www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVE OF MECHANICAL ENGINEERING

DOI: 10.24425/ame.2025.153733 2025, Vol. 72, No. 1, pp. 131–152

Vadym STUPNYTSKYY[1], Oleh PRODANCHUK[1], Oleksandr DYSHEV[1]

Analyzing the use of rigid- or elastic-plastic finite models for the simulating of cutting processes

Received 27 December 2023, **Revised** 21 December 2024, **Accepted** 9 January 2025, **Published online** 3 February 2025

Keywords: finite element analysis, software, rigid-plastic model, elasto-plastic model, simulation, cutting, residual stress, Deform 2D, acoustic elasticity

The simulation modeling of cutting processes represents a powerful scientific instrument for investigating stress-strain and thermodynamic processes in machined materials. Nevertheless, the principal obstacle to the extensive deployment of this scientific approach is inadequate precision of the resulting research outcomes. This is due to the complexity of formalizing the physical and mechanical forming pattern, considering all the dominant factors in building a high-quality cutting model. Additionally, there is a need for professional experience from the researcher to correctly describe the physical model of the material, as well as a logical selection of fracture criteria, among other factors. One of the most significant challenges in ensuring the accuracy of cutting modeling processes is formalization of the description of a rigid-plastic or elasto-plastic FEA model for analyzing the behavior of materials during machining. The article presents a scientifically based argument for the practicality of using these techniques in simulation modeling systems. It also provides practical recommendations for researchers on constructing an accurate FEA simulation model in DEFORM 2D. The conclusions drawn from the analysis of simulation studies of cutting-induced residual stresses for heterogeneous materials are confirmed by experimental investigations.

1. Introduction

The rapid advancement of mechanical engineering and the advent of innovative tool materials and machining technologies have underscored the imperative for the expeditious development of scientifically founded solutions applicabie to

✉ Vadym STUPNYTSKYY, e-mail: Vadym.Stupnytskyi@lpnu.ua

[1]Lviv Polytechnic National University, Lviv, Ukraine

machining parameters, tooling, and the selection of the most optimal process environment (lubricating and cooling liquids, etc.). The economic, technical, and organizational efficiency of the structure and parameters of the machining operation can be achieved only as a result of analyzing the influence of these factors on the formation of the thermodynamic and stress-strain state of the workpiece (including the formation of a zone of tensile or compressive residual stresses) [1–3]. Furthermore, the necessity for such a comprehensive analysis arises when the workpiece is subjected to significant loads during its operation as part of a machine or mechanism. Consequently, the principles of functionally oriented technologies should be employed to select the structure and parameters of machining products subjected to high-intensity power, dynamic, or temperature loads in the future. This methodology is founded upon the primacy of effective operational properties of the product rather than the cost of its machining.

Analytical models of the machining process can provide sufficiently thorough results on the workpiece's stress-strain, force, and thermodynamic behavior. However, it is practically impossible to consider many factors and their priority in forming the parameters of accuracy and quality of the surface layer. In this case, simulation research is the most effective option. However, summarizing the experience of using such a software as Deform 2/3D, Abaqus, LSDyna, and AdvantEdge [5, 6], one can conclude that the main disadvantages of using such research methods are as follows:

- first, the insufficient adequacy of the simulation results, which can reach 30% or more [7, 8];
- secondly, the modeling process need a high labor intensity, where tenths of a second of the cutting process requires several hours of modeling software operation;
- thirdly, creating an adequate mathematical model requires professional experience from the researcher for a correct description of the physical model of the material, logical selection of fracture criteria, applying the most effective mathematical research methods, selection of the finite element method, etc.

Regarding these problems, the following counterarguments can be given regarding the advisability of using simulation modeling as an effective means of researching machining processes.

First of all, the continuous improvement of the mathematical technique, the detailed description of the physical and mechanical properties of the machined and tool models of materials, and especially the adaptation of the classical orthogonal cutting model to the simulation of complex machining and the prediction of combined thermo-mechanical phenomena gives optimism in the approximation of the obtained theoretical and accurate cutting parameters. It is known that researchers in contemporary companies have learned how to adapt modeling results to parameters obtained in actual production conditions. At the same time, they use the corrected models to implement innovative cutting conditions, the latest tool materials, machining modes, etc., relying primarily on the adequacy and versatility of qualitative cutting patterns!

