

Features of Creation of Surface Layer Mechanical Condition Parameters in Orthogonal Cutting

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Abstract. In this article, the technique and research results on creation of surface layer mechanical conditions parameters at orthogonal cutting are presented. Stress tensor, strain rate tensor and general mechanical condition factors distribution along flow lines were obtained. Distributions of stresses, strain rates, mean normal stress and stress state index along flow lines consist of three steps of quasi-monotonous deformation. On every step there is a monotonous increasing or decreasing of these parameters. It is demonstrated that creation of surface layer mechanical condition parameters in metal cutting and surface plastic deformation methods follow common patterns. Experimental research results confirmed the validity of proposed analytical models for stressing programs in orthogonal metal cutting.

1 Introduction

Metal cutting is one of the most widely used processes in machine-building industry. Properly assigned cutting modes enable to provide specified dimensional accuracy and surface integrity of components. During the cutting process, metal undergoes severe plastic deformation with high strain rates in restricted areas. Orthogonal cutting is known to be the most commonly used model to make various geometric and boundary conditions more simple. Metal cutting processes feature complex stress distribution and strain accumulation on chip-tool boundary and in surface layer. Over the last decades, a number of numerical simulations and research works have been carried out on the machining of metals.

V. P. Astakhov, M. O. M. Osman and M. T. Hayajneh [1] investigated the velocity diagram in orthogonal metal cutting. They asserted that the chip-formation process had a cyclic nature. Each cycle consisted of three stages. The frequency of chip formation was also studied and the virtual work equation was derived. To estimate the variation of stress and strain in the deformation zone quantitatively, a micro-hardness scanning test was conducted.

A. G. Atkins focuses on single shear plane model using both FEM simulations of cutting and modern ductile fracture mechanics [2]. It is shown that primary shear plane angle depends on material as well as tool rake angle and friction. The author introduces the

material toughness/strength ratio, which depends upon material chemistry and prior thermo-mechanical treatment, as well as strain rate and temperature during cutting.

A. Racz and al. [3] applied an Eulerian finite element model to predict the stress distribution, strain distribution and cutting forces arising in the material ahead of the tool tip in commercial purity copper. Both an elastic plastic hydrodynamic and Johnson-Cook constitutive model were used. The authors distinguish three regions in which deformation occurs: the primary deformation zone, the secondary deformation zone, and the machined surface. It was discovered that the maximum stress in the hydrodynamic material (410 MPa) and in the Johnson-Cook material (438 MPa) were located at the tool tip, and showed good correlation to the maximum experimental stress of 422 MPa, also occurring at the tool tip. The depth of plastic deformation beneath the machined surface (400 μm) and the width of the secondary deformation zone (60 μm) predicted by the numerical model were in good agreement with experimental observations.

R.Yu. Nekrasova and al. studied the relation of the cut-down layer strains with the stress distribution in the cutting area [4]. As a result, the cut-down layer strain parameters and the system of strains acting in the cutting area that allow forming the loading model of a tool have been determined. Cutting area stress distribution model obtained can be used in strength calculation and working capacity of machine tools.

J. M. Rodriguez, P. Jonson and A. Svoboda [5] used a dislocation density model along with FEM simulation to reproduce the orthogonal cutting of AISI 316L steel in 2D plain strain conditions. As a result, the effective plastic strain rate, dislocation density distribution and excess of vacancy concentration distribution on the chip-tool boundary and surface layer has been obtained.

T. Baizeau and al. investigated the strain field induced by cutting process of aluminum alloy using a high-speed double-frame imaging device with pulsed laser lighting [6]. The displacement fields were measured using a global Q4-digital-image-correlation (DIC) method. The authors calculated the residual strain field, displacement field and equivalent strain distribution by the depth of surface layer. In their research, the authors gave much attention to surface layer rather than chip formation.

Dong Zhang, Xiao-Ming Zhang, Wen-Jie Xu and Han Ding [7] proposed a new methodology to obtain the cutting stress field. Deformation field containing both elastic and plastic components were obtained by DIC technique. In order to compensate the inaccuracy of elastic deformation components, a special method has been proposed to modify the hydrostatic pressure. In addition, the geometry of shear plane and material separation in the vicinity of the cutting edge was derived. The stress distributions along the rake surface and the shear plane were also calculated.

