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The assessment of plastic deformation in metal cutting

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Abstract

Because plastic deformation is a nuisance in the metal cutting process, its proper account is of high interest. A new meaning for the chip compression ratio is discussed showing that, on the contrary to shear strain, this parameter represents the true plastic deformation in metal cutting. The chip compression ratio can be used to calculate the total work done by the external force applied to the tool and then might be used for optimization of the cutting process. It is demonstrated that the cutting speed influences the energy spent on the deformation of the chip through temperature, dimensions of the deformation zone adjacent to the cutting edge and velocity of deformation. The separate impacts of these factors have been analyzed and the physical background behind the known experimental dependence of the chip compression ratio on the cutting speed is revealed. The influence of the cutting feed, tool cutting edge angle, cutting edge inclination angle and tool rake angle have also been analyzed.

Keywords: Plastic deformation; Measure; Chip ratio; Metal cutting; Energy

1. Introduction

Although machining is defined as a deforming process that forms and shapes metals and alloys [1], it seems that no single study points out the principal difference that exists between machining and all other metal forming processes which is the physical separation of the layer being removed (in the form of chips) from the rest of the workpiece. This separation must occur in machining. The process of physical separation of a solid body into two or more parts is known as FRACTURE [1] and thus machining must be treated as the purposeful fracture of the layer being removed.

To achieve this, the stress in the chip formation zone should exceed the strength of the work material (under a given state of stress imposed by the cutting tool), whereas other forming processes are performed by applying stress sufficient to achieve the well-known shear flow stress in the deformation zone. The ultimate objective of machining is to separate a certain layer from the rest of the workpiece with minimum possible plastic deformation and thus energy consumption. Therefore, the energy spent on plastic deformation in machining must be considered as wasted. On the other hand, any other metal forming process, especially involving high strains (deep drawing, extrusion) uses plastic deformation to accomplish the process. Parts are formed into useful shapes such as tubes, rods, and sheets by displacing the material from one location to another [2]. Therefore, the better material, from the viewpoint of metal forming, should exhibit higher strain before fracture occurs. It is understood that this is not the case in metal cutting where it is desired that the work material exhibits the strain at fracture as small as possible. Unfortunately, this does not follow from the traditional metal cutting theory [3–11] which normally utilizes the shear strength or, at best, the shear flow stress (the term was specially invented for metal cutting to cover the discrepancies between the theoretical and experimental results) to calculate the process parameters (cutting force, temperatures, contact characteristics) although everyday machining practice shows that these parameters are lower in cutting brittle materials having higher strength.

Historically, the chip compression ratio (hereafter, CCR), ζ (or its reciprocal, the chip ratio), which is determined as the ratio of the length of cut, L_1 to the corresponding length of the chip, L_c or the ratio of the chip thickness, t_2 to the uncut chip thickness, t_1, i.e.

$$\zeta = \frac{L_1}{L_c} = \frac{t_2}{t_1} \quad (1)$$

was introduced in earlier studies on metal cutting as a measure of plastic deformation in metal cutting [12,13] (Fig. 1). Due to relative simplicity of its experimental determination, the chip (compression) ratio was widely used in metal

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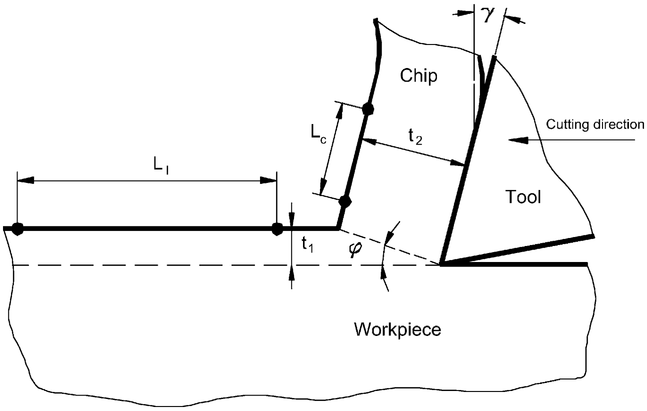

Fig. 1. Scheme of chip deformation in cutting.

cutting studies as a quantitative measure of the total plastic deformation [4]. Numerous attempts have been made to establish analytically a relationship to predict CCR in terms of fundamental variables of the cutting process. However, none of these attempts has produced results matching experimentally obtained data for a reasonable variety of input conditions. Later researchers abandoned this route in favor of a "modern" metal cutting approach in which this parameter is expected to be determined experimentally [3–11]. Because the chip compression ratio competes with shear strain for the role of a measure of plastic deformation encountered in metal cutting, it seems only logical to verify the justification of its usage as such a measure.

Merchant [3] proposed the following expression for shear strain ε:

$$\varepsilon = \frac{\cos\gamma}{\cos(\varphi-\gamma)\sin\varphi} = \frac{\zeta^2 - 2\zeta\sin\gamma + 1}{\zeta\cos\gamma} \quad (2)$$

where γ is the cutting tool rake angle, φ the shear angle.

To better visualize the correlation between shear strain, which should be actually called the final shear strain [13], and CCR, the results of calculations using Eq. (2) illustrated in Fig. 2 for different rake angles. As might be expected, the

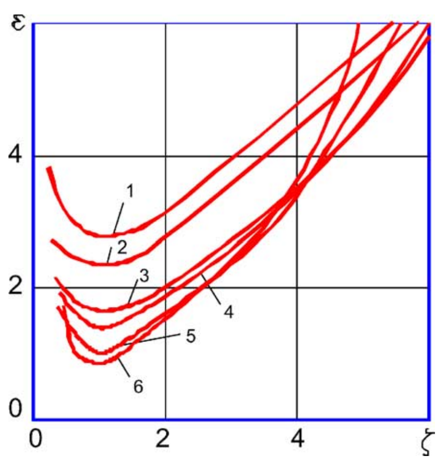

Fig. 2. Shear strain vs. the chip compression ratio for different rake angles: (1) −15°, (2) 0°, (3) 15°, (4) 30°, (5) 45°, (6) 60°.

shear strain depends on a large extent of the rake angle and decreases rapidly when CCRn tends to 1.