Secondly, the intensive development of computer technology almost eliminates the problem of the duration of calculation processes. That is, if ten years ago it took 10–15 hours of computer work to solve a similar problem, now it takes 1–2 hours, and in another 5–7 years, such studies will require minutes of calculations, and eventually this task will be carried out in "real-time" mode.

Thirdly, continuous improvement of the interface for existing simulation softwares, such as Deform 2/3D, Abaqus, LSDyna and AdvantEdge [1, 2, 9], greatly simplifies and automates the process of inputting data, selecting optimal mathematical procedures based on the analysis of the efficiency of previous calculations, taking into account critical errors in the formation of degenerate FEM meshes, discretization of dynamic processes, significant expansion of the database of the most common materials in industry, their physical and mechanical properties, introduction of an intuitive algorithm for interpreting research results, their quality, etc. On the one hand, this reduces the time needed for researchers to master the software product; on the other hand, it significantly reduces the probability of errors or imperfections made by the designer both at the data input stage and at the stage of interpretation of research results.

Accurately describing the rigid-plastic or elastic-plastic model of material behavior during machining represents a significant challenge in ensuring the adequacy of finite element analysis of cutting processes. The reason for the research community's interest in this subject is the necessity to address the myriad challenges associated with the deformation of machined materials, particularly within the chip formation zone and the post-processing zone. It should be noted that the solution of specific problems of simulation analysis may be achieved through a rigid-plastic model (e.g., for force and thermo-deformation studies). In contrast, other studies require only elastic-plastic modeling (e.g., residual stresses and deformation analysis). Furthermore, mechanical and physical properties of the workpiece material have a considerable impact on the discrepancy observed in simulation studies when utilizing these models. Regrettably, a comprehensive and systematic analysis of the nature of these processes is scarce in the current scientific literature. Nevertheless, findings of this study may prove valuable to both experienced researchers who have been utilizing cutting process simulation programs for a long time and the engineers who are just beginning to employ such a software. This article is dedicated to solving this problem.

2. Literature review of the application of methods for studying rigid- and elasto-plastic material flow behavior

The machined surface's high-speed forming is characterized by several features, including high metal deformation rates and accelerations, a brief process duration, significant plastic deformation, high deformation intensity, and the presence of residual stresses. The deformation of the workpiece material primarily depends upon the physical and mechanical properties of the metal undergoing deformation at the appropriate temperature and speed conditions, as well as the amount of energy transferred to the workpiece during cutting. Furthermore, the brief interaction of the deformed metal with the cutting tool gives rise to inertial forces within the metal, which, in turn, result in additional dynamic loads. The zones of primary, secondary, and tertiary plastic deformation are formed. Concurrently, the propagation of deformations in the cutting zone is impeded by inertial forces, which consequently diminish or localize the areas of plastic deformation. When the workpiece interacts with the front and rear surfaces of the cutting tool, a braking effect is exerted, resulting in the formation of additional zones of plastic deformation. Concurrently, the existence of elastic deformations within the "Machine-Tool-Workpiece" system gives rise to relaxation phenomena, which are a consequence of the dynamics of thermal effects, fluctuations in the components of the cutting force, and alterations in the mechanical properties of metals [10–12]. The intricate nature of the formalized description of the processes occurring during high-speed shaping of the machined surface precludes the possibility of achieving sufficient accuracy in the application of analytical methods for the resolution of metal flow problems based on the joint solution of equilibrium equations with the condition of plasticity and elasticity of the material. Consequently, the mechanic's theory of deformable solids cannot provide an analytical description of the elasto-plastic flow pattern, determine the velocity of metal particles, or take into account the effects of inertia and thermal deformation during cutting [13–16].

Assuming that we define the motion of the material in Euler's variables, the measure of total deformation is the Eulerian-Almansi finite strain tensor A_{ij}, which, according to the Finite Strain Theory [13], coincides with the elastic (reversible) strain tensor ε_{ij}. In other words, to describe the equation of state of a material deformed during cutting, it is necessary to specify the internal energy as a function of entropy and tensor ε_{ij}. These relations must be supplemented by energy conservation laws [17], and the initial and boundary conditions and cutting modes must be formulated. Only then can the resulting system of equations be considered closed, thereby enabling the description of the thermomechanical flow of the material within the model of an elastic continuum.

