ELSEVIER

Journal of Materials Processing Technology 113 (2001) 360–367

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Investigation of chip formation in high speed end milling

Yuan Ning*, M. Rahman, Y.S. Wong

Department of Mechanical and Production Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore

Abstract

Ball-nose end mill cutters are used extensively in the die and mold industry. However, very little work has been done in the research of chip formation in high speed ball-nose end milling. An experimental investigation has been conducted in this study to establish the chip formation mechanism. Common mold steel H13 hardened to HR_c 55 is machined on a high speed machining center under dry conditions at a spindle speed range of 10–30k rpm. Four typical types of chip and three types of chatter have been encountered in this study. Images of the chips are obtained by the use of SEM. The EDX method is used to analyze the interaction between the cutting edge and the chip in the formation process. Based on the findings of this study, the chip formation mechanism has been proposed in this paper. The locus of cutter movement for the three types of chatter is illustrated to explain the relationship between the chip formation and the chatter behavior. A method to judge process stability by analysis of the chip has been suggested based on the findings of the experiment. It has also been established through this study that the classical "adiabatic shear" does not occur in chip formation in high speed ball-nose end milling.

Keywords: Ball-nose end mill; Chip formation mechanism; Chatter; High speed machining; Adiabatic shear

1. Introduction

In metal cutting, the present tendency is toward achieving increased material removal rates with a high degree of automation and without close human supervision. This requires very reliable machining processes, where the predictability of surface finish, workpiece accuracy, and tool life are of prime importance. But to maintain stable machining, much attention must also be given to the formation of the desired type of chip and chip controls to facilitate its easy removal. This is because the chip formation and breaking aspect is very significant in machining. Problems with surface finish, workpiece accuracy, and tool life can be caused even by minor changes in the chip formation process, especially in high speed machining, where undesirable chip formation will have a more detrimental effect because of the high cutting speed.

Much research work has been done in the chip formation in turning, drilling and face milling. Shaw [1] proposed a cyclic saw-toothed type chip in face milling, and related it to other types of cyclic and non-cyclic chip. Nakayama [2] explained the essential meaning of the direction of side curling and chip tool flow angle on the chip form and made clear the proceeding of a helical chip. Komanduri [3,4] has made some remarkable progress in the research of chip segmentation and instability in chip formation. Nevertheless it appears that very few works have been done to investigate the nature of chip formation in ball-nose end milling because of its complexity and geometrical difficulty, even though it is applied widely in the high speed milling of dies and molds. The effect of the dynamics of the cutting process is seldom considered, i.e. chatter. This paper presents an experimental investigation and a discussion of the basic chip formation mechanism in high speed ball-nose end milling.

2. Theory

Within a short time after Merchant published his world-famous model of continuous chip formation, several authors suggested that not all chips behave in accordance with this model [5–8]. It was also soon discovered [2,4] that in high speed turning a great deal of cutting involved cyclic chip formation. The mechanism of this type of chip formation has been reviewed thoroughly reviewed by Komanduri [4] and some important observations concerning this topic have been published by Nakayama [2]

Toenshoff [8] proposed the basic chip formation mechanism as "adiabatic shear" at high cutting speed. During a deformation process, plastic strain incompatibilities are initiated near defects, thus achieving localized stress

* Corresponding author.
E-mail address: engp8755@nus.edu.sg (Y. Ning).

0924-0136/01/$ – see front matter
PII: S0924-0136(01)00628-8

Nomenclature

A_p	depth of cut (mm)
EDX	energy dispersive X-ray
F	feed rate (mm/min)
HR_c	Rockwell hardness
N	spindle rotating speed
rpm	revolution per minute
SEM	scanning electron microscope
T	chip temperature
T_c	one tooth contact period $= \frac{1}{120}$ ns
V_c	cutting speed (m/min)

concentrations. If the strain rate is high enough, the process is adiabatic and the overheating of these localized narrow areas involves a localized softening, thus increasing the local strain and so on until instantaneous shearing occurs. The adiabatic shear instability modifies the chip form, the chip becomes segmented, and the chip breaking becomes easier. All of these previous works were carried out in turning. It will be worthwhile to determine whether these theories apply to high speed ball-nose end milling or not. In ball-nose end milling, there is much instability that determines the chip formation. Usually the following factors are taken into consideration for analysis of chip formation: (a) the metallurgical and thermal plastic characteristics of the work-piece material; (b) the cutting conditions; (c) varying shear in the primary shear zone; (d) varying frictional conditions on the tool face (secondary shear zone); (e) interactions between the primary and secondary zones and (f) the response of the machine tool structure and its interactions with the cutting process, i.e., the dynamic factors.

