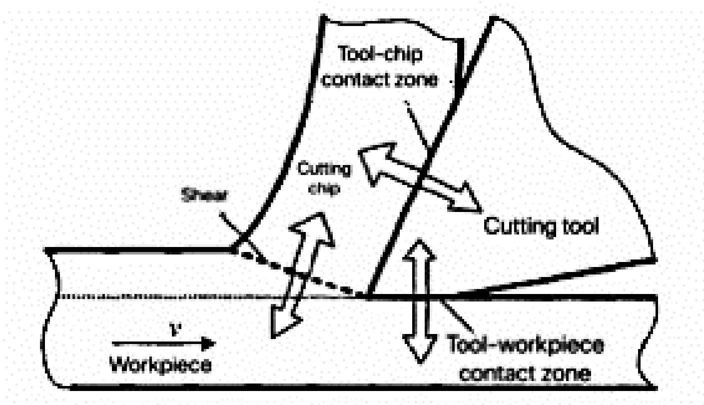

Figure 4-1 Generation and transmission of cutting heat

If we neglect the power consumed by the feed motion, and assuming that all the power consumed by the main motion is converted into heat, the cutting heat generated per unit time can be calculated by the following formula:

$$Q = F_C V_C \qquad (4-1)$$

Table 4-1 Parameters in formula 4-1

Q	Cutting heat (J/s)
F_C	Main cutting fore (N)
V_C	Cutting speed (m/s)

4.2. Cutting temperature

4.2.1. The influence of cutting amount on cutting temperature

The empirical formula of cutting temperature is as follows:

$$\theta = C_\theta {V_C}^{z_\theta} f^{y_\theta} {a_p}^{x_\theta} \qquad (4-2)$$

Table 4-2 Parameters in formula 4-2

C_θ	Coefficient of cutting temperature
$z_\theta, y_\theta, x_\theta$	Corresponding index

4.2.2. The influence of tool geometry parameters on cutting temperature

Rake angle γ

During the cutting process, the deformation of the workpiece and the friction between the workpiece and cutting tool will change due to the changing of the rake angle. If the rake angle increases, the cutting temperature will decrease; otherwise, the cutting temperature will increase. When the value of rake angle is about 20°, the influence of cutting temperature will be much smaller at this time, because smaller wedge angle will reduce the heat dissipation area. Therefore, the choice of tool rake angle will have a greater impact on cutting temperature.

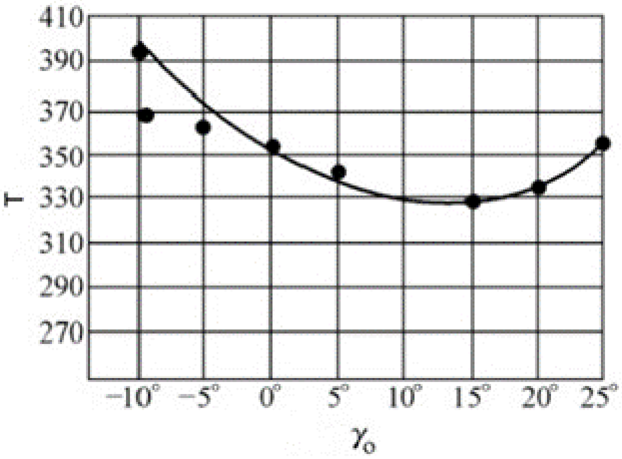

Figure 4-2 Relationship between cutting temperature and rake angle

Tool cutting edge angle k_r

When we increase the tool cutting edge angle, the actual working length of the cutting edge of the tool will become shorter, and the cutting heat will be concentrated in a certain range, if the nose angle is reduced, the heat dissipation condition will become worse, causing the cutting temperature to rise.

