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A system concept in metal cutting

V.P. Astakhov [a,*], S.V. Shvets [b]

[a] Deep-Hole Machining Centre, Mechanical Engineering Department, Concordia University, 1455 de Maisonneuve Boulevard, West, Montreal, Que. H3G1M8, Canada

[b] The American Heller Corporation, 33632 Doreka Drive, Fraser, MI 48026, USA

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Abstract

A study of orthogonal cutting mechanisms has been conducted using a system concept. The cutting process is considered as taking place within the cutting system, which is defined as consisting of the following components: the cutting tool, the chip and the workpiece. The term 'system' emphasizes that an overall operation process, within a frame of the system time, is under consideration rather than a collection of pieces. Using the introduced concept, the chip-formation process in the cutting of brittle and elasto-plastic workpiece materials is considered as a result of the dynamic interactions of the systems components. The system consideration reveals that: (i) the formation of the chip is caused by the bending stress when it is combined with the shear stress in the deformation zone; and (ii) the chip formation process is cyclical. Sample calculation and results of experiments are used to illustrate the existence, role and significance of the bending stress.

Keywords: Metal cutting; Cutting system; Bending stress

1. Introduction

Considerable effort has been expended in the past on the developing of the theory of chip formation. For the purpose of this presentation of new developments in this field is not necessary to review, even briefly, all of the approaches taken by investigators in this field, which recently have been analyzed by Astakhov et al. [1]. The number of approaches used indicates that task was not an easy one and in each subsequent attempt the approach was changed somewhat by each investigator in the hope of obtaining better agreement of theory with experiment, thus to make better use of the theory in practical applications.

Unfortunately, the theory of metal cutting has been experiencing a kind of dead-end for many years. Shaw in his book, which summarize his many-many-years of experience, concluded that"…All this suggests that it is next to impossible to predict metal cutting performance…" (p. 200 [2]). A recent working paper of the CIRP Working Group on Modelling of Machining Operations [3] has ventured to state: "A review of the machining literature reveals that very few of these (practical machining) operations have been modeled to any reasonable degree. Some of these operations have in fact never been modeled." This report further states: "However we believe that the time for changing our focus has come. Presently, we are able to quantitatively predict only a few of the output (performance) parameters for only a few of practical machining operations. This is dismal record when compared with other engineering disciplines." As a result: "A recent survey by a leading tool manufacturer indicates that in the USA the correct cutting tool is selected less than 50% of the time, the tool is used at the rated cutting speed only 58% of the time, and only 38% of the tools are used up to their full tool-life capability. One of the reasons for this poor performance is the lack of the predictive models for machining."

Because it was felt by the authors that the theory of chip formation based on the analytical description of the shear process alone had reached its maximum development, it is hoped that further progress can be achieved by introducing into the theory some other mechanism that may be present in the deformation

* Corresponding author. Tel.: +1 514 848-8671; fax: +1 514 848-175; e-mail: astvik@vax2.concordia.ca

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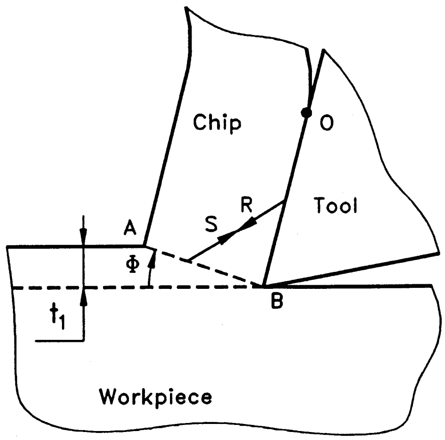

Fig. 1. Configuration of the metal cutting mechanism used in the development of chip formation theory by previous investigators.

zone and which, together with shearing, affect chip formation. This paper aims to introduce the bending moment as the cause of chip formation.

2. Observational part of the chip formation theory

An overall impression of previous work on chip formation theory indicates that the observation part, which usually precedes the derivation of the analytical model of chip formation, was left essentially unchanged in each case.

The observational part of the studies on chip formation resulted in an idealized picture that is known as the model for orthogonal cutting (Fig. 1). This diagram indicates that the tool removes the stock of thickness t_1 by shearing (as assumed) it ahead of the tool in a zone that is quite thin compared to its length, and can thus be well represented by the shear plane AB. The position of the shear plane is customarily defined by means of the so-called shear angle ϕ, as shown in Fig. 1. After being sheared, the layer to be cut becomes a chip, which slides first along the tool rake face, following its shape (the straight portion of the chip in Fig. 1), and then, beyond a particular point O on the tool face, curls away from that tool face. To this picture, gained by visual observation, was added a force system that consist of a resultant force R_f on the tool face and a resultant force R_s on the shear plane. The most essential feature here is that both forces are assumed to be collinear, and, in order to satisfy the requirement of static equilibrium, they must be equal in magnitude and are opposite in direction (Fig. 1).

The picture described was used by investigators of the chip formation process almost without exception. In some work a few changes were made when studying the plastic deformation in the shear zone or when taking into account the presence of built-up edge. However, the two most essential features of the model (Fig. 1) have never been questioned and thus remain unchanged. They are: (i) the chip forms by the process of simple (pure) shearing and (ii) the resultant force R_f on the tool face and the resultant force R_f on the shear plane are equal in magnitude and are opposite in direction.