When $\zeta = 1$, the chip thickness is equal to the uncut chip thickness (Eq. (1)). This reveals a contradiction; as CCR, considered to be a measure of plastic deformation, indicates that no plastic deformation occurs while the final shear strain remains significant (Fig. 2). Moreover, if one compares the strains in Fig. 2 with the standard mechanical characteristic of work materials, he can conclude that the strains in metal cutting significantly exceed (200–1000% depending on the rake angle) the strains at fracture of even very ductile materials [1]. To the best of our knowledge, no one study pointed out and/or explains this abnormality in the mechanical properties of work materials in machining.

At this point it is worthwhile to explain that the equation final shear strain (Eq. (2)) was derived using pure geometrical considerations, i.e. it does not consider the change of the internal energy of the chip due to the changed chip density, the increased dislocation concentration, or the stress imposed on the boundaries of the grains, etc., even though all of these increase the shear strength of the chip compared to the original work material. Shear strain, according to Eq. (2) is defined only by the changes in the dimensions of a deformed body as compared with the original dimensions. As CCR indicates that there is no change in the dimensions, there is no "geometrical deformation", so the strain should be equal to zero. However, it does not follow from the equation for strain.

It was pointed out in [13] that although CCR may not be a perfect measure of plastic deformation in metal cutting, it does directly reflect (when properly measured) the final plastic deformation that takes place in this process. Although this parameter was widely used in metal cutting tests of the past [4], it was always considered as a secondary parameter to provide qualitative support to certain conclusions. Because the real significance of this parameter had not been revealed, it was gradually disregarded in metal cutting studies. For example, although Shaw in his book [5] dedicated a full chapter to the analysis of plastic deformation in metal cutting, this parameter is not even mentioned. The same can be said about books by Trent and Wright [9], Oxley [7] and Gorczyca [6]; Altintas [10] just mentioned its definition in the consideration of the single shear plane model; Childs et al. [11] mentioned this parameter as related to the friction coefficient at the tool–chip interface. No one modern study on metal cutting correlates this parameter with the extent of plastic deformation in metal cutting.

The ultimate object of this paper is to reveal the meaning and significance of CCR as the true measure of plastic deformation in metal cutting.

2. Work of plastic deformation in metal cutting

The applied external forces, which result in the work done over the system, are not uniformly distributed over the

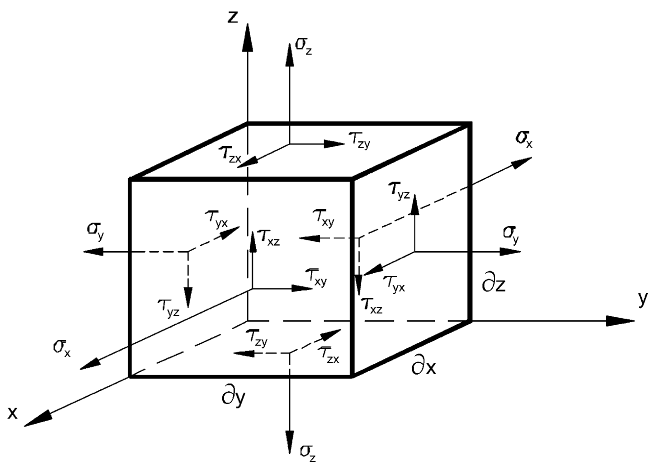

Fig. 3. Stresses acting on elemental free body.

system's components. To define the action of an external force on the different region of a body, the notion of stress is used. It is considered that if a body subjected to a general system of body and surface forces, stresses of variable magnitude and direction are produced through the body. The distribution of these stresses must be such that the overall equilibrium of the body is maintained; furthermore, equilibrium of each element in the body must be maintained.

Consider an infinitesimal element in the form of parallelepiped with its faces oriented parallel to the coordinate planes as shown in Fig. 3. When body and inertia forces are insignificant then the following three differential equations of force (stress) equilibrium are obtained [13,14]:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = 0 \quad (3)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} = 0 \quad (4)$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} = 0 \quad (5)$$

When a stress field applied to a body and, as a result, the relative position of its parts is changed then the body is said to be deformed or strained. A deformed state in a point can be represented by the strain components if the projections u_x, u_y, and u_z, of the displacement of this point into corresponding coordinate planes are known

$$e_x = \frac{\partial u_x}{\partial x}, \quad e_y = \frac{\partial u_y}{\partial y}, \quad e_z = \frac{\partial u_z}{\partial z},$$
$$\gamma_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}, \quad \gamma_{yz} = \frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y},$$
$$\gamma_{zx} = \frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \quad (6)$$

Here, components e_x, e_y and e_z are called the direct strains while γ_{xy}, γ_{yz}, and γ_{zx} are known as the engineering shear strains.

Using the generalized Hooke's law, we can write the following relationship between strains and stresses [14]:

$$e_x = \frac{1}{E}[\sigma_x - \nu(\sigma_y + \sigma_z)], \quad e_y = \frac{1}{E}[\sigma_y - \nu(\sigma_z + \sigma_x)],$$
$$e_z = \frac{1}{E}[\sigma_z - \nu(\sigma_x + \sigma_y)], \quad e_{xy} = \frac{2}{E}(1+\nu)\tau_{xy},$$
$$e_{yz} = \frac{2}{E}(1+\nu)\tau_{yz}, \quad e_{zx} = \frac{2}{E}(1+\nu)\tau_{zx} \quad (7)$$

where E is the modulus of elasticity, ν the Poisson's ratio.