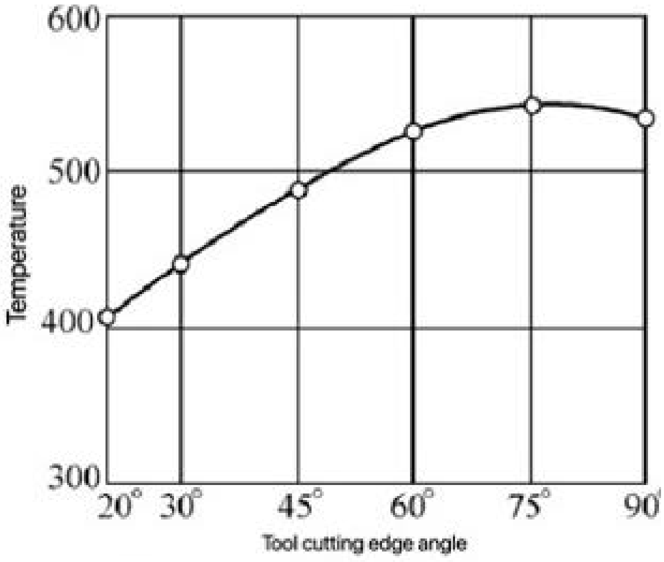

Figure 4-3 Relationship between temperature and tool cutting edge angle

4.2.3. Influence of tool wear on cutting temperature

If cutting titanium alloys with carbide tools, there are three main ways of wear: bonding wear, diffusion wear and a certain amount of abrasive wear.

Bond wear

When cutting titanium alloy, the chips stick to the tool. If the bonding phenomenon is serious, a built-up edge will be formed, which will seriously affect the life of the tool.

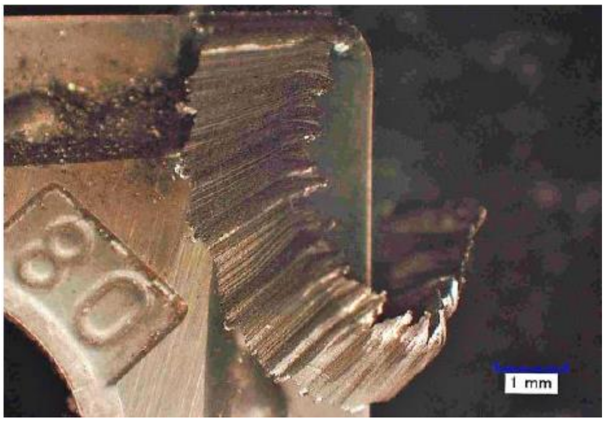

Figure 4-4 Bond wear

Diffusion wear

Under the condition of normal temperature and low speed, the speed of metal diffusion and wear is very slow. Under high-speed cutting conditions, high temperature in the contact zone, large plastic deformation and bite will greatly promote the mutual dissolution of the tool and the processed material, resulting in weakening and destruction of the surface of the tool.

Figure 4-5 shows the energy spectrum of the tool after a period of cutting. It can be seen that inter-diffusion has occurred between the elements in the tool and the workpiece. This diffusion will undoubtedly weaken the surface of the tool, so that the weakened surface of decarburization will be taken away, and the wear of the tool will be accelerated.

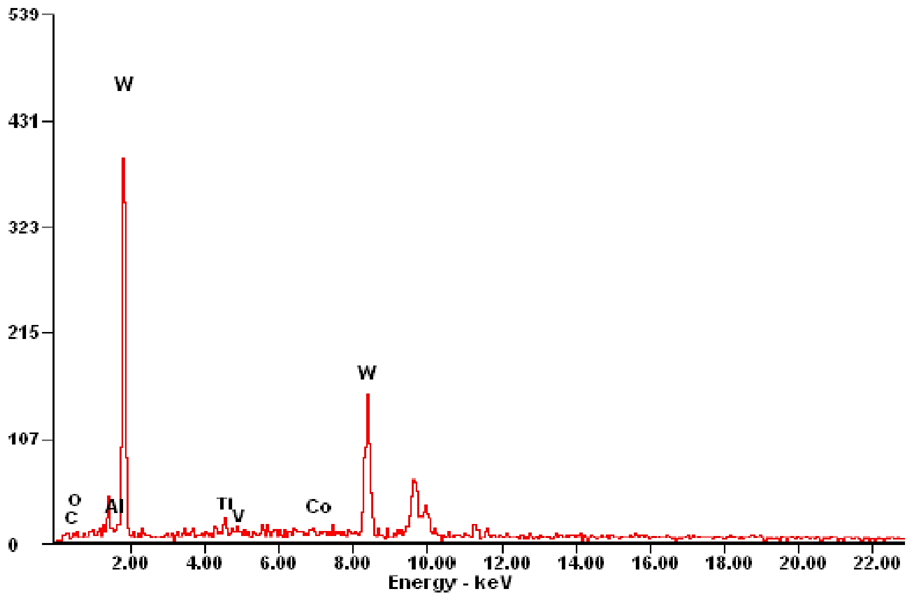

Figure 4-5 Energy spectrum of the tool

Abrasive wear

Abrasive wear is caused by the movement of some hard points on the friction surface.