The model discussed constitutes the very core of the metal-cutting process, which can be represented, in the simplest terms, as a cutting tool removing a particular part of the workpiece by means of shearing. However, there are a number of other, closely-related manufacturing processes known as the shearing press operations [4] that can be characterized using the identical definition. Naturally, all of the shearing press operations as well as the metal cutting possess have features in common: (i) they all include a tool having a sharp cutting edge(s); (ii) they all include a workpiece having a particular part to be removed; (iii) the removal takes place by means of the interaction of the cutting edge(s) and the workpiece; (iv) the interaction between the workpiece and the tool takes place at a particular speed that is limited by tool wear; and (v) the part to be removed is deformed and then separated from the rest of the workpiece by means of simple shearing.

The above considerations suggests that, if the known model for orthogonal cutting (Fig. 1) is considered to be the case, metal cutting does not have any specific technical features to distinguish it amongst other closely-related manufacturing processes. It may be concluded then that metal cutting has been attracting much more attention than other shearing press operations only because it is a very important component in the overall manufacturing activity.

In addition to the foregoing thoughts, the following questions should be answered:

1. What is the difference between metal cutting and cutting?
2. If a polymer or any other non-metal (wood, stone) material is cut by means of turning, milling, drilling, etc., what should this process be called?
3. What kind of cutting is performed by a knife or by a pair of scissors?

To be able to answer these and many other questions, a more general, thus important, question should be answered: what is metal cutting all about? The right answer to this question has enormous significance, both theoretical and practical.

To be able to answer the question, it is necessary first to understand why metal cutting cannot be distinguished amongst other shear processes on the base of the existent model for chip formation (Fig. 1). In the opinion of the present authors two significant aspects are overlooked in the model. Firstly, it leaves out of consideration a number of workpiece materials that cannot be deformed by shearing [1]. Secondly, when being applied to analyze the cutting process of ductile materials, it does not provide a answer to a simple question about the cause for chip formation under conditions of pure or simple shearing. A number of closely-related manufacturing processes such as blanking, punching, etc. are accomplished by simple shearing, however no chip has been observed. Moreover, the indentation of a semi-infinite mass of rigid–perfectly plastic material by a rigid straight-sided, acute-angled indenter or by a flat punch causes extensive shearing, however a chip does not form even if extremely high force is applied [5]. Bearing in mind these aspects and that the theoretical results derived using the existent model are in poor agreement with experiment, the authors would like to present a new approach aimed at bridging the gap that exists between theory and experiment in the theory of chip formation. By this is meant that the proposed approach leads to a better understanding of the metal-cutting mechanism, its unique features and the explaining of its well-known paradoxes.

3. Proposed approach

A good case can be made for the position advanced by Astakhov et al. [1] that cutting takes place within a cutting system that is defined as consisting of three components: the workpiece, the cutting tool, and the chip. However, one may argue that the existent model, shown in Fig. 1, has the same components. It may be answered that the set of objects, namely, the cutting edge, the chip, and the workpiece, shown in Fig. 1 has never been considered as a system. To explain this point it is worthwhile discussing an issue that is quite often troublesome for many researchers, namely a system concept [6].

Modern technological concepts make it possible to define the present stage of technique development as the ‘system era’. Management makes use of the ‘system concept’, ‘system philosophy’, and ‘system approach’. Engineers and physical scientists speak of ‘system analysis’, ‘system engineering’, and ‘system theory’. Even in medicine or biology the specialists speak of the nervous system, homeostatic system, the gene system, etc. However, the picture is not so bright as it seemed to be in the 1960s when the system approach began to boom. Only in particular fields, as for example computer science has the system concept been developing rapidly with a great practical significance. Only in this field are there system specialists (system analyzers, system programmers).

Unfortunately although highly attractive, the system concept or system philosophy is not too easy to implement in engineering. It requires the highest level of generalization, which is called system engineering.

A mathematical theory of system engineering considers two aggregates, namely, the system and the assemblage [6]. Here, only the definition of a system will be considered. According to the theory, a system is a device, procedure, or scheme that behaves according to some description, its function being to operate on information and/or energy and/or matter in a time reference to yield information and/or energy and/or matter. A significantly simplified mathematical definition of ‘system’, which supports the intuitive definition, is [7]: A system is a set:

$$Z = \{B, D, F, M, T, \sigma\} \quad (1)$$

Here B is a non empty set; D is a non empty set; F is an admissible set of input functions with values in D; M is a set of functions each defined on B with values in B; T is a sub-set of R containing 0; σ is a function defined on $F \otimes T$ with values in M such that σ is mapping onto and:

1. the identity mapping $\omega \in M$ and for every $f \in F$, $\sigma(f, 0) = \omega$;
2. if $f \in F$, s, t, and $s + t \in T$, then $\sigma(f \rightarrow s, t)\sigma(f, s) = \sigma(f, s+t)$;
3. if f and $g \in F$, $s \in T$, and $f(t) = g(t)$ for all $t \in R(s)$, then $\sigma(f, s) = \sigma(g, s)$.

If Z is a system, then B is called the set of states of the system Z, D is called the set of states of the system Z, D is called the set of input states of the system Z, F is called the set of output functions for the system Z, M is called the set of transition functions of the system Z, T is called the time scale of the system Z, and σ is called the state transition function of the system Z. If $f \in F$, $x \in B$, and $t \in T$, then the state of the system at time t given the input function f and initial state x is $(\sigma(f, t))(x)$. The time trajectory of Z determined by if$\in F$ and $x \in B$, denoted timetraj (f, x), is a function, defined on T with values in B, as follows. For every $t \in T$: (timetraj $(f, x))(x) = \sigma(f, t)x)$. The input trajectory of Z, determined by $t \in T$ and $x \in B$, denoted inputtraj (t, x), is a function, defined on F with values in B as follows. For every $f \in F$: (inputtraj $(t, x)(x)$. If Q is an arbitrary non empty set, then any $\zeta \in \Psi(B, Q)$ is an output function for Z with values in Q. The output trajectory of Z is determined by $f \in F$, $x \in B$, $Q \neq \emptyset$, and $\zeta \in \Psi(B, Q)$ is the function ζ (timetraj (f, x)): $(\zeta(\text{timetrai}(f, x))(t) = \zeta(\sigma(f, t)(x))$ for every $t \in T$.

