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A treatise on material characterization in the metal cutting process. Part 2: cutting as the fracture of workpiece material

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Abstract

Part 1 of this two-part paper presents a novel approach to the characterization of the resistance of workpiece material to cutting. It is shown that the strain at fracture is the most general material behavior characteristic. This second part offers a novel approach towards the meaning of plasticity in metal cutting and its relationship to the strain at fracture. It is shown that the strain-rate sensitivity is one of the plasticity criteria. The influences of defect population in metals and the state of stress in the deformation zone on fracture in metal cutting are considered. It is shown that, by changing the state of stress, the strain at fracture and thus the energy consumption in cutting can be varied over a wide range. This approach appears to be a new ground for choosing cutting tool geometry and cutting regime. The final part of the paper establishes that ductile fracture along the line which separates the layer to be removed from the rest of the workpiece takes place in metal cutting. For the first time, a definition of the metal cutting process is proposed. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Metal cutting process; Strain at fracture; Plasticity

1. Introduction

As discussed in part 1, at the present stage of development, the predictability of a metal cutting theory depends entirely on the accuracy with which it accounts for the energy involved in the process. It is also shown that this energy is defined by the strain at fracture of the workpiece material. Works dealing with the fracture of engineering materials are directed to define the conditions under which the material should not fracture or fail in service. In contrast, in metal cutting, the opposite effect is desired, namely, how to fracture a given material with minimum effort. Therefore, studies of fracture processes in materials should be conducted in this direction. Such studies might give a valuable insight into why materials behave as they do; also, why some materials exhibit more resistance to cutting than others; and what is really meant by stiffness, strength, brittleness and toughness when these characteristics are considered in terms of metal cutting. It is mainly by means of such studies that better metal removing processes can be developed.

Several failure theories, which have been identified during the past 200 years, are based on the concept that the stress conditions causing failure in a standard tensile test of a bar specimen are also responsible for failure in a component subjected to combined loads [1]. These works utilize the failure criterion that is referred to as the stress criterion. The maximum normal stress theory is perhaps the simplest failure theory, and describes failure as occurring when the maximum tensile or compressive stress exceeds the uniaxial tensile or compressive strength, respectively, of the material. This theory is suitable generally for brittle materials.

Another group of failure theories utilizes the concept that yielding of a material occurs when the distortion energy in the tensile test associated with the shape change is equal to the distortional energy in the component that experienced multi axial loading. These works utilize the maximum distortion energy or Von Mises' yield criterion which is in a reasonable correlation with actual test data [1]. This criterion is in wide use today and defines only the beginning of plastic deformation, which is good enough in the calculations used in design. However, this criterion cannot be used to define the fracture strain ε_f, i.e., the total amount of plastic deformation at failure. Therefore, it is not applicable in the analysis of the metal cutting process.

The discussed criteria are of no importance in the study of metal cutting since the mathematical theory of plasticity does not consider the real structure of polycrystalline mate-

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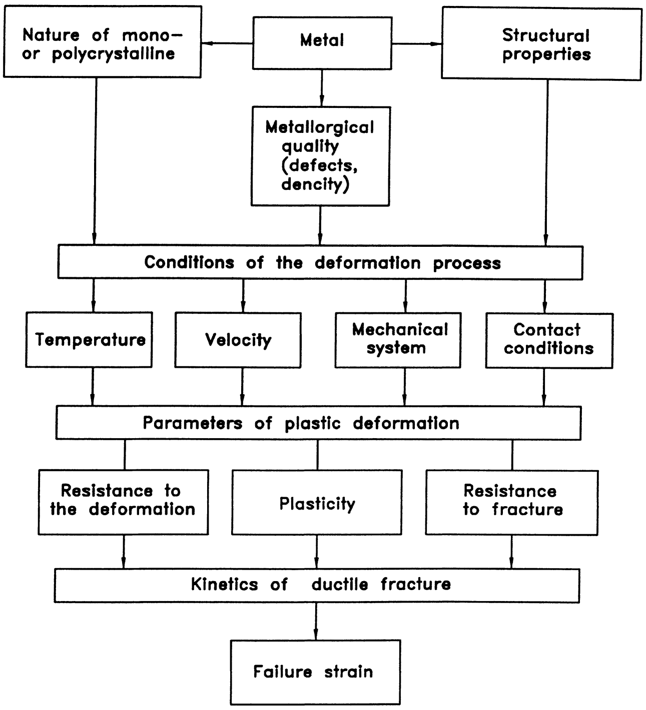

Fig. 1. Major interactions between the fracture strain and other structural-deformation parameters.

rials so that it cannot be used to define the fracture strain of a material as well as other important process parameters.