The details of the effect of the above factors are discussed later in the paper. However, in this paper, the main effort has been put on the effects of process dynamics.

3. Experimental set-up

The experiments were conducted on a high speed machining center Makino V-55. The machining conditions used in this study are as follows: spindle speed, 10–30k rpm; the axial cutting depth varies from 0.1 to 0.8 mm; and the feed rate is in the range of 0.025–0.05 mm/tooth. The test material is AISI H13 hardened to HR_c 55, and its chemical composition is: C: 0.37%, Cr: 5.3%; W: 1.4%; Mo: 0.4%; Mn: 1.0%; Si: 1.0%. The milling cutter is a 12 mm solid carbide ball-nose end mill with TiAlN coating. It has a helix angle of 30°, with the rake angle γ_0 varying from 0° to 3° in the cutting edge and the clearance angle varying from 11° to 13°. The cutter is kept perpendicular to the workpiece in the experiment.

A Kistler dynamometer is used to measure the cutting force. The force signals are recorded by a multi-channel DAT (digital audio tape) recorder at a sampling rate of 12,000 samples/s/channel. An optical microscope is adopted to observe tool wear. The process is monitored by an HP oscilloscope. All the cuttings are conducted under dry conditions. SEM and EDX analysis of the chip are carried out and the respective images are taken. The chip samples are collected at the end of each cutting, the rest are being blown away by a high pressure air nozzle to avoid the mixing of chips from different cuttings.

4. Results and discussion

The chips found in the study are classified into four types. Type I: complete chip, Type II: unstable chip, Type III: critical chip and Type IV: severe chip. Type I chip is the product of a stable machining process. Type II–IV chips are generated by a process with chatter of different severity. All chips are obtained from the machining process when the tool is within its wear criteria to exclude the effects of tool wear.

4.1. Type I chip formation

Fig. 1A shows the chip obtained from stable cutting, which is defined as a stable chip, because its shape and geometry agrees well with the in-cut segment of the cutter in the stable process which is shown in Fig. 2.

Milling with ball-nose cutters normally produces a chip that is curved twice [5]. From Fig. 1A, the shape of the chip in stable cutting is similar to a cone. This is attributed to the geometry of the in-cut segment of the ball-nose end mill. Chip formation occurs on a spherical cap. Therefore, equal chip volumes of equivalent chip geometry are cut, so it is to

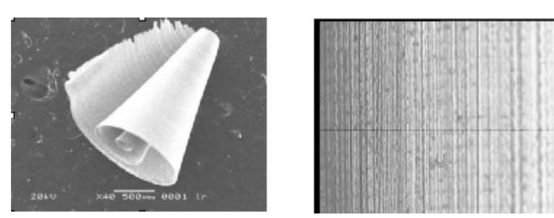

Fig. 1. (A) SEM photo of stable chips; (B) surface finish × 40. Cutting condition: rpm 28k, feed rate = 1350 mm/min, $A_p = 0.6$ mm.

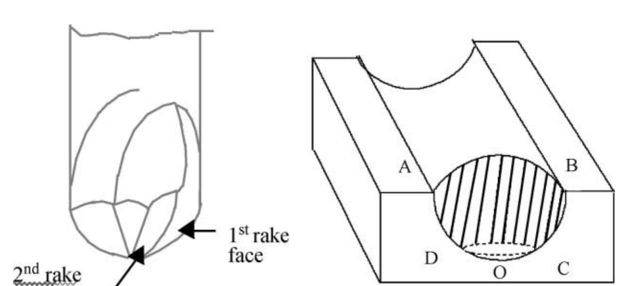

Fig. 2. (A) Geometry of the ball-nose end mill cutter; (B) in-cut segment area of stable cutting.

be expected, as observed, that the size and shape of each segment will be approximately the same for a reasonably homogeneous work material. During the cutting process, different parts of the cutting edge are engaged. Additionally, all points of the cutting edge, according to their different cutting angle, have to bear different loads. The shaded area in Fig. 2B represents the area that the cutting edge travels through in one rotation, i.e. the tool–workpiece contact area.