The set B, formally representing the set of possible states of the system, describes the internal workings of the machine or system.

The set D represents the set of possible input states or input conditions for the system.

The set F represents the class of possible or admissible input schedules, or input histories, or input functions for the system.

Two major system properties follow from the above definition:

1. The most important, but often overlooked, is the system time (T in Eq. (1)). The system time is a new variable and, thus, a new axis in the system analysis so that the systems output parameters should be time-dependent.
2. Dynamic interactions of the system components (B in Eq. (1)).

In the light of the foregoing consideration, it is evident that the existent model shown in Fig. 1 is not a system since it does not possess the major system properties. As a result, the input and output parameters in the studies of the existent model (as for example the cutting force, the stress and temperature distributions along the tool/chip contact areas, the shear angle, the strain rate, etc) are considered as time-invariant. For example, the cutting tool is always considered separately and its interactions with the chip and the workpiece are substituted for by the static loads, heat sources, etc. [2,4]. In the opinion of the present authors, this is the principle problem in the known metal cutting studies.

4. System consideration of a metal cutting process

Now consider the changes that the approach indicated will bring into the conventional picture of the chip formation process. All of these changes will be introduced step-by-step, illustrating each of them by a separate picture.

As noted in the previous section, pure shearing cannot cause chip formation regardless of the level of the applied load. Therefore, the model shown in Fig. 1 (and all others that consider pure shearing as causing chip formation) has an internal contradiction. Although this model includes chip formation, pure shearing is assumed to be the controlling mechanism for the plastic deformation of the workpiece material. It is considered that this contradiction makes the known model unrealistic.

It is apparent from the above discussion that another factor for the cause of chip formation should be introduced. Astakhov et al. [1] suggested that the bending moment occurring in the deformation zone due to the interaction between the chip and the tool rake face may be considered. The present study aims to illustrate the significance of the bending moment in the chip formation process. To do this, a three-stage approach is selected. The first stage may be called observational. Here, the known phenomena observed in cutting are discussed qualitatively. The essence of the second stage is the experimental verification of the ideas gained in the first stage. The third stage includes the mathematical treatment of the observed results to estimate their significance.

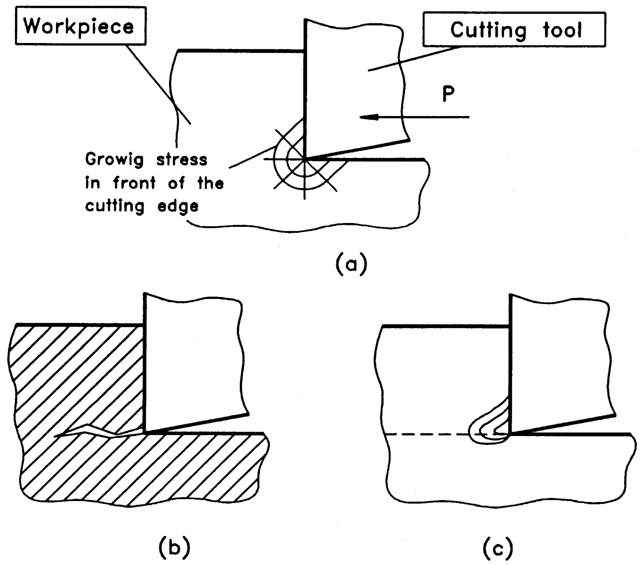

Fig. 2. The cutting tool starting to advance into the workpiece.

4.1. Observational part

Consider the cutting wedge starting to advance into the workpiece (Fig. 2(a)). As a result, the stresses grows in the workpiece and, as might be expected, the maximum stress occurs in front of the cutting edge. When this maximum stress reaches a particular limit, the following may happen:

(i) If the workpiece material is brittle, a crack appears in front of the cutting edge, which in turn leads to the fracture of the layer being removed (Fig. 2(b)).

(ii) If the workpiece material is ductile, a visible crack will not form because of the healing effect, instead, a zone of high plasticity being formed (Fig. 2(c)). The workpiece material adjacent to this zone is deformed elastically, thus an elastro-plastic zone forms within the workpiece. The dimensions of the plastic and elastic zones depending on the ductility of the workpiece material. It is understood that for a perfectly plastic material, the elastic zone will not form at all, whilst for a perfectly brittle material the plastic zone would never form.

Therefore, this simple consideration shows that the properties of the workpiece material play an important role from the beginning of chip formation. Since the general behavior of materials can be classified as ductile or brittle depending upon whether or not the material exhibits the ability to undergo plastic deformation [8], this feature should be incorporated in the chip formation theory.

It is apparent from the above discussion that the system concept along with the concept of the bending moments can be applied to the analysis of chip formation for a variety of cutting conditions.