When developing a model of the elasto-plastic strain of a workpiece during cutting, it is necessary to expand the number of description parameters significantly. In this case, dividing the Almansi strain tensor A_{ij} into separate tensors of elastic ε_{ij} (reversible) deformation and plastic π_{ij} (irreversible) deformation becomes necessary. In this case, to describe the parameters ε_{ij} and π_{ij}, taking into account their thermodynamic changes, it is required to set the relations that determine the relationship of these tensors with other kinematic and dynamic characteristics of the cutting model. The construction of the specific dependence of A_{ij} on ε_{ij} and π_{ij} is defined by the researchers as based on the formalization of nonequilibrium thermodynamics, which can be written by means of the equation of state of the material through two experimentally measured independent functions - internal energy and dissipative potential. Under the assumption of additive dependence of the Almansi tensor on the elastic and plastic deformation tensor, this approach was implemented in [18] to generate a class of models of elasto-plastic materials at arbitrary total strains.

The possibility of using different plastic or elasto-plastic cutting models exists only for some software products used in FEA simulation cutting systems. The DEFORM 2D/3D software can most fully evaluate these models.

3. Features of formalizing the rigid-plastic and elasto-plastic cutting model in DEFORM 2D software

DEFORM is a finite element modeling system that analyzes metal's two-dimensional (2D version) and three-dimensional (3D version) behavior during various machining processes. The advantages of this software are its versatility, compatibility with most software packages for creating geometric models and generating a finite element mesh, availability of a wide database with physical and mechanical characteristics of tool and structural materials; the ability to model various friction conditions between the workpiece and the tool; the possibility to implement cutting schemes with complex forming tool movements, as well as the provision of a convenient and helpful interface [19]. In addition, a significant advantage of this software package is the option of using different models of material plasticity to solve various research problems.

The DEFORM material database contains data on the yield strength during cutting for more than 200 of the most commonly used structural materials in mechanical engineering. It should be noted that the data about these parameters are highly variable, especially those concerning the heat and effective strain of the workpiece material that occurs in the chip-forming zone.

Furthermore, suppose the material modeling conditions exceed the strain, strain rate, or temperature parameters delineated in the tabular data. In that case, the program will extrapolate these parameters based on the two most recent data points. However, using a program-specific algorithm to address the convergence issue in calculation results may reduce the simulation's accuracy. Nevertheless, as the data regarding the actual material flow stresses is accessible as a data table (as illustrated in Fig. 1), the customer can transform these parameters into equations representing an approximate model using the integrated Conversion utility. Moreover, the selected material can be adapted to the model parameters according to the points in the data table using the curve fitting technique (Fig. 2). Subsequently, both forms of data are displayed for further analysis and manipulation. The system suggests using the solid-type lines on the graph as the original data and the dashed-type lines as the extrapolated data calculated based on the selected model parameters and the machined material.

After the user accepts the conversion, the transformed model data replaces the original table data. Deform 2D has a particular utility that allows importing several

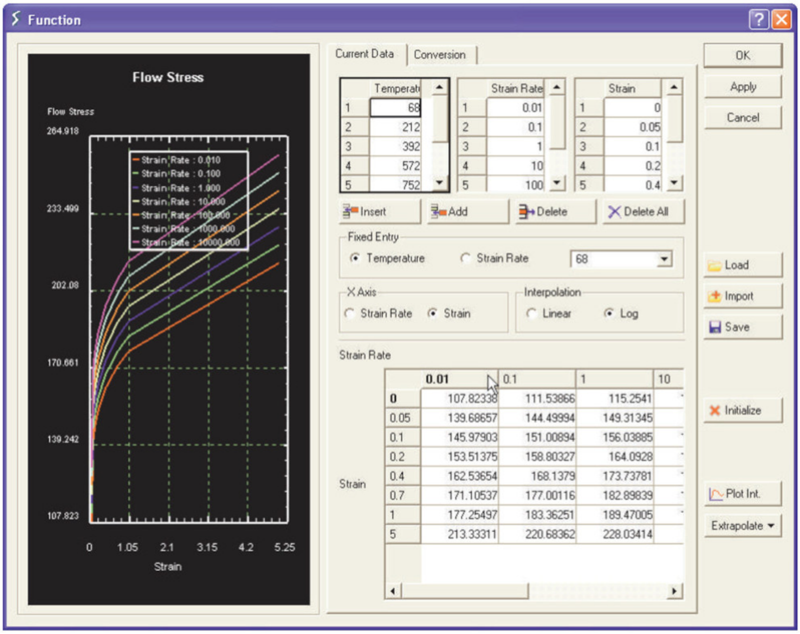


Fig. 1. Material flow stress data in table form in temperature, strain rate, and strain dimensions

