

A new slip-line theory for orthogonal cutting and its application

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Abstract

Precision machining and burr formation problems are closely connected with chip formation process. Still there is no general opinion about behavior of work material during cutting. In the paper the classical theory of plasticity is applied to the problem of metal cutting mechanics and new slip-line solution is proposed. The suggested model make possible to solve analytically main tasks of metal cutting mechanics such as stress distribution on tool rake face, chip/tool contact length, cutting forces and shear angle for cutting by tool with whole rake face. It is shown that constant of plasticity in cutting corresponds Tresca plastic flow criterion and stress state in conventional shear plane is found. Several proofs of presented theory are given using experimental data of other researchers.

Keywords: Orthogonal cutting; Slip-line solution; Chip-tool contact length; Stress distribution; Cutting forces; Shear angle

1. Introduction

The problems of precision surface generation and burr formation mechanism are closely connected with chip formation mechanics. Indeed, burr formation can be characterized as transition phenomenon from steady state cutting to tool exit or entrance. In particular cutting forces, acted on tool faces, play a very important role in burr formation influencing significantly to the burr dimensions and other parameters. The same can be also said about precision machining. Thereupon the first task of every research concerning burr formation and precision machining is to analyze metal cutting mechanics and chip formation mechanism.

Machining of metals by chip remove is known in many centuries but still now there is no general theory of this process. It could say that there are only different opinions and different approaches to this process. The difficulties of creation of this theory are in the complexity and variety of phenomena, which accompany metal cutting. In particular this concerns to the large strain rate, temperature effect, material hardening and other physical phenomena.

The first known study of metal cutting mechanics were carried out in 19th century by Timae [1], who proposed the model of chip formation with single shear plane. This

model was developed in following works by Zvorykin [2], Merchant [3], Shaw et. al. [4], Oxley [5] and many other researchers [6, 7, 8]. Zvorykin and Merchant applied minimum force and energy principles and found the expressions for conventional shear angle and cutting forces depending on coefficient of friction, tool geometry and mechanical properties of work material. In other studies the equations of plastic state were used and balance force and moment equations applied.

The main problem of model with single shear plane is that material particles accelerate infinitely in this plane while in reality the deformation occurs in a zone with definite size. In this connection the models with several shear lines and shear planes were developed [9, 10, 11]. Using “fan” slip-line field, proposed by Bricks [9], Zorev [10] considered the equations of balance forces acted on tool rake face and corresponding slip line including hardening effect for each slip line. This approach make possible to find the location or, in other words, the inclination angle of each line in the “fan”. Palmer and Oxley [11] used cinema technique and found experimentally the behavior of material particles in the primary deformation zone. On the base of these experiments they presented slip-line field in this area. For determination of slip-lines location they used modified Henky and balance moment equations and concluded about acceptability of their model. The main problem in this approach is that the stress distribution on tool rake face is unknown and it is necessary to make an assumption about this distribution for solution of balance force equations. There are different opinions about this problem and discrepant experimental data are presented [10,12,13] and until now the general law of stress distribution on tool rake face is not found.

This problem is closely connected with the solution of slip-line field inside chip body. Indeed if chip curls in result of cutting then plastic deformation zone must be inside chip. Probably Lee and Shaffer [14] were the first, who proposed the continuation of plastic deformation after primary shear. Klushin [15] expressed the same opinion and stated that deformation of chip continues all the time when tool and chip are in contact. In particular the change of chip radius in cutting by tool with restricted rake face in comparison with cutting by tool with whole rake face marginally proves this moment. The known solutions of slip-line field inside chip [14,16,17] come to the suggestion about uniform stress state on tool/chip contact region that is significant simplification. The presented work is one more attempt to explain metal cutting mechanics based on a new slip-line solution.

2. Slip-line model and tool/chip contact length

The suggested slip-line field is presented in Fig.1. Following to the previous experimental studies [9,10,11] the primary deformation zone can be simplified by central slip-line field ABD, which is composed of straight rays of β -slip lines and arcs of α -slip lines. Line AB is the initial boundary of this zone and AD is final one. Lines AB and AD are inclined to the tool path at an angle Φ_1 and Φ_2 respectively. Angle Φ is conventional shear angle. It is well known that material particles are hardened intensively during passing through this zone. Stress state of work material on line AB can be presented by yield stress for given temperature-stress-strain rate conditions of deformation. On final boundary AD of primary deformation zone the material hardening is saturated and chip can be considered as ideal plastic body and in this case the constant of plasticity k_f , which is maximum shear stress, includes hardening factor.

