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Mechanisms of formation of different types of metal chips

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ABSTRACT

The aim of the work is to determine the cause-and-effect relationships of the formation of different types of chips during the processing of metal alloys. The research methodology involved the use of both experimental work and Finite Element Analysis. Deformations during the cutting of steels AISI 1045 and AISI 321 were studied. It was established that during cutting, depending on the ratio of compression and bending deformations, three types of chips are formed: solid, segmented, and fragmented. Finite element calculations prove that regardless of the properties of the material being processed, the maximum stresses in the workpiece arise near the cutting edge, which is a stress concentrator. Subsequently, if the tool contacts a brittle material, a crack appears in front of the cutting edge. If the material demonstrates plastic properties, a zone of increased plasticity is formed. In both cases, a console is formed, which creates bending deformation in the cutting zone. Analysis of the distribution of deformations in the cutting zone showed that the formation of chips during the cutting of elastic-plastic materials can occur either as a result of simultaneous fracture along the shear plane and the surface between the allowance and the workpiece, or exclusively along the surface between the allowance and the workpiece. In the first case, a segmented chip is formed, and in the second – a solid one. When a crack forms near the cutting edge, further bending destroys the console, and fragmented chips appear. If bending is impossible, a compression fracture occurs, and small fragments and dust are formed. Controlling the chip formation mechanism by adjusting the parameters of the cutting mode and using cooling allows for improving its transportation, increasing the safety of equipment operation, and the quality of the machined surface.

Keywords: chip types, bending and compression, cutting edge, zone of increased plasticity, industrial growth, process safety.

INTRODUCTION

The process of chip formation is a complex phenomenon based on the interaction between the cutting tool and the workpiece. As a result of this interaction, material undergoes deformation and destruction, leading to the separation of its particles in the form of chips. This process is considered one of the most intricate in the theory of mechanical engineering. It is evident that understanding the mechanism of chip formation is a key factor for deeper comprehension of the entire cutting process, as noted by Pedroso et al. [1]. Various methods of experimental research and mathematical modeling are applied for its detailed analysis.

The morphology of chips depends on several factors, including: cutting thickness, a_1; tool rake angle, γ; cutting edge radius, r; and the influence of previous cuts [1].

Metal cutting is a widely used manufacturing process in the industry, as demonstrated by Arshad Qureshi et al. [2]. Research in this field focuses on tool characteristics and equipment parameters that affect the process and product quality. High-speed machining technologies and modern machines enable improved surface roughness by precisely controlling tool motion and ensuring high-quality machining. However, relying solely on high-speed machining is insufficient for optimizing production quality due to challenges in its precise control, which complicates the application of this technology. Therefore, selecting optimal cutting parameters such as feed rate, depth, and cutting speed is crucial for creating favorable machining conditions and meeting industrial processing requirements.

Understanding the mechanism of chip formation allows predicting the formation of the type to improve its transportation, safety of equipment maintenance, and the quality of the machined surface. The type of chip is determined by the ratio between compression and bending deformations when changing the parameters of the cutting mode or the mechanical properties of the processed metal (due to the chemical composition or because of cooling).

BACKGROUND

The first step in analyzing the chip formation mechanism is the correct identification of its type. This task is quite challenging for accurate prediction. As noted by Shaw [3], the most reliable approach is experimental determination. finite element analysis (FEA) enables the prediction of parameters such as processing temperature, tool wear, surface roughness, and residual stresses. However, despite the visualization capabilities of FEA, this method does not fully reflect real cutting conditions. Due to the phenomenon of chip shrinkage, its coefficient (K) usually exceeds one and, according to the research by Filonenko [4], can reach up to eight (except for titanium alloys, where $K < 1$).

According to Pedroso et al. [1], who analyzed 125 reports, 25 book chapters, 5 standards and 266 articles, in most studies conducted using the finite element method, the shrinkage coefficient usually takes the value $\zeta = a/a_1 \approx 1$ (Figure 1) or even $\zeta < 1$. Nevertheless, this method is highly illustrative, convenient, and allows for evaluative judgments regarding the formation of stress and strain regions.

Martina Panico et al. [5] found that the type of chip depends on the properties of the processed material. Chip morphology is an important intrinsic characteristic of the machining process that determines its quality. During the machining of materials with low machinability, a long, continuous chip is typically formed, which is difficult to break, as noted by Robles et al. [6]. To avoid the negative consequences of chip accumulation during machining, its fragmentation and effective removal from the working zone have become necessary.

Jun Eto et al. [7] discovered that chip shape depends on cutting speed, tool rake angle, and the coefficient of friction. Chip shape is associated with tool wear. Monitoring tool wear and real-time quality control are key elements of smart manufacturing, as they directly impact accuracy and productivity. ISO 3685:1993 [8] and Filonenko [4] define a tool as worn when uniform flank wear reaches VB = 0.3 mm.

In the work by Wang et al. [9], a novel indirect method is proposed that uses spindle vibration analysis as a proxy for evaluating cutting forces. Compared to traditional methods relying on vibration analysis or direct force measurement, this approach is safer, simpler, more cost-effective, and has lower computational requirements. This makes it ideal for real-time monitoring and long-term analysis, particularly for tool life prediction and assessing changes in surface roughness due to wear.

The article by Yang et al. [10] is dedicated to studying the viscoplastic deformation of S32760 DSS steel during the cutting process. To account for the dual-phase viscous properties of the material under high strain rate conditions, a corresponding viscoplastic constitutive model was developed. The authors analyzed the impact of strain rate in the shear zone on chip morphology, as well as the effects of deformation, strain rate, and temperature on phase microhardness. They identified a strengthening effect of the processed material with increasing strain rate, characteristic of viscoplastic deformation during cutting, and investigated the influence of these parameters on dynamic recrystallization of the surface layer. As a result, rules for changes in the microstructure of the processed surface were established, considering chip morphology, microhardness, and microstructural transformations.