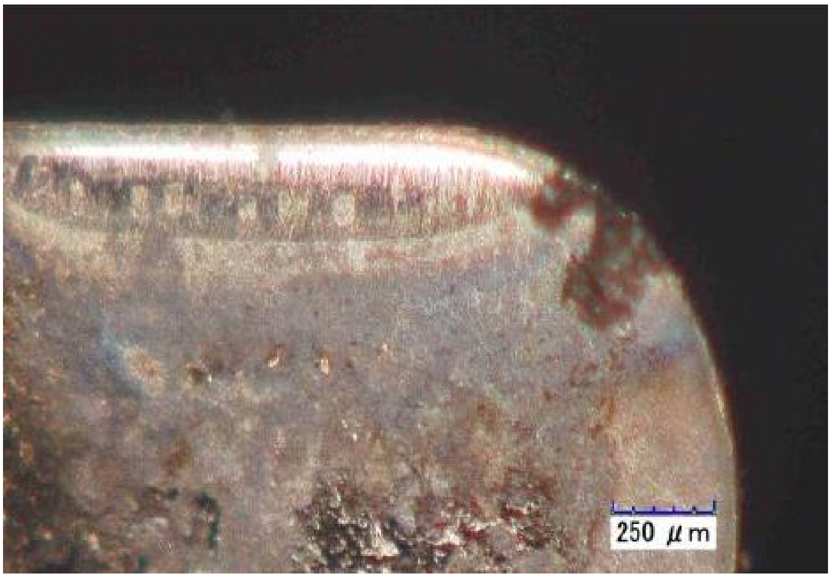

Figure 4-6 Abrasive wear

4.2.4. Influence of workpiece on cutting temperature

When the hardness and strength of the workpiece material are high, the more power will be consumed during cutting, and the more cutting heat will be generated, which will cause the cutting temperature to rise.

The thermal conductivity value of the workpiece material itself will also affect the heat dissipation.

When cutting brittle materials, such as gray cast iron, the possibility of metal deformation is very small during cutting.

However, the chip removed from the metal material will show a small crushed shape, so that the friction between the chip and the rake face of the tool will be reduced, therefore only relatively little cutting heat will be generated. On the contrary, when cutting plastic materials, the resulting cutting temperature will be higher than that of brittle materials.

4.2.5. Influence of cutting fluid on cutting temperature

In order to actively improve the heat dissipation conditions between the tool and the workpiece. During cutting, a certain amount of cutting fluid can be poured to effectively reduce the cutting temperature. Figure 4-7 shows the effect of cutting fluid on cutting temperature when drilling 45 steel with a φ21.5 drill and selecting feed rate f=0.4mm/r.

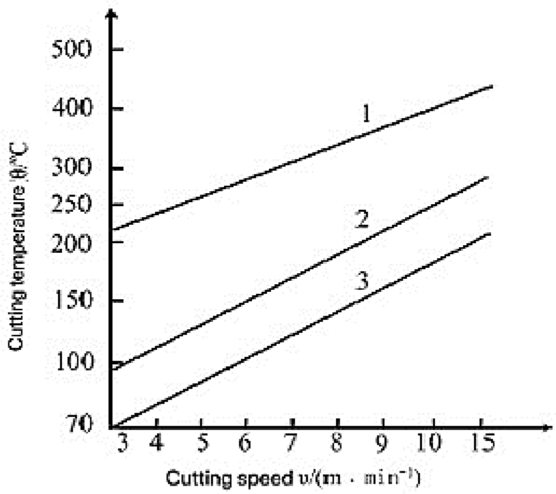

Figure 4-7 Effect of cutting fluid on cutting temperature

Table 4-3 Different cutting fluids

1	No cutting fluid
2	10% emulsion
3	1% sodium borate and 0.3% sodium phosphate aqueous solution

5. Chapter 5 The influence analysis and optimization design of compound cutter structure parameters

5.1. The establishment of optimization mathematical model

In turning processing, the choice of cutting parameters is very important. The optimized cutting parameters can enable the machine tool to obtain the maximum processing efficiency under the premise of ensuring the processing accuracy. Since cutting parameters directly affect cutting force, tool life and workpiece machining accuracy, the optimal selection of cutting parameters needs to consider many factors.

