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Journal of Materials Processing Technology 71 (1997) 247–257

Journal of
Materials
Processing
Technology

Chip structure classification based on mechanics of its formation

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Received 19 January 1996

Abstract

Understanding chip formation is the first step to good chip control, a necessity for automated machining. Such understanding results in the prediction of chip breakability for a wide range of machining conditions. This paper presents a generalized model of chip formation in metal cutting. The mechanical properties of the workpiece are of prime concern. A new classification of chip structure is proposed, according to which classification, seven different chip structures are distinguished, namely: the regular broken chip, the irregular broken chip, the continuous fragmentary chip, the continuous fragmentary chip with a wedge-shaped texture, the continuous chip, the continuous hump-back chip, and the fragmentary hump-back chip. Unlike the known classifications which often have a post-process nature, the proposed classification considers the chip structure, the chip stress and strains as the results of chip-formation dynamics. The methodology presented in this paper provides a new and viable means to predict chip breakability. The results of this study give clear ideas to the tool designer, technologist, or even to the foreman, as to what kind of chip-breaking should be used for a given set of machining conditions. © 1997 Elsevier Science S.A.

Keywords: Chip formation; Chip structure; Metal cutting; Automated machining

1. Introduction

Understanding chip formation is the first step to good chip control, a necessity for automated machining. Moreover, a lack of chip control often leads to coarse surface finish, poor machining accuracy, and problems with chip removal from the machining zone. Using chip-breakers on inserts has proven an effective way to curl chips, but their design is a matter of experimental findings and users' experience rather than the result of deep understanding of the mechanics of chip formation. Even the chip flow direction and the causes of chip curling are not yet clear [1–3].

In metal cutting, the term 'chip formation' has been used since the last century. Its initial meaning is the formation of the chip in the primary and secondary deformation zones. Main attention was paid to the cutting force and contact process at the tool/chip interface. Later on, the chip-breaking problem became more and more important with increasing cutting speed, and the development of new aerospace and stainless materials. Even though the term 'chip formation' is still in use, its original meaning has been transformed. The modern sense of this term implies the chip which just left the tool/chip interface and has yet to be broken.

As for the geometry of chip formation, it has been pointed out by Ernst [4] that there are three basic types of chip found in the cutting of metal: discontinuous, continuous, and continuous with a built-up edge interposed between the chip and the tool in the vicinity of the cutting edge. This classification is generally accepted at least in the theory of metal cutting and will be referred to as the 'known classification'.

The above-mentioned classification cannot satisfy growing practical requirements. As a result, the national industries of the developed countries have accepted some more practical chip classifications. For example, in Japan the Sub-committee 'Chip Disposal' of JSPE formulated a revised system of chip form classification which included nine chip types basically according to their length [5].

Unfortunately, the known classifications originate only from the difference in the chip appearance but pay no attention to the chip's physical state including its state of stress and strain, hardness, texture, etc. More-

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PII S0924-0136(97)00081-2

over, neither the tool geometry nor the cutting regime are taken into consideration. Thus, the known classifications have a post-process nature rather than helping in making pre-process decisions about chip-breaking. As a result, chip-breaking in metal cutting remains one of the fundamental problems that has to be solved for further advance in automated manufacturing [5].

The purpose of this paper is to present a new classification of chips' structure which relates the chip types to their formation mechanisms. Such knowledge enables an engineer to design a chip-breaker that is capable of breaking the chip with minimum energy consumption.

2. Chip formation – past work

To break a chip predictably, the mechanical properties of the chip have to be known, such properties including the stress and strain distribution in the chip body as a function of the cutting geometry and regime. Ideally, the chip-breaking, considered as a process of breaking chips into small and manageable sizes, should only increase the stress that arose in the chip in cutting, up to the chip's fracture point, which then makes the chip-breaking natural and efficient. Since the involved forces are at a particular minimum level which is just necessary to accomplish the job, it would seem reasonable to point out that the energy consumption of such a breaking is also at the minimum. In turn, a smaller amount of the energy entering into the machining zone results in an increase of the tool life and machining quality. Therefore, to deal with the problem of chip-breaking, it is necessary to know the values and distribution of the stress(es) and strain(s) that this chip gains up to the last instant of its formation. Furthermore, to make the chip-breaking process controllable, not only are the ultimate values needed, but also the dynamics of the stress and strain formation is vitally important in showing to the designer the easiest way to break the chip.

A comprehensive analysis of metal-cutting studies shows that there are several known models of this process resulting in different states of stress and strain in the chip. Even though the proposed models are called the theories of metal cutting [6], they may be considered only as approaches with some experimental evidence.

2.1. The Timme approach

In his model of chip formation (Fig. 1) Timme [7] considered the interaction of the model's components, namely the cutting tool, the workpiece, and the chip. A cutting tool starts to penetrate into a workpiece, overcoming its resistance, the resistance to the penetration growing proportionally to the compressed area of the workpiece material, which results in an increase in the penetration force P. This process continues until the force becomes sufficiently large to break up a small fragment of the workpiece material, which moves along a particular sliding plane at angle Θ_1, the penetration force decreasing abruptly, a new cycle of chip formation being about to occur. This process has a cyclic character and its repetition constitutes the metal-cutting process. Besides all interesting findings, the main result of this study by Timme is a systematic approach to the object under study. For the first time (and for the last since then), the relative movement of the cutting system's components (the workpiece, the tool, and the chip) was defined as the main condition for the existence of the cutting system.

Further investigations have taken place in the direction of simplification of the real cutting process. The introduction of the so-called 'steady-state' cutting process met the practical needs to define some average values of the cutting force, the tool life, the quality of machining, etc. on one hand, whilst on the other hand, the steady-state models create the impression of steady-state (time invariant) stress distributions; thus no logical way to control the chip-formation process (considered as the process where the chip gains stresses and deformations) has been provided.

