Simulation Research of Machining-Induced Surface Layer Operational Characteristics

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Abstract. The analysis of the rheological model, which formalizes the influence of the main technological factors on the formation of residual stresses and strains in the cutting process, is described in the article. An explanation of the physical phenomena of deformation processes during cutting and comparing theoretical conclusions with simulation studies results are given. The main task, the solution of which is proposed, is the generalization and system analysis of methodological studies of the influence of the technological factors and the cutting tool's geometry on the formation of the stress-strain and thermodynamic state of the surfaces of the workpieces during the cutting. Such problem-oriented modeling results are the basis for predicting the impact of technological process parameters on the formation of product's operational properties. An original scheme for determining the residual strains on top and in the machined surface depth is proposed. The analysis of the influence of technological operation data on residual strain formation was carried out using DEFORM 3D simulation.

Keywords: Functional-oriented process · Residual strain · Simulation study · Finite element analysis · Cutting parameters

1 Introduction

The lifecycle of mechanical engineering products depends on a large number of different factors [1]. Most scientific research usually focuses on the design and operation phases of a product. Undoubtedly, the macrogeometric shape of the part, material, quality of loaded surfaces of structural parts, conditions of their operation, the efficiency of scheduled repair, and service are of great importance for ensuring a machine's reliable and long-term operation or mechanism. However, a large number of properties of an engineering product are also formed at the manufacturing stage (machining and assembly). Additionally, in the process of machining, only the requirements that the designer assigned are met. However, this statement is only partially correct. For example, a given surface quality requirement can be achieved by different machining technologies. However, due to the use of some technologies, residual compressive stresses will appear in the processed layer of the workpiece (as a result of edge-tool cutting), and otherwise, residual tensile stresses appear on the surface layer (if abrasive processing technologies were used). The designer cannot influence the formation of these properties since they result

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from the subsequent design stage of the product manufacturing technology. However, the sign of the residual stresses has a significant impact on ensuring the product's fatigue resistance. There are many examples of the importance of the impact of technological process performance on the operational properties of a machine.

Thus, for a comprehensive increase in the efficiency of the engineering products life cycle, the creation and implementation of scientific and applied foundations for the design of functionally oriented technologies are relevant [2]. The function of the goal in the formation of the optimal data of technological operations is to provide using concurrent engineering a complex of functional and operational properties of the product while observing the parameters of accuracy and quality of surfaces, service life, as well as organizational, technical and economic constraints specified by the designer [3].

2 Literature Review

The section of technological science, "Surface Integrity", is devoted to solving these issues. The most important studies were carried out by such scientists as J. Paulo Davim [3], Fritz Klocke [4], Viktor P. Astakhov [3], Wit Grzesik [5]. There are two aspects of surface integrity: topography characteristics and surface layer characteristics. The topography consists of surface roughness, waviness, shape errors, and imperfections. Characteristics of the surface layer can change during machining: plastic deformation, residual stresses, cracks, hardness, wear resistance, phase transitions, recrystallization, intergranular fracture, and hydrogen embrittlement. In traditional manufacturing processes (such as machining), the surface layer can withstand localized plastic deformation [6].

The chemical composition, mechanical properties, microstructure of the workpiece surface layer primarily affect the workability of the processed materials and thermal state in the cutting zone [7, 8]. Besides, there are intense processes in the chip-forming zone, accompanied by significant differences in force and stress-strain state of the machined layer and are a source of self-oscillations of the tool [9], loss of workpiece stability, various thermal deformation phenomena [10]. All this will affect the formation of the accuracy and other performance properties of the product.

It is known [7] that the cutting tool's forceful action causes the compaction of the crystal lattice of the processed surface layer of the workpiece. A layer of material with increased hardness is formed on the surface as a result of work hardening. However, the thermal state in the cutting zone within the range (0.25–0.30) of the processed material's melting temperature causes the tempering of the deformed metal of the surface layer, and the temperature above 0.4 of the melting temperature causes its recrystallization. A partial decrease in strain hardening accompanies this process. That is, in the process of cutting in the surface layer of the workpiece to be machined, two opposite processes simultaneously occur: strain hardening and thermodynamic softening. The physical state of the machined layer of the workpiece is determined by the ratio of these processes' intensity and velocity.