The imbalanced external forces applied to a body cause its deformation and thus lead to the displacement of its points until the equilibrium is established. As such, a certain amount of energy is absorbed. This energy depends on the work done in displacement of all points of the body. Such work calculates by integrating the work per unit volume. The work per unit volume done in the displacement of each point of the body is calculated as the product of the generalized force acting on a point and the change of the generalized displacement of this point caused by this force. The Von-Mises' stress [14]

$$\sigma_i = \tfrac{1}{\sqrt{2}}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)]^{1/2} \quad (8)$$

was considered as the generalized force and the equivalent strain [13]

$$e_i = \tfrac{\sqrt{2}}{3}[(e_x - e_y)^2 + (e_y - e_z)^2 + (e_z - e_x)^2 + 6(e_{xy}^2 + e_{yz}^2 + e_{zx}^2)]^{1/2} \quad (9)$$

should be considered as the generalized displacement.

Because the elementary work is $\mathrm{d}A = \sigma_i e_i$, the total work done over a volume V then calculates as

$$A = \int_V \sigma_i e_i \, \mathrm{d}V \quad (10)$$

As mentioned, CCR is used for coarse estimation of plastic deformation in experimental studies of the metal cutting process [13]. As such, the distribution of the mechanical energy over the chip cross-section is assumed to be uniform. Using such an assumption, an engineering equation to calculate the energy spent in cutting can be obtained. If it is possible, CCR can be used to compare the power consumed in cutting of the same work material using different cutting processes. Moreover, the amount of the power consumed allows comparison of machining different work materials.

The mentioned engineering equation for coarse estimation of the energy spent in the cutting process can be obtained in the assumption of homogeneous distribution of strain in Eqs. (8)–(10). To derive it, the *xyz*-coordinate system is set so that the *y*-axis is directed along the chip length, L_{ch}, the *x*-axis is directed along the chip width, b_2, and the *z*-axis is directed along its thickness, t_2. As such, the following expressions for the components of the true strain along the introduced coordinate axes can be written according to the definition of CCR, ζ [13]

$$\varepsilon_z = \ln \zeta_t, \qquad \varepsilon_x = \ln \zeta_b, \qquad \varepsilon_y = -\ln \zeta_L \tag{11}$$

As shown in [13], in orthogonal cutting, the direction of the principal stress coincides with the introduced coordinate system. Then, Eq. (9) could be re-written accounting to Eq. (11) as

$$\varepsilon_i = \frac{\sqrt{2}}{3}[(-\ln \zeta_L - \ln \zeta_t)^2 + (\ln \zeta_t - \ln \zeta_b)^2 + (\ln \zeta_b + \ln \zeta_L)^2]^{1/2} \tag{12}$$

As shown in [13], if the chip parameters are properly measured in the orthogonal cutting test then $\zeta_b = 1$ and $\zeta_t = \zeta_L = \zeta$, and therefore plane strain condition is the case in such a process. Therefore

$$\varepsilon_i = 1.15 \ln \zeta \tag{13}$$

In the considered coordinate system, stress components σ_z and σ_y do not depend on the x-coordinate (measured along chip width) and σ_x component is determined as

$$\sigma_x = 0.5(\sigma_z + \sigma_y) \tag{14}$$

Substituting these results in Eq. (8), on can obtain

$$\sigma_i = \frac{1}{\sqrt{2}}\{[\sigma_z - 0.5(\sigma_z + \sigma_y)]^2 + [0.5(\sigma_z + \sigma_y) - \sigma_y]^2 + (\sigma_y - \sigma_z)^2\}^{1/2} \tag{15}$$

or after simplification

$$\sigma_i = 0.87(\sigma_z - \sigma_y) \tag{16}$$

A true stress–strain curve is known as a flow curve because it gives the stress required to cause the metal to flow plastically to any given strain [1]. Although many attempts have been made to fit mathematical equations to this curve [15], the most common is a power expression of the form

$$\sigma = K\varepsilon^n \tag{17}$$

where K is the stress at $\varepsilon = 1.0$ and n the strain-hardening coefficient is the slope of a log–log plot of Eq. (17).

Substitution of Eq. (17) into Eq. (16) yields

$$\begin{aligned}\sigma_i &= 0.87(K\varepsilon_z^n - K\varepsilon_y^n) = 0.87K(\varepsilon_z^n - \varepsilon_y^n) \\ &= 0.87K[(\ln \zeta_t)^n - (\ln \zeta_L)^n] = 0.87K2(\ln \zeta)^n \\ &= 1.74K(\ln \zeta)^n\end{aligned} \tag{18}$$

Because it was assumed that the chip has uniform deformation, the elementary work spent over plastic deformation of a unit volume of the work material calculates as

$$\mathrm{d}A = A_u = \sigma_i\varepsilon_i = 1.74K(\ln \zeta)^n 1.15 \ln \zeta = 2K(\ln \zeta)^{n+1} \tag{19}$$

The obtained result is of great significance to the experimental studies in metal cutting because it correlates in a simple manner the work of plastic deformation done in cutting with a measurable, post-process characteristic of the cutting process as CCR. Knowing the elementary work, the total work done by the external force applied to the tool is then calculated as

$$A = A_u v f d \tau \tag{20}$$

where d is the depth of cut, τ the cutting time.

Table 1
Work materials used in the tests

Material	K (GPa)	n
AISI steel E52100, HB280 (0.981.10%C, 1.45%Cr, 0.35%Mn)	1.34	0.25
Copper (99.7%)	0.40	0.24
Aluminum 1050-0, HB21	0.14	0.27

A series of cutting tests were carried out to compare the power consumption under different cutting conditions. The test setup, methodology and conditions were the same as discussed in [16]. All the tests were conducted using the same cutting feed $f = 0.07$ mm/rev and the depth of cut $d = 1$ mm. Three different types of the work material listed in Table 1 were used in the tests. For each work material, the influence of the cutting speed on CCR was established and the elementary work spent over plastic deformation of the work material was calculated using Eq. (19).