2.2. The Ernst and Merchant approach

The chip was considered to be formed by a process of shear that is confined approximately to a single plane expanding from the cutting edge to the workpiece surface ahead of the tool [4], Fig. 2(a). This plane was termed the shear plane, and the angle it makes with the surface generated was referred to as the shear angle. The mechanism of formation of a continuous chip was

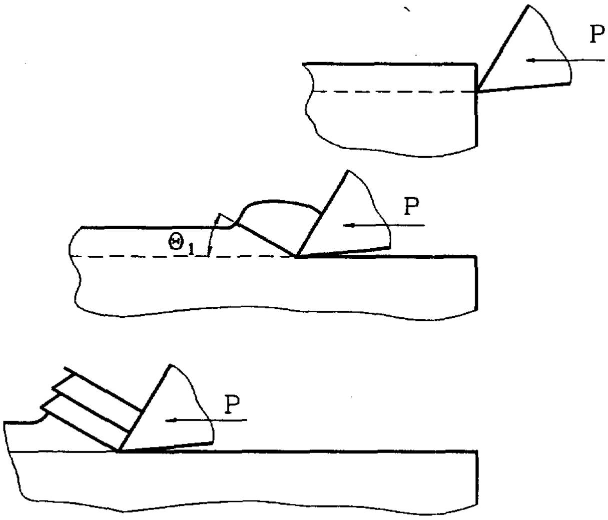


Fig. 1. The model for chip formation proposed by Timme.

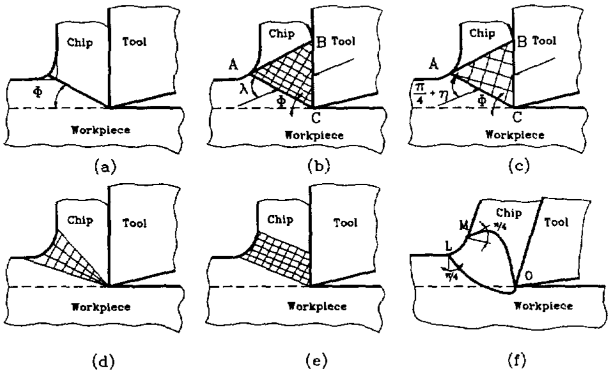


Fig. 2. Models for orthogonal metal cutting.

illustrated by a simple model of a stack of cards, which implies that the chip is subjected to simple unidirectional shear deformation.

At this point it is worthwhile to discuss an issue that made a significant impact on the further development of metal cutting. Even though Ernst and Merchant pointed out in the title of their work that this approach is valid only for one type of continuous chip, unfortunately, later researches did not pay enough attention to this point. No one even thought why Ernst and Merchant did not extend their approach to other types of chip even though they continued publishing on different aspects of metal cutting. Nowadays, this approach is classic in metal cutting and has been applied to the analysis of the cutting of a vast variety of materials even where shearing cannot occur at all. All warnings, that either this approach is wrongly based [8] or that shearing cannot be a cause of chip fracture [9], did not make any difference in the further studies in this direction.

Further studies tried to solve the most severe contradictions by introducing artificial process parameters [10], which actually made such an approval more complicated rather than to increase its prediction ability.

2.3. The Lee and Shafer approach

Lee and Shafer [11], in applying slip-line theory of perfect plastic solids to the problem of metal cutting, assumed that a particular slip line field (the plastic zone) exists within the chip which is composed of two families of parallel straight lines, as shown in Fig. 2(b). Since the region is created only within triangle ABC (Fig. 2(b)) and is represented by two families of parallel straight lines, the uniform stress condition takes place in the plastic region; the shear stress is at its maximum along line AC; there is no force acting on the chip above line AB; and there is no change of the physical properties of the workpiece material in the cutting process.

Since almost all real workpiece materials have elastoplastic rather then perfectly plastic properties, the approach considered has limited application.

2.4. The Shaw, Cook, and Finnie approach

After carefully examining the assumptions made in the previously-discussed approaches, Shaw, Cook, and Finnie [12] drew attention to the inter-relationship between the shear and friction process in metal cutting. The assumption that the shear plane may not be in the direction of maximum shear stress was incorporated into a slip-line solution, as shown in Fig. 2(c). Despite particular anomalies, this approach appears to suggest an important concept, namely, that the compatibility relationship between the shear and friction process is a decisive factor for determining the final steady-state configuration in the cutting process. However, pure shearing is assumed, thus a perfectly-plastic solid is chosen to model the workpiece material. As a result, the chip is continuous infinitely (shearing does not cause fracture) having directed elongation and residual shear stress and strain.

2.5. The Hill approach

According to Hill [13], the conditions under which one looks for a steady-state configuration in metal cutting do not necessarily ensure a unique solution. In reality, there is always a permissible range of steady-state solutions rather than a unique solution. Therefore, there is no unique state of stress and strain in the chip, thus the chip control should be conducted under uncertain conditions.

2.6. Okushima and Hitomi approach

Okushima and Hitomi [14] assumed that shearing takes place within a particular triangular flow region rather than along a single shear plane (Fig. 2(d)). For the first time, the existence of the discontinuous chip was recognized in cutting theory and the mechanics of its formation analyzed. Even though the known conflicts associated with the single shear plane are solved by applying the flow-region concept and the state of stress and strain in the chip is much more certain than in other approaches, the shear stress and shear strain are still the only residual stress and deformation in the chip.

It may be derived easily from results of Okushima and Hitomi that both the final strain and stress in the chip are similar to those obtained using the Ernst and Merchant approach. Therefore, this approach did not add a new dimension to the solution of the problem of chip control.