In the present study, general correlations of the strain at fracture with the material and process parameters are considered, as shown in Fig. 1. The objective of this paper is to reveal the influence of the process parameters on the strain at fracture, making a step towards prediction of the metal cutting process.

2. Plasticity and stress relaxation

The plasticity of a material can be defined as its ability to undergo irreversible plastic deformation when a sufficient external load is applied. Here, the word "ability" assumes that certain plastic mechanisms of stress relaxation exist in the material.

Plastic deformation including its final stage (fracture) takes place under complicated non-homogeneous stress and structural changing, and a transient temperature field, and is accompanied by, at least, five different energy fluxes: release of the elastic energy, crack formation, heat flow, mass transfer (pure diffusion), and the movement and multiplication of dislocations. The probability of each energy flux to predominate under given conditions may be estimated by means of the Einstein equation [2]:

$$p \sim \exp\left(\frac{S_{\rm cur} - S_{\rm eq}}{k}\right) \sim \exp\left(-\frac{J_{\rm d} t_{\rm p}}{k}\right), \qquad (1)$$

where $S_{\rm cur}$ and $S_{\rm eq}$ are the system energy in the current and equilibrium states, respectively; k the Boltzmann constant; $J_{\rm d}$ the density of dissipated energy flux equal to the derivative of the entropy of the system with respect to the temperature, that is dS/dT; and $t_{\rm p}$ is the time necessary for relaxation which characterizes the duration of the restoration of the system's equilibrium state and depends on the nature of the restoration process.

According to Eq. (1), the probability of predomination of one of the five listed irreversible processes with respect to the others is defined by both the density of dissipated energy flux $J_{\rm d}$ and the time necessary for relaxation $t_{\rm p}$. When two or more processess have equal densities of dissipated energy (which is quite common), the greater probability is for the process possessing the lower relaxation time $t_{\rm p}$.

Maxwell was probably the first who interpreted the relaxation time as a measure of plasticity [2]. The relaxation of stress in plastic deformation may be represented as:

$$\sigma_t = \sigma_0 \exp\left(-\frac{t}{t_{\rm p}}\right) \approx \sigma_0 \exp(-v_{\rm p} t), \qquad (2)$$

where σ_0 and $\sigma_{\rm t}$ are the applied initial and current stresses, respectively; t the current time; $t_{\rm p}=1/v_{\rm p}$ the period of time during which the stress is reduced by e ($\approx$2.71) times; and $v_{\rm p}$ is the velocity of relaxation per unit time.

Kurnakov [3] used a specially designed mechanical test to measure the relaxation time and showed that this can be used as a measure of the plasticity (brittleness) of solids. According to him, the longer the relaxation time (smaller $v_{\rm p}$), the slower the elastic deformation is transformed into plastic deformation, and the greater the brittleness of the material and vice versa. When the strain-rate, as a measure of the velocity of deformation, is lower than the velocity of relaxation per unit time, the material exhibits plastic behavior, whilst when the strain-rate exceeds $v_{\rm p}$ the same material exhibits brittle behavior. Consequently, in deforming processes, ductility and brittleness are not absolute properties of the materials and can be altered by the process parameters.

Considering the ratio of Eq. (2) written for two independent time instants t_1 and t_2 and after taking natural logarithms of both sides, one may obtain:

$$v_{\rm p} \approx \frac{\ln(\sigma_1/\sigma_2)}{t_1 - t_2} \sim cm = \frac{\ln(\sigma_1/\sigma_2)}{\dot{\varepsilon}_1 - \dot{\varepsilon}_2}, \qquad (3)$$

where m is known as the strain-rate sensitivity [4], and c is a constant.