According to the theory of plasticity slip-lines intersect free transition machined/inward chip surface BD at the angle 45° . For satisfying this condition here is made an assumption that close to the mentioned surface BD slip lines change their direction and pass this surface at the angle 45° but this change occurs at a very small distance from BD line and so it can be neglected.

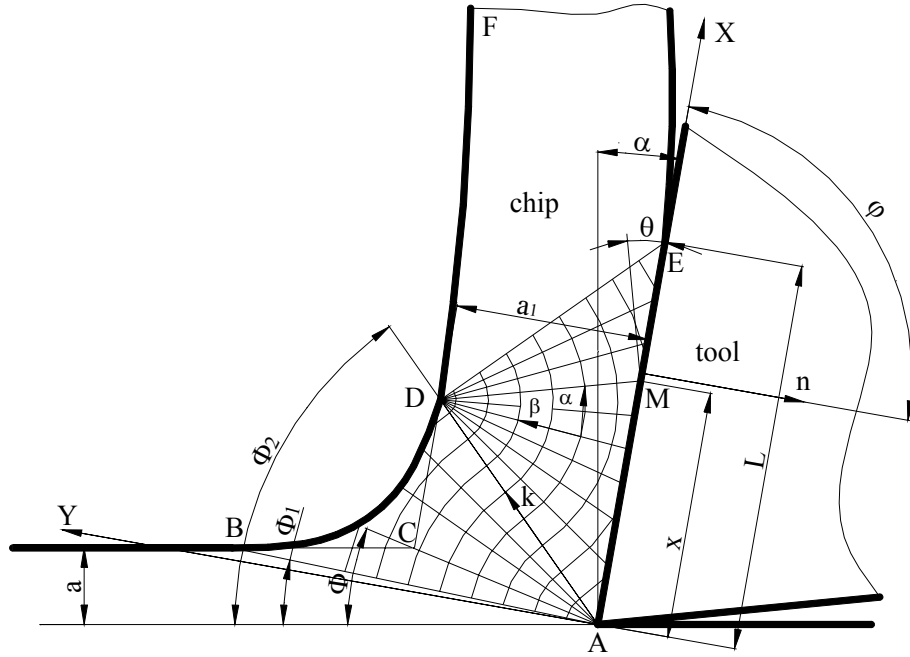


Fig.1. Slip-line field for cutting by tool with whole rake face

Inside chip body there is a second central slip-line field ADE. Line DE is final boundary of plastic zone in the chip. It is obvious that at the point E shear stress on tool/chip contact is zero. Thus according to the boundary conditions for slip lines [18] this line DE passes tool rake face at angle 45° or in other words angle DEA is equal to 45° . At the same time as first approximation it is possible to assume that chip surface close to point D is parallel to the rake face. Since chip surface is free from the stress then line DE passes this surface at the same angle 45° according to the boundary conditions for stress and so line DE is straight one passing tool rake face and inward chip surface at the same angle 45° .

Using experimental data [13] it can be assumed that in general case there is no shear stress on tool/chip interface at tool tip (see point A in Fig.1). According to the theory of plasticity it means that angle Φ_2 in suggested slip-line solution is constant and equal to $\pi/4 + \alpha$, in other words $\angle DAE = \angle DEA = \pi/4$ and so triangular ADE is isosceles.

From the suggested geometry of slip-line field, tool/chip contact length is obtained as

$$L = \frac{2 \cdot a \cdot \cos(\alpha - \Phi)}{\sin \Phi} \quad (1)$$

where a is undeformed chip thickness and α is tool rake angle.

3. Stress distribution on tool rake face

ADE area (see Fig.1) is the region of compression. Since ED and AD lines pass free chip surface at the same angle 45° then according to the theory of plasticity the same average normal stress/hydrostatical pressure $\sigma = -k_f$ is acted on these lines. It follows that there is a uniform stress state in ADE.