Hao Pan and al. [8] carried out FEM simulations of orthogonal cutting of aluminum alloy in which both the Johnson-Cook constitutive relation and the Johnson-Cook separation (fracture or damage) criterion were used. The Johnson-Cook damage criterion is expressed as a plastic work/volume, i. e. plastic strain energy density). The simulation was carried out for a wide range of cutting parameters: rake angle varied from -20° to 40° , depth of cut varied from 50 to 500 μm . Feed rate was 800 m/min. It was determined, that the size of the damaged boundary layer is about 35 μm and appears to be independent of cutting depth and rake angle over the range investigated within the mode of continuous chip formation. Both analytical and simulation results indicate greater fracture toughness value at smaller rake angle. This is associated with increasing part of shear fracture mode in comparison with tensile.

There are many other papers [9-13] dedicated to chip and surface layer formation in metal cutting.

As it is well known, when designing a route for strengthening mechanical treatment, allowance of technological inheritance (TI) should be provided. Efficient evaluation and

prediction of surface layer properties are possible on the grounds of TI mechanics, developed by prof. V. Yu Blumenstein [16].

The theory of quality TI at machining and service stages is based on the fundamental phenomenological model of continuous surface layer formation exposed to surface plastic deformation. Key mechanical characteristics include mean normal stress σ , shear stress intensity T , degree of shear deformation Λ , indicator of stress state I , degree of plasticity reserve depletion (DPRD) Ψ .

When a cutting tool moves by a certain feed rate within the contact area the deformation site (DS) occurs, where metal flows, deformation accumulates, plasticity reserve depletes and surface layer properties generate along flow lines (Fig. 1). There are two metal flows in the DS: one of them turns into a chip, while another moves under the tool. Separation of two different metal flows takes place along critical flow line l in the vicinity of C point.

Key feature of TI mechanics is stressing program (SP), which appears as variation of degree of shear deformation Λ with indicator of stress state I . SP comprises three steps of quasi-monotonous deformation. On each step, continuous strain accumulation takes place in the conditions of changing indicator of stress state. At the key points of SP partial healing of defects and plasticity reserve recovery occur. SP which depends on cutting parameters defines stress-strain state and forms surface layer properties. By SP action in DS, plasticity reserve depletion takes place, which in turn results in surface layer properties forming.

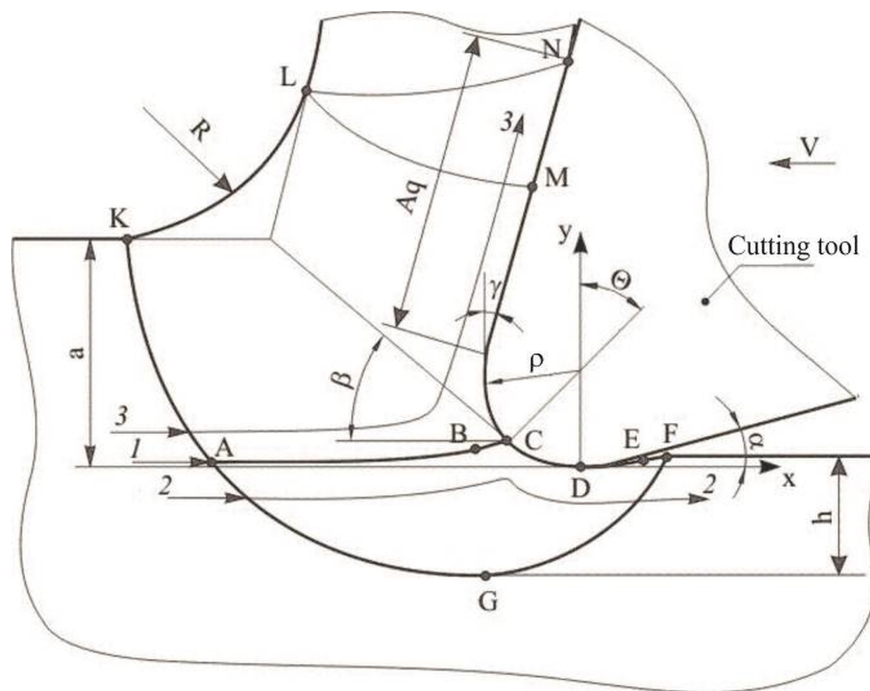


Fig 1. Deformation site scheme: γ – rake angle, α – clearance angle, Θ – indentation angle, ρ – tool edge radius, a – cutting depth, V – cutting speed