Furthermore, such a dynamic process's analytical description is extremely complicated and often inadequate [11, 12]. The decrease in the yield stress's actual value can be explained by the dominant influence of the thermal factor, which leads to the softening of the material. An increase in the shear stress of the cut layer can be explained by the fact that a leading strain zone leads to an intensive increase in the dislocation density near the shear zone and, consequently, strengthening the material. This is explained by the fact that the layers of material from the main cutting edge, rounding the edge, and the auxiliary cutting edge are superimposed when they move along the corresponding shear planes. Therefore, there is a "self-locking" of the material layers [7].

The residual stresses imposed in this way from all these factors are diverse and opposite in signs. Establishing the dominant factor and not taking into account others is a difficult task that requires additional experimental research. Besides, in many cases, the actions of all these factors are approximately equivalent and interrelated. Therefore, the possibility of imitating rheological simulation of the cutting processes is the only way to quickly and adequately analyze the influence of cutting technological parameters (e.g., the structure of technological operation, machining parameters, tool coating, selection of an external technological environment) on the formation of residual stresses [13].

Another essential property of the machined layer is a residual strain (mechanical hardening). This deep inhomogeneity of properties is primarily due to the uneven distribution of the deformation accumulated due to cutting. Deformation anisotropy and the associated residual stresses can significantly reduce the product's strength when it is not subject to further heat treatment. In other cases, the machined layer's hardening has a positive effect on the wear resistance, as soon as an increase in corrosion resistance. A negative consequence of this phenomenon is a reduced oil-holding property of the surface layer, which is especially important for high-speed moving joints' efficiency. The calculation of residual stresses is performed according to the unloading theorem [14], according to which the residual stresses after plastic deformation are equal to the difference in stresses during plastic deformation and the so-called unloading stresses, which the material is deprived of during unloading. If during unloading, purely elastic deformations occur, then the unloading stress can be determined using the theory of elasticity [15]. The hardening of the surface layer of the machined surfaces is characterized by its microhardness and X-ray characteristics (expansion or blurring of interference lines), which is a consequence of the fragmentation of crystal blocks, an increase in crystal lattice distortions, and the development of dislocations. In the cutting process, the hardening of the surface layer increases with an increase in feed and depth of cut due to an increase in the cutting edge rounding and the transition from positive rake angles of the cutter to negative [16].

3 Research Methodology

The given research's primary purpose is to assess the mutual influence of the main technological parameters (cutting modes) on the formation of residual stresses and strains during the cutting process with an edge tool. The influence of cutting parameters on the formation of stress-strain state (including the residual) is usually presented in the form of statistic equations [17], based on conducting experiments using one- or multifactor experiments. Therefore, the main task, the solution of which is proposed in this article, is the generalization and system analysis of methodological studies of the influence of force, thermal factors and parameters of the tool geometry on the stress-strain and thermal state of the workpiece surfaces during the cutting process. The analysis of such problem-oriented modeling is the basis for building predictive models of the technological process parameters' effect on the formation of product's operational properties.

The machined surface layer's mechanical state has mainly resulted from the after-effect of elastic-plastic strains, which occurs in the cutting zone, thermal exposure, and chemical reactions of the machined material with the cutting tool material and with the external technological environment (including coolant and lubricant). When the tool is cut-in into the metal being processed, the wave of plastic deformation, propagating in front of the tool's cutting edge, covers the chips and the metal located along the cut line. Therefore, machined material at the cutting edge itself is subjected to the normal force and the friction force acting in the shear line's direction. The normal force causes the compressive stress, and the friction force induces tensile stresses of the surface layer adjacent to the tool's flank face (Fig. 1). The surface layer of the part is subject to inhomogeneous plastic strain, monotonically damping, and cutting depth [13].