It follows from Eq. (3) that the strain-rate sensitivity may be considered as one of the plasticity criteria. This conclusion is also supported by the results of mechanical tests at high pressure [4] which revealed the direct correlation between the strain-rate sensitivity m and the elongation ε_f. An important warning, however, follows from the results of studies conducted on pressing, upsetting, extrusion, cutting, etc., that shows that m does not depend on a particular mechanical system whereas the fracture strain does [3]. It has been also proven that an increase (decrease) in m

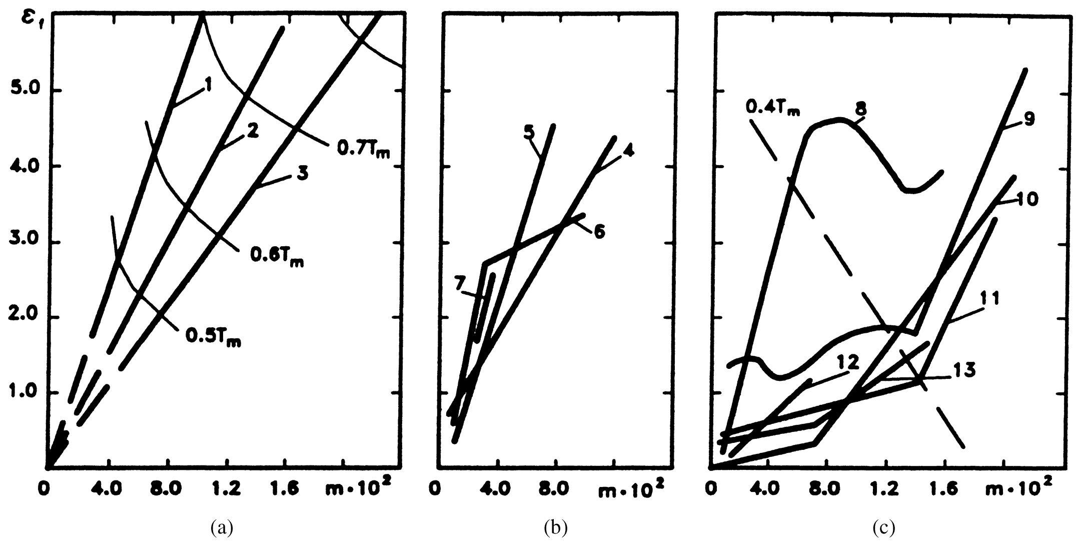

Fig. 2. Effect of the strain-rate sensitivity on the fracture strain in the tensile test over the test temperature range 0.1–0.8 T_m for: (a) face-centered cubic metals: (1) silver, (2) copper, (3) aluminium; (b) body-centered cubic metals: (4) iron, (5) vanadium, (6) molybdenum, (7) chromium; (c) hexagonal close-packed metals: (8) cadmium, (9) titanium, (10) zinc, (11) cobalt, (12) magnesium, (13) lanthanum.

corresponds to an increase (decrease) in ε_f even though particular values of ε_f, depending on the state of stress, on the homogeneity of deformation and on many other mechanical factors, may vary over a broad range. Experimental relationships $\varepsilon_f = f(m)$ obtained over the test temperature range 0.1–0.8 T_m (T_m is the melting temperature) in tensile tests ($\dot{\varepsilon} = 10^{-1}\,s^{-1}$) for different materials are shown in Fig. 2. One important conclusion may be drawn from this figure. Within each particular type of crystal structure (face-centered cubic, body-centered cubic, and hexagonal close-packed), metals of higher density exhibit higher fracture strains than those of lower density, even though both have approximately the same technical purity and strain-rate sensitivity.

3. Defect population in metals

It is known that materials possess low fracture strength relative to their theoretical capacity because most materials deform at much lower stress levels due to the defects that are microstructural in origin and induced during the manufacturing process [4]. The defects and impurities in metals are classified in Table 1.