2.7. The Kececiogly approach

It may be seen in Fig. 3 of Merchant's classical paper [4] that the deformation zone, where the layer to be cut becomes the chip, actually is the zone with parallel boundaries. Using this shape of deformation zone as a model, Kececiogly studies the metal cutting mechanics [15] assuming a uniform stress-state in this zone (Fig. 2(e)). His main suggestion for the future, which dramatically affected many further studies of metal cutting, was that there is a true combined functional relationship amongst the strain, the strain rate, the shear-rate size, the compressive stress acting in the shear zone, the temperature, and the shear strength. In this way he explained his paradoxical (from the viewpoint of his approach) experimental results. By playing with these variables and arranging them in a polynomial, practically any experimental — sometimes even opposite — results may be explained, as has been demonstrated for many years [16]. The problem is that such an approach does not have any potential of predictability, thus it cannot be considered as a way to build metal cutting theory. Therefore, there is no way to gain any useful information about the state of stress and strain in the chip that may be useful in the design of a chip breaker.

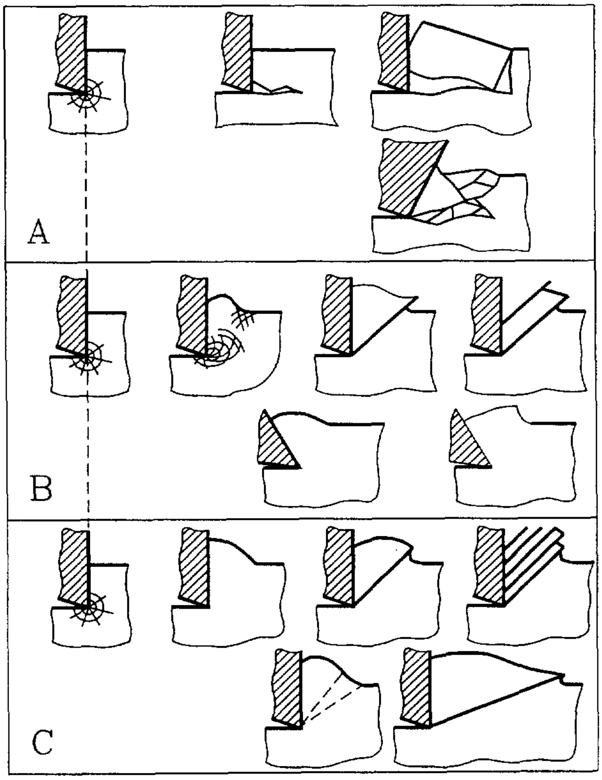


Fig. 3. The proposed model for chip formation.

2.8. The Zorev approach

Zorev [17] proposed a model for the cutting of ductile materials (Fig. 2(f)). Referring to this figure, plastic region LOM is limited by shear lines OL (along which the first plastic deformation occurs) and OM (along which the last plastic deformation occurs), and line LM, which is the deformed section of the workpiece's outer surface. The particles of the work material pass through the plastic region intersecting the shear lines and are in turn subjected to successively increasing deformation from zero to a particular maximum value peculiar to the final chip. This model is distinguished from the other considered above by its clear logic and is in agreement with the theory of plasticity. The boundaries OL and OM are the slip lines and they can be observed using a metallography test of the work region adjacent to the edge. These boundaries first appear in the zone adjacent to the cutting edge and then intersect the free surface of the work with angle $\alpha = \pi/4$. These boundaries exist in reality but the model does not explain the mechanism of their formation. If the plastic region is born in the zone adjacent to the tool tip (since the tip is a stress concentrator and this assumption is in agreement with the theory) and further develops to reach the work surface (points L and M), then the boundaries of the plastic zone as shown by lines LO and MO should not be formed.

Summarizing the above considerations, it can be concluded that each observed cutting model reflects a particular aspect of metal cutting practice. In reality, the cutting conditions may be created where one or another model is valid, but no one model covers the whole variation of cutting conditions.

As one might expect, the stresses and strains in the deformation zone also affect the chip formation dynamics. At this stage, three major approaches to determine the shear strength of the workpiece material in cutting may be distinguished.

The first approach originates from Merchant [4] and is based on the assumption that the shear stress on the shear plane is equal to the yield shear strength of the workpiece material. A few studies did consider the effect of the strain rate and temperature occurring in cutting on the yield shear strength of the workpiece material, however, it was proven theoretically [6] and experimentally [18] that these two factors do not affect the shear stress on the shear plane.

According to the second approach, the shear stress on the shear plane is much greater than the yield shear strength of the workpiece material obtained in a standard mechanical test. This is explained by the strain hardening of the workpiece material taking place in cutting [19–24]. This strain hardening is considered to be affected by the strain, the strain rate, and/or their combination. As before, these studies also provide theo-

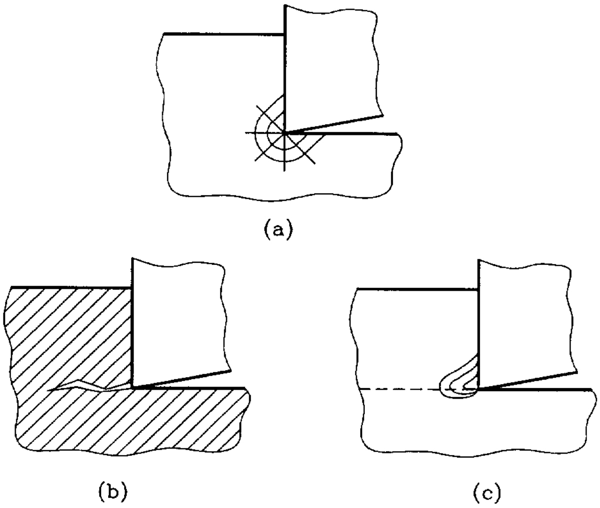


Fig. 4. Cutting edge starting to penetrate into the workpiece.

retical and experimental evidence supporting such an approach.