Using suggested slip-line solution it is possible to determine stress distribution on tool rake face analytically. From the geometry it can be derived that the angle θ (see Fig.1) is changed for given distance x from tool tip as

$$\theta(x) = \frac{\pi}{2} - \arctan \frac{a \cdot \cos(\Phi - \alpha)}{x \cdot \sin \Phi - a \cdot \cos(\Phi - \alpha)} \quad \text{for } \arctan \frac{a \cdot \cos(\Phi - \alpha)}{x \cdot \sin \Phi - a \cdot \cos(\Phi - \alpha)} > 0$$

$$\theta(x) = -\arctan \frac{a \cdot \cos(\Phi - \alpha)}{x \cdot \sin \Phi - a \cdot \cos(\Phi - \alpha)} - \frac{\pi}{2} \quad \text{for } \arctan \frac{a \cdot \cos(\Phi - \alpha)}{x \cdot \sin \Phi - a \cdot \cos(\Phi - \alpha)} \leq 0.$$
(2)

Angle θ is the angle between tangent to α -slip line at current point M on tool/chip interface and X-axis, which coincides with this interface.

From the theory of plasticity [18], boundary normal and shear stresses are related with the hydrostatical pressure σ and angle θ in the general form as followed

$$\begin{aligned} \sigma_n &= \sigma - k \cdot \sin 2(\theta - \varphi) \\ \tau_n &= k \cdot \cos 2(\theta - \varphi) \end{aligned}$$
(3)

where φ is the angle between normal to the given contour and X-axis. In our case the contour is outward chip surface AE (see Fig.1) contacted with tool rake face. It is obvious that in given case angle φ is equal to $-\frac{\pi}{2}$ thus the law of normal and shear stress distribution on tool rake face are defined as

$$\begin{aligned} \sigma_n(x) &= -k_f \cdot (1 - \sin(2\theta(x))) \\ \tau_n(x) &= -k_f \cdot \cos(2\theta(x)) \end{aligned}$$
(4)

It is obvious that stress distribution on outward chip surface AE is defined by the same formulas (4) taken with reverse signs.

General view of normal and shear stress distribution on chip/rake face interface predicted by formulas (4) is presented on Fig.2(b).

4. Forces on tool/chip interface

Since stresses distribution on chip and tool surfaces are known then it is possible to find resulting normal and friction forces. These forces can be simply obtained by integrating of normal $\sigma_n(x)$ and shear $\tau_n(x)$ stresses on contact length L as followed

$$N = \int_0^L \sigma_n(x) dx = L \cdot k_f = \frac{2 \cdot a \cdot k_f \cdot \cos(\Phi - \alpha)}{\sin \Phi},$$
(5)

$$F = \int_0^L \tau_n(x) dx = \frac{2 \cdot a \cdot k_f \cdot \cos(\Phi - \alpha)}{\sin \Phi} \left(\frac{\pi}{2} - 1 \right).$$
(6)

From (5) and (6) it follows that average coefficient of friction f on chip/tool interface is independent on cutting conditions and has a constant value

$$f = const = \frac{\pi}{2} - 1. \quad (7)$$

From (5) and (6) it follows that forces in cutting depend on mechanical property of work material (constant of plasticity k_f), undeformed chip thickness a , tool rake angle α and conventional shear angle Φ .

5. Determination of constant of plasticity k_f in cutting

As we can see from (4), (5) and (6) this constant is very important parameter, which defines value of stress distribution on rake face and resulting cutting forces. In part 1.2 of this paper we assumed that value of constant of plasticity probably corresponds to extreme stress state of material when its hardening is almost finished and its behavior can be considered as ideal plastic. The suggested theory makes possible to find exact value of constant of plasticity k_f and connect it with general theory of plasticity.

From formulas (1) for tool/chip contact length and (6) for total friction force, it can be obtained that average shear stress on tool/chip interface is defined as

$$\tau_{n_{aver}} = k_f \cdot \left(\frac{\pi}{2} - 1 \right). \quad (8)$$

M.F. Poletika [12] found experimentally that for 22 different materials as carbon, alloyed and superalloyed steels, copper, aluminum, cadmium and bronze with different hardness, the value of average shear stress on tool/chip interface is independent on cutting conditions and tool geometry and defines by tensile strength S_f of work material at the moment of fracture as

$$\tau_{n_{aver}} = const = 0.28 \cdot S_f. \quad (9)$$

From the analysis of (8) and (9) it can be concluded that constant of plasticity k_f of chip material is really constant and defined as:

$$k_f = const = \frac{S_f}{2}. \quad (10)$$

Here we have found very important result, which proves our theory. The expression (10) presents Tresca criterion of plasticity considering hardening effect in result of deformation, which is reflected by presence of tensile strength S_f in this formula. In other words formula (10) expresses the plastic flow state of material at the extreme point when material is “destroyed”. Just these conditions occur at the final boundary AD of primary deformation zone (see Fig.1). After passing through primary deformation zone ABD, material reaches extreme hardening at AD and its behavior is like ideal plastic body but it is not fractured like in tensile test because ADE is compression area and destroyed material particles “weld” or “stick” with each other under the action of compression stress.