Table 1
Defects and impurities in metals

Type	Minimum size	Point and line defects		Surface defects
		'+' defect	'−' defect	
Submicro-defects	$(1...5)\times10^{-10}$ m	Interstitial impurity atoms, substitutional impurity atoms	Vacancies of different types	
	$(5...10)\times10^{-10}$ m	Clusters, Guinier–Priston zones, gas subnuclei, dislocation loops	Concentrations of vacancies, dislocation loops	Surface of the material, disclinations, imperfections in the crystal structure, grains boundaries, inter-phase boundaries, submicro-cracks
	$(50...2000)\times10^{-10}$ m	Microblisters, fine precipitates throughout the alloy (for example, carbides in tempered steels)	Submicropores	
Micro-defects	$(0.2...1000)\times10^{-7}$ m	Fine inclusions dispersed throughout steels (for example, nonmetallic–metallic inclusions and carbides in tempered steels)	Micropores	Residual microstresses, micro-cracks, blasters, non-fusion zones, variable grain size, overburned and overheated zones
Macro-defects	$>10^{-3}$ m	Non-metallic inclusions, shrinkage cavities, porosity, blasters	Pores	Residual macrostresses, cracks including quenching cracks, machining marks (gouges, burns, tears, scratches, etc.)

The defects affect the density of metals. For example, the theoretical density of copper ($\rho_{Cu(T)}$=8988 kg/m^3) is greater than that of monocrystal by 0.4% and than that of polycrystal by 0.52%. The density of ferrite structure of 0.0001% impurity is ρ_f=7874 kg/m^3 and is greater by 0.33% that of pearlight structure (ρ_p=7848 kg/m^3), and than that of cementite structure by 2.7% (ρ_c=7662 kg/m^3). Since the discussed difference in density occurs mainly due to the presence of the defect population in a real material having a certain real structure, this difference might have direct correlations with fracture kinetics and strain.

The presence of macro-defects is always undesirable from the design point of view since it lowers the levels of mechanical properties, including strength and ductility. However, these defects increase machinability since the energy expended in cutting is reduced. This is widely used in well-known free-machining steels, which are produced with addition of 0.1–0.3% sulfur or 0.1–0.35% lead or combinations of both to reduce the cutting forces, and cutting temperatures and hence the tool wear rates [5].

The role of micro- and submicro-defects is dual. On one hand, the strength of most metals increases with increase in their concentration to a certain limit. Moreover, ductility and thus fracture strain increases with the increasing mobility of defects. On the other hand, when the concentration of micro- and submicro-defects exceeds the critical limit, the strength of most metals decreases since these defects promote the development and propagation of micro- and macro-cracks. Although the latter may reduce the fracture strain significantly, thus increase machinability, there are few studies on the behavior of metals having supercritical micro-defect concentrations since it is of no importance in the design practice where the opposite effect is desired. In the opinion of the present author, use can be made of such defects taking into consideration the healing effect and the actual state of stress.

4. Influence of the state of stress

The state of stress in a body that undergoes plastic deformation affects the fracture strain. For example, it is known that hydrostatic compression increases and tension decreases the fracture strain [6]. However, this general knowledge is not sufficient to control the cutting process. Therefore, a certain generalized parameter characterizing the state of stress should be chosen to study the correlation between the state of stress and the fracture shear strain. A detailed analysis of the different criteria has shown that the factor and Lode parameters [1] may be chosen.

Fig. 3 shows the relationship between the fracture strain and the state of stress represented by the Π-factor:

$$\Pi = \frac{3I_1(\sigma)}{2\sqrt{I_1^2(\sigma) - 3I_2^2(\sigma)}}, \quad (4)$$

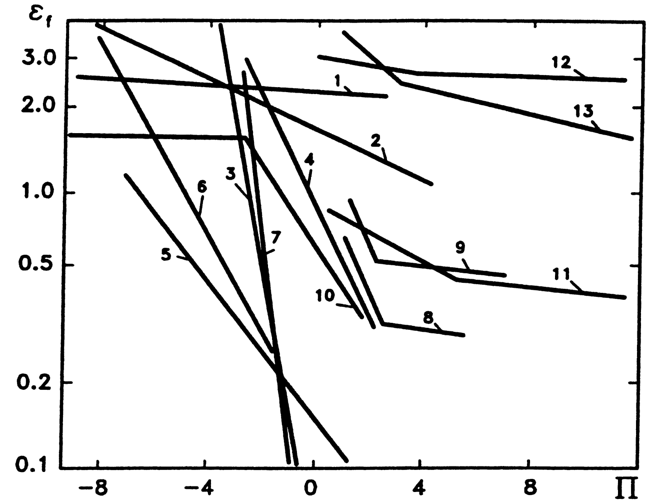

Fig. 3. Effect of the Π-factor on the fracture strain: (1) niobium, (2) iron, (3) tungsten, (4) molybdenum, (5) beryllium, (6) magnesium, (7) zinc, (8) tin alloy, (9) brass, (10) brass alloy, (11) tin bronze, (12) deformed lead, (13) cast lead.