Strengthening mechanical treatment route includes cutting and burnishing operations. The ultimate creation of surface layer properties occurs during burnishing operations with previously accumulated properties taken into account. Cutting operations serve for achieving desired shape from blocks of metal and dimensional accuracy. Studies conducted until date [14-16] indicate, that there is common pattern of surface layer parameters

creation along with stressing programs in cutting and burnishing processes. Such pattern can be described by analytical models using DS parameters.

2. Materials and methods

In order to validate early obtained analytical models of stressing programs, experimental researches on orthogonal cutting of plane specimens made of 1045 carbon steel (table 1) on horizontal milling machine 6N80G were carried out.

Table 1: Chemical composition of 1045 steel, %

C	Si	Mn	Cr	S	P
0.42-0.50	0.17-0.37	0.50-0.80	less than		
			0.25	0.040	0.035

The cutting parameters are presented in Table 2.

Table 2: Cutting parameters

Specimen number	Cutting speed V , m/min	Tool edge radius ρ , mm	Rake angle γ , °	Clearance angle α , °	Cutting depth a , mm
12	0.07	0.15	35	10	0.3
13	0.05				
14	0.025				
15	0.0335				
16	0.1				

Specimens were fixed on the special machine-retaining device with wedge clamp (Fig. 2), which was mounted on the milling machine table.

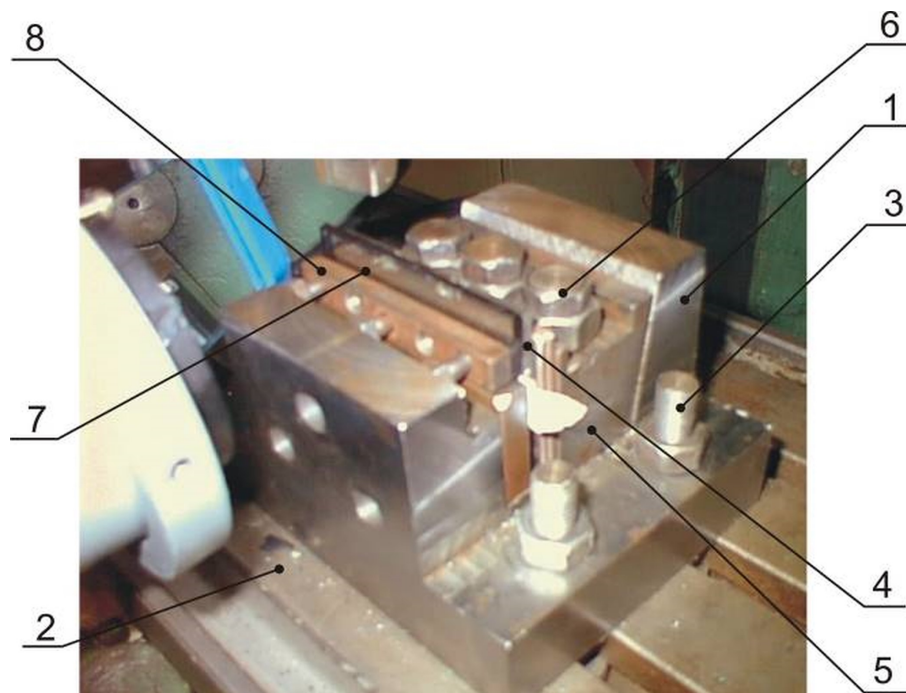


Fig 2. General view of special machine-retaining device

Device body 1 was clamped on the horizontal milling machine table by screws 3. Plane specimen 4 was inserted into the body and fixed by wedge clamp 5 with screws 6. To ensure the plane strain condition and to provide high-speed filming of cutting process, hardened glass plate was mounted in front of the specimen. Specimen and glass plate position adjustment was performed by plate 8 with screws. The required tool geometry was achieved by grinding regular carbide cutting inserts on optical grinding machine and tool holders made of 5140 steel.