The essence of the third approach is the consideration of the combined influence of the strain-hardening and thermal-softening effects on the shear yield strength on the shear plane [25–29]. Numerous theoretical and experimental proofs to support this point have also been provided.

From the above discussion, it is seen that the models and approaches considered cannot give a tool designer any clear idea about the dynamics of chip formation and the final stress and strain in the chip. The known approaches, classifications, etc., dealing with chip formation do not consider the existence of workpiece materials with different mechanical properties and metallurgical states.

3. Proposed model of chip formation

The analysis and generalization of results obtained in metal cutting theory and practice enable the proposal of a generalized model for chip formation (Fig. 3). With the penetration of the cutting tool into the workpiece, stress concentration occurs in front of the tool tip. Depending on the properties of the workpiece material, the mechanics of chip formation would be as follows.

3.1. The work material has mainly elastic properties (region A, Fig. 3)

With the cutting edge penetration, the maximum stress in the workpiece material begins to occur in front of this edge (Fig. 4(a)). When this stress reaches its limit, a crack is formed in front of the cutting edge (Fig. 4(b)). At this stage, compressive stress in the deformation zone exists exclusively. The propagation of this crack results in the formation of the chip-cantilever and the state of stress becomes complex, because not only the compressive stress, but also the bending stress created by the chip, acts in the deformation zone.

Two basically different situations can be identified here. The first takes place when the bending stress plays an active role in chip formation and its failure. This occurs when the resultant force R intersects the axis of the formed cantilever (Fig. 5(a)). When the load from the cutting edge reaches a particular limiting value, chip fracture takes place in section 1-1. When this occurs, separate, almost rectangular, chip elements are produced, such a chip being referred to as regularly broken. The second case takes over when the resultant force is directed so that there is no bending stress in the forming chip (Fig. 5(b)). Here, the failure of the chip occurs due to almost pure compression of a fragment of the layer being removed located between the tool's rake face and the undeformed part of the workpiece. Thus, the common failure of a brittle sample compressed as on a testing machine takes place. As a result, several irregular-shaped chip fragments of different size are produced, the smallest fragments forming the dust which is an inherent feature of machine shops dealing with the machining of cast iron. Such a chip is referred to as irregularly broken.

Therefore, even in the cutting of brittle workpieces, the chip shape is a controllable parameter. It is understood that when the compression and bending act together, much less energy has to be supplied to the machining zone and better working conditions (at least the absence of the dust) may be achieved. The tool geometry plays a main role here. As one might argue, a positive rake angle is not very practical in cutting cast iron due to the presence of a significant amount of hard inclusions. In such a case, a carbide, as a tool material, cannot withstand peak bending stress. As a result, practically all recommendations for the tool's geometry are the same, suggesting a high negative rake angle that

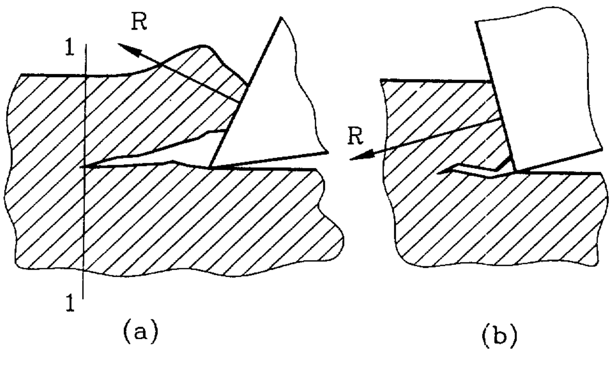


Fig. 5. Two cases in the cutting of a brittle workpiece.

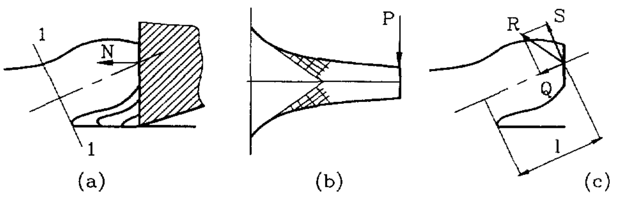


Fig. 6. A chip as an elastoplastic cantilever with a curved contour.

unavoidably leads to the second case of chip failure. To achieve bending stress in the chip, a high inclination angle of the cutting edge may be recommended as a compromise.

3.2. The work material has elastoplastic properties (region B, Fig. 3)

This is a common case in the cutting of most engineering materials. Here, the stress concentration in front of the tool tip (Fig. 4(a)) leads to the formation of the plastic zone (Fig. 4(c)). The chip as an elastoplastic cantilever is formed. This chip is subjected to the forces from the tool and the plastic zone so its fracture takes place along section 1-1 (Fig. 6(a)).

The study of cantilevers with curved contours shows [30] that the maximum plastic deformation occurs in the vicinity of the cantilever's free surface adjacent to its clamping side. Fig. 6(b) shows the intensity of this deformation by the corresponding slip lines. The resultant force R, applied to the cantilever, may be represented by its two components, namely the compressive force Q and the bending force S (Fig. 6(c)). Therefore, the plastic deformation in the vicinity of the chip-cantilever support is a result of the mutual action of the compressive force Q and the bending moment M ($= Sl$).

Bearing in mind the above considerations, the general field of plastic deformation was obtained (Fig. 7(a)) by combining the fields of slip lines due to compression with those due to bending. The lower boundary (where the plastic deformation begins to occur) of the resultant field obtained in this way (Fig. 7(a)) is in agreement with experimental data (Fig. 7(b)) and such a shape of this boundary has been reported in many studies.