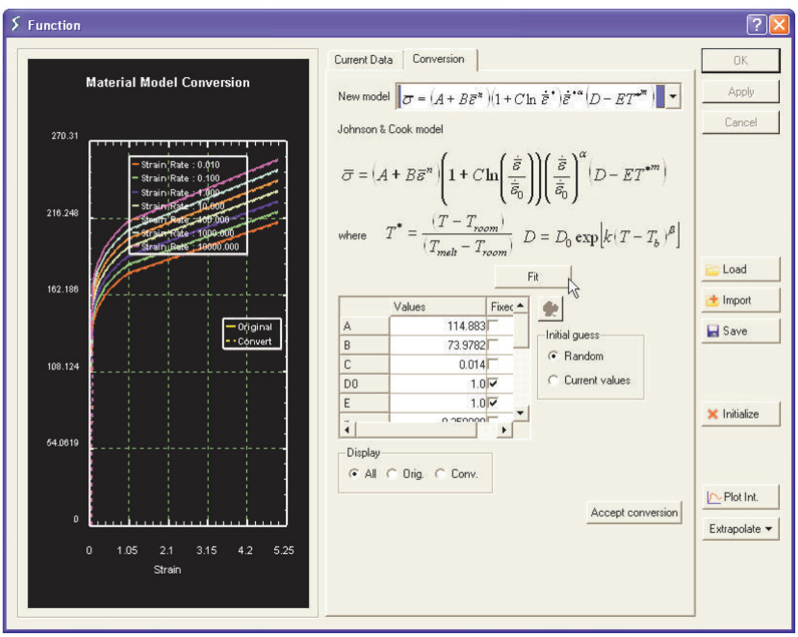


Fig. 2. Results from material model data conversion

files of measured flow stresses, each set at a specific temperature and strain rate, as shown in Fig. 3.

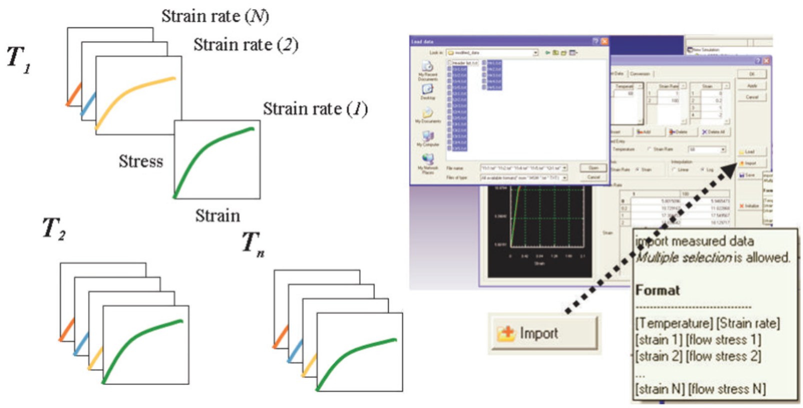


Fig. 3. Utilities to upload the measured flow stress data into DEFORM 2D [19]

DEFORM implements several types of priority descriptions of the material state of the tool and workpiece during the cutting process. These are the rigid, plastic, or elasto-plastic states, which are defined by the objects of the study. The analysis of each of these states significantly changes the cutting pattern and the behavior of the tool-workpiece technological system. Before describing the features of modeling such systems, it is necessary to briefly describe the characteristics of the objects of study in different initial states.

Rigid objects are modeled as ideally non-deformable materials. In deformation analysis, the geometry of an object is represented by a geometric profile (DIEGEO) [19]. As a rule, the cutting tools are assumed to be rigid only if the main object of the study is a workpiece. In such a case, tool deformation and stress parameters are not analyzed by the system, which, on the one hand, simplifies the overall model and speeds up the calculation process but, on the other hand, deprives the user of analyzing the tool condition. Moreover, the adequacy of the tool wear model (Usui or Archard) built into DEFORM is questionable and needs to be corrected [20]. The geometric profile of the tool is unchanged throughout the deformation analysis, and the mesh for rigid objects is used only for all thermal, transformational, and diffusion calculations.