where $I_1(\sigma)$ and $I_2(\sigma)$ are the stress invariants, which may be expressed in terms of the principal stresses as:

$$\begin{aligned} I_1 &= \sigma_1 + \sigma_2 + \sigma_3, \\ I_2 &= -(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1) \end{aligned} . \quad (5)$$

Lode [7] investigated the validity of the yield criteria using thin-walled tubes made of steel, copper and nickel subjected to various combinations of uniaxial tension and internal hydrostatic pressure. In doing this, he devised a sensitive method to determine the effect of the intermediate principal stress on yielding. This was expressed in the form of two parameters. To characterize the influence of the intermediate principal stress, σ_2, Lode introduced the parameter μ_L as,

$$\mu_L = \frac{2\sigma_2 - \sigma_3 - \sigma_1}{\sigma_1 - \sigma_3} = \frac{\sigma_2 - (\sigma_1 + \sigma_3)/2}{(\sigma_1 - \sigma_3)/2}, \quad (6)$$

which is known as the Lode stress parameter [8]. In addition to the stress parameter, μ_L, defined by Eq. (6), Lode also introduced the plastic strain parameter, ν_L, defined by:

$$\nu_L = \frac{2d\varepsilon_2^p - d\varepsilon_3^p - d\varepsilon_1^p}{d\varepsilon_3^p - d\varepsilon_1^p} = \frac{d\varepsilon_2^p - (1/2)(d\varepsilon_3^p + d\varepsilon_1^p)}{(1/2)(d\varepsilon_3^p - d\varepsilon_1^p)}, \quad (7)$$

where $d\varepsilon_1^p, d\varepsilon_2^p$, and εd_3^p are plastic strain increments in the principal directions.

Fig. 4 represents diagrammatically the relation between the Lode stress and the strain parameters for ideal plastic and strain-hardening materials.

A generalization of the available experimental data on the deformation of metals results in the following conclusions:

1. The strain at fracture depends significantly on the characteristic of the state of stress as, shown in Figs. 3 and 4. Therefore, by changing this state, the fracture strain and thus the energy consumption per unit volume

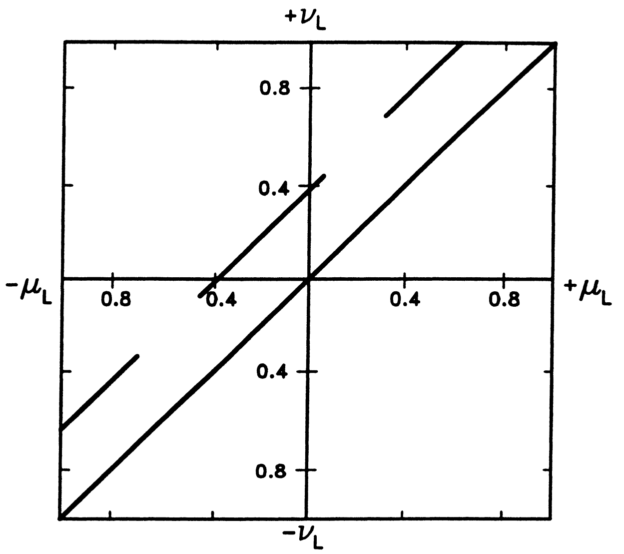

Fig. 4. Diagrammatic representation of the Lode parameters for ideal plastic (- - - -) and strain-hardening (—) materials.

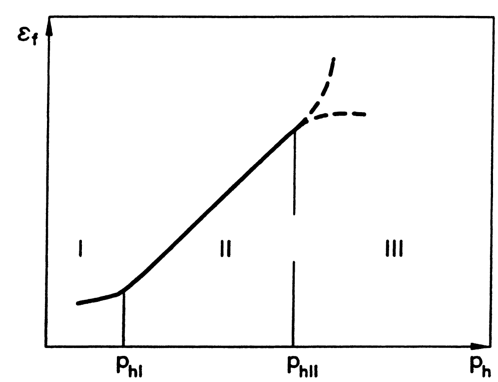

Fig. 5. Generalized dependence of the fracture strain ε_f on the hydrostatic stress σ_m.

of the layer to be removed in cutting can be minimized. In the opinion of the author, the easiest way to do this is to change the geometry of the cutting tool used to achieve the necessary value of μ_L. This approach appears to be a new way of choosing both the cutting geometry and the cutting regime.