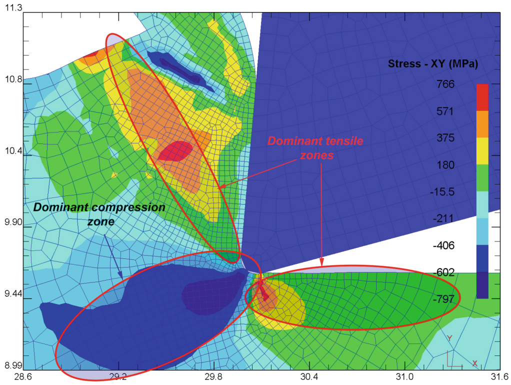

Fig. 1. Simulation pattern of residual stresses causal factors as interference of the compression and tension phenomena in the cutting zone.

Another reason for the occurrence of residual stresses is the thermal deep processes analysis [13]. The outer layer of the workpiece, heating up during the cutting process, tends to linear expansion. However, this is prevented by the cold inner layer, which is compressed. With intense heating, the current stresses on the surface exceed the yield stress, which causes plastic compression strain of the outer metal layer. The outer layer shrinks to a size less than the original by the value same as additional compression strain during subsequent cooling. This will be blocked by the stressed workpiece inner layer (Fig. 1). Therefore, either the mechanical factor can be dominant, and then the macrostress of compression prevails on the processed surface; or the heat factor, and then tensile stresses on the surface will become superior. However, this sequence will be violated if the cutting process is accompanied by significant phase transformations that are significant in intensity and depth. This phenomenon is sometimes a stronger source of stress formation in surface layers than mechanical and thermal factors.

The disadvantage of analytical modeling of the macrostress formation process is conventionality in the differentiated analysis of the influence of mechanical or temperature indicators, dependence on experimentally obtained correction factors, and the fact that it does not consider the force acting on the machined layer. This relativism does not correspond to the actual process of the temporary or residual stresses appearance. Until now, the only way of analysis was considered by the methods of experimental research: X-ray, experimental-mechanical, and the method of measuring microhardness [18]. The problem-oriented analysis of the corresponding simulation rheological modeling results will comprehensively and adequately assess the picture of the mutual influence of the force, mechanical and metallographic factors. This will contribute to implementing the optimal structure and parameters of the technological processing operation to minimize residual stress and strain.

One of the effective tools for the operational study of local characteristics of the stress-strain state in the chip's formation zone is the finite element analyses implemented in such well-known software products as DEFORM, ABAQUS, LS DYNA, AdvantEdge. These software products allow accurately calculating the cutting forces, chip thickness ratio, configuration, and area of the contact surface of the workpiece with the tool and the boundaries of the plastic zone, to make the distribution of force and deformation, obtain strain rates, and temperatures in the machined zone and the tool [2].

4 Results

The results of microhardness studies prove the presence of residual stresses and plastic deformations. The thin surface layer of machine parts has various mechanical, physical, chemical properties and stress than in the deep of the part. As noted above, the difference in the properties along the depth of the part is caused by a defect of mechanical, thermal, and physicochemical factors of different intensity and is obtained as a result of power and thermodynamic machining processes. This contributes to an increase in the free energy of the surface, increasing its adsorption activity and other changes that significantly impact the performance of the machined products [17].

The plastic strain must be accompanied by structural changes in the material of the machined layer. The number of dislocations, vacancies, and other defects in the crystal lattice increases sharply. During cutting, plastic deformation occurs, accompanied by fragmentation and drawing of crystal grains in the direction of deformation (texture formation), the curvature of sliding planes, and the appearance of fragments of crystal grains, the emergence of intercrystalline stresses. Besides, when processing plastic metals, the subsurface layer is deformed not only due to the force field of the rake face but also simultaneously deformed under the action of flowing chips. Due to the intensity of plastic strain of the metal chips is much higher than the intensity of deformation of the metal under the shear surface, the deformed particles under the influence of the upper layer of metal going into the chips are further stretched in the direction of chip's moving at the angle greater than 45°. This increases the specific volume of the metal and decreases its density, increases the strength, hardness, and brittleness, decreases ductility and viscosity, changes the magnetic and some other properties of the metal.