Zhang et al. [11] employed polycrystalline finite element modeling to study intergranular compression, which can cause surface bulging and contribute to the formation of cracks under tensile stress. With increasing cutting speed, intense plastic flow leads to the formation of serrated chips. At speeds exceeding 200 m/min, increased temperature and strain rates promote

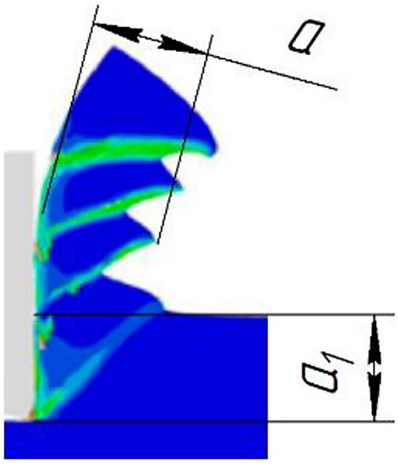


Figure 1. Modeling of elemental chips using FEA [1]

material bending and adhesion to the tool, resulting in the formation of large folds.

During the cutting process, chip formation occurs through a sequence of elastic-plastic deformations of the metal. The mechanical and physical properties of the metal, the temperature in the cutting zone, and tool wear determine chip flow regimes and instabilities, which significantly affect the quality of the workpiece surface (roughness, residual stress, microstructure). In stable flow regimes, uniform material deformation produces continuous structures of consistent thickness. Unstable regimes are accompanied by periodic ruptures and adiabatic shear zones, leading to serrated chips due to the separation of large material blocks.

For modeling serrated chips and localized shear, the finite element method with constitutive equations is applied, incorporating damage criteria and thermomechanical effects. Plastic materials, such as copper and its alloys, demonstrate different behavior: uneven plastic flow and folding result in heterogeneous deformations and cracks characteristic of polycrystalline metals.

In recent years, an increasing number of experimental studies indicate that the microstructure of metals, particularly the characteristics of polycrystalline aggregation, plays a key role in cutting processes. Grain structure significantly affects the plastic flow of metal, which substantially alters cutting forces and the types of chips formed. Models that account for grain effects provide better insights into chip formation and the condition of the machined surface.

In ductile metals, the fracture process is often accompanied by a transition from plastic deformation to failure. Studies of significant plastic deformation in polycrystalline metals have shown that chips undergo periodic bending regardless of their crystalline structure. Thus, during cutting, macroscopic flow characteristics, metal deformation behavior, and the dynamic response of the microstructure to loads influence the geometry and physical properties of chips, offering valuable information for understanding cutting mechanisms.

Interestingly, as noted by Zhang et al. [11], the hardness distribution across different regions of Invar 36 alloy chips is relatively uniform. This differs significantly from traditional serrated chips, where shear zones show much higher hardness compared to the central part. Changes in cutting regimes resulted in the emergence of new chip morphologies, including a "fan-shaped" form (Figure 2), which demonstrates specific flow mechanisms and cutting instabilities unique to the Invar 36 alloy. These findings differ significantly from previous studies. Consequently, Zhang observes that new, unexplored types of chips are emerging.

As Black [12] notes, the relative motion between the tool and the workpiece during cutting compresses the material near the tool, causing shear deformation that forms chips.

Monkova et al. [13] investigated certain aspects of chip formation during the machining of EN 16MnCr5 steel. It was found that the geometry of the cutting tool and cutting conditions influence chip shape. In modern unmanned production systems, ensuring efficiency and process continuity is crucial. Therefore, controlling chip formation becomes a critical task. The machining process, based on controlled material fracture, should ensure stable operation. The study aimed to understand the mechanisms of chip formation, as uncontrolled processes can lead to microcracks on the machined surface and tool breakage.

Sutter and List [14] studied chip formation in the Ti–6Al–4V alloy at different cutting speeds. A hypothesis was proposed regarding the chip formation mechanism within a specific range of speeds. Cutting speed was identified as the most critical factor influencing segmentation frequency, shear angle, and crack length. The significant reduction in cutting forces with increasing speed was attributed to thermal softening and the strain dependency of chip segments.

A review of the literature reveals that chip formation is influenced by factors such as the

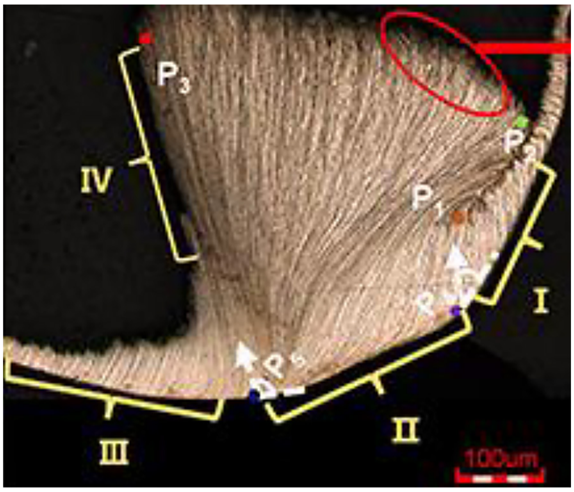


Figure 2. Fan-shaped chip [11]

workpiece material (its strength, plasticity, and structure), the geometry and material of the cutting tool, cutting conditions, and cooling environments. Depending on these parameters, different types of chips may form. Several classifications of chips exist, but the most common are based on shape and formation method.