2. The dependence of the fracture strain ε_f on the hydrostatic stress σ_m may be characterized by three distinct zones (Fig. 5): (I) zone of insignificant dependence, wherein ε_f is independent or depends insignificantly on σ_m until a certain limit σ_{m1}. This behavior is observed in tensile tests of brittle materials (cast iron, chromium); (II) zone of significant, approximately linear, dependence of ε_f on σ_m. This behavior was observed in the testing of all metals; (III) zone of a parabolic increase in plasticity. The boundary between zones II and III (the limit σ_{m2}) is not a line as shown in Fig. 5. Rather, it is a small zone. The exact behavior of metals in zone III is not yet known.
3. The temperature under which a test is carried out has a significant influence on the fracture strain. However, over the range of temperatures involved in cutting, temperature may not affect significantly the dependence of the fracture strain on the Lode stress parameter, as shown in Fig. 6.

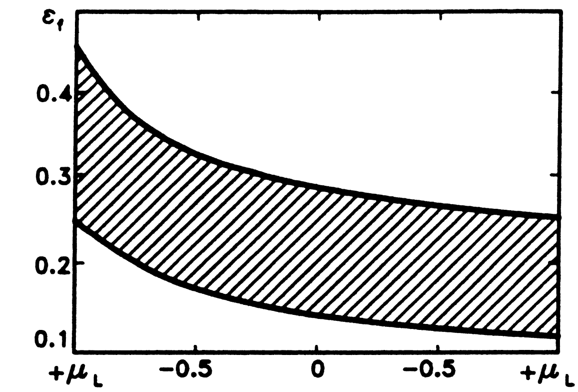

Fig. 6. Changes in the effect of the Lode stress parameter on the fracture strain.

5. Mechanism of fracture in metal cutting

Since it is known [4] that brittle and ductile fracture may occur in the deformation of even ductile materials such as a mild steel, it is important to understand what kind of fracture takes place in metal cutting.

It is well-known that brittle fractures occur in a transgranular manner whilst ductile fracture takes place in an inter-granular manner [4]. It is also known [9] that brittle fracture may occur in ductile materials. For example, in the brittle fracture of mild steel, the large micro-cracks observed in the ferrite grains are invariably associated with fractured carbide particles located somewhere in the grain or in the surrounding grain boundary. Fracture of the carbide particle by the stress field of a pile up is an essential intermediate event between the formation of a dislocation pile up and cleavage of the ferrite. The formation of a crack in a carbide can initiate cleavage fracture in the adjacent ferrite if the local stress is sufficiently high. Therefore, it is very important for the further analysis and development of a theoretical model to understand what kind of fracture takes place in metal cutting.

To distinguish what kind of fracture takes place in metal cutting, pinhole photography and the diffractometer technique was employed [10].

The following background was considered prior to the measurements [11–13]. In cutting ductile materials, plastic deformation takes place by shearing under the action of the combined stress. The shearing occurs along the surface of the maximum combined stress that does not exist throughout the whole cycle of chip formation. Rather, it forms at its end as the result of stress redistribution in this cycle. The fracture of the layer to be removed takes place along the line that separates this layer from the rest of the workpiece in a relatively small deformation zone. The workpiece material from this zone that is spread over the chip–tool interface forms the well-known chip contact layer which is believed now as to be formed due to severe friction conditions in the so-called secondary deformation zone. Therefore, to distinguish the mechanics of fracture, it is sufficient to compare the sized and orientation of the crystals (by their slip planes which is, for example, the basal plane (0 0 0 1) for hcp crystals) in the original material and in the chip contact layer. The result obtained then can be interpreted easily as follows. If fracture is the case, as suggested, the size of the grains (crystals) in the chip contact layer should be much smaller than that in the rest of the chip. If severe plastic deformation is the case, the size of the grains in the chip contact layer and in the rest of the chip should be the same, since plastic deformation cannot change the grain size.