The test results are shown in Fig. 4. As seen, although CCR is greatest in machining of copper and lowest in machining of steel, the elementary work is the greatest for steel. This results in greater amount of heat generated and in more significant tool wear in the machining of steel. This conclusion is supported by multiple facts known from everyday practice of machining.

It follows from Fig. 4 that CCR is a representative measure of the work of plastic deformation in metal cutting within the same work material. For steel 52100, CCR varied within 67% under the experimental conditions used in the test while the elementary work varied within 89%, for

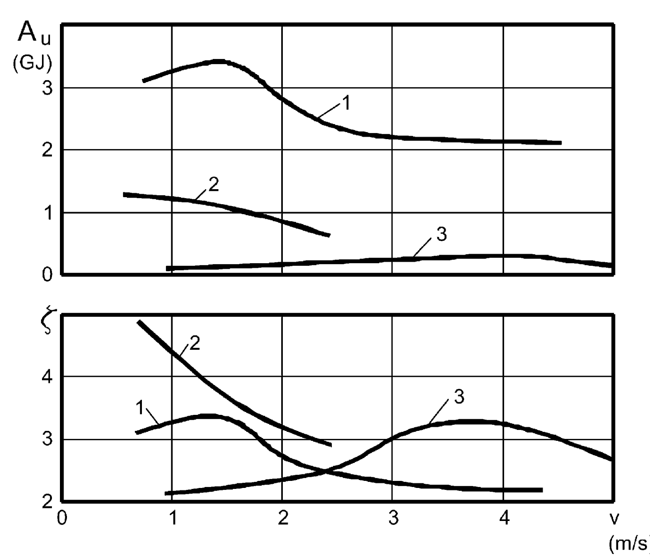

Fig. 4. Influence of the cutting speed on the chip compression ration and the work done in plastic deformation.

copper and aluminum CCR varied within 60 and 55%, respectively, while the elementary work varied within 55 and 71%, respectively.

The accuracy of the estimation of the work done in plastic deformation can be improved if one accounts for the change in the parameters K and n depending on the cutting speed (strain rate) and actual temperature in the chip formation zone. As such, two important issues should be accounted for:

- The first is that orthogonal metal cutting is essentially a cold working process because the velocity of the heat conduction is much lower that the cutting speed and thus the thermal energy generated in the plastic deformation of the layer being removed does not affect the resistance of the work material to cutting ahead of the tool. [13]. In other cutting processes as turning or drilling, the only residual heat from the previous position of the cutting tool may affect the temperature of the deformation zone at the current tool position [16].
- The second issue is about strain rate in metal cutting. As conclusively proven in [13], it is not as high as considered by many researches in the filed so that there is no need for special high strain rate tests to determine the value of constants K and n.

The proposed method for estimating the work of plastic deformation in metal cutting gives new meaning of CCR. In the proposed sense, it can be used as the prime parameter for the optimization of the metal cutting process because considered together with the work of plastic deformation, it reveals the energy spent in cutting. Moreover, CCR is the post-process parameter and thus there are a number of simple though forgotten ways to measure this parameter accurately in metal cutting. Some simple methods of measuring CCR are discussed in Appendix A.

3. Influence of the cutting speed and other parameters

It is well-known that the cutting speed has the strongest influence on CCR [4,13]. Fig. 5 shows an example of such an influence in the format commonly used in metal cutting studies. The explanation for the shape of the graphs shown in Fig. 4 is still the same as it was 50 years ago when the only data obtained at low cutting speed were available. The built-up-edge is believed to be a prime factor affecting the shown dependences [4]. The problem with this explanation is that the built-up-edge does not exist at the speeds used to obtain data shown in Fig. 5. Therefore, another explanation should be provided.

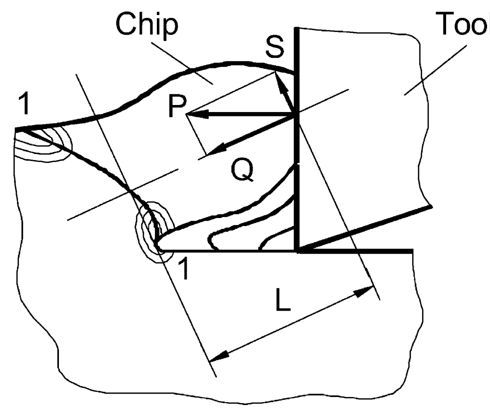

Fig. 6. Interaction between the tool rake face and the chip results in the formation of the compressive force Q and the bending force S as the components of the penetration force P.

To understand the nature of chip deformation, one should be familiar with the authors' concept of chip formation [13,17,18], specifically, what causes the chip to form. According to the metal cutting theory discussed in [1–11], simple shearing causes chip formation in metal cutting and thus metal cutting is regarded as one of the shearing processes such as blanking, punching, etc. However, no chips are produced in such processes. Moreover, the indentation of a ductile material, in which a pointed or rounded indenter pressed into a surface under a substantially static load, causes extensive shearing; however, the chip does not form even if extremely high load in applied. The real cause for chip formation is the combined stress in the deformation zone consisting of the compression and bending stresses [17]. Fig. 6 shows the formation of the surface of the maximum combined stress (1–1) due to the action of the compressive force P_c and bending moment $M = P_c L$. As such, the chip serves

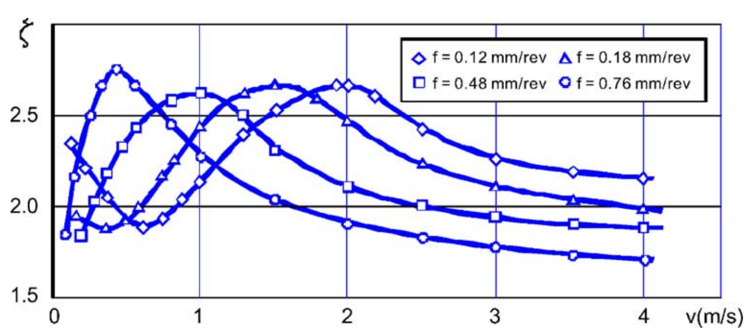

Fig. 5. Influence of the cutting speed on the chip compression ratio. Operation: longitudinal turning, workpiece diameter: 100 mm, work material: steel AISI 1045, tool material: carbide P20, tool cutting edge angle $\kappa_r = 60^\circ$, normal rake angle $\gamma_n = 7^\circ$, depth of cut $d_1 = 3.5$ mm.

as a cantilever that transmits the force P applied to the cutting tool into the chip formation zone.