The cutting speed and feed have the most significant influence on the deformation of the surface layer because these parameters of the cutting mode determine mainly the mechanical and thermal effects on the metal. As the cutting speed increases, the strain rates and the heating temperature increase, but the duration of stresses and the heating time of the surface layer of the workpiece decrease. Increasing heating of the deformed metal with increasing cutting speed increases the diffusion mobility of atoms, activates the softening processes due to recrystallization, reducing the intensity of deformation hardening of the surface layer. If the strain rate exceeds the recrystallization rate, only partial removal of the strain hardening is observed, despite the deformation will occur at a temperature exceeding the recrystallization temperature. The simulated rheological studies of technological transitions of machining of parts from the most representative machinery materials show that with increasing cutting speed, the thermal effect on the deformed metal of the surface layer increases and hardness decreases.

Compared with other parameters of the cutting parameters, the feed rate has the most significant effect on the deformation hardening of the surface layer. The values of the depth and hardening depending on the feed have extremes, i.e., there is an optimal feed, in which this hardening is the least important. The optimal feed for heat-resistant alloys is about 0.10–0.15 mm/rev. The increase in strain hardening with decreasing feed outside the optimal feed values is explained by the influence of the sliding process of the cutting edge, which creates additional deformation of the surface layer. The force load and the heating temperature of the metal in the cutting zone determine the nature of these dependencies. The feed has the most critical effect on the force acting on the surface layer. With an increase in cutting depth in turning, planning, and drawing, the main parameters of deformation hardening are increased. The rake angle of the tool cutter also affects the conditions of chip formation, which determine the formation of the surface layer. For example, when turning a NiCr20TiAl alloy with a change in the rake angle from +15° to –15°, the depth of hardening increases 3 times, which is associated with an increase in the resistance of the chips on the rake face of the cutter.

Rheological simulation of the heat-resistant alloy IN 718 turning, determined based on the analysis of the simulation model in Deform 2D, showed a decrease of the hardness by 55% compared with the processing of steel AISI 1045 in cutting parameters – feed $S = 0.25$ mm; cutting depth t = 1 mm; cutting speed V = 120 mm/min. The reduction of hardness, in this case, can help increase the strength and decrease the plastic properties of alloys and significantly reduce the coefficient of friction on the flank face of the cutter.

It is known [3] that the degree of hardening is defined as the ratio of the initial H_0 and the newly created (after machining) H hardness of the workpiece to its initial value:

$$N = \frac{H - H_0}{H_0}, \tag{1}$$

when turning heat-resistant alloys, the degree of hardening can be calculated according to the empirical equation [19]:

$$N = 40\,hT_0^{-0,72}, \tag{2}$$

where h is the depth of hardening, which is determined by the results of rheological simulation of machining, μm; T_0 - the temperature in the cutting zone when working with a carbide tool, which can also be determined by the results of rheological simulation.

Plastic strain and hardening of the surface layer of the metal occur in oppositely oriented grains of different compositions with different intensities; at that, ferrite grains are deformed more intensely than pearlitic. This causes an uneven increase in energy and various changes in the electrode potential. During turning, more hardened ferrite grains and martensitic domains become anodes, less hardened pearlite grains are cathodes. For the same reasons, the distortion of atomic lattices in different crystal grains is different.