Based on shape, chips are categorized into continuous, discontinuous, and combined types. Continuous chips form during the machining of ductile materials at high cutting speeds and low feed rates, appearing as a continuous ribbon often coiled into a spiral. Discontinuous chips consist of separate elements connected to one another and occur when machining hard materials or at high feed rates. Combined chips exhibit features of both continuous and discontinuous types.

Based on the formation method, chips are classified as shear, crack, or fracture chips. Shear chips result from the cutting tool shearing off a layer of material. Crack chips form due to material separation along a specific plane, while fracture chips appear during the brittle failure of the material.

Identifying the chip type is essential as it helps evaluate the appropriateness of the chosen cutting regime, tool condition, and material properties. Chip analysis assists in optimizing machining parameters to achieve the required productivity and surface quality. Changes in chip type may indicate tool wear or alterations in cutting conditions. Some chip types can pose a health hazard to workers. The chip type may even change during the machining of a single workpiece due to variations in cutting conditions.

However, the conditions for forming different chip types are still insufficiently studied, making it challenging to accurately predict chip types and resulting in the existence of various classifications. The study aims to determine the cause-and-effect relationships influencing the formation of different chip types.

RESEARCH METHODOLOGY AND RESULTS

To identify modern concepts regarding the causes of the formation of different types of chips during the machining of parts, a literature search was conducted. A simulation of chip formation was performed, aimed at determining the shapes of stress and deformation fields, which was performed using the DEFORM–3D numerical modeling system. The FEM allows you to effectively work with geometrically complex objects, inhomogeneous materials and various boundary conditions, ensuring high accuracy and adaptability. After creating a 3D model of the workpiece and tool, setting the temperature, speed, friction, heat transfer, the program calculates the stress-strain state. It is possible to visualize the distribution of stresses and deformations. A triangular plate with a flat front surface was used as a tool. The plate was installed in such a way that the tool cutting edge angle was $\varphi = 90°$, rake angle $\gamma = -5°$, and tool orthogonal clearance $\alpha = 5°$. The tool is "absolutely sharp", i.e. the radius of the cutting edge is zero and therefore its influence on the chip formation process was not determined in this work. A simplified workpiece model was selected and the following cutting mode parameters were used: $v = 1.75$ m/s, $a = 0.5$ mm, $f = 0.3$ mm/rev.

For experimental research, austenitic class steels AISI 321 and AISI 1045 were used. Deformations in the cutting zone were observed on polished chip samples. To reveal the structure, the samples were etched with a mixture of HNO_3 and HCl (1:3). Cutting forces were measured using an electric dynamometer UDM-600, which was modified to transmit output signals to a computer instead of being displayed on an analog device.

The cutting system consists of three elements: e_1 – the blade, e_2 – the workpiece, and e_3 – the chip. Therefore, the mechanism of chip formation represents a logical sequence of elementary interaction acts (q_1 – blade-workpiece, q_2 – blade-chip, q_3 – chip-workpiece) of the cutting system elements,

$$E = \{e_i, q_i\}, i = 3 \quad (1)$$

Initially, the interaction between the blade and the workpiece generates compressive deformation. At the same time, regardless of the properties of the material being processed, the maximum stresses in the material occur near the cutting edge (Figure 3a), which acts as a stress concentrator, as noted by Sivák et al. [15], Wahl and Beeuwkes [16], Hardy and Pipelzadeh [17]. During the further advancement of the blade, when the stress in the area of the tip reaches the limit for the material being processed, the following occurs.

If the blade contacts a brittle material, a crack appears in front of the tip - a sign of destruction (Figure 3b), as evidenced by Gogotsi and Galenko [18], Souguir et al. [19]. After the crack forms near the tip of the blade, bending stresses may occur if the resultant vector of all forces is directed in such a way that it lifts the cantilever formed after the crack. Separate, almost rectangular chip elements are formed. If, after the crack forms, the resultant is directed in such a way that bending does not occur, destruction occurs as a result of compression with the formation of fragments and dust. In this case, the stresses correspond to the condition of compressing the material between parallel plates.

For example, during the cutting of cast iron, chips are formed in the form of very small particles that are easily removed from the cutting zone. The processing of cast iron is a rather dirty and dusty operation due to the presence of fine graphite dust in the air, which requires measures to protect the operator, as indicated by the studies of Xiao Bin Huang and Xing Chang [20], Yang and Li [21], Aslan et al. [22], de Sousa et al. [23].

In the case of processing a material with plastic properties, a crack does not form near the tip (so-called "healing" occurs), and a zone of increased plasticity appears there. The rest of the metal that contacts the front surface of the tool is in an elastic-plastic state, deforms (Figure 3c), and bends as it moves along the front surface of the blade.

Changes in stresses in the "clamping" area of such a cantilever can be observed during the step-by-step loading of the cutting system, as shown in Figure 4. The sequence of stress formation (positions 1-6) corresponds to the conditions for the occurrence of a "plastic hinge" according to Van Long [24], Hoang et al. [25], Scott and Fenves [26], Megalooikonomou et al. [27]. In this zone, destruction along the so-called shear plane is possible.

The shear plane may not appear at all if the stresses are distributed in such a way that destruction at the end of the cycle occurs only along the separation surface between the allowance and the workpiece. Thus, the shear plane is a static concept that should be understood as one of the possible results of the completion of the chip formation cycle and the interaction of the elements of the cutting system.

Therefore, with the same movements, unchanged blade shape, and other conditions, a change in the properties of the material being processed causes significant changes in the process at the very beginning of chip formation. At the same time, it is obvious that both the crack near the tip of the blade (processing of brittle materials) and the plastic and elastic-plastic zones (materials with elastic-plastic properties) are the result of compressing the metal with the blade surface during its advancement.