When the stress in the considered plastic zone reaches its limit, all the cantilever material starts to slide along the planes where the limit was achieved. The sliding fragment does not disconnect from the remaining part of the workpiece due to the healing of micro cracks and seizuring of newly-formed surfaces of the relative sliding. The latter happens at a particular instant when relative sliding stops, since the force acting on this sliding fragment is redistributed between this fragment and a new portion of the workpiece material coming into contact with the tool. As a result, the stress along the sliding plane becomes less than the limiting stress. A new chip fragment starts to form. As such, the formed chip has a saw-shaped free side and a smooth contact surface (Fig. 8).

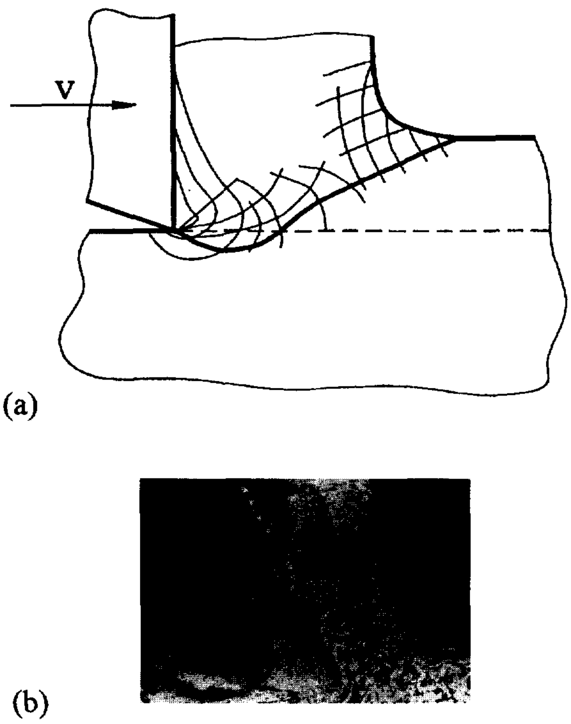
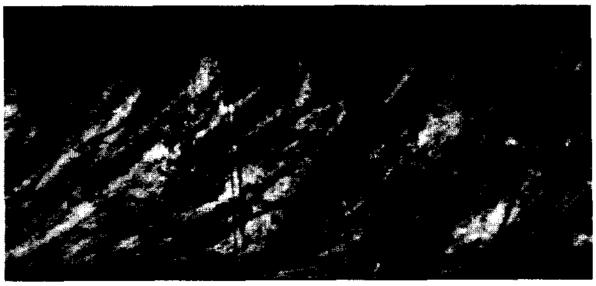


Fig. 7. Plastic deformation field in the cutting of elastoplastic materials. ((b) mag.: × 40).

The chip formed in this way is referred to as the continuous fragmentary chip. It has a non-uniform strength along its length. The shear strength of the fragments is much greater than the shear strength of the fragment connections. Therefore, to brake this type of chip into separate pieces, only a relatively small shear stress needs to be applied. This can be done by grinding a chip-breaking step onto the tool's rake face. The optimum size of the broken chips depends on the step's length. Naturally, the step's length depends mainly on the feed rate. Thus, there are two choices: select the



, Fig. 8. Microphotograph of the fragmentary chip (mag: × 80).

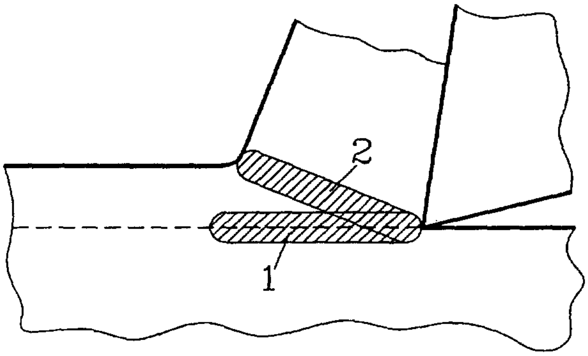


Fig. 9. Regions where the limiting stress occurs.

step's length for a given feed rate (less common) or select a feed rate for a given step's length: it is understood that the latter is a common practice due to its simplicity. Once again, it can be done if and only if one deals with the continuous fragmentary chip.

A comprehensive analysis of the formation of the continuously fragmentary chip shows that, depending on the interactions of the cutting system's components, the limiting (for a given work material) stress occurs (Fig. 9): (a) in region 1 (adjacent to the tool tip) along the plane which divides the workpiece and the layer being removed; (b) in region 2 along the chip-cantilever's support. The latter case has been considered widely whilst the former case has been studied insufficiently.

Region 1 is the region of high stress since the tool tip causes concentration of the compressive stress, and the chip-cantilever 'tears off' a layer of metal being removed from the workpiece, creating tensile stress. It is worth showing here that a very special kind of chip may be formed under these conditions in cutting with high rake angles. This consideration has also practical significance in the design of special cutting tools with high kinematic rake angles.

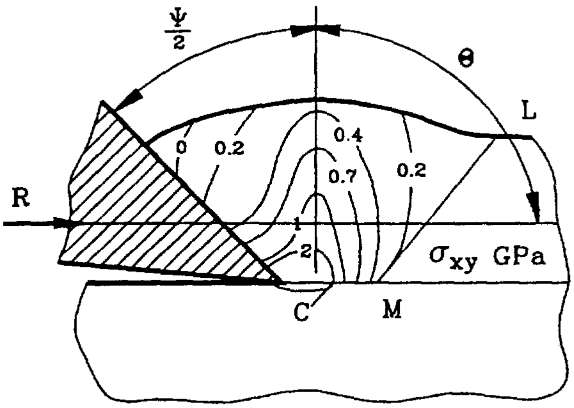


Fig. 10. A model for cutting with a high rake angle.

Fig. 11. Microphotograph of the continuous fragmentary chip with a wedge-shaped texture (mag: × 80).