Hardening of the machined surface layer in most cases is harmful and reduces the performance of machine parts. Consequently, after the plastic deformation of the surface layer metal at room temperature, its specific volume increases, and the density decreases, promoting faster diffusion processes at high temperatures and thus accelerating the processes that reduce the resistance of the metal to dynamic destruction. Prolonged exposure to high temperatures on the hardened metal quickly leads to its intensive softening, which reduces the overall performance of the parts. The microhardness of the metal surface layer is responsible after its operation at high operating temperatures. Reducing the density of hardened metal facilitates the process of burning alloying elements of heat-resistant alloys, which leads to a decrease in the strength of alloys. A sign of burnout of alloying elements may be a change in the crystal lattice parameter of the heat-resistant alloys. With increasing degree and depth of hardening of heat-resistant alloys, their fatigue strength when working in an environment with high temperatures decreases significantly. Thus, at a hardening depth of 190 μm, which occurs during rough turning, the number of cycles before the destruction of the alloy at 700 °C is approximately twice lower than after electropolishing, which does not cause hardening [4].

Scheme for determining residual strains on the basis of a 2D model of milling a workpiece made of steel AISI-N-13 by the CoroMill 300 cutter with a R300-1032E-PL S30T insert $\gamma = 8°$, $\alpha = 15°$ (S = 0.1 mm; t = 0.25 mm; V = 120 m/min) is shown in Fig. 2. The total path of the tool along the length of the machined part of the part is separated into 22 ranges, and along with the depth - into 10 measurement ranges in order to analyze the dynamics of attenuation and studying the residual component of the stress-strain state as the aftereffect of the machining process.

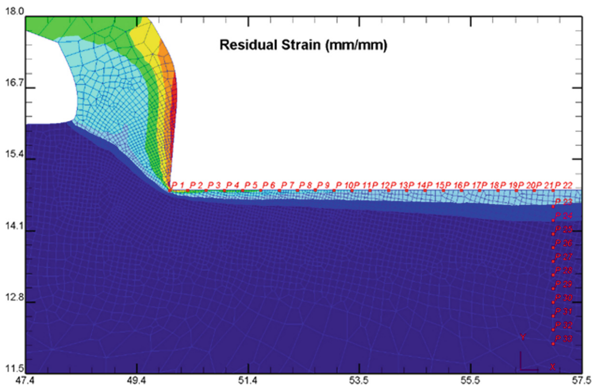

Fig. 2. Scheme for determining residual strains on the basis of a 2D model of milling a workpiece made of AISI-N-13 by the CoroMill 300 cutter with a R300-1032E-PL S30T insert $\gamma = 8°$, $\alpha = 15°$ (S = 0.1 mm; t = 0.25 mm; V = 120 m/min).

The pattern of residual strains rheological simulation during milling a workpiece (material is alloyed steel X40CrMoV5) by the CoroMill 300 cutter with the R300-1032E-PL S30T insert ($\gamma = 8°$, $\alpha = 15°$; S = 0.1 mm; t = 0.25 mm; V = 120 m/min) is shown in Fig. 3. As a result of thermal relaxation with increasing distance from the head of the cutting wedge, these deformations exponentially decrease to some steady-state value in the zone of thermal deformation stabilization. It is this value that is the residual strain. The curve of residual strains (Fig. 3) shows the interference pattern of the fluctuations in thermal, load, and frictional processes arising in the cutting process. The average statistical value of residual strain in the zone of thermal stabilization (at a temperature of about 100 °C) will be approximately $\varepsilon \approx 2.5$ (mm/mm).

The method for determining the depth of residual strains is similar, but the test points for measuring deformations are not located along the length of the processed surface but into the deep (Fig. 2). The modeling of the depth pattern should also be done in the zone of thermal stabilization of the machined surface. The simulation results are shown in Fig. 4.