5.1.1. Objective function

The optimization goal is to improve production efficiency, that is, to obtain the maximum material removal rate. Therefore, the following objective function is established:

$$w = v \cdot a_p \cdot f = max \qquad (5)$$

Since a_p is determined by the machining allowance, it is a predetermined value and does not need to be optimized, so the objective function is transformed into:

$$\mathrm{w} = \mathrm{v} \cdot \mathrm{f} = \mathrm{max} \qquad (5-1)$$

5.1.2. Restrictions

Tool life

The constraint condition can be expressed as: actual tool life ≥ expected tool life.

The generalized Taylor formula of the relationship between cutting parameters and tool life is:

$$T = \frac{C^T}{{v_c}^x \cdot f^y \cdot {a_p}^z} \geq T_1 \qquad (5-2)$$

Table 5-1 Parameters in formula 5-2

C_T, x, y, z	They are the coefficients related to workpiece material, tool material and other cutting conditions, which can be found in the literature
T_1	Expected tool life

Cutting power

Machine cutting power can generally be calculated according to the main cutting force and cutting speed.

$$P_c = \frac{F_c v}{6120} = \frac{C_{F_c} \cdot {a_p}^{xF_c} \cdot f^{yF_c} \cdot v^{1+nF_c}}{6120} \leq P_E \cdot \eta_m \qquad (5-3)$$

Table 5-2 Parameters in formula 5-3

$C_{F_c}, xF_c, yF_c, nF_c$	They are the coefficients related to workpiece material, tool material and other cutting conditions, which can be found in the literature.
P_E	Motor Power of CNC machine
η_m	Transmission efficiency

Workpiece deformation

During the turning process, the cutting force will cause the workpiece to deform. In order to ensure the machining accuracy, the deformation of the workpiece cannot exceed the allowable value, so the following formula must be satisfied:

$$\frac{C_{F_c} \cdot a_p{}^{xF_c} \cdot f^{yF_c} \cdot v^{nF_c} \cdot \beta}{K \cdot E \cdot I} \leq \delta \qquad (5-4)$$

Table 5-3 Parameters in formula 5-4

E	The elastic modulus of the workpiece material
I	Sectional moment of inertia of the workpiece
δ	Allowable deformation of workpiece
K	k is the coefficient determined by the different clamping methods of the workpiece

Deformation of toolholder

The cutting force in turning will also cause deformation of the toolholder, and the deformation of the toolholder cannot exceed the allowable value. Using the knowledge of material mechanics, the following formula is derived:

$$\frac{4C_{F_c} \cdot a_p{}^{xF_c} \cdot f^{yF_c} \cdot v^{nF_c} \cdot L^3}{EBH^3} \leq \Delta_n \qquad (5-5)$$

Table 5-4 Parameters in formula 5-5

L	Length of Toolholder
E	The modulus of elasticity of the toolholder material
B	Sectional width of the toolholder
H	Sectional height of the toolholder
Δ_n	The amount of bending deformation of the toolholder permitted by the machining accuracy of the workpiece

Surface roughness

It is beneficial to use the exponential formula to predict the surface roughness of finishing.

$$R_z = C \cdot f^{k1} \cdot {a_p}^{k2} \cdot v^{k3} \leq R_{z1} \qquad (5-6)$$

R_{z1} is the allowable roughness of workpiece surface

Allowable feed amount and cutting speed

The optimized feed amount and cutting speed must be within the allowable feed amount and cutting speed range:

$$V_{min} \leq V \leq V_{max} \qquad (5-7)$$

$$f_{min} \leq f \leq f_{max} \qquad (5-8)$$

5.1.3. Optimization algorithm

According to the characteristic that the objective function and constraint conditions can be linearly transformed, the system adopts geometric analysis method for optimization, which is simple and reliable. Therefore, the objective function (5-1) and constraint conditions (5-2) ~ (5-8) need to perform the following operations:

$$W_1 = X_1 + X_2 = max$$

$$X_1 = lgv, X_2 = lgf$$

$$x \cdot X_1 + y \cdot Y_2 \leq lg \frac{C_T}{T_1 \cdot {a_p}^z}$$

$$(1 + nF_C)X_1 + yF_C \cdot X_2 \leq lg \frac{6120P_E \cdot \eta_m}{C_{F_C} \cdot {a_p}^{xF_C}}$$

$$nF_C \cdot X_1 + yF_C \cdot X_2 \leq lg \frac{\delta KEI}{C_{F_C} \cdot a_p{}^{xF_C} \cdot l^3}$$

$$nF_C \cdot X_1 + yF_C \cdot X_2 \leq lg \frac{EBH^3\Delta_n}{4L^3 \cdot C_{F_C} \cdot a_p{}^{xF_C}}$$

$$k_3 \cdot X_1 + k_1 \cdot X_2 = lg \frac{R_{z1}}{C \cdot a_p{}^{k2}}$$

$$lgV_{min} \leq X_1 \leq lgV_{max}$$

$$lgf_{min} \leq X_2 \leq lgf_{max} \qquad (5-9)$$

The optimization principle of this method is shown in Figure 5-1. All constraint conditions in the figure can be expressed by straight lines, and the optimized solution must be located in the area enclosed by the constraint straight lines.