A model of cutting with a high rake angle is shown in Fig. 10. Here, the rake angle may reach 30–45°. As such, the reduction in the rate of plastic deformation with increasing rake angle leads to the condition where the angle, Θ, between the plane of maximum-shear-stress and the direction of the compressive force, R, becomes 90° (Fig. 10). Such a model allows one to compare the compression of the work material by the tool face with the pressing of wedge-shaped workpieces between a pair of flat plates inclined with a small angle relative to each other. In cutting, one of the plates plays the role of tool face and the other plate plays the role of the layer of metal being removed where plastic deformation has not yet occurred (the conditional boundary between the plastic and elastic zone is shown in Fig. 10 as line ML). Under such conditions, the main part of the work material flows in the direction of the 'thick' part of the wedge-shaped plastic-deformation zone; the internal layers flow much more intensively than the external layers; and the deformation rate in the 'thin' part of the wedge-shaped plastic-deformation zone is much higher than in the 'thick' part. In cutting, the 'thin' part is located in region 1 (Fig. 9), which explains the above statement.

Above considerations of cutting with high rake angles lead to the conclusion that, if the interaction of the metal-cutting-system components is as shown in Fig. 10, the work material fractures only along the line separating the workpiece and the layer being removed. A continuous uniform-strength chip with wedge-shaped texture is formed. Such a chip may be referred to as a continuous chip with wedge-shaped texture.

The wedge-shaped grains in the chip texture can be seen clearly in the microphotographs (Fig. 11) where a higher strain is observed at the 'thin' part of the grains. However, the chip-breaking steps ground on the rake face would not be helpful in chip-breaking, whilst a radius groove may be beneficial. Such a groove should only increase the strain in the thin part of the grain to the level of chip fracture.

3.3. The work material has mainly plastic properties

In the cutting of highly plastic materials (region C, Fig. 3), the chip is only able to transmit an insignificant bending moment because of its low rigidity. Thus, chip failure takes place only along the shear planes, and, therefore, the chip formation process is a series of successive shearings. Such a mechanism is the subject of consideration in all metal cutting books and papers after having being proposed by Merchant [4].

The bending moment strongly influences the fracture of the work material in regions 1 or 2 (Fig. 9). This moment arises in the deformation zone from the chip side because the chip serves as a lever and plays a key role in the chip breaking. It is understood that the elasticity of the workpiece material is the main characteristic affecting the bending moment in regions 1 and 2. Moreover, as soon as the free end of chip makes contact with the workpiece, this bending moment becomes a decisive factor in chip-breaking, as does the chip elasticity. Therefore, the chip-formation process becomes difficult and eventually becomes impossible with the reduction in elasticity of the work material. For example, a chip does not form when cutting warmed plasticine but this plasticine can be cut easily by a sharp knife because of a very high stress concentration ahead of the knife's edge. Obviously, such a tool cannot be used in metal cutting because of lack of strength. Therefore, the above analysis explains the difficulties observed in the cutting of plastic materials. To support this point Fig. 12 shows chip formation in the cutting of a medium-carbon (AISI 1045) steel and an austenite stainless (8% Ni, 17% Cr) steel, which have approximately the same strength but considerably different elastic properties. As seen, the cutting tool should pass a much longer way to reach the limiting stress along the surface of fracture in the latter case. Thus, the size x_1 in this case is longer than that in the first case. Constant volume of the work-material during plastic deformation can be expressed mathematically as:

$$\epsilon_x + \epsilon_y + \epsilon_z = 0 \qquad (1)$$

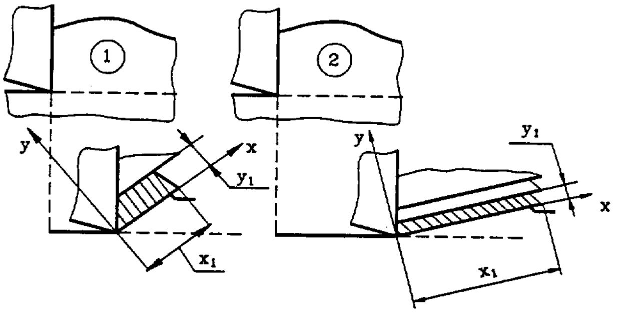


Fig. 12. Chip formation in the cutting of: (1) a medium carbon steel and (2) a stainless steel.

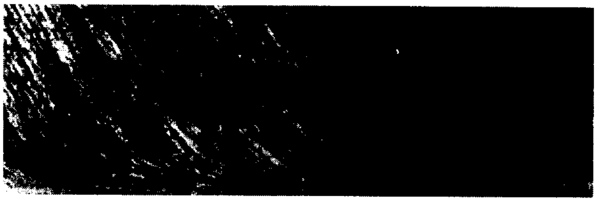


Fig. 13. Microphotograph of the chip obtained in the cutting of a high plasticity material (mag: × 125).

Here ϵ_x, ϵ_y, ϵ_z are the deformations along the corresponding coordinates.

Consider a volume of the work material located between two successive shear surfaces. The deformations of this volume can be expressed as:

$$\epsilon_x = \ln\frac{x_1}{x} \qquad \epsilon_y = \ln\frac{y_1}{y} \qquad \epsilon_z = \ln\frac{z_1}{z} \qquad (2)$$

where x, y, z and x_1, y_1, z_1 are the dimensions of the volume before and after deformation, respectively.

It is known that the chip width is equal to the width of the cut (when both are properly defined). Thus, $z = z_1$ and $\epsilon_x = 0$ can be accepted. Then

$$\ln\frac{x_1}{x} + \ln\frac{y_1}{y} = 0 \quad \text{or} \quad \frac{x_1}{x} = \frac{y_1}{y} \qquad (3)$$

This demonstrates that an increase in the plasticity of the workpiece material leads to the formation of a thicker chip, whereas the distance between two successive shear surfaces decreases.