The cutter is perpendicular to the workpiece. Consequently in the process, the tool tip, although very small in size, actually does not involve in shearing but rubs the workpiece in the feed direction instead, for its cutting velocity is zero. That is why the chip is not a complete cone and how the in-cut segment area in Fig. 2B is formed. The top of the cone is missing because it is rubbed away by the tool tip, which deteriorates the surface quality. Thus a better strategy is to tilt the cutter so that only the cutter edge is engaged with the tool, as Schulz [5] has suggested. In Fig. 2B, O stands for the tool tip, so that segment BOC represents the portion of the workpiece that is rubbed away by the tool tip. In stable cutting, the cutter–workpiece contact length is just the length of cutting edge engaged. The in-cut segment is shown in Fig. 2 as ABCD. Segment ABCD also stands for the cutting edge–workpiece contact area in the stable process. It is soon found that in an unstable machining process, the cutting edge–workpiece contact area and length differ substantially. It is noted for stable cutting that during one tooth contact period T_c, only one chip is produced.

Fig. 3 illustrates the locus of the movement of the cutting edge in stable cutting. This kind of chip formation is attributed to two factors: the shearing process, which is dependent on the geometry of the ball-nose cutter, i.e. the geometry of the in-cut segment area and the thermal effect of the cutting process.

The geometry of the ball-nose cutting tool, which determines the geometry of the in-cut segment in stable cutting, has a dominant effect on the formation process of a stable chip.

The shearing process begins when the cutting edge starts to penetrate the workpiece. As the cutter rotates, the primary deformation zone also moves accordingly. The chip slides over the tool rake face as it is formed and curls up until it reaches the second tool rake face. Simultaneously the center of the chip is extruded upward. This process continues until the movement of the upper side of the chip is obstruded by the tool's second rake face. Then the chip has no way to move but to curl in accordance with the cavity between the first and the second rake face as shown in Fig. 2A, which forms the second deformation zone. In stable cutting, the groove is the only possible path for the chip to move along. Noticing that the tool is rotating, this cavity is actually formed as a cone. That is how the chip comes into a shape of twice-curved cone. The shearing is finished when the created chip is shaven away and the chip curling also stops at the same time when the tooth leaves the workpiece. There will be no chip–workpiece contact in the chip formation process. One chip formation process finishes when the in-cut tooth leaves the workpiece. Another tooth will in turn be engaged with the workpiece and the chip formation starts again.

It is well known that in HSM, a large amount of the cutting heat is transferred into the chips. The temperature in the chip area, especially in the lower side of the chip, will be very high. Normally T2 is higher than T1, so that thermal stresses will result which cause the chip to curl to a smaller radius (refer to Fig. 4). The chip will behave like a thermal bimetallic spring, although there is little friction between the lower part of chip and the tool face. When T2 is much higher than T1, the chip will curl towards the center of the curvature. This is also verified by the analysis of the chip color. The color of the lower part of the chip is always darker than that of the upper side, which means a severer extent of oxidation that is caused by a higher temperature.

The friction between the chip and rake face is found to be insignificant. From the EDX analysis graph (Fig. 5), no elements of coating material (TiAlN) and bonding material (cobalt) are found, which establishes that no tool material has been transferred to the chip.

The dominant tool wear mechanism is found to be of classic flank wear (Fig. 6). The maximum wear always occurred at the part of the cutting edge where the highest cutting velocity is achieved. This also establishes that the friction on the rake face is trivial.

It is concluded that in stable cutting, the chip is produced as the result of shearing together with the interaction between the first and second rake face.