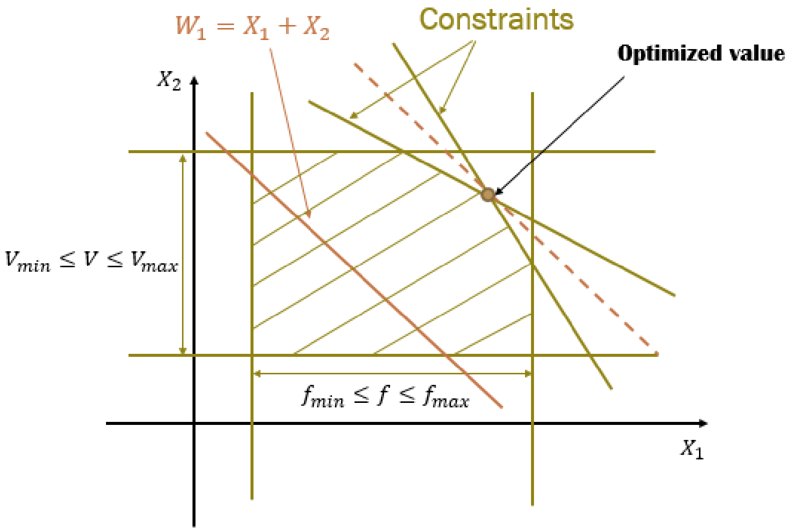

Figure 5-1 Optimized solution

5.1.4. Procedure flow chart

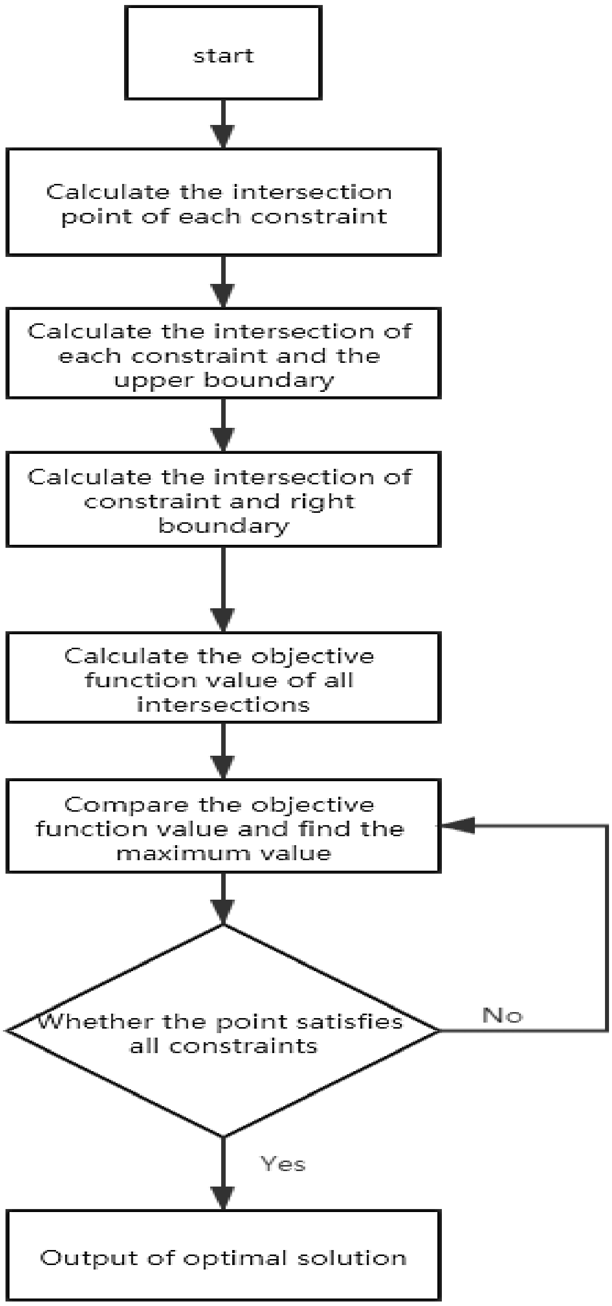

Figure 5-2 Procedure flow chart

6. Chapter 6 Monitoring of tool condition

During actual production and processing process, effective tool condition monitoring and diagnosis system can avoid damage to equipment or workpieces caused by processing abnormalities such as processing chatter, excessive tool wear, breakage, etc., reducing costs, improving production efficiency, and greatly improving economic benefits.

6.1. Monitoring methods of tool condition

Commonly used detection methods can be classified into two categories: direct method and indirect method. The direct method is to directly measure the shape change of each cutting surface of the tool, and its common methods include contact method, radiation method, optical image method, etc. The indirect method is using sensors to collect signals closely related to changes of tool status, extract effective features through signal processing, and then establish a mathematical model between tool status and signal features to achieve tool status acquisition, including force, acoustic emission, vibration, spindle and feed axis power signal detection methods.

The measurement accuracy of the direct method is high, but it needs to be stopped for detection, wastes a lot of production time, it is difficult to monitor the sudden damage of the tool in the production and processing, and the real-time performance is poor. These shortcomings hinder the wide application of the direct method. The indirect method can obtain the status information of the machining tool indirectly through a certain calibration relationship according to the changes of these signals during the cutting process, without affecting the cutting process of the tool, and can better realize the online real-time monitoring of the tool status.

6.2. Extraction method of the feature of tool condition

The sensor signal collected by the force sensor is non-stationary and in random, and contains various noise interference signals. It is not feasible to directly use these signals for online tool monitoring. Signal processing is required to extract useful features reflecting the tool status as the next step basis for classification and recognition of tool status.

Time domain analysis

The signal's time domain is represented as

$$x_t = x(t) \cdot \delta(t - \tau)dt \qquad (6-1)$$

and the pulse signal $\delta(t)$ is the basis function of the signal's time domain. The time domain signal cannot be used directly to identify and diagnose the tool condition, but through the statistics of the time domain features. The commonly used time domain features include mean, root mean square, variance, skewness, kurtosis, kurtosis, etc. Then we compare and diagnose these parameters to identify and diagnose the tool condition.