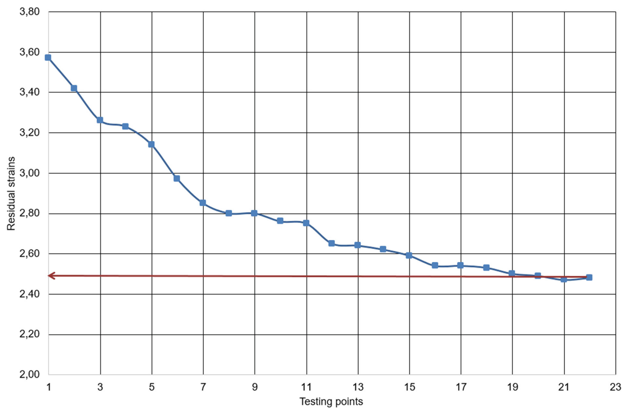

Fig. 3. Graph of surface residual strains obtained as a result of rheological simulation of milling a workpiece made of X40CrMoV5 (S = 0.1 mm; t = 0.25 mm; V = 120 m/min).

The presence of local traces of residual strains during the machining of plastic materials (for example, titanium alloys) is due to the complex nature of the dynamic load on the tool (Fig. 5). The sinusoidal and dissonant character of the longitudinal and transverse component of the cutting force causes local hardening zones of the surface layer's material and local softening zones. The most representative of this can be seen from modeling in Deform 3D (Fig. 6). The presence of alternating hardness zones significantly reduces the fatigue strength of the surface and the corrosion resistance of the machine part. Therefore, an essential step in assigning cutting parameters for such alloys is to reduce the dynamic component of the force action. The general recommendations of such a study are presented in [13].

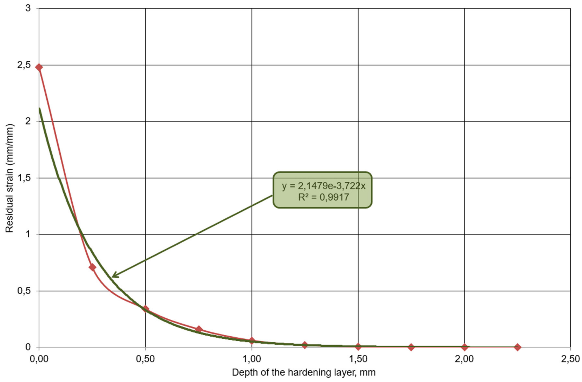

Fig. 4. Graph of residual strains into the deep obtained results from rheological simulation of milling a workpiece made of X40CrMoV5 (S = 0.1 mm; t = 0.25 mm; V = 120 m/min).

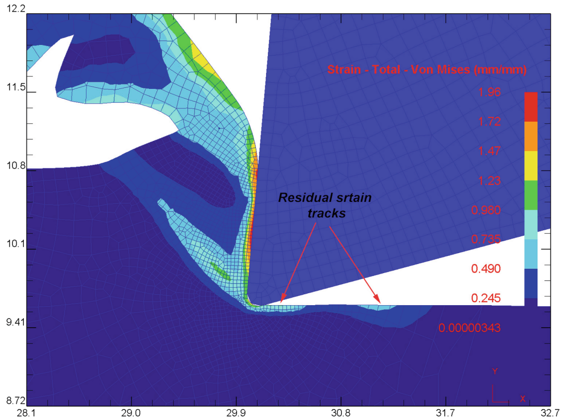

Fig. 5. Local traces of residual strains during the machining of titanium alloy Ti6Al4V.

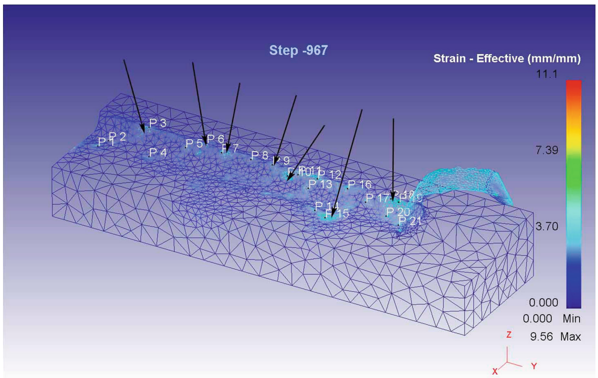

Fig. 6. Local traces of residual strains simulated in Deform 3D.