Plastic objects in cutting simulation are classified as rigid-plastic or rigid-viscoplastic models according to the machined materials' behavior. The stress for the purely plastic state of the workpiece material increases linearly with the strain rate up to a specific threshold strain rate, which is the limiting strain rate (LMTSTR). After reaching this limit, the material deforms only plastically. In this zone, the plasticity of the workpiece material is described by the material flow stress function (FSTRES). When used for modeling part forming, this formula provides a satisfactory simulation of the actual behavior of the material (sensitivity to strain rate) during its cutting [19]. The main disadvantage of this model is the inability to analyze springback deformation, and therefore, the model is unsuitable for residual stress analysis.

The elasto-plastic description of the behavior of the workpiece material during machining also employs the linear-elastic version of Hooke's law until the material reaches its yield strength. The distinction between the rigid-plastic description and this one lies in the fact that, upon reaching the parameter above, any FEM cells of the object of study that have exceeded the yield strength are treated as plastic ones. In contrast, any remaining cells are considered elastic. In this model, it is assumed that the general deformation of the workpiece, which is the primary object of study, is a combination of elastic and inelastic strain. The inelastic strain comprises plastic strain, thermal strain, and transformation strain, which vary depending on the characteristics of the material undergoing processing. This model provides a more realistic simulation of elastic recovery (springing) and deformation due to thermal expansion, which makes it suitable for calculating, for instance, residual cutting stresses. However, the calculations with this specific type of cutting deformation pattern are time-consuming (8–10 times more than the rigid-plastic model), as the stresses on the part are incremental and thus necessitate simulation of the loading and unloading procedure during and between forming operations.

A distinctive feature of the elasto-plastic model is a particular delineation of the flow stress. Consequently, at zero strain, this parameter is the yield strength of the material. However, as the accumulated effective plastic strain increases, the yield strength also rises. Given that the initial yield strength must adequately describe the current flow stress, information about the change in direction of the flow curve is crucial. DEFORM extrapolates the yield strength value if the flow stress data is only available for high strain values. Often, this value may be far from the actual yield strength [19]. In this case, the study's results must be more adequate. Thus, correcting some of the initial flow stress data at low effective plastic strain values can help to ensure the convergence of the modeling results (Fig. 4).

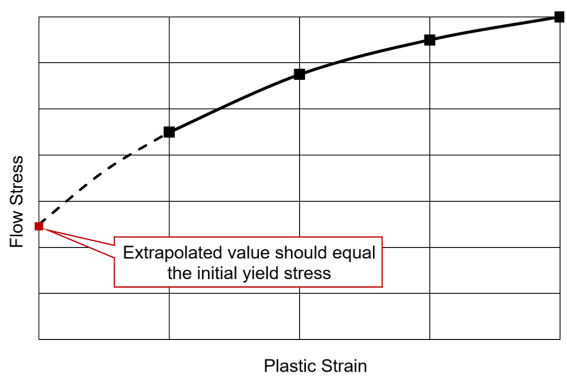


Fig. 4. Extrapolation of input data to determine the initial yield strength

For the researchers who need more experience in the machining process modeling of elasto-plastic materials, the following recommendations are suggested for the use in newly developed cutting simulation models.

a) When using an extrapolation function of the generated yield stress of the workpiece material in the form of an equation of $y = C\,e^{n+m} + y_0$ type, then y0 should be taken as the initial yield strength. A widespread mistake made by researchers is to use the conventional model where $y_0 = 0$. When extrapolating the tabulated values of yield strength as a function of temperature and strain of the material being processed, ensure that the inclination of the flow stress curve in the low-strain zone coincides with the initial yield strength. If this condition is not satisfied, then one or more data rows should be added to adequately correct the inclination of the yield stress curve.
b) Always use only the Newton-Raphson iteration method in the Simulation Controls/Iteration menu, as the sparse matrix method does not guarantee convergence.
c) When calculating elasto-plastic models, it is not uncommon for the solution to fail to converge due to the non-stationary behavior of the force error rate. In this case, it is recommended to increase the error rate of the cutting force making it two orders of magnitude greater than the error rate of the velocity in the Simulation Controls/Iteration menu. However, once the desired convergence effect is achieved, the force error rate will gradually be reduced until the system starts generating the above convergence error again.
d) Remember that the convergence of elasto-plastic cutting model results is very sensitive to the time step size. If one chooses a time step size that is too large (the size depends on the simulation), the probability of convergence error increases significantly. Reducing the time step size can improve convergence in many cases but will increase substantially the calculation time (usually exponentially).