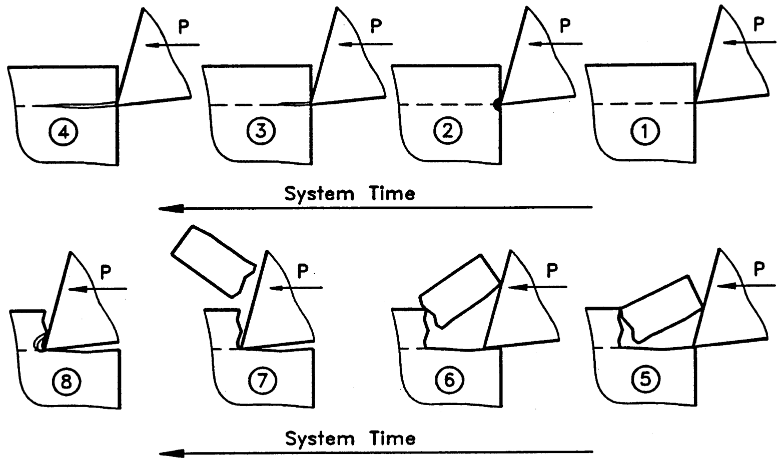

Fig. 3. System consideration of the chip formation in the cutting of a brittle material. The cutting tool has a positive rake angle.

4.1.1. Brittle workpiece materials

Consider the machining of a brittle material using the proposed system approach. Fig. 3 illustrates successive phases (1–8) in the machining of a brittle material using a cutting tool with a positive rake angle. Phase 1 shows the initial state. The stress ahead the cutting edge will increase with increasing applied load P (Phase 2). When this stress reaches a particular limit, a crack forms in front of the cutting edge (Phase 3). A further increase in the applied load leads to the development of the crack (Phase 4). A part of the separated workpiece material located above the crack now serves as a cantilever. When the applied force reaches a particular limit, the fracture of the workpiece material takes place at the cantilever support (Phase 5). As such, separate, almost rectangular chip elements are produced (Phases 6, 7). This case was studies in the cutting of cast irons and woods along the fibers [(1,6)]. Summarizing these considerations, a model of chip formation for the cutting of brittle materials with a tool having a positive rake angle may be introduced (Fig. 4(a)) This model shows that the bending stress occurs only when the direction of the resultant force R intersects the conditional axis of the formed chip-cantilever. When this force reaches a particular limit, the fracture of the workpiece material takes place in section 1-1, and the above-mentioned separate, almost rectangular chip elements are produced. This case was observed in the cutting of cast irons with a positive rake angle [9].

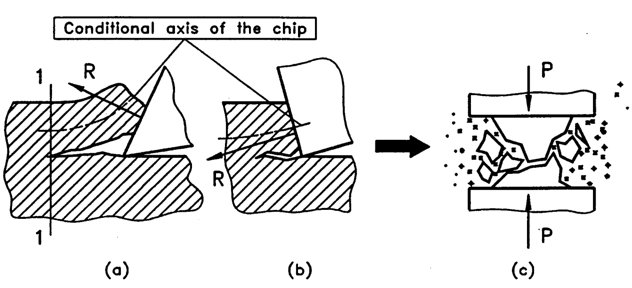

Fig. 4. Two models of chip formation for the machining of brittle materials: (a) the direction of the force resultant R intersects the conditonal axis of the formed chip-cantilever; (b) the direction of the force resultant R does not intersect the conditional axis of the formed chip-cantilever.

Now consider the case where, after crack formation, the resultant force is directed so that it does not intersect the conditional axis of the formed chip (Fig. 4(b)). As seen, there is no bending stress in the machining zone. As a result, final failure occurs due to pure compression of a fragment of the layer being removed. The common failure of a brittle material under compression takes place. As might be expected, a few fragments of work material and dust are formed (Fig. 4(c)). Such dust is an inherent feature of machine shops dealing with the machining of cast irons. To better visualize this consideration, successive phases (1–8) in the machining of a brittle material using a cutting tool with negative rake angle are shown in Fig. 5.

4.1.2. Ductile workpiece materials

At the initial stage of chip formation, an elasto-plastic zone in front of the cutting edge forms as the result of pure compression. In effect, the plastic deformation of the workpiece material takes place by shearing at this stage. As the tool advances further, the plastically deformed part of the workpiece material gradually comes into close contact with the tool rake face. When full contact is achieved, this part serves as a cantilever subjected to a penetration force P from the tool rake face (Fig. 6(a)). The penetration force P can be resolved into two components, namely, a compressive force Q, acting along the axial direction, and a bending force S, acting along the transverse direction (Fig. 6(b)). Therefore, the chip-cantilever is subjected to the mutual action of the compressive force Q and a bending moment $M(=Sl)$. Since the state of stress becomes com-

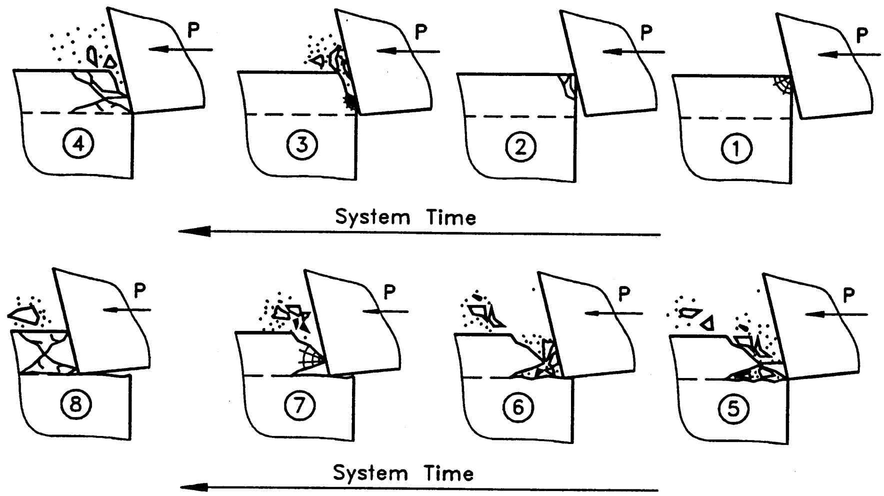

Fig. 5. System consideration of the model shown in Fig. 4(b).

plex including a combination of bending and compressive stresses, the deformation process will shift from one mechanism to another. As a result of the mutual action of compression and bending, the maximum stress occurs in the vicinity of the chip-cantilever support, thus fracture takes place along section 1-1, which is the plane of the maximum combined stress (Fig. 6(a)).