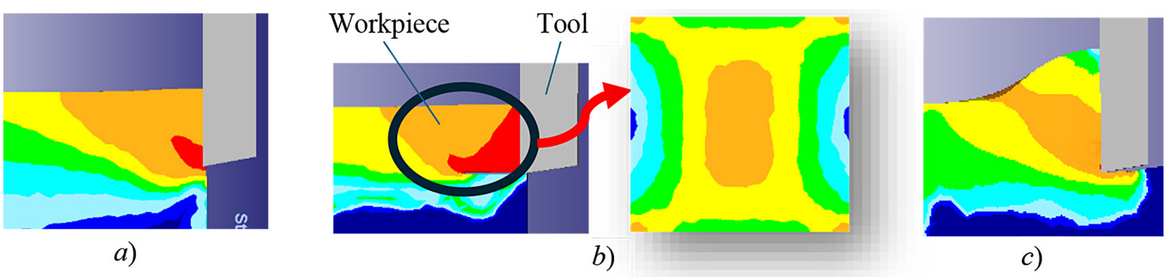


Figure 3. Formation of the stress field at the beginning of cutting:
a – stress concentration near the tip of the blade,
b – crack formation and stress in the allowance of brittle material,
c – deformation along the front surface of the blade of plastic material

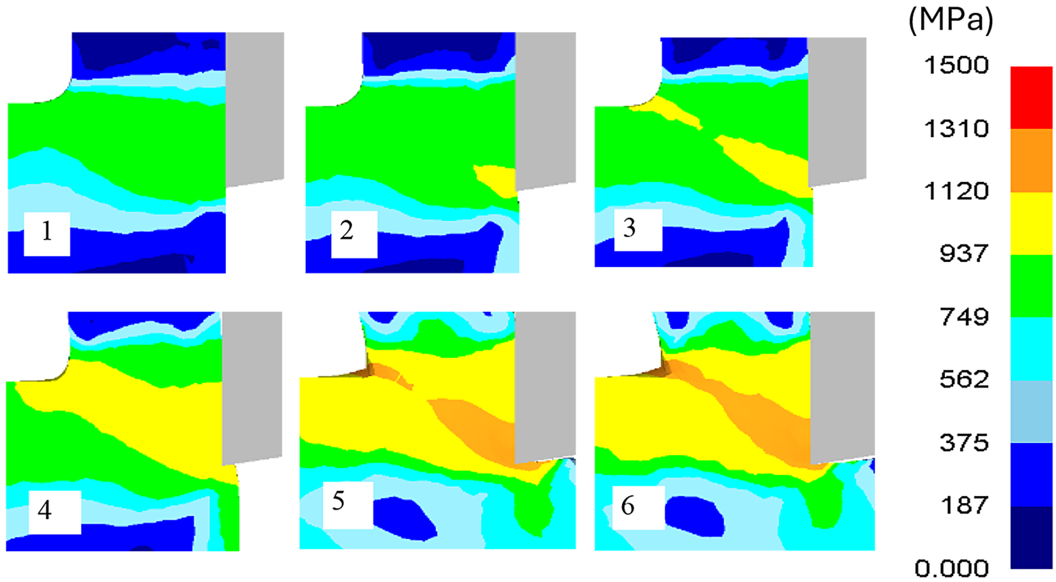


Figure 4. Change in stresses along the future cleavage plane with a stepwise (1–6) increase in load

After the formation of a crack or a plastic zone near the blade tip, the volume of metal compressed by the rake face also bears the load as a cantilever. This results in bending stress. When machining metals with elastic-plastic properties, the lower boundary of the plastic hinge zone is formed due to the simultaneous effect of compression and bending deformations (Figure 5a). Depending on the ratio between elasticity and plasticity, the tool geometry, and cutting conditions, the fracture (chip formation) may occur either simultaneously along surface AC (the base of the chip-cantilever) and surface AB (between the allowance and the workpiece) or only along surface AB (Figure 5b). In the first case, segmented chips are formed (Figure 5c), while in the second case, continuous chips are formed (Figure 5d, e).

To transition from punching to cutting, it is necessary to enable the movement of a certain cantilever, which forms after the metal is fractured near the blade tip, along the rake face. In this case, this cantilever can be considered a result of compression, but it cannot be removed from the interaction zone between the blade and the metal without active contact with the rake face. The interaction of this cantilever with the blade naturally leads to changes in the conditions of deformation and the formation of shear stresses in the cutting zone. This serves as further confirmation of the unity and mutual influence of the workpiece, blade, and chip during cutting. The cutting process is impossible without any of these elements.

If the two elements – the blade and the workpiece – form a compression scheme, no cutting occurs, and only indentation takes place. As soon as an additional type of deformation, bending, appears, the product of compression fracture – the chip – is immediately released, initiating the cutting process.

Studies of the bending of a cantilever with a curved profile under the action of force P, conducted by Bouadjadja et al. [28], Wu et al. [29], Hodžić [30] and Zagórski [31], have shown that maximum stresses occur near its surface at the point of fixation (Figure 6).

Considering the principle of independence of force actions, the resulting stress field during cutting can be visualized. To do this, we use the stress field that characterizes the compression process (see Figure 2a) and the field formed during bending (see Figure 6). By combining the fields from compression and bending deformations, the overall stress field during the cutting of elastic-plastic materials can be obtained (Figure 2 a, b). The lower boundary of these combined deformation fields is concave (due to the peculiarities of stress formation during bending) and marks the boundary of the onset of plastic deformation during cutting.