The analysis of the adequacy of modeling was carried out due to comparison with the results of experimental studies. Such comparative results were carried out using the method of measuring the microhardness of the surface layer before and after machining (Fig. 7). The analysis of the research results showed the comparability of the surface hardening value obtained from modeling and experimental research within 6–8%.

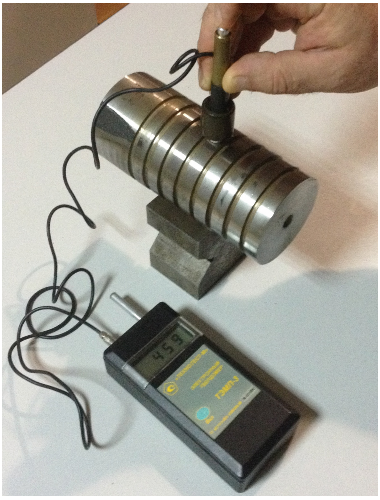

Fig. 7. Experimental study of the machined surface layer microhardness of the alloyed steel workpiece (X40CrMoV5).

5 Conclusions

Analysis of the influence of the technological operations data such as cutting parameters, tool's material, and the geometry of the cutting wedge on the residual strains, carried out based on rheological simulation in Deform 2D and 3D, allowed us to make the following conclusions.

Analysis of graphics (Figs. 3, 4) proves the exponential nature of the reduction of residual strains: if on the top of machined surface this value was $\varepsilon \approx 2.5$ (mm/mm), then for the depth of 0.25 mm, it is already $\varepsilon \approx 0.7$, and for the depth of 1.0 mm, the cutting-induced strain almost completely disappears and is only $\varepsilon \approx 0.06$ (mm/mm). The qualitative and quantitative nature of the distribution of strains proves the adequacy and effectiveness of the used methods for the formation of the analytical base in the functionally oriented technological process planning.

The influence of the cutting speed is declared, first, in the change in the duration of the thermal contact and force impact between the flowing chips, the treated surface, and the tool's cutting edge. Increasing the cutting speed contributes to the emergence of additional tensile strain, which increases the total residual tensile stress. When processing low-carbon steels (for example - AISI 1020), the increase in heat in the cutting zone, associated with increasing the cutting speed, can harden the surface layer. The increase in the specific volume of the metal of the surface layer during its hardening leads to a decrease in residual tensile stresses formed at low speeds (V = 40–80 m/min) and their conversion into compressive stresses during machining at high cutting speeds (V > 100 m/min). Besides, when processing plastic metals, the subsurface layer is deformed not only under the influence of the force field of the cutter's rake face but also deformed under the influence of the flowing chips. Since the intensity of plastic strain of the metal chips is much higher than the intensity of deformation of the metal under the shear surface, the deformed particles under the influence of the upper layer of metal going into the chips are further stretched in the direction of chip's moving at the angle greater than 45°. This increases the specific volume of the metal and decreases its density, increases the strength, hardness, and brittleness, decreases ductility and viscosity, changes the magnetic and some other properties of the metal.

The presence of local traces of residual strains during the machining of plastic materials (for example, titanium alloys) is due to the complex nature of the dynamic load on the tool. The sinusoidal and dissonant character of the longitudinal and transverse component of the cutting force causes local hardening zones of the surface layer's material and local softening zones. The presence of alternating hardness zones significantly reduces the fatigue strength of the surface and the corrosion resistance of the machine part. Therefore, an essential step in assigning cutting parameters for such alloys is to reduce the dynamic component of the force action.

When processing carbon steels (for example, AISI 1045) and low-alloy steels (34CrNiMo6), increasing the heating of the surface layer by increasing the cutting speed above 120 m/min can cause the material's tempering. As a result, there are changes in the material structure associated with a decrease in the specific volume of the metal, which leads to a decrease in residual compressive stresses. Increased feed rate during the processing of hard-to-cut steels and alloys (for example, IN718), in which residual tensile stress is formed, leads to an increase in the plastic strain of the surface layer and a corresponding increase in residual tensile stresses. This leads to a significant reduction in the fatigue strength of the machined surface. Rheological simulation of the heat-resistant alloy IN 718 turning, determined based on the analysis of the simulation model in Deform 2D, showed a decrease of the hardness by 55% compared with the processing of steel AISI 1045 in cutting parameters - feed S = 0.25 mm; cutting depth t = 1 mm; cutting speed V = 120 mm/min. The reduction of hardness, in this case, can help increase the strength and decrease the plastic properties of alloys and significantly reduce the coefficient of friction on the flank face of the cutter.