Thus limit stress state of chip corresponds to extreme stress state of material at fracture moment in tensile test, and constant of plasticity k_f in cutting defines by Tresca criterion of plasticity, where tensile strength S_f must be used according to formula (10).

It is interesting to note that tensile strength S_f is insensitive to preliminary hardening, alternating strain, strain rate, and corresponds to limit hardening of material, as

noted in [30]. This makes S_f value as base characteristic of material and from this point of view proves the constancy of k_f one more time.

6. Consideration of shear stress in shear plane and shear angle determination

Shear angle Φ is one of the most important parameter in cutting. Its value defines tool/chip contact length (see formula (1)), it influences on stress distribution on rake face (see formulas (2) and (4)) and play a significant role in resulting cutting forces (see formulas (5) and (6)). A value of shear angle is usually accepted as an angle between imaginary line, which connects tool tip and material surface/chip free surface intersection point, and tool path (line AC on Fig.1). It is general belief that this line corresponds to direction of maximum shear stress or in other words it is slip-line as assumed in suggested slip-line solution (see Fig.1).

The task about shear angle solution for each slip-line in the “fan” ABC (see Fig.1) can be solved if shear stress in corresponding line is known. However there has been no experimental data according to changes of this parameter in cutting conditions while many ways to determine shear stress k_s in imaginary shear plane have been proposed [10, 21, 25, 26, 27, 28, 29], which is usually called “shear strength”. Zorev [10] gave comparison between experimental stress in imaginary shear plane in cutting and stress-strain curve in tension and compression tests extrapolated to large deformation. This extrapolation is given in logarithmic scale from strain 0.4 – 1.0 (under tension and compression test) to 2 – 5 in cutting. The good correspondence was observed. Thus, Zorev supposed that the same curve in tension, compression and cutting exists. He assumed that shear strength is constant parameter and suggested simplified formula for its determination as followed:

$$k_s = \frac{0.6 \cdot \sigma_u}{1 - 1.7 \cdot \psi}, \quad (11)$$

where σ_u is ultimate tensile strength; ψ is reduction area coefficient.

Rozenberg and Eryomin [21] proposed to use the hypothesis of equality of works done for cutting and plastic compression at the same strain. Using this assumption they found the dependence of shear strength on shear strain γ in the form

$$k_s = \frac{B}{1.5} \frac{\gamma^c}{c+1}, \quad (12)$$

where B and c are the empirical coefficients from compression test. Shear strain is defined according Piispanen [6] model as

$$\gamma = \cot \Phi + \tan(\Phi - \alpha). \quad (13)$$

Thus according to (12) and (13) the shear strength is the function of shear angle and as shear angle increases then shear strength decreases.

Hastings, Mathew and Oxley [27] suggested defining shear strength according Mises criterion as

$$k_s = \frac{\sigma}{\sqrt{3}}. \quad (14)$$

In the formula (14) stress σ characterizes stress state of work material including work hardening effect in cutting, which can be expressed as power function of strain in the form as followed

$$\sigma = \sigma_1 \varepsilon^n, \quad (15)$$

where σ_1 and n are constants, which are defined from stress-strain curve.

Strain rate and temperature have great influence on material properties, including parameters σ_1 and n . This influence can be taken into account together by velocity-modified temperature [27]

$$T_{\text{mod}} = T \left(1 - \nu \lg \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right), \quad (16)$$

where T is temperature in shear plane, $\dot{\varepsilon}$ is direct strain rate; and ν and $\dot{\varepsilon}_0$ are constants.