Thus, in the cutting zone, there are compression and bending deformations, which result from the shape of the line marking the beginning of plastic deformations, obtained by modeling (Figure 5a) and experimentally – the line AB in Figure 5b. The chip in Figure 5b is formed using the

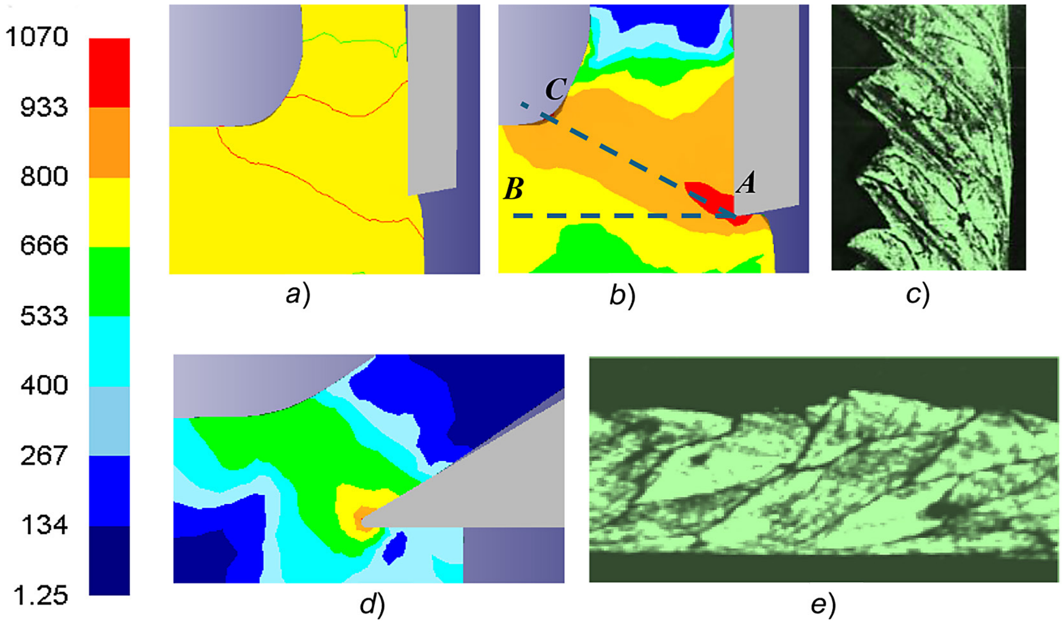


Figure 5. Formation of elemental and continuous chips: a – lower and upper boundaries of the chip formation zone; b – possible fracture directions; c – elemental chips (steel AISI 321, v = 2.3 m/s, f = 0.26 mm/rev, a = 0.5 mm); d – AISI 1045 steel, $\gamma = 30°$; e – continuous chips (steel AISI 321, $\gamma = 30^0$, v = 2.5 m/s, f = 0.17 mm/rev, a = 0.1 mm)

same algorithm as in Figure 3c: the formation of the plastic zone near the cutting edge, compression, and bending of the metal of the workpiece.

However, the reduction of the chip's elastic properties led to a decrease in the influence of bending deformation, which caused a reduction in the length of the formed elements. In this case, the element length approaches zero, creating the appearance of a continuous chip. However, the shape of the boundary of the beginning of plastic deformations (line AB) indicates the presence of compression and bending deformations, i.e., the mechanism of the formation of element chips.

Therefore, during metal cutting, it is possible to form chips of three main types: continuous, element, and granular. Depending on the material being processed, cutting conditions, and tool geometry, these types are further divided into subtypes. The first type, continuous chips, does not have many subtypes. In terms of structure, it differs by a greater or lesser degree of deformation, as shown in Figure 5d.

Elemental chips can consist of elements whose length approaches zero (Figure 7a), elements with a well-defined length that are firmly connected within the chip body (Figure 5c), or elements with weak bonding strength (Figure 7b).

When an element moves along the cutting surface, part of the plastic zone is pushed behind it, leading to the filling of the chip cavity from the front surface of the tool. The element assumes a trapezoidal shape. Unevenness that could appear on the side adjacent to the tool surface is smoothed by the part of the plastic zone extruded behind the element from the tool's tip, along with the deformation of the metal at the tool's tip when the next element forms. This creates a layer of elemental chips that contacts the front surface of the tool. The strength of the elemental chip is not uniform along its entire length; in the shear region, it is much lower than along the element.

Elemental chips can form with a variable shrinkage coefficient along their length (Figure 8), caused by the specific conditions of their formation. As the chip moves along the front surface at the beginning of cutting, due to friction, the heat in the contact zone increases, reaching a level where welding is possible. The movement of the chip stops, but the tool continues moving and compresses the workpiece metal. This is when the cutting force component Pz increases. The workpiece metal undergoes significant plastic deformation, as the welded chip obstructs free movement along the front surface of the tool. When the metal is compressed between inclined surfaces, the main mass of the metal flows toward the thick end of the wedge, so the metal accumulates on the outer side of the chip. Thus, the outer