As mentioned earlier, chip segmentation under high cutting speed is normally attributed to the ''adiabatic shear''

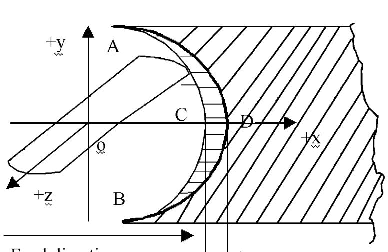

Fig. 3. The cutter movement of stable cutting. ACB — movement of the in-cut tooth. ADB — movement of the next tooth.

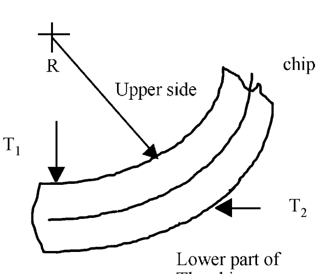

Fig. 4. The behavior of chip due to thermal effects.

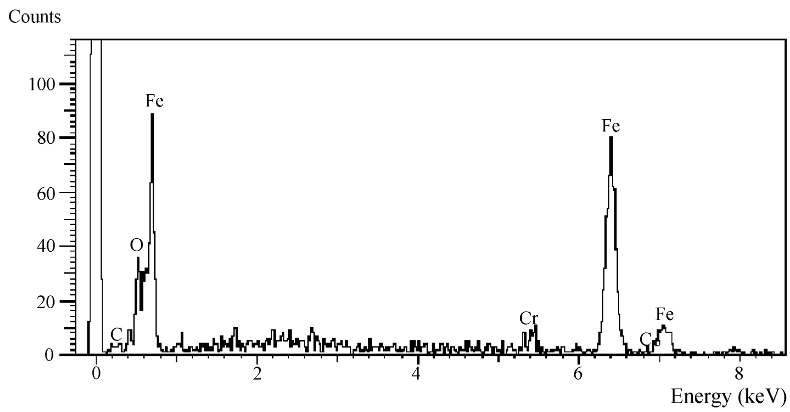

Fig. 5. Graph of EDX analysis of stable chip.

Fig. 6. SEM photo of tool wear.

phenomenon, which is usually found in continuous machining like turning or drilling [3–8]. It is doubtful that this occurs in ball-nose end milling. There are some prerequisites for adiabatic shear to occur. The material should have low thermal conductivity, as well as high strain-rate sensibilities. There will be cavity and voids found in the surface of the chip. From Fig. 1A, no such phenomenon is observed. Thus it is concluded that adiabatic shear is not the mechanism for chip segmentation in end milling; the chip is just shaven away by the rotating cutting edge.

In the chip formation process of ball-nose end milling, there also exists a ‘‘segmenting’’ phenomenon under certain cutting conditions. The reason is found to be self-excited vibration, not adiabatic shearing. This leads to the discussion of the Type II chip formation.

4.2. Type II chip formation

Fig. 7A shows a typical chip obtained from chatter. It is named an unstable chip or elemental chip. In turning, it usually results from periodic fracture that begins at the tool tip. Sometimes it is the result of adiabatic shear occurring in the work material. In this study, the reason is found to be self-excited chatter, which is named Type-A chatter.

The chatter marks for a Type II chip is distinctive (referring to Fig. 7B). In the experiment, when there is chattering, this is then a source of uneven surface roughness and the finished surface will consist of alternate unburnished (dull) and burnished (shiny) regions.

The chip is of the shape of a needle that agrees quite well with the geometry of the in-cut segment as shown in Fig. 8. The shape of the chatter marks shown in Fig. 7B is also in accordance with the shape of the chip. The cutting edge contact area is shown in Fig. 8, where it is seen clearly that the chip contact area for the formation of one chip is much smaller compared with that of stable cutting. The area is shown shaded. The several parts of the shaded area are separated. Each shaded area stands for one elemental chip.