Experiments were carried out for different groups of steels (plain low carbon, plain medium carbon, plain high carbon, low alloys, stainless, etc.), for nickel and chromium-based high alloys, for molybdenum and aluminum, and for high titanium alloys representing all kinds of crystallographic structures. In all of the cases considered, similar results have been obtained, which will be discussed in respect of the examples of the results obtained for the titanium and chromium–nickel based high alloy.

Fig. 7 shows diffractometer traces of the titanium alloy. Fig. 7(b) shows diffractometer traces for the initial material, where the crystals are oriented randomly, and Fig. 7(a) shows diffractometer traces for the chip, which is a kind of textured material. The chip was obtained in a cutting test conducted using the following regime: cutting speed – 0.1 m/s, cutting feed – 0.1 mm/rev, depth of cut – 5 mm, no coolant.

The results of Fig. 7(a) and (b) may be interpreted as follows. The picks in this figure are recommended to be considered as the random intensity [10], so they can be calculated by means of the normal density function:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left[-\frac{(a-x)^2}{2\sigma_x^2}\right]. \quad (8)$$

Therefore, the ratio of the height of the picks for the initial material and the chip defines the level of texturing of the crystals in the chip, whilst the ratio of their average widths defines the texturing of the crystals in chip formation. The results of the calculations show that the texturing of crystals in the chip is five times lower than that in the initial structure and that the average size of the crystals in the initial structure is 25 times greater than that of those in the chip.

The experimental results show that ductile fracture along the separation line between the layer to be removed and the rest of the workpiece takes place in metal cutting. Therefore, this type of fracture should be understood in order to predict metal cutting performance.

Since ductile fracture occurs only under a combined state of stress [4], it supports the earlier result [13] that the process

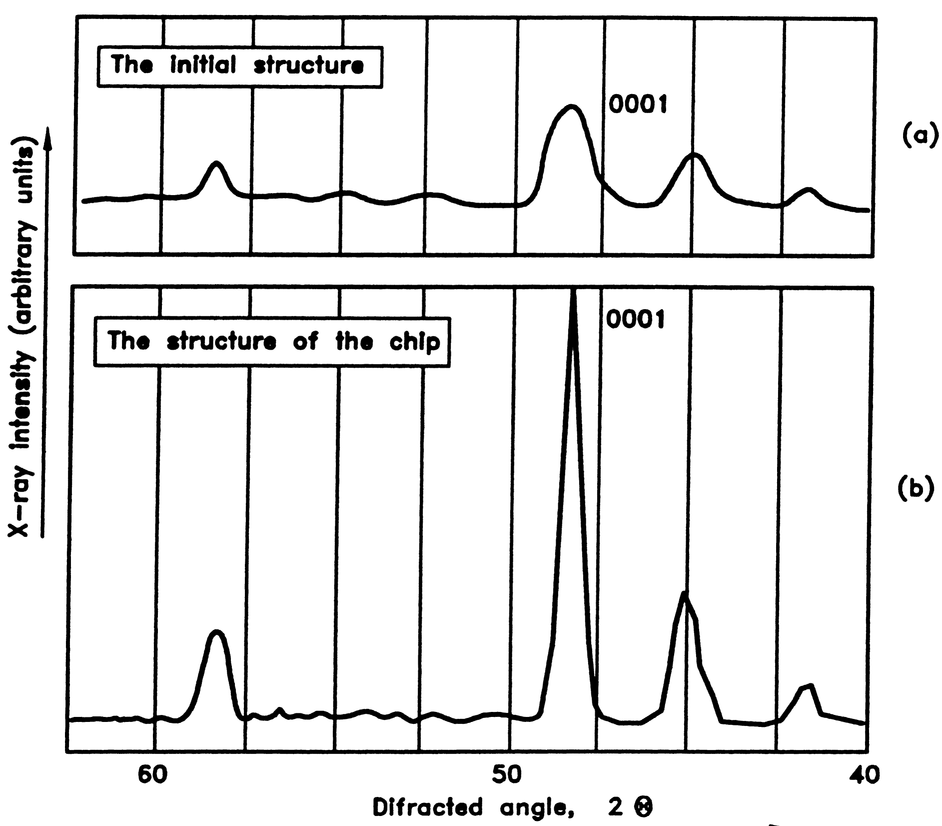

Fig. 7. Diffractometer traces of the titanium alloy: (a) the initial structure; (b) the structure of the chip.