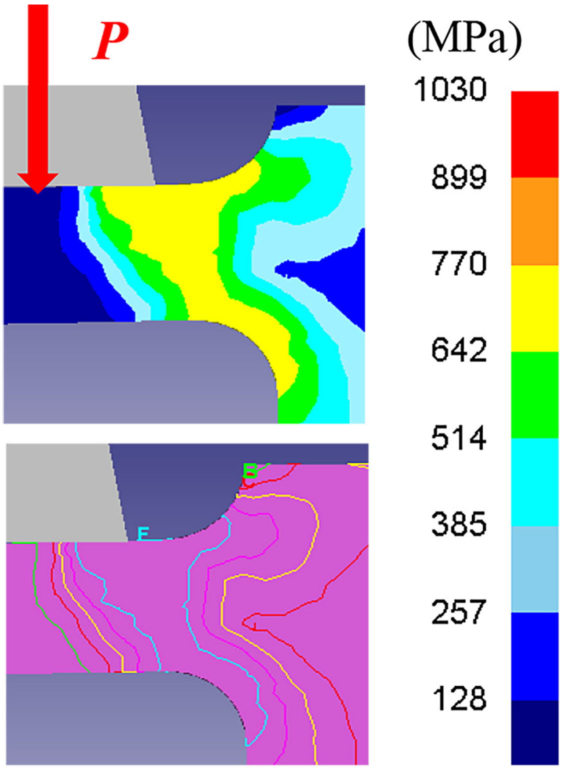


Figure 6. Stress during bending of the console

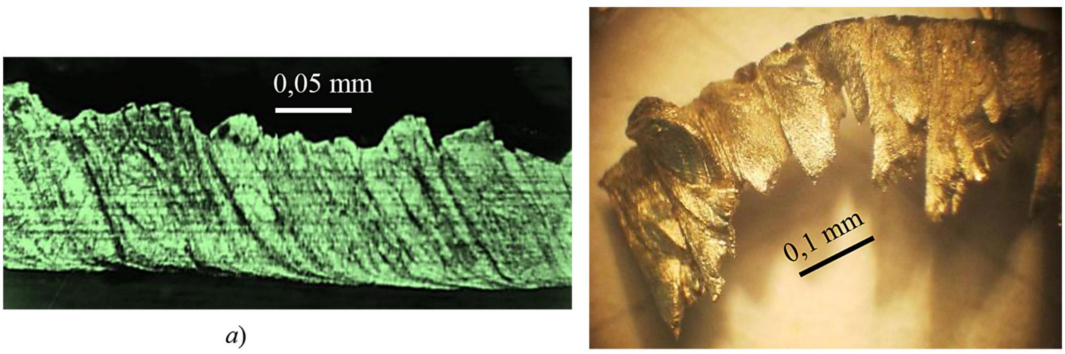
side of the buildup continually increases. On a longitudinal microgrind of the chip (Figure 8b), it is visible that the plane along which the build-up is displaced is perpendicular to the surface of the chip in contact with the front surface of the tool. The diverging lines correspond to the following positions of the plane of maximum shear stress during the formation of the buildup. When the buildup resumes movement along the front surface, it causes a sharp decrease in the cutting force. After the buildup shears off, normal cutting resumes until the next welding between the "tool-chip" pair occurs.

Granular chips form when processing brittle materials. They can appear as parallelepipeds, where the resulting force bends the volume of the workpiece metal created by the crack, or as small particles and dust, when a stress field forms in the mentioned volume, as shown in Figure 1b.

According to formula (1), the minimum number of actual objects capable of performing the cutting process is three. An analysis of the interactions within the cutting system shows that it functions only under specific mutual arrangements and movements of its elements. Since motion is always accompanied by energy transfer, the interactions within the system are reduced to the transfer of mechanical energy and heat.

The transfer of mechanical energy between the elements of the system occurs due to two main types of deformation: compression and bending. Therefore, the general mechanism of chip formation during the processing of materials with different physic and mechanical properties is based on a combination of compression and bending work, Table 1. The relationship between these types of deformations is determined by the geometry of the elements of the cutting system and their actual physic and mechanical characteristics, which depend on the parameters of their relative motion.

The chip type is determined by the ratio of compression and bending deformations in combination with the mechanical properties of the processed material. Therefore, an increase in cutting speed reduces the plasticity in the cutting zone and, thus, increases the chip elasticity, which increases the influence of bending deformation.



a) *b*)

Figure 7. Elemental shavings, steel AISI 321: a – minimum length of elements (v = 1.1 m/s, f = 0.17 mm/rev, a = 0.1 mm); b – insignificant strength of the combination of elements, (v = 0.16 m/s, f = 0.26 mm/rev, a = 0.5 mm)

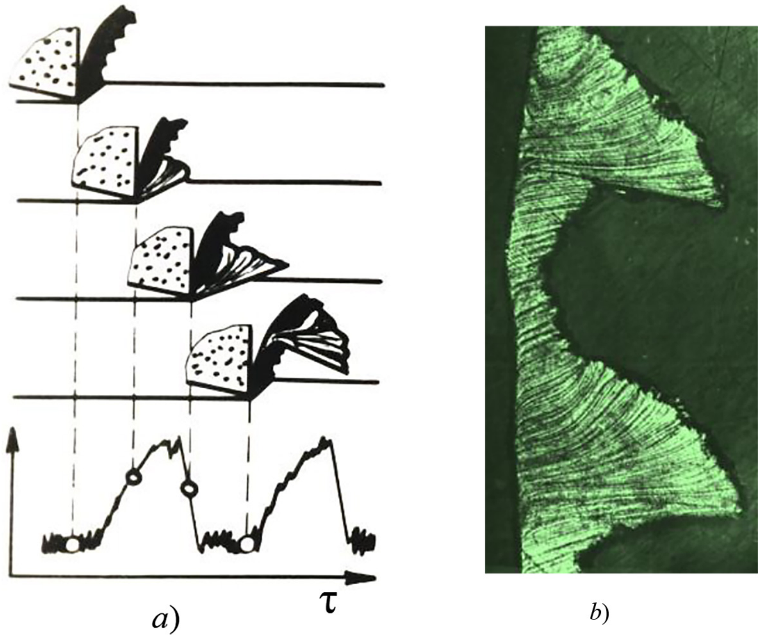


Figure 8. Chip formation with inflows: a – chip formation scheme; b – micro-section of chips (steel AISI 321, v = 0.56 m/s, f = 0.04 mm/rev, a = 0.1 mm)

Table 1. Dependence of the chip type on the interaction of the deformation type and material properties

Chip type	Deformation type			
	Bending		Compression	
	Material		Material	
	Plastic	Brittle	Plastic	Brittle
Fragmented		+		+
Elementary	+		+	
Solid	+			

In this case, either an element chip with a slight deformation of the elements or a solid chip is formed. Changing the feed and depth of cut does not affect the elastic chip properties, therefore, with constant compression and bending ratios, the chip type does not change. However, during cooling, when the feed and cutting depth are reduced, the chip elasticity increases as a result of the intensification of heat transfer with a decrease in its thickness. This also indicates in favor of bending deformation.