This kind of chip formation mechanism differs significantly from that of stable cutting. When chatter fully develops, the cutting edge no longer moves in the way as in stable cutting, but vibrates while it is rotating. During one tooth contact period T_c, the cutting edge does not have constant contact with the workpiece as in stable cutting, but jumps out of the workpiece completely when it shears away one elemental chip. To shear away another elemental

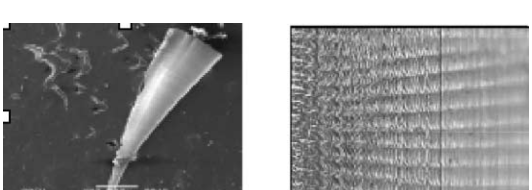

Fig. 7. (A) Unstable chips; (B) surface finish. Cutting condition: rpm = 28k, feed rate = 1400 mm/min, $A_p = 0.6$ mm.

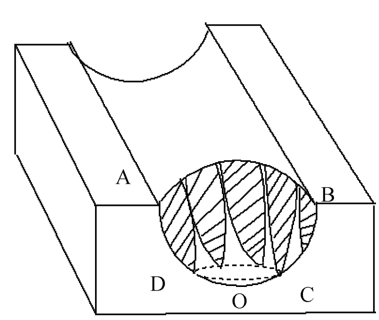

Fig. 8. In-cut segment area in Type II chatter.

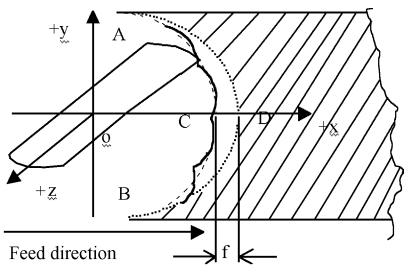

Fig. 9. Cutter movement in chatter process — Type II chip.

chip, it will bounce back to the workpiece surface again and repeat the process. The solid line in Fig. 9 shows the movement. The solid line intersects with the locus ACB that stands for stable cutting, which means the cutting edge will jump out of the surface for a while. It is observed that in one tooth contact period, multiple chips are produced, while in stable cutting, only one chip is produced.

The time to produce one chip is much shorter than that of the stable cutting process, for the cutting edge only needs to rotate through a much smaller angle. This is a kind of chatter that is generated completely, which is named Type A chatter. The direction of the chatter is in the axis that links the tool center with the cutting edge. Based on the fact that the chips are of the identical shape and size and the chatter marks are also evenly produced, the vibration is expected to be of a constant amplitude and period. It is well known that chatter is a kind of random vibration. Here the randomness lies in the constant change of vibration direction. This is the reason for the ‘‘segmenting’’ phenomenon in the chip formation process.

This kind of chip formation is again found irrelevant to adiabatic shear. It is obvious that the movement of the cutting edge causes the segmentation.

4.3. Type III chip formation

The Type III chip does not segment completely as a Type II — unstable chip. It is named the critical chip, which stands for Type B chatter. The resulting chip in Fig. 10A is wavy and nearly symmetrical, resembling a harmonic or sine wave. In this type of chip formation, only one chip is produced in a single cutting tooth contact period as in stable cutting, but it is not as ‘‘complete’’ for there are some wedges. The chatter marks are also different from those of the Type II chip judging from Fig. 10B.

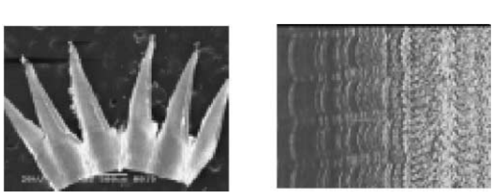

Fig. 10. (A) SEM photo of a critical chip; (B) surface texture. Cutting condition: $A_p = 0.6\,\text{mm}$, rpm = 29k, feed rate = 1.45k mm/min.

This kind of chip formation is also noted for its in-cut segment area and cutter movement, which distinguishes itself from the Type A chatter and stable cutting. These characteristics contributes to the formation of the Type III chip, which signifies Type B chatter.

The Type III chip is composed of a number of more or less connected elements. In turning, it usually results from a periodic variation of the height of the retarded layer, which leads to alternating zones of concentrated but very little shear deformation in the chip. In end milling, it is found to be the consequence of self-excited vibration. It is accompanied by cyclic variations in undeformed chip thickness (cutting depth) as well as shear, rake angle, and clearance angle. The movement of the cutting edge in the machining process brings all these variations forth in the cutting process.