of chip formation takes place due to a combination of bending and compressive stresses in the deformation zone. System considerations of the metal cutting process establish that the bending moment raised in the deformation zone, due to the interaction between the chip and tool rake face, is the cause of chip formation [11]. On the basis of the foregoing considerations the following definition of the metal cutting process is suggested:

The metal cutting process is a forming process, the components of which are so arranged that, by their means, the applied external energy causes the fracture of the layer to be removed that takes place due to the combined stress, including the bending stress.

The bending stress combined in the deformation zone with the shear stress due to compression causes chip formation. The presence of the bending stress in the deformation zone distinguishes the process of metal cutting from other deforming and separating manufacturing process. Regardless of the workpiece material (wood, stone, glass, plastic, metal), type, shape, geometry, etc., of the cutting tool used and the kinematics of the process, a forming process possessing this distinguishing feature should be called metal cutting.

6. Conclusions

1. The physical sense of the fracture strain is much broader than that of any available characteristic of plasticity accepted in the mathematical theory of plasticity or in metal forming, since the fracture strain correlates the ability of a material to undergo plastic deformation and the kinetics of internal defects formation and development such as crack formation, accumulation of porosity, etc. Moreover, the fracture strain, considered as a probability characteristic of plastic deformation, includes the probability of fracture depending on the structure, internal energy, and the state of stress in a material. Unfortunately, there are only a very few studies relating the fracture strain and the direct characteristics of the ductile fracture.
2. A great variety of different characteristics and criteria are used to characterize the fracture strain and the choice of each particular ones depends upon the required accuracy and the specific problem under consideration. The fracture strain is a functional depending upon a number of functions and state factors. As such, each of these can limit fracture strain.
3. Since the mathematical theory of plasticity considers only the macroscopic behavior of a plastically deforming solid in a uniform state of complex stress, it cannot help in studies of the nature of the fracture strain.
4. Multiple factors and function affecting the fracture strain may be grouped in to four categories: (1) defect population; (2) stress relaxation; (3) structural-energy strength level; and (4) the state of stress and deformation. However, none of these is a part (at least, directly) of the known characteristics of plastic deformation.
5. Multiple known particular relationships between the fracture strain and temperature, the rate of strain, porosity, purity, etc., obtained experimentally for common metals cannot be derived using any known theoretical expression for the fracture strain. Although there are a number of generalized parameters that may characterize experimental conditions, such as the state of stress and deformations (for example, the Lode stress and strain parameters), the strain-rate, the homologous temperature, etc., the known experimental relationship for fracture strain obtained within rather narrow ranges of parameters expressed differently (natural, average, true, relative, etc.) and represented using different scale (natural, semi- or log–log) makes it very difficult or even next to impossible to compare these parameters amongst themselves and with the known theoretical results.
6. The strain-rate sensitivity of a metal, considered as its ability to relax stresses, appears to be the most objective characteristic of the ductility of polycrystalline materials. All other characteristics of ductility used, such as elongation, reduction of area at fracture, fracture strain, etc., [1] may be thought of as the consequences of the strain-rate sensitivity. However, the strain-rate sensitivity does not account for a number of important parameters of the deformation process such as defect population in metals, the state of stress involved, the grain structure of the deformed material, etc., and thus, when considered alone, it appears to be irrelevant for computing the fracture strain in a complex practical deformation process.
7. To the first approximation, the strain at fracture may be considered as the ratio of the two functions:

$$\varepsilon_f = \frac{f_1(C_{\mathrm{def}})}{f_2(C_f)}, \tag{9}$$

where $f_1(C_{\mathrm{def}})$ is a function accounting for the material's ability for stress relaxation and may be thought of as $f_1(m)$; and $f_2(C_f)$ is a function accounting for the probability of fracture and thus depends on the defect population in the material, its microscopic structure, the state of stress, etc. Consequently, to derive a theoretical expression for computing the fracture strain, the functions f_1 and f_2 should be known.
8. Chip formation in metal cutting is the process of ductile fracture along the separation line between the layer to be removed and the rest of the workpiece.

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