The relative motion of the cutting system elements results from the action of external forces. The motion parameters are determined by the interaction of the thermodynamic cutting system with its environment. The work of external forces is essential for achieving the main goal of the cutting process—the directed destruction of the processed material. At the same time, all mechanical energy enters the system through the cutting edge, and the amount of work performed, related to a specific cutting system, determines the durability of the cutting edge and the motion parameters.

Among all the elements of the cutting system, only the cutting edge is subjected to constant loading. Chips are formed from new material volumes coming from the allowance zone, and their stress-strain state changes, with the load on them being temporary in nature.

Therefore, the durability of the cutting system is determined by the wear resistance of the cutting edge. If, due to friction or creep, the cutting edge deforms to the extent that it loses its ability to perform its function, the work of external forces causing this condition can be considered critical. According to the physical principle of reliability, the critical work for a specific system is a constant value. Thus, the operational life of the tool is exhausted regardless of cutting conditions.

Relative movement is associated with friction, which leads to the development of fatigue processes in the surface layers of the tool material and heat generation. The heat produced by friction, along with the heat generated during plastic deformation and the mechanical work of internal forces, increases the level of internal energy in the processed material, bringing it to a critical value.

The interaction of heat and mechanical energy in the cutting zone, which leads to the achievement of the critical energy level, influences the amount of external energy consumed.

CONCLUSIONS

The article presents the results of finite element modeling of the chip formation process during machining of AISI 1045, AISI 321 steels and the study of chips microsections of these steels. Based on the work performed, the following conclusions can be drawn:

1. During the first contact of the blade with the metal, due to the concentration of stresses near its tip, a crack or a zone of increased plasticity is formed there before failure.
2. The volume of metal above this zone perceives compression and bending.
3. The ratio between compression and bending deformations during machining of materials with different mechanical properties affects the formation of different types of chips.
4. When a crack occurs in a brittle material, the formed console can break off during bending or collapse due to compression. This leads to the formation of fragmented chips consisting of particles of different sizes, including dust-like particles.
5. If, when processing a material with elastic-plastic properties, increased plasticity occurs near the tip of the blade, then with increasing pressure from the front surface, the length of the elastic-plastic console increases, which increases the effect of bending and leads to failure not only along the surface of the separation of the allowance and the workpiece, but also along the surface of the plastic hinge, known as the shear surface. An element chip is formed. An element chip can be formed with a variable shrinkage coefficient along its length, which is due to changes in friction on the front surface.
6. Depending on the ratio of compression and bending deformations during processing of materials with elastic-plastic properties, several types of element chips are formed: a) the length of the element approaches zero; b) inside the element the deformation is not significant, and they are displaced relative to each other along the shear surface; c) elements are formed as a result of limiting plastic deformation with subsequent displacement along the shear surface.
7. In the case of processing an elastic-plastic material, when the limiting stresses are created only on the surface of the separation of the allowance and the workpiece during the bending of the console, a solid chip is formed.
8. The considered sequence of processes (elementary actions) leading to the separation of chips from the workpiece allows us to re-imagine the general mechanism of chip formation. Controlling the chip formation mechanism by adjusting the cutting mode parameters and using cooling allows us to improve its transportation, increase the safety of equipment operation and the quality of the machined surface.

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REFERENCES

1. Pedroso, A. F. V., Sebbe, N. P. V., Costa R. D. F. S., Barbosa, M. L. S., Sales-Contini, R. C. M., Silva, F. J. G., Campilho, R. D. S. G., de Jesus, A. M. P. INCONEL alloy machining and tool wear finite element analysis assessment: An extended review. Journal of Manufacturing and Materials Processing. 2024; 8(1), 37. https://doi.org/10.3390/jmmp8010037
2. Qureshi, A., Sorte, M., Teli, S. N. A literature review on optimization of cutting parameters for surface roughness in turning process. International Journal of Engineering Research and Development. 2015;