The two types of instabilities (material thermal instability and adiabatic shear) operative in segmental chip formation in turning do not play an important role in the formation of this chip. In ball-nose end milling, at high speeds of sliding, considerable thermal energy develops and with low thermal properties, this results in thermal softening and considerable subsurface flow along the sliding friction (fracture) surfaces. The segmentation is achieved by the movement of the cutting edge, not by the shear fracture.

It is interesting to find out the relation between these two kinds of chip. The chatter mark left on the surface finish suggests that the Type B chatter is less severe than the Type C chatter.

Figs. 11 and 12 provide a graphical demonstration for Type B chatter. In Fig. 11, the solid line does not intersect with the locus of cutter movement for stable cutting, which

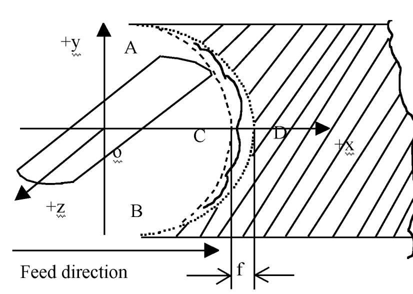

Fig. 11. Cutter movement in Type III chip formation.

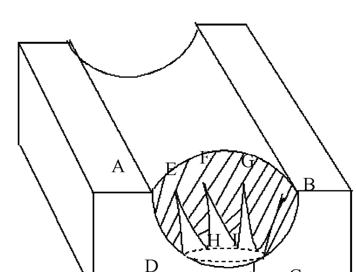

Fig. 12. In-cut segment area for Type III chip.

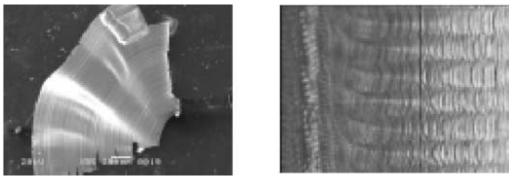

Fig. 13. (A) Extreme chips; (B) surface texture. Cutting condition: rpm 25k, feed rate = 1250 mm/min, $A_p = 0.9$ mm.

means that the cutter does not lose contact with the in-cut segment surface completely. In Type B chatter, the cutting edge moves in a similar pattern as for Type A chatter, and it usually happens at a ''critical'' cutting depth, beyond which chatter will generate completely and a Type II chip will be produced. At this cutting depth, the cutting edge shows a strong tendency to chatter, but the chatter does not generate completely. The cutting edge also vibrates while rotating. The amplitude is smaller than that of Type A chatter. It is seen the solid line in Fig. 12 does not intersect with ACB curve, which means the cutter does not jump out of the workpiece completely, This is the reason why the chip does not separate completely.

4.4. Type IV chip formation

The chip shown in Fig. 13A is obtained by applying a cutting depth that is far beyond the maximum stable cutting depth. It is defined as a severe chip. The shape is exactly like that of a stable chip that has been expanded horizontally. It means there is no chip curling process. Here obvious compression marks are observed on the chip surface, which come from the movement of the cutting edge (Fig. 14). Because of the high chip load and limited spindle power, the cutting edge vibrates at low frequency and small amplitude. The chip is mostly rubbed away from the workpiece, where very little shearing is involved. Thus the chip becomes flat.

In this chip formation process, only one chip is produced in a single tooth contact period. The chip contact area is the same as that in stable cutting, which is shown in Fig. 15.

The chatter marks are much wider than that of Type A chatter. They are also more obvious than that of Type B chatter. The chatter marks were left by the tool flank face, which rubs the surface in the chip formation process. This is defined as Type C chatter.

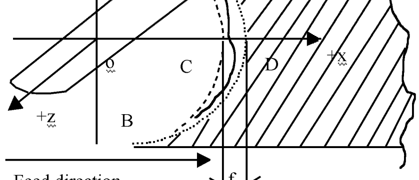

Fig. 14. Cutter movement in Type IV chip formation.