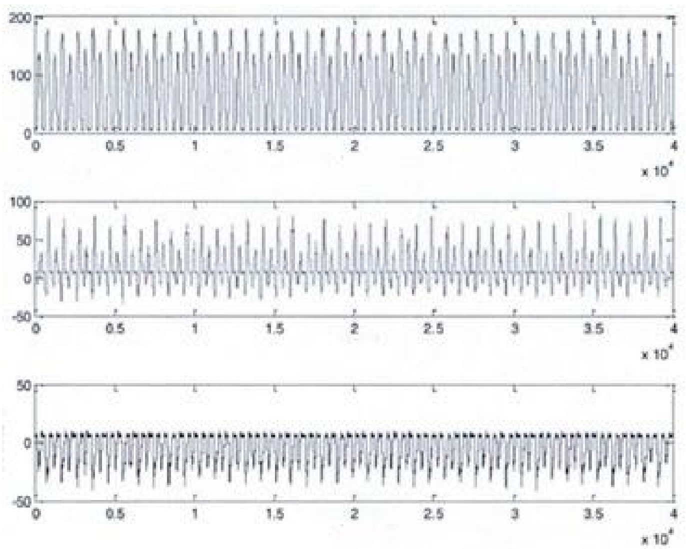

Figure 6-1 Time-domain waveform of three-direction cutting force under VB=0.08

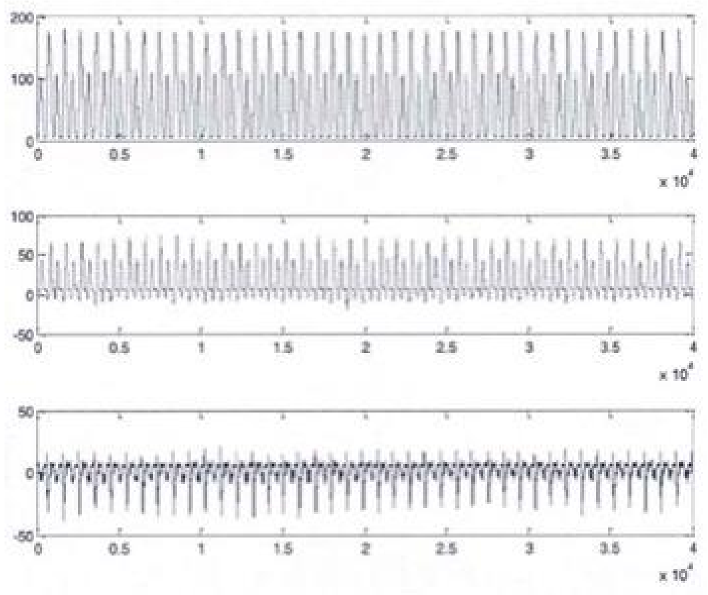

Figure 6-2 Time-domain waveform of three-direction cutting force under VB=0.18

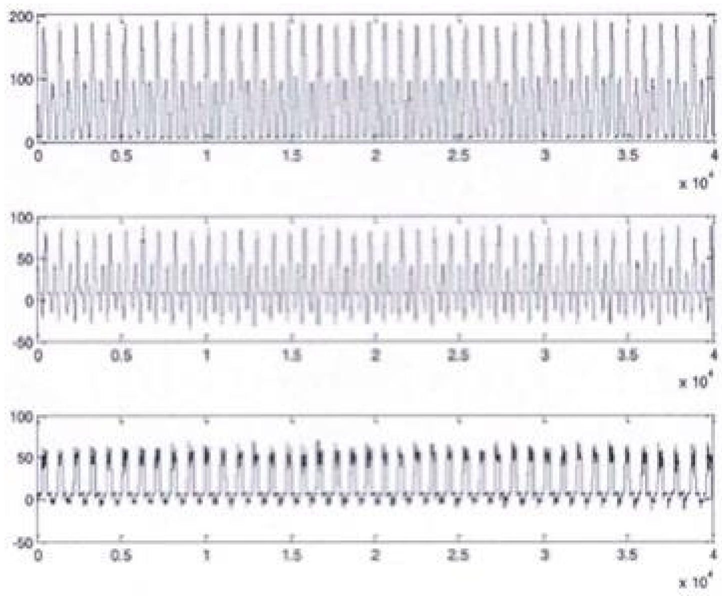

Figure 6-3 Time-domain waveform of three-direction cutting force under VB=0.35

7. Conclusion and Recommendation

Currently the applied numerical control machining simulation software regards the tool and the workpiece as rigid bodies, neglecting the influence of cutting parameters, cutting force and other factors on the cutting process. It just translates the numerical control program into generating the data of tool position, and use this data to control the tool to cut workpiece virtually to check whether there is collision or interference, that is, it only has the function of geometric simulation.

This paper proposes a virtual numerical control machining method to improve the machining accuracy of the workpiece. First, it analyzes the influence of the workpiece material, tool wear, tool material, cutting amount, geometric parameters, cutting heat, chips and other physical factors on the cutting force, and then adopts geometric analysis to optimize the parameter settings of the back-cutting amount and cutting speed. Combined with time domain analysis , the tool condition is monitored.

In the future, we need to do more experiments and research on the method proposed in this paper to make it more accurate.

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