Therefore, with an increase in work-material plasticity, the length of a chip fragment decreases under the same cutting conditions. On a microphotograph of the chip obtained in the cutting of a high-plasticity material (Fig. 13) a series of slip planes, one usually following another, is observed. Such a chip is heavily deformed and is referred to as the continuous type. However, it has to be pointed out that the conditions of its formation show that the chip is the continuous fragmentary chip but the length of its fragments tends to zero and when it reaches zero, the chip formation ceases. This explains the difficulties in chip-breaking under such conditions. The formed chip has a uniform strength and very severe deformation has to be applied to break it into pieces.

To deal with such a chip, Jawahir and Zhang [31] considered a four-staged chip-breaking cycle. The most important feature of this model is the necessity of the bending moment in the chip breaking. According to the model, a bending moment is created when the chip's free end comes into contact with the rotating workpiece. The weakest point of the model is to rely on a 'light' chip curling.

It is well known that chip curvature is a direct result of many observed characteristics of the cutting process although an exact reason for the chip curling is not yet clear [2–4,11,32,33]. Therefore, to increase the stability of chip breaking, forced chip curling is mandatory.

In the simplest case, such a curling is accomplished by providing a radiused groove on the tool rake surface, which works quite efficiently even in the machining of austenite stainless steels [34]. When the workpiece material properties are such that the formed chip is not sufficiently rigid to transmit the bending moment to its root, a groove-and-ride-type chip breaker must be used to increase the chip rigidity by changing its cross-sectional shape [5]. Such grooves are very helpful in machining with low cutting feeds when the chip thickness is small.

4. Unstable chip formation

Unstable chip formation occurs mainly when the workpiece material has plastic properties. As pointed out above, with increase in the plasticity of the work material, the length of individual chip fragments becomes smaller and approaches zero for a perfectly-plastic work material. When cutting a material of high plasticity, conditions may be created along the tool–chip interface such that the normal sliding of the work material over the tool face cannot occur because of continuous contact over both the hills and valleys of the tool surface: such a phenomenon is known as seizure [35].

Chip formation when seizure occurs is illustrated in Fig. 14. Surface bc of the motionless chip and surface ab (the boundary of the plastic and elastic zones in the work material) are located by angle ψ relative to each other. As the tool progresses in the cut, the material in the wedge-shaped zone abc is compressed and squeezed in the direction of the 'thick' end, i.e. in the direction of boundary ac. The load from the cutting wedge increases further and, as a result, the plastic zone in front of the tool expands and, finally, its boundary takes a particular position bm and hence region bcm is formed. Here, gradually increasing the angle, γ_{ϕ}, up to 90° leads to a change in the mode of deformation from the compression-type to the shear-type. When $\gamma_{\phi} = 90°$, fracture takes place along the boundary bm. At the instant of fracture the resistance to the wedge penetration is maximum and the direction of the reaction R (from the elastically-deformed part of layer being removed) becomes parallel to the rake face. Therefore, the condition for shearing the whole layer along the rake surface is created. The region in the vicinity of the cutting edge becomes free and a new layer to be sheared starts to form. Fig. 15(a) shows the process of chip formation obtained using a high-speed TV-camera and Fig. 15(b) shows the formed chip in two cross-sections. As such, it was clearly observed that the chip velocity is changed according to the above explanations of the proposed model for 'seizure' chip formation.

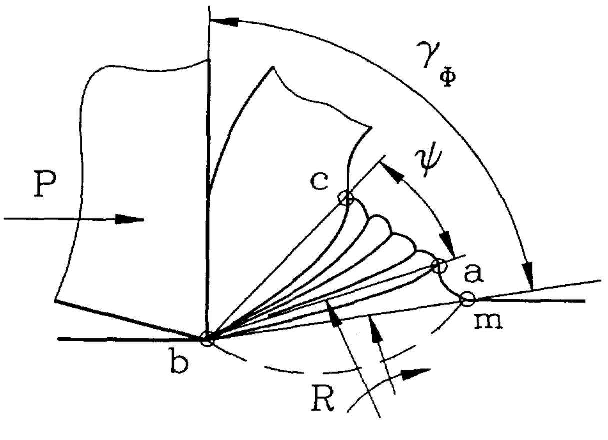


Fig. 14. A model for chip formation when seizure occurs.

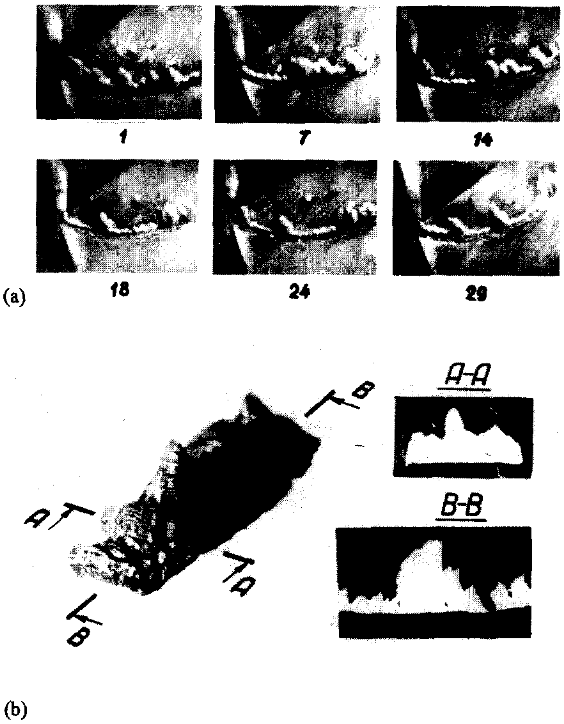


Fig. 15. Showing: (a) the unstable chip formation process captured by a high-speed TV camera; and (b) the resulting continuous hump-back chip ((b) mag: × 60).