11(05): 66–69. https://www.ijerd.com/paper/vol11-issue5/Version_2/H1156669.pdf

3. Shaw, M. C. Metal cutting principles. Second Edition. Oxford university press, New York, USA. 2005.
4. Filonenko, S. N. Cutting of metals. Tekhnika, Kyiv, Ukraine. 1975.
5. Panico, M., Boccarusso, L., Formisano, A., Villani, G., Langella, A. An Experimental procedure to study the high-speed orthogonal cutting of unidirectional GFRP. Journal of Manufacturing and Materials Processing. 2024; 8(3). 87. https://doi.org/10.3390/jmmp8030087.
6. Robles, A., Astarloa, A., Llanos, I., Mancisidor, I., Fernandes, M. H., Munoa, J. Comparison of modulation-assisted machining strategies for achieving chip breakage when turning 17-4 PH stainless steel. Journal of Manufacturing and Materials Processing. 2024; 8(4), 167. https://doi.org/10.3390/jmmp8040167
7. Eto, J., Hayasaka, T., Shamoto, E., Xu, L.. Study on extraordinarily high-speed cutting mechanics and its application to dry cutting of aluminum alloys with non-coated carbide tools. Journal of Manufacturing and Materials Processing. 2024; 8(5), 198. https://doi.org/10.3390/jmmp8050198
8. ISO 3685:1993: Tool-life testing with single-point turning tools. https://www.iso.org/standard/9151.html
9. Wang, S.-M., Tsou, W.-S., Huang, J.-W., Chen, S.-E., Wu, C.-C. Development of a method and a smart system for tool critical life real-time monitoring. Journal of Manufacturing and Materials Processing. 2024; 8(5), 194. https://doi.org/10.3390/jmmp8050194
10. Yang, L., Gong, F., Zheng, M., Zhang, X., Xia, J., Liu, X. Visco plastic deformation behavior of S32760 duplex stainless steel during the cutting process. Journal of Manufacturing Processes. 2024; 132: 53–62. https://doi.org/10.1016/j.jmapro.2024.10.069
11. Zhang P., Chen Z., Guo L., Li, C., Lu, S., Sun, J. Machining of Invar 36 alloy: Chip-flow behaviors and formation mechanisms. Journal of Manufacturing Processes. 2024; 132: 477–493. https://doi.org/10.1016/j.jmapro.2024.10.070
12. Black, J. T. Mechanics of Chip Formation. ASM Handbook. Machining. 1989; 16: 7–12. https://doi.org/10.31399/asm.hb.v16.a0002117
13. Monkova, K., Monka, P. P., Sekerakova, A., Hruzik, L., Burecek, A., Urban, M. Comparative study of chip formation in orthogonal and oblique slow-rate machining of EN 16MnCr5 steel. Metals. 2019; 9(6), 698. https://doi.org/10.3390/met9060698
14. Sutter, G., List, G. (2013). Very high speed cutting of Ti-6Al-4V titanium alloy – Change in morphology and mechanism of chip formation. International Journal of Machine Tools and Manufacture. 2013; 66: 37–43. http://doi.org/10.1016/j.ijmachtools.2012.11.004
15. Sivák, P., Delyová, I., Bocko, J. Comparison of stress concentration factors obtained by different methods. Applied Sciences. 2023; 13(24), 13328. https://doi.org/10.3390/app132413328
16. Wahl, A. M., Beeuwkes, R. Stress concentration produced by holes and notches. Journal of Fluids Engineering. 2023; 56(6): 617–623. https://doi.org/10.1115/1.4019833
17. Hardy, S. J., Pipelzadeh, M. K. Stress concentration factors for axial and shear loading applied to short flat bars with projections. The Journal of Strain Analysis for Engineering Design. 1994; 29(2): 93–100. https://doi.org/10.1243/03093247V292093
18. Gogotsi, G. A., Galenko, V. Y. Sensitivity of brittle materials to local stress concentrations on their fracture. Strength of Materials. 2022; 54: 250–255. https://doi.org/10.1007/s11223-022-00398-z
19. Souguir, S., Brochard, L., Sab, K. Stress concentration and instabilities in the atomistic process of brittle failure initiation. International Journal of Fracture. 2020; 224: 235–249, https://link.springer.com/article/10.1007/s10704-020-00459-x
20. Huang, X. B., Chang, X. A study on forming process of chips during cutting cast iron. Advanced Materials Research. 2011; 399–401: 1650–1653. https://doi.org/10.4028/www.scientific.net/AMR.399-401.1650
21. Yang, Y., Li, J. F. Study on mechanism of chip formation during high-speed milling of alloy cast iron. The International Journal of Advanced Manufacturing Technology. 2010; 46: 43–50. https://doi.org/10.1007/s00170-009-2064-1
22. Aslan, A., Gunes, A., Salur, E., Sahin, O. S., Karadag, H. B., Akdemir, A. Mechanical properties and microstructure of composites produced by recycling metal chips. International Journal of Minerals, Metallurgy and Materials. 2018; 25: 1070–1079. https://doi.org/10.1007/s12613-018-1658-8
23. Jose Aecio G. de Sousa, Wisley Falco Sales, Alisson Machado. A review on the machining of cast irons. The International Journal of Advanced Manufacturing Technology. 2018; 94: 4073–4092, https://doi.org/10.1007/s00170-017-1140-1
24. Long, H. V. Plastic-hinge methods for framed structures. LAP Lambert Academic Publishing, India. 2010. https://www.amazon.in/Plastic-Hinge-Methods-Framed-Structures-Hoang/dp/3838389646
25. Hoang, V.-L., Dang, H. N., Jaspart, J.-P., Demonceau, J.-F. An overview of the plastic-hinge analysis of 3D steel frames. Asia Pacific Journal on Computational Engineering. 2015; 2(4): 1–34. https://doi.org/10.1186/s40540-015-0016-9

26. Scott, M. H., Fenves, G. L. Plastic hinge integration methods for force-based beam–column elements. Journal of Structural Engineering. 2006; 132(2): 244–252. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:2(244)
27. Megalooikonomou, K. G., Tastani, S. P., Pantazopoulou, S. J. (2018). Effect of yield penetration on column plastic hinge length. Engineering Structures. 2018; 156: 161–174, https://doi.org/10.1016/j.engstruct.2017.11.003
28. Bouadjadja, S., Tati, A., Sadgui, A. Nonlinear bending analysis of composite cantilever beams. Australian Journal of Basic and Applied Sciences. 2019; 13(7): 28–34. https://doi.10.22587/ajbas.2019.13.7.5
29. Wu, X., Jiao, Y., Chen, Z. An analytical model of a rotating radial cantilever beam considering the coupling between bending, stretching, and torsion. Journal of Vibration and Acoustics. 2021; 144(2): 021004 (12 pp.). https://doi.org/10.1115/1.4051494
30. Hodžić, D. Bending analysis of cantilever beam in finite element method. International journal of engineering. 2021; 19(4): 23–26. https://annals.fih.upt.ro/pdf-full/2021/ANNALS-2021-4-02.pdf
31. Zagórski K. Cutting forces during milling of vertical thin-walled structures of aerospace alloys. Advances in Science and Technology Research Journal. 2025; 19(7): 197–210. https://doi.org/10.12913/22998624/203976