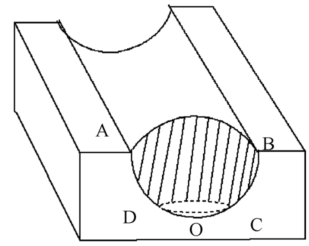

Fig. 15. In-cut segment area in Type IV chip formation.

4.5. Effects of cutting condition on chip morphology

The cutting depth has a dominant effect on process stability, as Tlusty and Ismail [9] proposed, and determines the chip formation in this study. There exists a ''stability lobe'' for a certain tool–workpiece combination.

Changing speed during the machining process or finding a optimum speed are the commonest tactics to avoid chatter, which is also verified in the present experiment. Various methods have been proposed by many researchers [9–14]. It is found that in some instances changing the spindle speed as well as the feed rate could increase the maximum cutting depth. At a certain spindle speed, it is usually found that a larger maximum stable cutting depth is obtained by applying a higher feed rate. As a result, the chip formation is improved and the desired stable chip is obtained.

To take full advantage of high speed milling, the cutting strategy must be optimized. In this experiment, the cutter is kept perpendicular to the workpiece, thus the maximum cutting speed is not achieved, and there is no difference using down milling or up milling. Thus tertiary milling is strongly suggested, i.e. the cutter is tilted to the workpiece at a certain degree. Thus at the cutting edge, maximum speed is achieved and normally down milling could be applied for better surface accuracy and longer tool life.

4.6. Judging cutting temperature by analyzing chip color

Knowledge of the temperature in the chip formation zone is crucial in order to explain the phenomena occurring during machining. Since it is impossible to measure the temperature in the formation zone itself, one can only determine the temperature of regions near the zone where the chips are generated. The situation is more complicated in milling, for the cutter is rotating while traveling in the feed direction, so in this study the temperature was predicted by examining the color of the chips. Several kinds of chip color are found in the experiments. They are shown in Table 1.

Venkatesh [6] founded the chip temperature vs. color chart shown in Table 2, from which it is seen that the highest temperature encountered in the experiment is around 1000°C. For different chip colors, the cutting temperature is different. It is clear that the cutting process stability also more or less indicates the temperature. For the light brown color chip, the lack of color is due to the intimate contact between the chip and tool that prevents oxidation.

Table 1
Chip color for different types of chip

Chip color	Chip form
1. Dark blue + purple	Stable and unstable chip
2. Blue + green	Critical, unstable, severe chip
3. Light brown	Stable chip only
4. Green + purple	Critical chip
5. Brown + green	Critical chip

Table 2
Chip temperature vs. chip color

Chip temperature (°C)	Chip color
981	Dark blue
900	Dark blue + brown
881	Brown
837	Light brown

It is found in the study that the higher is the cutting speed and the feed rate, the darker is the color of the chip, which means a higher extent of oxidation that leads to a higher temperature.

The temperature rises monotonously with the increase of cutting speed and cutting depth. The results are shown in Tables 3 and 4. This denies Salomon's famous estimation [8] that the cutting temperature will decrease for a cutting speed above a certain value in high speed ball-nose end milling. This suggests that the optimum cutting speed is not the highest possible speed because the high temperature will increase the tool wear as well as the tendency to oxidation of the chips, thus the surface finish and texture are adversely affected. Different chip colors occur all over the speed range being used.

Table 3
Cutting temperature vs. change of cutting speed

rpm (k)	A_p (mm)	Chip color	Temperature (°C)
30	0.5	Dark blue + green	>1000
25	0.5	Dark blue	960–1000
24	0.5	Blue + purple	920–960
22	0.5	Blue + brown	860–920
20	0.5	Brown	820–880
18	0.5	Light brown	800–840

Table 4
Cutting temperature vs. change of cutting depth

rpm (k)	A_p (mm)	Chip color	Temperature (°C)
20	0.7	Dark blue + green	>1000
20	0.6	Dark blue	960–1000
20	0.5	Blue + purple	920–960
20	0.4	Blue + brown	860–920
20	0.3	Brown	820–880
20	0.2	Light brown	800–840

For a certain type of chip shape, there is not a particular chip color, which means that this kind of chip shape could be generated under different temperatures. For example, a complete type of chip is found in brown, blue and green colors. Thus here a conclusion can be drawn that it is the cutting process dynamics and the property of material that determine the chip formation.