Parameters σ_1 and n are dependent on velocity-modified temperature. Thus if it is possible to determine temperature, shear strain and strain rate in shear zone then we can find velocity-modified temperature and to define strength of material under known dependences of σ_1 and n from T_{mod} . This methodology to define shear strength is most correct now and reflects real processes in primary shear zone from physical point of view. However application of the way proposed in [27] is rather difficult. At first for every material it needs test curves for parameters σ_1 and n depending on velocity-modified temperature. The second is that correct definition of temperature, strain and strain rate is necessary, which requires some additional assumptions and experimental coefficients. Finally it leads to complication and inconvenience to find shear strength.

From this discussion we can conclude that there are three points of view to behavior of shear strength in cutting depending on shear angle. First proposes to consider shear strength as constant of material as Zorev [10] assumed. The second is that shear strength increases under decrease of shear angle [21]. The third considers temperature-softening effect under the increase of strain rate.

The softening effect of temperature when strain increases was also proved in other studies. In particular Kushner [26] found this phenomenon in cutting of different carbon, alloyed and stainless steels. On the base of thermo-dynamical analysis he suggested simplified formula connected shear stress in shear plane and temperature in the form

$$k_s = K S_u (1 - b_\theta \theta) \quad (17)$$

where S_u is true ultimate tensile strength; K and b_θ are thermal constants of work material and θ is temperature in imaginary shear plane. Kushner [26] notes that for steels constants K and b_θ are 1 and $0.5 \cdot 10^{-3}$ respectively then formula (17) comes to

$$k_s = S_u (1 - 0.5 \cdot 10^{-3} \theta). \quad (18)$$

For temperature θ Kushner suggested to use approximate half-empirical formula, which connected true ultimate tensile strength and thermal characteristics of work material and shear strain as

$$\theta = 0.82 \frac{S_u}{c\rho} \gamma, \quad (19)$$

where $c\rho$ is heat capacity of work material and shear strain γ is defined according formula (13).

Finally, shear stress in imaginary shear plane comes to the expression

$$k_s = S_u \left(1 - 0.41 \cdot 10^{-3} \cdot \frac{S_u}{c\rho} (\cot \Phi + \tan(\Phi - \alpha)) \right). \quad (20)$$

If the value of stress k_s is known then shear angle Φ can be found from the equation of balance forces on rake face and line AC. Here is assumed that point C (see Fig.1) is located in a very short distance from transition surface BD. Then the balance equation has the general form as followed

$$k_s \cdot \frac{a}{\sin \Phi} - N \cdot \cos(\Phi - \alpha) + F \cdot \sin(\Phi - \alpha) = 0. \quad (21)$$

After some simplifications the equation (21) can be presented in the form

$$k_s + k_f \cdot \left[\left(\frac{\pi}{2} - 1 \right) \sin 2(\Phi - \alpha) - \cos 2(\Phi - \alpha) - 1 \right] = 0. \quad (22)$$

From (22) it can be seen that shear angle depends only on given rake angle and the ratio between stress in plane AC and constant of plasticity k_f . The analytical expression of solution of equation (22) is rather long and inconvenient. For shear angle definition it is easier to use special software. In particular, the authors used Mathcad 2001.

It is necessary to note that formula (19) is only average estimation of temperature in shear plane. It particularly concerns to the influence of cutting velocity. As we can see, cutting speed doesn't appear in this formula in explicit form and considered only indirectly by its influence on shear angle that we need to find. Therefore formula (19) can be applied as average estimation of temperature for cutting speed range, which is usually used in practice. This means that resulting shear angle taken from equation (22), using k_s value from (20), is also its average estimation for practical range of cutting speed. However in practical range of cutting speed, shear angle doesn't change significantly as well known from experience. For example in our experiments for carbon steel SM45C at cutting speed from 150 up to 300 m/min this difference in measured shear angle formed 13 per cent, which is comparative with measurement errors. The same trend has been found for copper, aluminum 6061 and stainless steel STS 304. Thus proposed methodology to find shear stress in shear plane and determination of shear angle can be applied successfully without large errors in practical interval of cutting speeds.

From the other hand if we have any reliable experimental relations concerning influence of cutting conditions on temperature in shear plane, we can use their analytical form in formulas (17) or (18) to find shear stress in shear plane more correctly, and use this corrected shear stress in equation (22) to obtain right value of shear angle. At the same time direct experimental dependences of shear strength on cutting conditions and tool geometry could be very useful.