A system consideration of chip formation in the cutting of ductile materials (besides the special cases that have been discussed in [1]) is shown in Fig. 7. In this figure, phase 1 shows the initial state. When the tool is in contact with the workpiece, the application of the penetration force P leads to the formation of a deformation zone ahead the cutting edge. As might be expected, the workpiece at first deforms elastically (phase 2). When the load from the tool exceeds a value corresponding to the yield strength, the workpiece undergoes plastic deformation. Therefore, a elasto-plastic zone occurs in the workpiece ahead of the tool, which allows the tool to advance into the workpiece so that a part of the layer to be removed comes into close contact with the rake face (phase 3). When full contact is achieved, this part serves as a cantilever subjected to the penetration force P from the tool rake face. Thereafter, the state of stress in the deformation zone becomes complex, including a combination of bending and compressive stresses. Therefore, the process of further deformation is controlled by the combined stress. As such, the relative dimension of the plastic part of the deformation zone will increase with the increase in the applied load P (phase 4). When the combined stress in this zone reaches the limit (for a given workpiece material), a sliding surface forms in the direction of the maximum combined stress (phase 5): this may be considered as the beginning of chip formation. As soon as the sliding surface is formed, all of the cantilever material starts to slide along this surface, thus along the tool face (phase 6). On sliding, the resistance to the tool penetration decreases which in turn, leads to a decrease in the dimensions of the plastic part of the deformation zone (phase 7). However, the structure of the workpiece material that has been deformed plastically and now returns to the elastic state is different from that of the original material. This structure is heavily deformed and its appearance corresponds to the structure of the cold-worked material [8]. In effect, the hardness of this material is much higher than that of the original material. It may be assumed here that this material, spread over the tool–chip interface by the moving chip, forms the so-called chip contact layer [10,11], which is now known to be formed by severe friction conditions along the so-called secondary deformation zone, which is in fact the plastic part of the tool–chip interface (phase 8). The sliding of the chip fragment continues until the force acting on this fragment from the tool is reduced because a new portion of the work material enters into contact with the rake face. The new portion attracts a part of the penetration force P. In effect, the stress along the slide plane diminishes and thus becomes less than the limiting stress, which terminates the sliding (phase 9). A new fragment of the chip starts to form (phase 10). It is worthwhile to note here that since the resistance to the penetration of the tool into the workpiece varies within the period of time necessary to form a chip fragment, the bending moment and thus the bending stress in the deformation zone should be variable rather than static.

The chip formed in this way is referred to as the continuous fragmentary chip. It has a saw-shaped free side (Fig. 8).

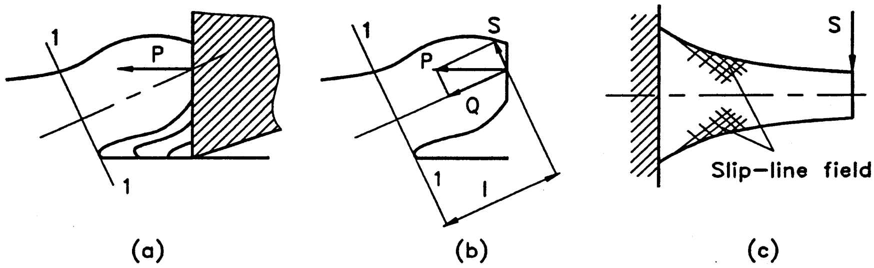

Fig. 6. The interaction between the tool rake face and the chip: (a) penetration force P acting on the chip; (b) two components of the penetration force, namely, the compressive force Q and the bending force S; (c) plastic deformation of an elastoplastic cantilever having a curved contour by the bending force S.

4.2. Experimental verification

The models discussed of chip formation in the cutting of brittle materials are supported by a number of known experimental observations [9,12,13]. Moreover, the results discussed can be examined directly by a simple cutting experiment. On the contrary, the model of chip formation in the cutting of ductile materials has to be proven. Here, to prove that the model is adequate for the real cutting process, two essential factors should be examined. Firstly, the presence and significance of the bending stress in the deformation zone should be examined. Secondly, the variation of this stress within the period of time necessary to form a chip fragment should be verified.

The presence of the bending stress in the deformation zone was confirmed by modeling as follows. The general field of plastic deformation in the cutting of elastro-plastic materials was modeled using the method of graphical superposition of the texture lines [10]. The determination of the shape of the lower boundary of the deformation zone in the workpiece has been based on the following. Firstly, it is known that if a cantilever with a curved contour (as a model for the partially formed chip) is loaded by the bending moment then maximum plastic deformation occurs in the vicinity of it's external surfaces adjacent to the support, and its slip (texture) lines are located as shown in Fig. 6(c) [14]. Secondly, the plastic deformation occurring under compression is the result of a series of shears. As such, the plane of the maximum shear stress inclines at an angle of 45° to the direction of action of the compressive force thus the slip (texture) [8]. Since it was assumed that the plastic deformation of the workpiece is governed by the combined stress, the general field of plastic deformation in the workpiece shown in Fig. 9(a) was modeled by graphical superposition of the slip line fields due to compression and that due to bending. Although the lower boundary of the plastic zone obtained in this way is in good agreement with reported experimental data (Fig. 5A, 36, and 47 in [10]; Figs. 9.37, 9.6, and 10.15 in [11]), an additional experiment was carried out.