The strongest influence on the energy distributing in the cutting system has the cutting speed because it determines the intensity of heat sources. An increase in the cutting speed leads to a decrease of the plastic deformation in the chip formation zone and, as a result, a lesser portion of the applied mechanical energy converts into heat in this zone so that the chip is "born" less hot. Simultaneously, however, the amounts of heat generated at the tool–chip and tool–workpiece interfaces increase so the chip, sliding over the tool rake face, receives more thermal energy. The total energy absorbed by the chip is equal to the sum of the heat gained by the chip in its formation, i.e. during plastic deformation of the layer to be removed and that transferred into the chip from the tool–chip interface. The averaged temperature of the chip can be represented as [13]

$$\theta = C_\theta v^{x_\theta}, \quad 0 < x_\theta < 1 \tag{21}$$

Multiple tests of different metallic materials showed [1] that if no metallurgical (chemical) transformations occurred on heating of a material from temperature θ_1 to θ_2, the elasticity modulus changes according to the following exponential equation:

$$E_{\theta_2} = E_{\theta_1}\,\mathrm{e}^{\alpha_\theta(\theta_1-\theta_2)} \tag{22}$$

where α_θ is a constant for a given material.

An increase in the thermal energy transferred to the chip while increasing the cutting speed results in lowering the rigidity of the chip and its 'effectiveness' as the lever to transmit bending moment to the chip formation zone. As a result, the compressive stress takes a greater share in the combined stress in the chip formation zone. As such, the required external energy applied to the cutting system and spent on plastic deformation of the layer to be removed increases.

In cutting, the external force is applied to the tool, and it is transmitted from its rake face into the chip formation zone through the chip. As such, certain energy losses occur in such transmission. To estimate these losses, consider the work done by the force applied to the chip from the tool rake face. If l_u designates the elementary length of the chip then the work done over the chip by the force from the tool rake face consists of the work done by the bending moment and the compressive force

$$\mathrm{d}W_{\mathrm{ch}} = \frac{M^2\,\mathrm{d}l_u}{2EI} + \frac{F\,\mathrm{d}l_u}{2A_{\mathrm{ch}}E} \tag{23}$$

where M is the bending moment, E the elasticity modulus of the material of the chip, I the second moment or moment of inertia of the cross-section of the chip, F the compressive force, A_{ch} the cross-sectional area of the chip.

If the elasticity modulus of the material of the chip tends to infinity then, as it follows from Eq. (23) that $\mathrm{d}W_{\mathrm{ch}} = 0$, i.e. all the energy applied to the cutting tool is transmitted through the chip without losses. In reality, however, the modulus of elasticity is a finite value and, moreover, it decreases with the temperature of the chip (Eq. (22)) so that the part of the energy transmitted through the chip is spent on its deformation. As such, the work of plastic deformation and fracture of the layer to be removed done by the external force calculates as

$$\mathrm{d}W = \mathrm{d}W_{\mathrm{F}} - \mathrm{d}W_{\mathrm{ch}} \tag{24}$$

As discussed above, according to energy theory of failure, a given volume of the work material fails when the critical internal energy is accumulated in this volume. As a result, $\mathrm{d}W$ can be considered as a constant for a given cutting system. According to Eq. (24), to keep $\mathrm{d}W$ constant when $\mathrm{d}W_{\mathrm{ch}}$ increases, the energy supplied to the cutting tool by the external force, $\mathrm{d}W_{\mathrm{F}}$ should be increased.

Flexural and compression rigidities of the chip, EI and $A_{\mathrm{ch}}E$, respectively, decrease with temperature according to Eq. (22). Therefore, an increase of the heat flow into the chip with the cutting speed leads to an increase in $\mathrm{d}W_{\mathrm{ch}}$, i.e. to an increase in the energy needed for chip formation.

The cutting speed affects the shape and dimensions of the chip formation zone [4,13] or the extent of the region of plastic deformation ahead of the tool. When the cutting speed increases, this region of plastic deformations becomes smaller. Instead, an elastically deformed or rigid zone starts to occupy more and more cross-sectional areas of the chip. The emerging of this elastically deformed region can be thought of as the formation of amplification means. In other words, the formation of the elastic zone leads to a decrease of the energy required from the tool for chip formation. It is equivalent to an increase in I and A_{ch} in Eq. (23) and leads to a decrease in chip plastic deformation. Moreover, it is possible to limit the region of plastic deformation attached to the cutting edge to certain optimum limits so that the chip–cantilever transmits the maximum energy from the cutting tool to this region. As such, the contribution of the bending stress in the formation of the combined stress in the chip formation region is the greatest.

The formation of the elastically deformed part of the chip begins at a certain cutting speed at which dramatic change in the energy spent in the plastic deformation should be observed. Then, as the cutting speed increases, the dimensions of the elastic region increase stabilizing at certain point because it is evident that the dimensions of the elastic region cannot exceed those of the layer to be removed.

The cutting speed, v is the velocity of deformation of the layer being removed. As known [13], the stain rate can be represented through this velocity as

$$\dot{e} = \frac{v}{L} \tag{25}$$

where L is the specimen length in the direction of the cutting speed.