7. Determination of normal stress on shear plane

If the location of imaginary shear plane from equation (22) is known then it is possible to find normal stress σ_s in this plane. The balance equation relative to the normal to the shear plane AC (see Fig.1) has a view as followed

$$F \cos(\Phi - \alpha) + N \sin(\Phi - \alpha) = \sigma_s \frac{a}{\sin \Phi}. \quad (23)$$

Taking into account (5) and (6) and after simplification the expression for normal stress in shear plane is obtained as

$$\sigma_s = 2k_f \left[\left(\frac{\pi}{2} - 1 \right) \cos^2(\Phi - \alpha) + \frac{1}{2} \sin 2(\Phi - \alpha) \right]. \quad (24)$$

Thus the stress state of material in shear plane is found completely. It characterizes by shear stress (formula (20)) and normal stress (formula (24)). The imaginary shear angle is defined from equation (22).

In the same way the stress state in each slip-line in “fan” ABC can be found if shear stress is known there.

8. Some proofs of suggested theory

The first assumption of given theory is the construction of slip-line field. Possible simplification of primary shear zone (ABD in Fig.1) by “fan” of slip-lines is not doubt now for everybody for it was proved by many experimental research mentioned above [9,10,11].

The construction of slip-line field in chip body ADE is proved by two moments. First is the form of stress distribution on tool rake face, which follows from given slip-line solution. The general theoretical view of stress distribution is presented in Fig.2 (b). The form of shear stress distribution, that shear stress increases from tool tip to some maximum value and then decreases to zero at the end of tool/chip contact, was experimentally proved by many researchers [12, 13, 19, 20]. Bagchi and Wright [13] carried out the experiments about stress distribution on tool rake face using photoelastic sapphire. They found that in cutting 1020 steel and 12L14 steel the character of stress distribution independent on depth of cut and cutting velocity and has the form presented on Fig.2 (a). In this research [13] it is well seen that for every case shear stress is zero at tool tip and at the end of tool/chip contact, and has pronounced maximum approximately at the center of tool/chip contact. According to the slip-line theory this situation possible only in the case of suggested slip-line field ADE presented in Fig.1.

According to the formulas (4) theoretical normal stress on tool/chip interface is maximum close to the tool tip and then it decreases up to zero at the end of tool/chip contact. The form of normal stress distribution corresponds well to the experimental data especially at the end of tool/chip contact (see Fig.2 (a), (b)).

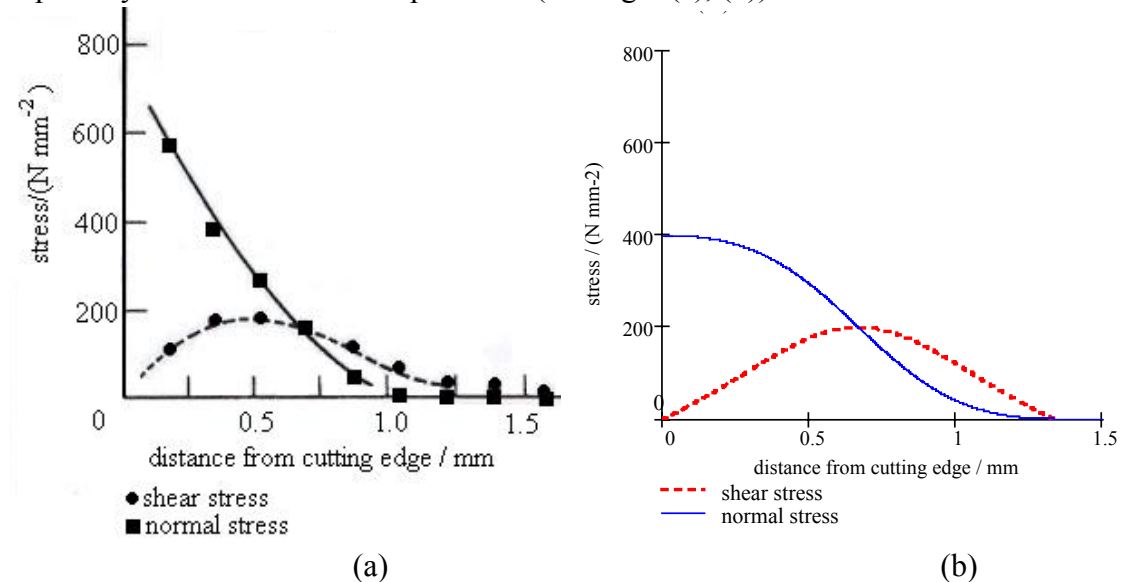


Fig.2. Experimental (a) (after Bagchi and Wright [13]) and theoretical (b) (using given slip-line solution) stress distributions on tool rake face