The micrograph in Fig. 9(b) shows a frozen picture of the region adjacent to the cutting edge where the shape of the lower boundary of the deformation zone can be seen clearly. This is a micrograph of a sample obtained using a quick-stop device. The sample, made of AISI 1040 steel, was machined within the standard cutting within the standard cutting regime (a C6 carbide cutter, cutting speed 120 m min $^{-1}$, cutting feed 0.26 mm rev $^{-1}$, no coolant). At the end of a chip-formation cycle, the cutting systems components were disengaged almost instantly. Then the sample was cut off from the rest of the workpiece, polished and etched, and finally examined by optical microscopy. The structure of the deformation zone, obtained in this way, is in close agreements with the results of the modeling.

To confirm that the bending stress in the deformation zone: (i) plays a significant role in chip formation; and (ii) varies within a cycle of chip formation with specific limits; a special experiment was curried out. The essence of the experiment was the analysis of the chip structure, which should reflect the influence and the variation of the bending stress if this is the case.

For the experiment, the general methodology, preparation stage, machine, measuring instruments and their calibration, data collection and acquisition procedure as suggested in [15–19] were used. A nickel-based high alloy was cut using the following cutting regime: cutting speed 5 m min $^{-1}$ (chosen experimentally to be the optimum cutting speed as recommended in [18]); feed 0.45 mm rev $^{-1}$; dept of cut 2 mm. Cutting tool parameters: tool material carbide C6; rake angle 0°; flank angle 8°. The variation of the location angle of the plane of maximum deformation was observed in the samples of the partially formed chip obtained using a quick-stop device. A known procedure was used for sample preparation [10]. A bar of workpiece material was loaded into the quick-stop device. Then, whilst cutting at a particular defined (by a cutting force transducer and the data acquisition system which triggered the quick-stop devise) instance [1], the cutting systems components were disengaged almost instantly. It is understood that a time constant (a system lag) for the quick-stop device was determined and the triggering

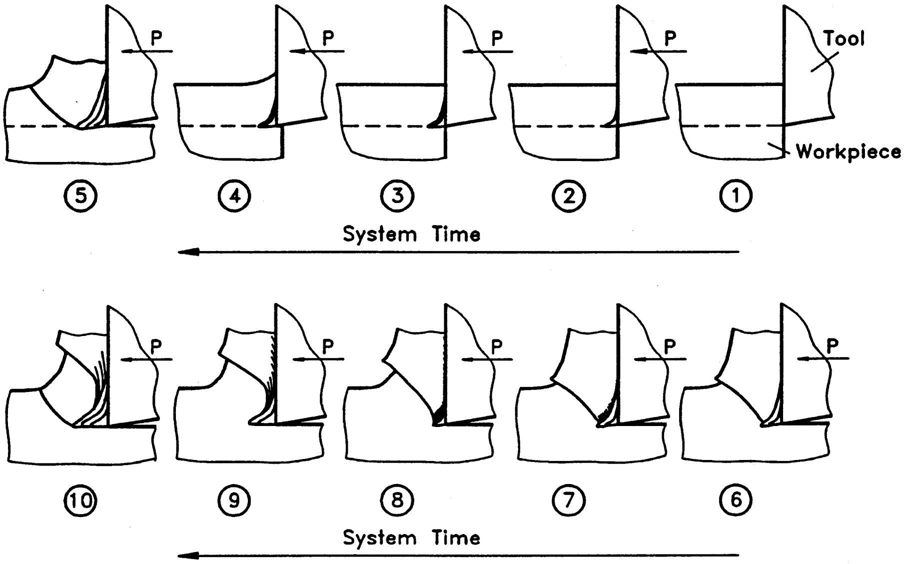

Fig. 7. System consideration of chip formation in the cutting of ductile materials.

was shifted by programming the data acquisition system. Then the sample was cut off from the rest of workpiece, polished and etched, and finally examined by optical microscopy. To distinguish the variation of the load conditions within the chip-formation cycle, a microhardness test was carried out [18]; a Tukon hardness tester with a Vickers indenter being used to obtain the microhardness measurements. A testing load 10 N was used throughout the testing program, this load causing indentations small enough to be capable of establishing meaningful hardness gradients and yet being sufficiently large to average out hardness variations within the ferrite and perlite matrix of the work material.

Fig. 10(a) shows the reconstructed picture, which summarizes the results of the experiment. In this figure, the beginning and the end of a chip-formation cycle are show by a dashed and solid line respectively. At the beginning of a chip-formation cycle, the surface of maximum stress (which was approximated by a plane) was located at angle $\delta_1 = 45°$, which corresponds to pure shearing [8]. At the end of a chip-formation cycle, the plane of maximum stress is located at angle $\delta_2 = 30°$, which corresponds to the combined stress when the bending stress is at its maximum.

The analysis of the chip structure shows that it is not uniform. At the beginning of a chip-formation cycle, the chip has a structure with slightly deformed grains (Fig. 10(b)), this structure being quite similar to those taken from samples experiencing plastic deformation by pure shearing (Fig. 32 in [19]). At the end of a chip-formation cycle, the chip has a structure with heavily deformed grains (Fig. 10(c)), this structure being similar to those taken from samples experiencing plastic deformation under combined stress [20]. The corresponding variation of microhardness was found to be in the range of from 3800 Mpa at the beginning of a chip-for-

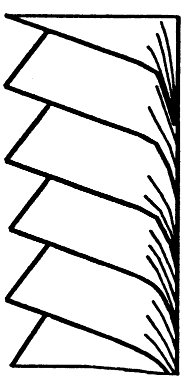

Fig. 8. Structure of the continous fragmental chip.