The components of stress-strain condition were calculated by using finite element method (FEM) and dividing grid method (DGM). Bottom edge of the work-piece was rigidly fixed. The cutting tool, which was treated as a rigid body, was pressed and then shifted along horizontal line by the speed rate. There was no vertical displacement of the tool. Initial conditions were Young's modulus $E = 200 \text{ GPa}$, Poisson's ratio $\nu = 0.3$, density $\rho = 7800 \text{ kg/m}^3$, friction coefficient on the contact area $f = 0.21$. DS geometric parameters were used as boundary conditions [17]. Fig. 3 shows a deformed dividing grid of No. 16 specimen.

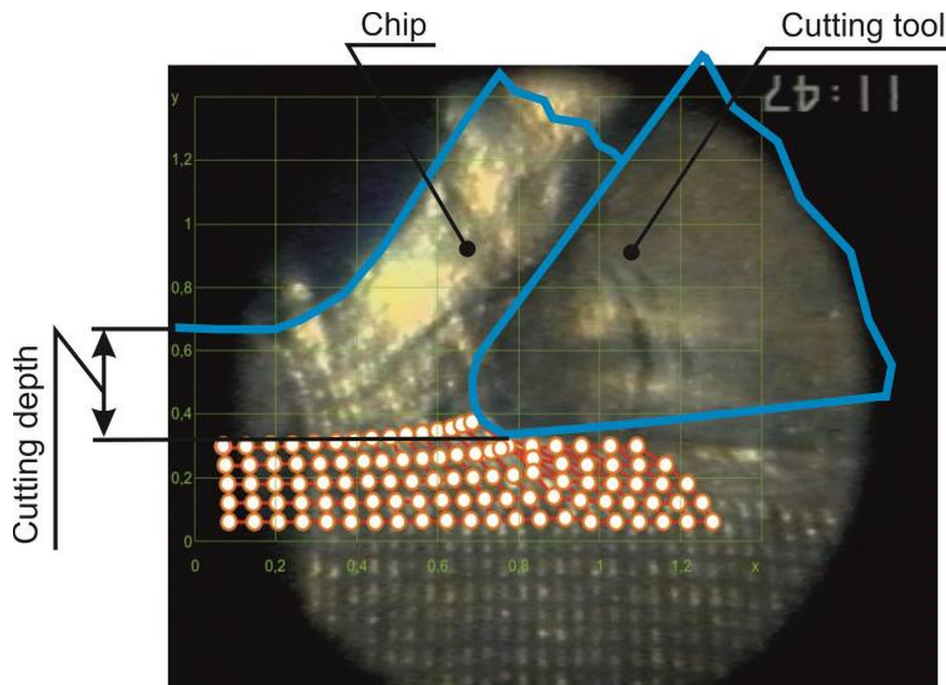


Fig. 3. Deformed dividing grid of No. 16 specimen

3 Results and discussion

Fig. 4-5 shows stress tensor and strain rate tensor components distribution respectively for critical flow line of No. 16 specimen, calculated using FEM and DGM. Fig 6 illustrates mean normal stress, shear stress intensity and indicator of stress state distribution for critical flow line of No. 16 specimen, calculated using FEM and DGM.