Close to the tool tip experimental curves of normal stress usually has some pick [12, 13, 19, 20]. This difference of experimental and theoretical data can be explained by errors of stress measurement by known methods. These methods, especially cutting by split tool, don't consider the action of forces on clearance face, which can be very significant and lead to the serious distortion of real picture of stress distribution, especially close to the tool tip. Neglecting these forces on the clearance face, the "additional" error stresses are added to the real stresses on tool rake face and make wrong picture of stresses. The method of cutting by photoelastic sapphire using by Bagchi and Wright [13] seems to be the most reliable because it can reduce the influence of forces acted on tool clearance face in comparison with split tool method. However it also creates some parasitical stresses, which probably are the reason of difference in theoretical and experimental picture of stresses, especially concerning normal stress close to the tool tip.

Ideal plastic behavior of chip material in ADE zone (see Fig.1) has been proved in chapter 1.5 of this paper, where the constancy of shear stress k_f has been shown in this field. One more evidence of this constancy can be micro hardness tests of quick-stop microsections, which show permanency of material hardness after deformation in primary shear zone [12,30]. This also means that chip material can be considered as ideal plastic.

The other proof of given slip-line solution is experimental verification of accuracy of formula (1). This formula for determination of chip/tool contact length reflects geometrical construction of suggested slip-line field and if this formula gives wrong results then given slip-line solution is doubt.

One of the most widespread methods to determine shear angle experimentally bases on measurement of chip thickness a_1 . From the scheme, given in Fig.1, it can be easily obtained geometrically that

$$\Phi = \arctan\left(\frac{\cos \alpha}{\xi - \sin \alpha}\right), \quad (25)$$

where $\xi = \frac{a_1}{a}$ is called "chip thickness coefficient".

Numerous experiments with different material (as armco-iron, carbon and stainless steels, different coppers and bronzes with different hardness) and cutting conditions conducted by Poletika M.F. [5] show that tool/chip contact length is related with chip thickness coefficient ξ and undeformed chip thickness a . For the range of $1 \leq \xi \leq 10$ this experimental dependence is expressed by formula as followed [30]

$$L_e = a \cdot (2.05 \cdot \xi - 0.55). \quad (26)$$

Lets compare this experimental formula (26) with our theoretical expression (1), which we deduced from suggested slip-line solution, given in Fig.1. Substituting (25) into (1) and presenting formula (1) in relative unit L/a , and after some mathematical transformations we get very simple formula

$$\frac{L}{a} = 2 \cdot \xi. \quad (27)$$

In the same way, experimental formula (26) can be presented in relative unit as

$$\frac{L_e}{a} = 2.05 \cdot \xi - 0.55. \quad (28)$$

In Fig.3 the graphical comparison of theoretical (27) and experimental (28) formulas is shown.

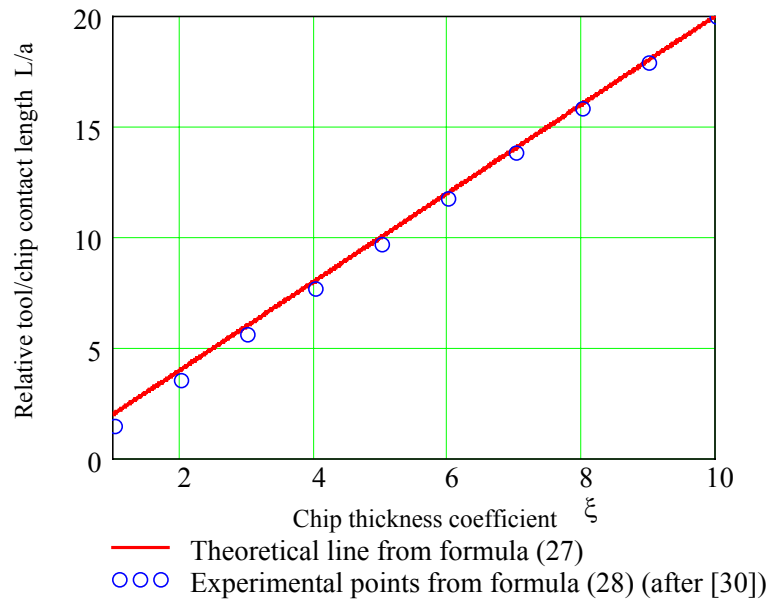


Fig.3. Comparison of theoretical and experimental results for relative tool/chip contact length L/a .