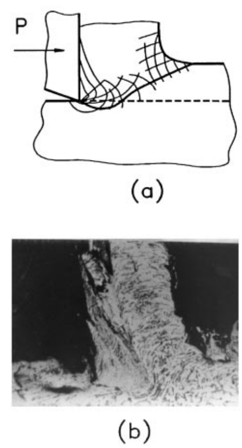

Fig. 9. Shape of the lower boundary of the deformation zone: (a) as modeled by superposition of the slip-line fields due to bending; (b) a ‘frozen’ picture of the deformation zone obtained using a quick-stop device (× 60).

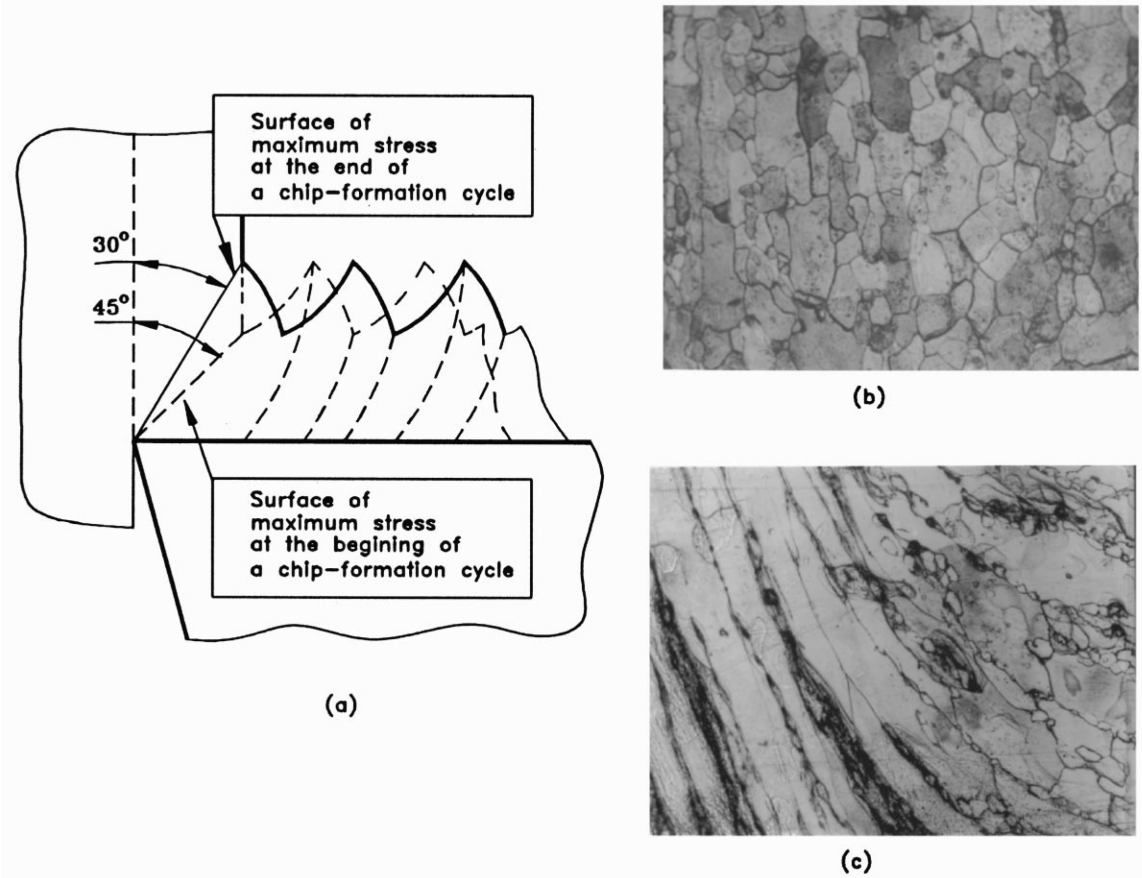

Fig. 10. Model of chip formation reconstructed using experimental results obtained in the cutting of a nickle-based high alloy: (a) a variation of the location of the surface of maximum combined stress within a cycle of chip formation; (b) chip structure at the beginning (× 125); (c) chip structure at the end (× 125) of a chip-formation cycle.

mation cycle to 5900 Mpa at the end. Moreover, it was found that the continuous fragmentary chip has a non-uniform strength along its length, the shear strength of the fragments being much higher than the strength of the fragment connections.

The experimental results presented above show clearly the presence of the bending stress in the deformation zone.

4.3. Quantitative analysis of the bending stress

As soon as it has been established experimentally that the bending stress affects the chip-formation process, an essential question about the significance of the bending stress should be answered. In order to be able to answer this question, the ratio of bending stress/shear stress has to be estimated. In order to do this, experimental results obtained for a representative case (Fig. 10) are essential.

Consider the state of the cutting system shown in Fig. 10 at the moment when the bending stress is at is at a maximum (Fig. 11). Referring to Fig. 11, the average shear stress in the plane of maximum deformation can be computed by using the equation [2,10]:

$$\tau = \frac{P}{ab} \sin 30° \cos 30° \tag{2}$$

The equation for the bending stress acting along the sliding plane (which should be considered as the plane of the maximum combined stress) can be deduced using the model shown in Fig. 11 accounting for the following:

(i) the root of the chip-cantilever is in the plastic state, thus the bending stress distribution along the surface of maximum combined stress is as shown in Fig. 11 [21]. As such, the value of the bending moment, which corresponds to a fully plastic support condition, is called the plastic moment, which for a rectangular member made of an elasto-plastic material is [21]:

$$M_p = \frac{3}{2} \frac{\sigma_b}{S_b} \tag{3}$$

Here, σ_b is the bending stress and S_b is the elastic section modulus.