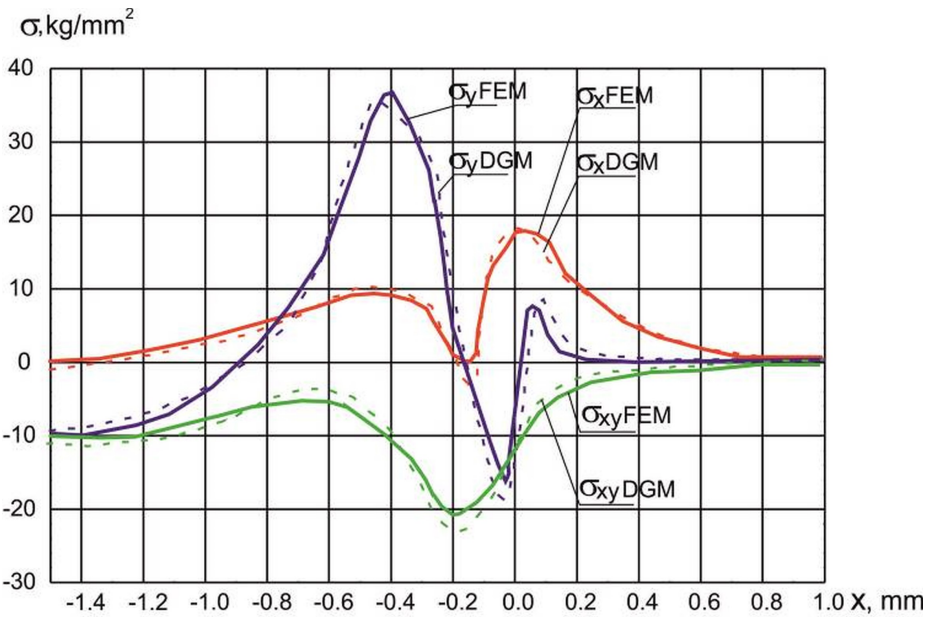


Fig. 4. Stress tensor components distribution along critical flow line

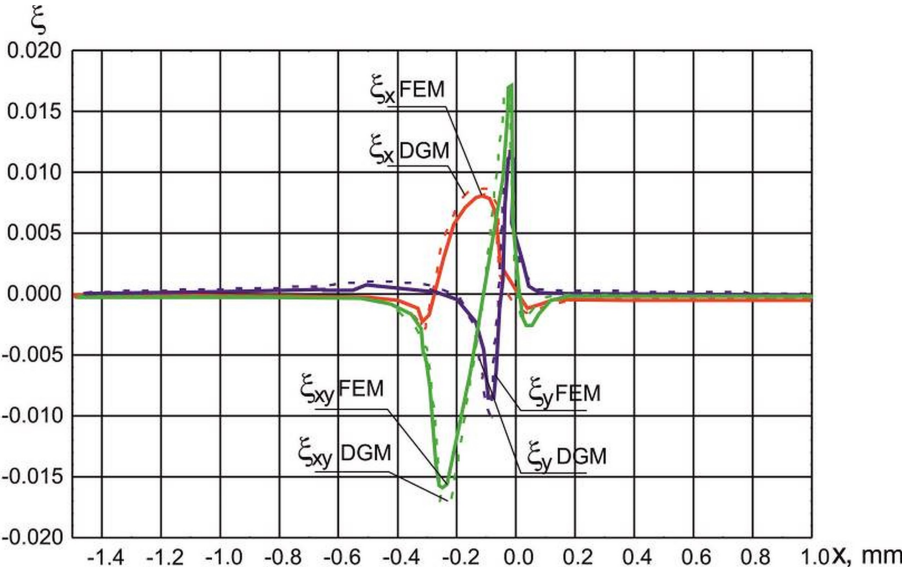


Fig. 5. Strain rate tensor components distribution along critical flow line

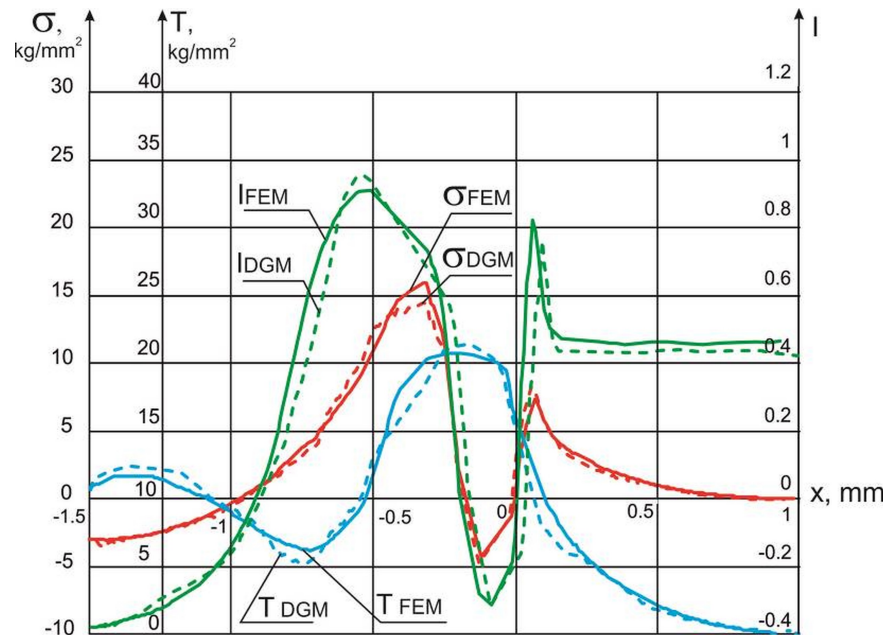


Fig. 6. Mean normal stress, shear stress intensity and indicator of stress state distribution for critical flow line