From this Figure 3 it is easy to see that theoretical line corresponds to experimental dependence almost perfectly. Thus formula (1) for tool/contact length is right and so the suggested construction of slip-line field in Fig.1 is true.

Indirect proofs of presented stress distribution are crater wear and temperature distribution in tool. Indeed, since crater wear and maximum temperature on tool/chip interface take place at some distance from tool tip, it can be assumed that maximum shear stress acts in this region since value of shear stress defines wear intensity and temperature value. The absence of shear stress close to the tool tip means that no friction in this area. Thus tool rake face cannot be worn in this region and no temperature effect can be expected. As friction stress increases along rake face, wear intensity and temperature grow and make crater wear, which corresponds to the form of shear stress distribution on the rake face.

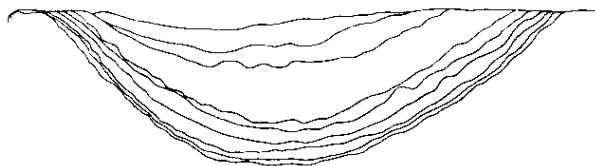


Fig.4 Consistent changes of crater wear form [23]

The same can be said about temperature distribution in the tool. Typical crater wear form and temperature distribution in tool are shown on Fig.4, 5. These figures can be compared with Fig.2 where typical shear stress distribution is presented. It is well seen that form of shear stress curve, crater wear boundaries and temperature layers in tool show the same tendency.

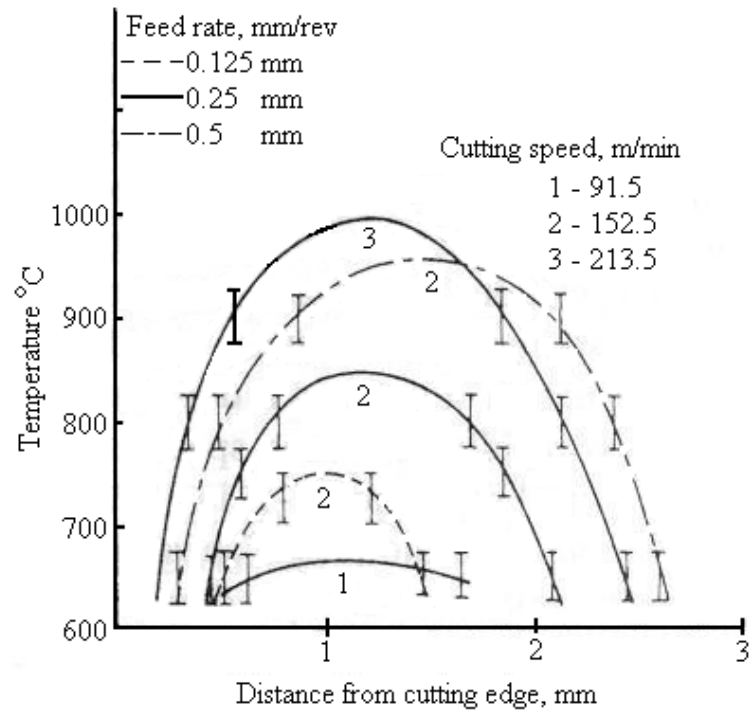


Fig.5 Temperature distribution on rake face of tools used to cut very low carbon steel at different speeds and feeds [24]

9. Conclusion

The new slip-line solution for metal cutting by tool with whole rake face is presented. Friction and normal stress distribution on tool/chip interface is found analytically using classical theory of plasticity. It is shown that constant of plasticity in cutting corresponds Tresca plastic flow criterion considering hardening effect and constancy of average friction stress on the rake face is proved. The comparison of theoretical and experimental stress distribution is presented that show good correspondence of model to the real cutting conditions. The influence of forces, acted on the clearance face, to the experimental stress distribution on the rake has been explained. Using given stress distribution the formulas for cutting forces prediction is found. The problem of material strength in cutting has been considered and the most appropriate method is chosen. The stress state of material in shear plane is defined and the analytical way to predict shear angle is suggested.

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