4.7. A method to judge chatter

From the analysis done so far, it can be concluded that the analysis of the chip is a reliable method to judge the process stability. When a stable type of chip is obtained, the cutting process is stable. When severe and unstable chips are encountered, there is always chatter.

For the critical type of chip, it is very useful to determine the critical cutting conditions. When such chips appear, one is aware that the maximum stable cutting depth is reached. As far as the surface finish is concerned, there are always some small chatter marks for the chatter does not generate completely. The chatter marks are not so obvious as in Type A and Type C chatter.

5. Conclusions

High speed ball-nose end milling of hardened steel Assab 8407 (AISI H13) has been performed with TiAlN coated solid carbide tools. The following conclusion can be drawn from the study:

1. Four types of chips, namely stable, chatter, critical and severe type of chip, are observed at a spindle speed range of 10k–30k rpm. The mechanism of different chip formations is found to be the movement of cutting edge under different cutting conditions. It is found that chatter could be reliably recognized by analysis of the chips. Thus the relationship between the process stability and chip formation is established.
2. Three kinds of chatter in high speed ball-nose end milling were found and defined, namely Types A–C. They are distinguished for the different kinds of chip obtained in the in-cut segment area and the locus of the cutter movement.
3. The dominant tool wear mechanism is found to be typical classic flank wear.
4. By choosing suitable cutting conditions, as well as the chip production, the process stability could be significantly improved. Tactics such as changing the spindle speed and increasing the feed rate have been proven effective in the experiment.
5. The machining process temperature increases with increase of the cutting speed and cutting depth.
6. The theory of adiabatic shear at high cutting speeds was examined together with consideration of the milling dynamics, which includes the process during chip

formation and the effect of chatter within the chip formation zone as well as the flow properties of the material. SEM analysis of chip shows that "adiabatic shear" does not happen in the chip formation in high speed end milling.

7. To make better use of the advantages of HSM, the design of the cutting tool and the adoption of the cutting conditions should be able to provide the desirable chip forms. There is not a unique stability chart for a given machine because the dynamic compliance is not unique. This is the most serious difficulty in choosing the right cutting conditions. From this study, it is found that chip analysis provides a simple and cost-efficient way to determine and optimize the compliance of the machine, as well as the cutting conditions.

References

[1] M.C. Shaw, Chip formation in the machining of hardened steel, CIRP Ann. 42 (1) (1993).
[2] K. Nakayama, Comprehensive chip formation classification on the cutting mechanism, Ann. CIRP 41 (1) (1992).
[3] R. Komanduri, T. Schroeder, On the catastrophic shear instability of high speed machining of an AISI 4340 steel, J. Eng. Ind. 104 (1982).
[4] R. Komanduri, On the mechanism of chip segmentation in machining, J. Eng. Ind. 103 (1981).
[5] H. Schulz, High speed milling of dies and molds — cutting conditions and technology, Ann. CIRP 44 (1995).
[6] Venkatesh, A study of chip surface characteristics during the machining of steel, Ann. CIRP 42 (1993).
[7] I.S. Jawahir, Recent developments in chip control research and application, Ann. CIRP 42 (1993).
[8] H.K. Toenshoff, Chip formation at high cutting speed, ASME Winter Meeting, 1969.
[9] J. Tlusty, F. Ismail, Special aspects of chatter in milling, ASME J. Acoust., Stress, Reliability 105 (1983).
[10] Tobias, Machine Tool Vibration (1963).
[11] S. Smith, Update on high speed milling dynamics, ASME J. Eng. Ind. 112 (1990).
[12] M.A. Elbestawi, High speed milling of dies and molds in their hardened state, Ann. CIRP 46 (1997).
[13] Altintas, End milling force algorithms for CAD systems, Ann. CIRP 40 (1991).
[14] I. Minis, A new theoretical approach for the prediction of machine tool chatter in milling. ASME J. Eng. Ind. 115 (1993).