On the other hand, by definition, the strain rate is defined as

$$\dot{\varepsilon} = \frac{d\varepsilon}{d\tau} \qquad (26)$$

Combining Eqs. (25) and (26), we obtain the following differential equation:

$$\frac{d\varepsilon}{d\tau} = \frac{v}{L} \qquad (27)$$

which has the solution

$$\frac{\tau v}{L} = \varepsilon + C \qquad (28)$$

where τ is the cutting time, $\epsilon = \ln \zeta$ the true strain, C is a constant equal to the value of $\ln \zeta$ when $v = 0$.

Finally, the correlation between CCR and cutting speed (deformation velocity) can be obtained from Eq. (28) as

$$\zeta = e^{(C-(\tau v/L))} \qquad (29)$$

As follows from Eq. (29), CCR decreases with the cutting speed following an exponential curve.

As follows from the foregoing analysis, the cutting speed influences the energy spent on the deformation of the chip through the temperature, dimensions of the deformation zone adjacent to the cutting edge and velocity of deformation. The impacts of these factors are as follows:

- The influence of the chip temperature on the work done over the chip in its plastic deformation can be estimated through CCR as follows: an increase in the cutting speed leads to an increase in the temperature of the chip so its plastic deformation increases (curve 1 in Fig. 7).
- The work done in the plastic deformation of the chip decreases when the deformation velocity increases according to Eq. (29). It is reflected by curve 2 in Fig. 7.
- The elastic zone at the tool–chip contact formed at certain cutting speed leads to the reduction of the plastic deformation of the chip and thus lowers CCR beginning from this cutting speed. Then, the amount of plastic deformation due to formation of the elastic zone increases and stabilizes at a certain level as reflected by curve 3 in Fig. 7.

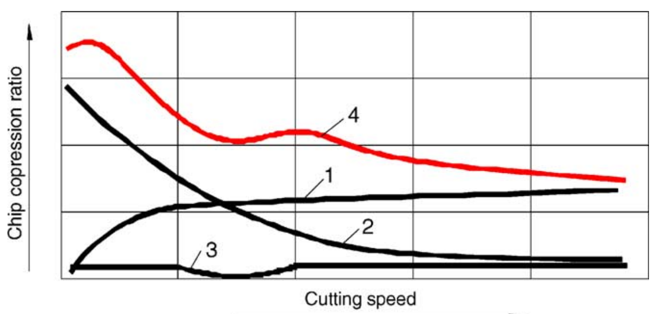

Fig. 7. Formation of the resultant dependence of the chip compression ratio on the cutting speed.

Summing up the influence of these factors caused by and dependant on the cutting speed, one can obtain the resultant curve 4 (Fig. 7) that resembles the known curve of the influence of the cutting speed upon CCR obtained experimentally [4]. The presented analysis, however, allows to understand the relative impact of different factors correlated with the cutting speed on the plastic deformation of the chip and thus to understand the physics of the phenomenon. The influence of many important external parameters as the cutting fluid, pre-heating, cryogenic cooling, MQL technique and many others can be evaluated in terms of their influence on the efficiency of the chip formation process.

Other parameters that have strong influence on CCR are the cutting feed, f, tool cutting edge angle, κ_r, cutting edge inclination angle, λ_s, and tool rake angle, γ_n.

It is known [13], however, that the cutting feed, f, tool cutting edge angle, κ_r, cutting edge inclination angle, λ_s affect CCR through the uncut chip thickness, t_1 which, in turn, may have a different influence at different cutting speeds, v. This probably was the root cause for many inaccurate conclusions drawn from experimental results in the past. To resolve the problem, CCR should be determined as a function of the Peclet criterion defined as [13]

$$Pe = \frac{v t_1}{w_w} \qquad (30)$$

where w_w is the thermal diffusivity of workpiece material, m^2/s

$$w_w = \frac{k_w}{(c\rho)_w} \qquad (31)$$

where k_w is the thermal conductivity of workpiece material, J/(m s °C), $(c\rho)_w$ the volume specific heat of workpiece material, J/(m^3 °C).

The Peclet number is a similarity number, which characterizes the relative influence of the cutting regime $v_1 t$ with respect to the thermal properties of the workpiece material (w_w). If $Pe > 10$ [19,20] then the heat source (the cutting tool) moves over the workpiece faster than the velocity of heat wave propagation [16] in the work material so the relative influence of the thermal energy generated in cutting on the plastic deformation of the work material is only due to residual heat from the previous tool position. If $2 < Pe < 10$ then the thermal energy makes its strong contribution in the process of plastic deformation during cutting.

Fig. 8a shows the influence of the cutting speed on CCR for different feeds. Fig. 8b shows what happens if the Peclet criterion is used as the independent variable. Fig. 9 presents another example of experimental data obtained in machining of tool steel H13. Such a representation allows one to reduce the number of cutting tests needed to study the amount of plastic deformation in the metal cutting process. Moreover, it allows revealing the mutual influence of the cutting regime, tool geometry and physical properties of the