The chip formed under these conditions may be referred to as the continuous hump-back chip. Such a chip is common in the machining of aerospace materials with a high content of chromium and nickel. Even though this chip looks easy to break, special obstruction-type chip breakers must be used [36]. Finally, it is worth mentioning here that such a chip should not be mistaken for the discontinuous hump-back chip (Fig. 16) which is formed when seizure occurs in fragmentary chip formation.

An emergency situation can occur in this type of cutting when the adhesion forces within the tool-chip interface are so high that the chip–tool contact cannot be separated by the cutting forces. As a result the chip cannot slide over the tool face and the chip formation process becomes impossible, with known consequences.

5. Summary and conclusions

Recent progress in metal cutting tools and machines has improved the efficiency and productivity of cutting operations remarkably. Such high productivity, however, has brought problems such as the establishment of a secure chip-disposal system and the protection of the machined surface, the cutting tool, the machine tool and the machine operator from damage and injury due to the chip. These problems are the most serious problems in flexible manufacturing systems.

To deal with the above-mentioned problems, a pertinent classification of the chip structure is necessary. There are several known systems of the chip classification, most of which are simple and easy to use. However, when one tries to solve a chip problem, these are too simple to provide the necessary information. The real problem here is that the known classifications have a post-process nature.

Two basically different types of chip classifications can be identified. The first considers the chip structure, even though this classifies the chips by their appearance [4], whilst the second is based only on the chip appearance, having nothing to do with its texture or structure [5]. The former is used in metal cutting theory whilst the latter is used in practice. The problem is that both types of classification often use the same terminology, which confuse the tool designer when he/she tries to select the optimum chip-breaker for a given cutting tool.

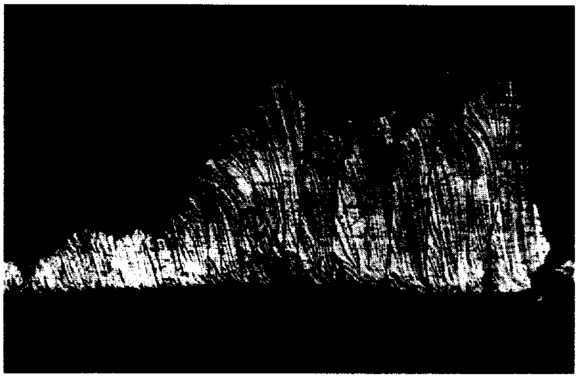


Fig. 16. Microphotograph of the fragmentary hump-back chip (mag: × 80).

To select a proper chip-breaker for a particular set of cutting conditions, knowledge of the chip structure is essential. Based on this, the chip-breaker should only increase the stress, formed at the previous stages of chip formation, up to the chip's fracture point. Such an approach makes chip-breaking natural and efficient and hence consumes the minimum possible amount of energy.

The chip structure depends on the mechanical properties of the workpiece, the tool geometry and the cutting regime.

When the workpiece has mainly elastic properties, a regular broken chip or an irregular broken chip may be formed, depending on the tool geometry: no chip breakers should be provided here. However, to achieve better working conditions, a bending stress in the machining zone is essential. When compression and bending act together, much less energy has to be supplied to the machining zone and better working conditions (at least the absence of the dust) may be achieved. In such cases, to activate the bending stress in the chip, a high inclination angle of the cutting edge may be recommended as a compromise between a brittle tool material and the necessity of the bending stress.

When the workpiece has mainly elastoplastic properties, a continuous fragmentary chip or a continuous chip with a wedge-shaped texture are formed, depending on the tool geometry. The continuous fragmentary chip has a non-uniform strength along its length. The shear strength of the fragments is much greater than the shear strength of the fragment connections. Therefore, to break this type of chip into separate pieces only, a relatively small shear stress needs to be applied. This can be done by grinding a chip-breaking step on the tool's rake face, the optimum size of the broken chips depending on the step's length. A continuous fragmentary chip with a wedge-shaped texture forms in cutting with high rake angles. Chip-breaking steps ground on the rake face would not be helpful in the chip-breaking of such a chip, whilst a radiused groove may be helpful Such a groove should only increase the strain in the thin part of the grain to the level of chip fracture.

When the workpiece has mainly plastic properties, a continuous type of chip is formed. Here, the chip texture appears as a series of slip planes, one following another. Under the same cutting conditions, with an increase in the work-material plasticity, the length of the chip fragments decreases. However, the conditions of its formation show that the chip is the fragmentary chip but the length of its fragments tends to zero: when it reaches zero, chip formation is stopped. A radiused groove on the tool rake surface may work well as a chip breaker in most cases. When the workpiece material properties are such that the formed chip does not have sufficient rigidity to transmit the bending moment to its root, special shapes of radiused grooves must be used to increase the chip rigidity by changing its cross-sectional shape. Such grooves are very helpful in the machining with low cutting feeds when the chip thickness is small.

Unstable chip formation occurs mainly when seizure occurs at the chip/tool interface. Two basically different types of chip structure may be formed. When the workpiece material has plastic properties, the continuous hump-back chip is formed. Such a chip is common in the machining of aerospace materials with a high content of chromium and nickel. Even though this chip looks easy to break, special obstruction-type chip breakers must be used. When the workpiece has elasto-plastic properties, the fragmentary hump-backed chip is formed.

Acknowledgements

The financial support of the Natural Science and Engineering Research Council of Canada is acknowledged. We are grateful to Dr. Xinran Xiao for her practical advice relating to materials science, support throughout the experiments, and corrections to the final draft of this manuscript.

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