(ii) the surface of maximum combined stress approximated by a plane has a rectangular cross-section $b \times a/\sin 30°$(Fig. 11) where b is the width of the cut, and a is the uncut chip thickness.

For the rectangular cross-section considered here:

$$S_b = \frac{2}{3}\frac{ba^2}{\sin^2 30°} \quad (4)$$

Combining Eqs. (3) and (4) one may obtain the equation for the bending stress:

$$\sigma_b = \frac{M_p}{ba^2}\sin^2 30° \quad (5)$$

To calculate the bending moment, only the power component of the resultant cutting force is considered, as shown in Fig. 11. The most conservative approach is taken by not considering the bending moment due to the weight of the partially formed chip [22] or due to the chip interaction with any other obstacles. Moreover, it is considered that the cutting force P is applied at the middle of tool/chip contact length c, which latter can be calculated knowing the chip compression ratio ζ as follows [17]:

$$c = a\zeta^{1.5} \quad (6)$$

The expression for the bending moment, therefore, is:

$$M_p = Pl = P\left(\frac{a\zeta^{1.5}}{2} - \frac{a}{2}\right) = 0.5Pa(\zeta^{1.5} - 1) \quad (7)$$

By substituting Eq. (7) into Eq. (5), one may obtain the final expression for the bending stress:

$$\sigma_b = \frac{0.5P(\zeta^{1.5} - 1)}{ba}\sin^2 30° \quad (8)$$

Finally, the ratio of the bending and shear stresses may be obtained using Eqs. (8) and (2):

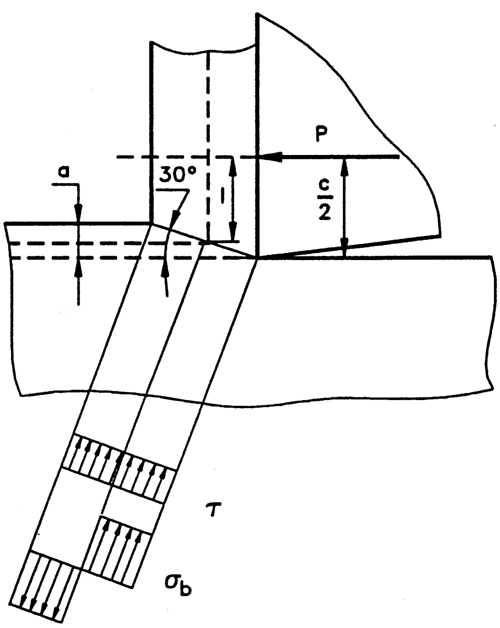

Fig. 11. Model of the cutting mechanism used for the derivation of the analytical expression for the bending stress on the surface of maximum combined stress.

$$\frac{\sigma_b}{\tau} = 0.5(\zeta^{1.5} - 1)\tan 30° \quad (9)$$

Substituting the experimentally obtained value of the chip compression ratio, $\zeta = 3.45$, into Eq. (9), $\sigma_b/\tau = 1.56$ is obtained.

According to Eq. (9), the bending stress varies within a cycle of chip formation from zero, when the surface of maximum combined stress is inclined at an angle of 45° with a corresponding chip compression ration equal to unity, to a particular value that is 1.56 times greater than the average shear stress on this surface. Therefore, the bending stress in the deformation zone is sufficiently large to affect chip formation.

5. Discussion and conclusions

5.1. Discussion

It is evident from the above considerations that the metal forming process known as metal cutting has one distinguished feature, namely, the bending stress in the deformation zone causing chip formation. Regardless of the workpiece material (wood, plastic, metal, stone) and cutting tool used, a forming process having this distinguishing feature should be called metal cutting. From this, it is understood that, regardless of the workpiece material, cutting by a knife or by a pair of scissors is splitting by shearing and does not correlate with metal cutting, even though a thin metal sheet can serve as the workpiece because there is no bending moment in such cutting and, thus, a chip does not occur.

System consideration of the chip-formation process reveals that this process is periodic. As a result, the process parameters are continually varying in a cyclical nature. This variation results at the macro-level in a fragmental chip structure and at the micro-level in a variable chip fragment structure. Bearing this in mind, it would be expected that all of the known process parameters vary within a chip-formation cycle. It may be further assumed that these features give the impression that the metal cutting process is random because if the measurements of its parameters are taken without referring to the system time, they really may appear as having a stochastic nature [23]

5.2. Conclusions

(1) A cutting process is the purposeful fracture of the work material taking place within a cutting system composed of the following components: the tool, the workpiece and the chip. (2) The main system property is the dynamic interactions of the systems components. As a result of these interactions, the state of stress in the deformation zone includes a variable combination

of shear and bending stresses. (3) The variation of the stress in the deformation zone constitutes the cyclical character of the chip formation process. As a result, the sliding plane, formed in the cutting of ductile materials, does not exist throughout the whole period of the process. Rather, the sliding plane forms at the end of each cycle as a result of the stress redistribution in this cycle and appears as the surface of maximum combined stress. (4) The presence of the bending stress in the deformation zone that causes chip formation, distinguishes the process of metal cutting from other, closely related manufacturing processes.

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