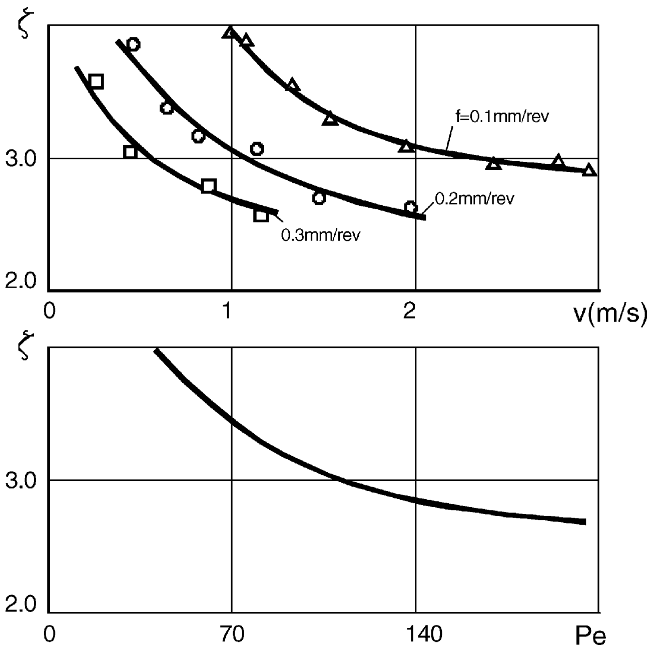

Fig. 8. The chip compression ratio vs. cutting speed for different feeds (a) and generalized correlation between the chip compression ratio and *Pe* criterion (b). Work material: steel AISI 1030, tool material: carbide P20, rake angle $\gamma = 10^{\circ}$, cutting edge angle $\kappa_1 = 60^{\circ}$, depth of cut $d = 2$ mm.

work material on this plastic deformation. For example, it is clearly shown that the amount of plastic deformation in cutting for a work material having low thermal conductivity is greater compared with that in cutting a work material hav-

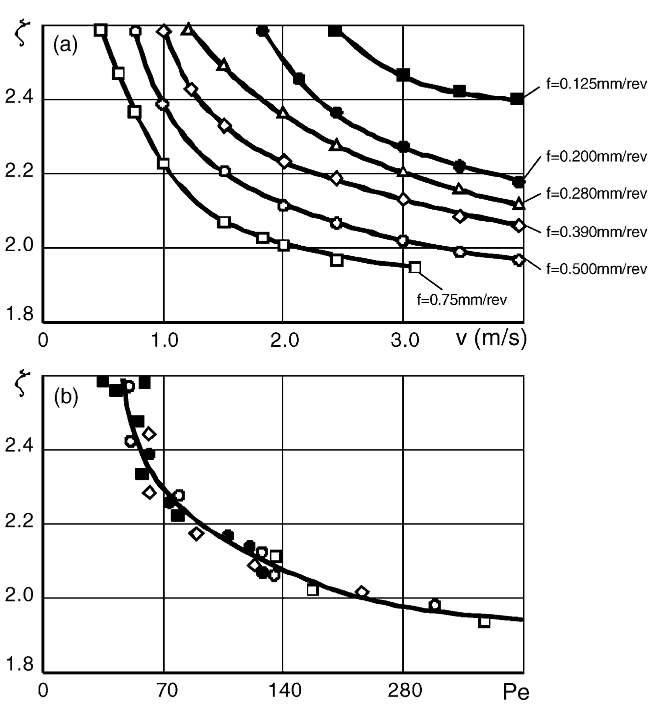

Fig. 9. The chip compression ratio vs. *Pe* criterion. Work material: tool steel H13, tool material: carbide K10, rake angle $\gamma = -10^{\circ}$, cutting edge angle $\kappa_1 = 60^{\circ}$, depth of cut $d = 2$ mm.

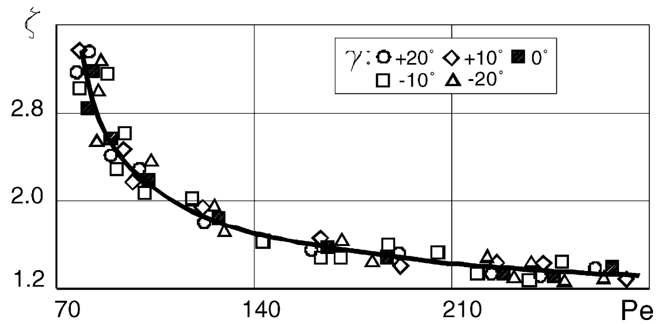

Fig. 10. Chip compression ratio vs. *Pe* criterion for different rake angles. Work material: steel AISI 1045, tool material: carbide P20, cutting edge angle $\kappa_1 = 60^{\circ}$, depth of cut $d = 2$ mm.

ing higher thermal conductivity if other cutting conditions remain the same.

The influence of the tool rake angle on CCR is shown in Fig. 10. As seen, CCR does not depend on the tool rake angle.

4. Conclusions

1. Plastic deformation is a nuisance in the metal cutting process and thus it should be reduced in order to increase the process efficiency. The rule of thumb here is: less plastic deformation, better the cutting process.
2. The final shear strain used to assess plastic deformation in metal cutting (Eq. (2)) is not a relevant characteristic because it does not correlate with the known properties of the work material.
3. The chip compression ratio represents the true strain in plastic deformation and should be used to calculate the elementary work spent over plastic deformation of a unit volume of the work material. Knowing the elementary work, the total work done by the external force applied to the tool can then be calculated. As a result, the chip compression ratio can be used as the prime parameter for the optimization of the metal cutting process because considered together with the work of plastic deformation; it reveals the energy spent in cutting. Moreover, the chip compression ratio is the post-process parameter and thus there are a number of simple though forgotten ways to measure this parameter accurately in metal cutting.
4. The cutting speed influences the energy spent on the deformation of the chip through the temperature, dimensions of the deformation zone adjacent to the cutting edge and velocity of deformation. For the first time, the relative impact of these parameters on the chip compression ratio is revealed and thus the known experimental dependence of the chip compression ratio on the cutting speed is explained.
5. To avoid typical misrepresentation of the experimental data on the chip compression ratio, it is proposed to

determine this parameter as a function of the Peclet criterion. Such a representation allows accounting for the combined influence of the cutting regime and physical properties of the work material.

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Appendix A. Experimental methods for the determination of the chip compression ratio (CCR) for different metalworking operations

Although a number of experimental methods for the determination of the chip compression ratio (CCR) were known to researchers, the modern books and other publications on metal cutting do not consider any of them because CCR is not regarded as an important parameter in metal cutting studies. Because this paper explains that these parameters are of prime importance in metal cutting studies and in process optimization even at the shop floor level, a need is felt to present few common experimental methods for the determination of CCR.