References

1. Krueger, C.W.: Mechanical product lifecycle management meets product line engineering. In: Proceedings of the 19th International Conference on Software Product Line, vol. 1, pp. 316–320. Association for Computing Machinery, New York (2015)
2. Palagin, A.V.: Functionally oriented approach in research-related design. Cybern. Syst. Anal. **53**(6), 986–992 (2017). https://doi.org/10.1007/s10559-017-0001-0
3. Davim, J.P.: Surface Integrity in Machining. Springer, London (2010)

4. Klocke, F., Harst, S., Ehle, L., Zeis, M., Klink, A.: Surface integrity in electrochemical machining processes: an analysis on material modifications occurring during electrochemical machining. Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf. **4**(232), 578–585 (2018)
5. Grzesik, W., Żak, K.: Characterization of surface integrity produced by sequential dry hard turning and ball burnishing operations. J. Manuf. Sci. Eng. **136**(3), 031017 (2014)
6. Degarmo, E.P., Black, J.T., Kohser, R.A.: Materials and Processes in Manufacturing, 9th edn. Wiley, Hoboken (2003)
7. Klocke, F.: Manufacturing Processes 1: Cutting. Springer, Heidelberg (2011). https://doi.org/10.1007/978-3-642-11979-8
8. Klocke, F.: Manufacturing Processes 4: Forming. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-36772-4
9. Astashev, V.K., Korendyasev, G.K.: Thermomechanical model of cutter self-oscillation in perpendicular free cutting. J. Mach. Manuf. Reliab. **41**, 435–440 (2012)
10. Abukhshim, N.A., Mativenga, P.T., Sheikh, M.A.: Heat generation and temperature prediction in metal cutting: A review and implications for high speed machining. Int. J. Mach. Tools Manuf. **46**(7–8), 782–800 (2006)
11. Gygax, P.E.: Cutting dynamics and process-structure interactions applied to milling. Wear **62**(1), 161–184 (1980)
12. Czán, A., Šajgalík, M., Martikáň, A., Mrázik, J.: Dynamic process analysis in cutting zone during machining of nickel alloys. Technol. Eng. **12**(1), 15–20 (2015)
13. Stupnytskyy, V., Hrytsay, I.: Simulation study of cutting-induced residual stress. In: Ivanov, V., et al. (eds.) DSMIE 2019. LNME, pp. 341–350. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-22365-6_34
14. Eraslan, A.N., Apatay, T.: Analytical solution to thermal loading and unloading of a cylinder subjected to periodic surface heating. J. Therm. Stresses **39**(8), 928–941 (2016)
15. Perez, N.: Theory of elasticity. In: Perez, N. (ed.) Fracture Mechanics. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-24999-5_1
16. Shen, Q., Liu, Z., Hua, Y., Zhao, J., Mohsan, A.W.: Effects of cutting edge microgeometry on residual stress in orthogonal cutting of Inconel 718 by FEM. Materials **11**(6), 1015 (2018)
17. Stupnytskyy, V., Hrytsay, I.: Comprehensive analysis of the product's operational properties formation considering machining technology. Arch. Mech. Eng. **67**(2), 149–167 (2020)
18. Montanari, R., Fava, A., Barbieri, G.: Experimental techniques to investigate residual stress in joints. In: Residual Stress Analysis on Welded Joints by Means of Numerical Simulation and Experiments (2018).
19. Silin, S.: Similarity Methods in Metal Cutting. Mechanical Engineering, Moscow (1979)