Fig 7. shows analytical (calculated by DS parameters) and experimental (calculated using DGM) stressing programs along critical flow line for No. 16 specimen.

It is evident that the distribution of stresses within the boundaries of DS is quite complex. Analysis of above relationships shows that maximum magnitude of stresses and strain rates occurs at the tool point area. Compressive stresses are generated ahead of the cutting tool. Tensile stresses form in the area situated behind tool edge due to attrition on the tool-workpiece boundary and chip formation. The highest shear stresses as well as maximal strains develop in the area, situated under the tool point.

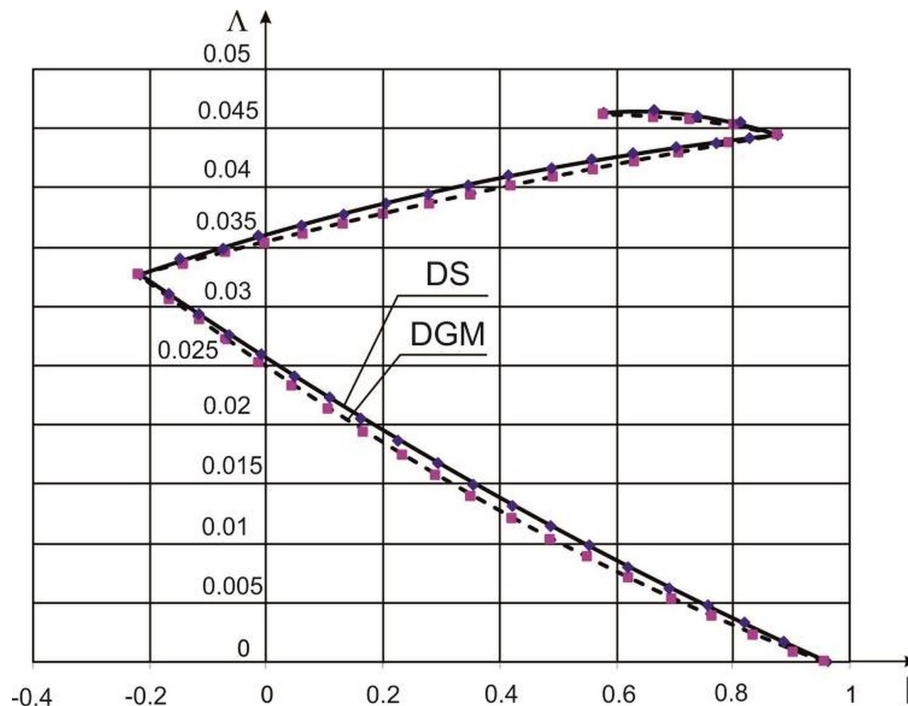


Fig. 7. Analytical and experimental stressing programs for critical flow line

Abrupt change in shear stress magnitude as the tool tip is approached indicates of the alteration of metal flow direction: metal particles fall into chip stream. The occurrence of maximal strain magnitude causes metal damage: metal flow separates into two portions, one of which turns into chip and another goes under the tool tip.

4 Conclusions

1. It has been determined that mechanical state parameters creation in cutting and burnishing obey common patterns.
2. Analysis of mechanical state parameters distribution along flow lines showed similarity in both individual stress and strain rate tensor and integrated parameters of surface layer mechanical condition: degree of shear deformation, mean normal stress, indicator of stress state etc.
3. Distributions of stresses, strain rates, mean normal stress and stress state index along flow lines consist of three steps of quasi-monotonous deformation. On every step, there is a monotonous increasing or decreasing of parameters mentioned above.
4. Experimental research results confirmed the validity of developed analytical models of stressing programs in orthogonal metal cutting.

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