The simplest method is to measure the chip thickness and then, using Eq. (1), to calculate CCR. However it is not always possible because the chip: (a) might have a saw-toothed free surface; (b) be so small and 3D-curved.

The second method is the weighting method. A small (5–10 mm long) straight piece of the chip is separated from the rest of the chip. Then, its length, L_c and width b_c are measured (when the piece of the chip selected for the study is not straight, a computer vision system available nowadays in most shops is used to measure its length properly). Then, it is weighed so its weight G (N) is determined. The chip thickness is then calculated as

$$t_2 = \frac{G}{b_c L_c \rho g} \tag{A.1}$$

where ρ is the density of the work material (kg/m^3), $g = 9.81$ m/s^2 is the gravity constant.

For finishing operations when the depth of cut is really shallow, it becomes rather difficult to measure the width of the chip. CCR is determined in this case using the ratio of the chip and uncut chip cross-sectional areas, A_c and A_{uc}, respectively, i.e.

$$\zeta = \frac{A_c}{A_{uc}} \tag{A.2}$$

As such, the chip cross-sectional area is determined using the weighing method as

$$A = \frac{G}{L_c \rho g} \tag{A.3}$$

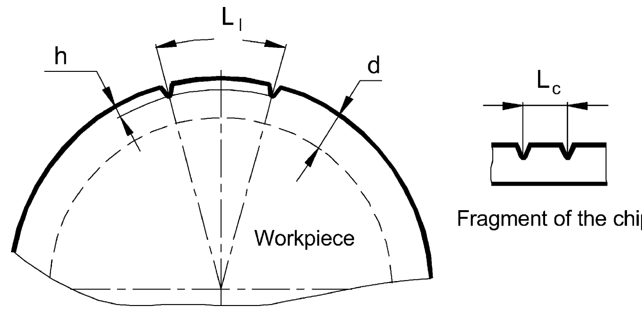

Fig. 11. Application in turning.

and the uncut chip cross-sectional area is determined as

$$A_{uc} = df \tag{A.4}$$

where d is the depth of the cut, f the cutting feed.

The third method is the direct method, which is applicable in turning, milling, drilling and other cutting operations. The essence of this method is that the workpiece is "marked" before cutting and then the resultant marks on the chip are compared with the originals marks. The realization of this method for longitudinal turning is shown in Fig. 11. As seen, two longitudinal grooves are made on the workpiece outer surface before testing and the arc distance between these grooves, L_l is measured. After the test, a chip section with these marks can easily be found and the distance L_c is measured. Using Eq. (1), CCR is determined.

The realization of the discussed method to measure CCR in drilling is shown in Fig. 12. Two small holes of diameter d_1 are drilled as shown in Fig. 12 along the trajectory of the point of the drill cutting edge. Diameter d is smaller than that (D) of the would-be-hole. The arc distance L_l between the centers of these holes is measured. After the test, a chip fragment having marks from two holes is found and the arc distance L_c between their centers is measured at high magnification using an optical comparator or a computer vision system. Using Eq. (1), CCR is determined.

The realization of the discussed method for face milling is shown in Fig. 13. As shown, the surface of the workpiece is made with a step having width $L_l = 3$–6 mm and height which is 4–6 times smaller that the depth of cut, i.e. $h/h_l =$

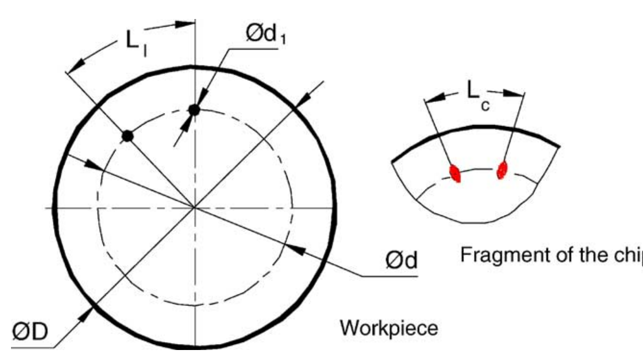

Fig. 12. Application in drilling.

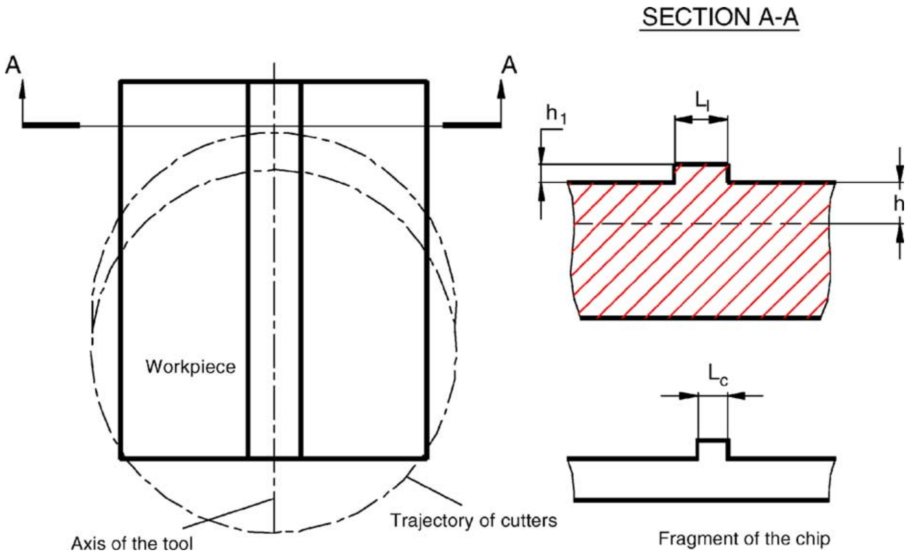

Fig. 13. Application in face milling.

4–6. After the test, the width L_c is measured and CCR is determined using Eq. (1).

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