The 2D Deformations database contains a reference value for static frictional coefficients for different machining materials against counterparts contact (tool material - WC). For instance, this value for AISI 1020 steel is 0.33, aluminum 6061 is 0.52, and Nickel Alloy Inconel 718 is 0.75. However, the kinetic (sliding) coefficient varies significantly depending on the temperature of the contact medium. For example, for Inconel 718 at 20°C, the coefficient is 0.75; at 200°C, it is 0.65; at 600°C, it is 0.4; and at 800°C, it is 0.35 [20].

4. Research results

Given the pivotal role of cutting-induced residual stresses in determining the operational properties of manufactured products, it is evident that using advanced simulation modeling techniques for their analysis is a logical and crucial undertaking. Furthermore, the necessity for a qualitative and comprehensive theoretical analysis to predict the most probable pattern of residual stress distribution within the volume arises from the significant challenges associated with the experimental confirmation of analytical studies, the ambiguity of interpreting the results of such studies, and the identification of dominant technological factors in the formation of compressive or tensile stresses on the treated surface [22, 23]. In this study, the term "technological factors" encompasses a range of parameters, including cutting parameters, tool geometry, coating, lubricating and cooling fluids, and other pertinent variables.

It is well known from the literature [24, 25] that plastic deformation occurs during the machining of parts, accompanied by the crushing and elongation of crystalline grains in the direction of deformation, the curvature of sliding planes, and residual stresses. In this instance, two opposing processes occur concurrently in the surface layer of the workpiece: strain hardening and thermodynamic softening. The physical state of the surface layer of the workpiece is contingent upon the ratio of the intensity and speed of these processes. The analytical formalization of this dynamic process is a challenging endeavor. Rheological modeling can facilitate the determination of residual stress values, their depth, and distribution law. The first kind's changes in thermo-strain stresses reflect the interference pattern of fluctuating tensile (frictional) and compressive (force) loads and the variable pattern of thermal solid effects.

All these processes can be analyzed in DEFORM 2D system (Fig. 5). The results of such studies are quite extensive [21–25]. Still, these studies aim to establish the possibility, feasibility, and adequacy of using a rigid-plastic or elasto-plastic cutting model. In the context of this study, a cutting-edge geometry was proposed, comprising a rake angle of 5°, a flank angle of 10°, and a cutting-edge radius of 0.1 mm. The Newton-Raphson method was employed as an iterative research method. The deformation process in the cutting simulation model was

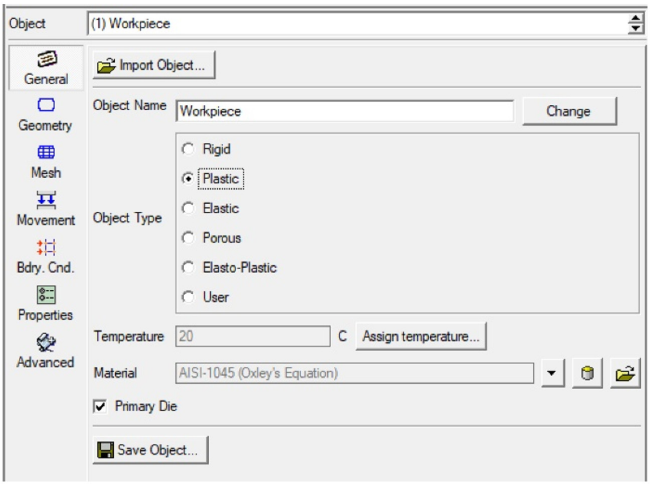


Fig. 5. Possibilities of formalizing the material model description in the DEFORM 2D

analyzed according to the Lagrangian Incremental Model. The primary solver of the system (computational kernel) was the Sparse Matrix Method [26].

The particularity of the finite element mesh development for investigating the residual stress zone is that the region of augmented cell density is not concentrated around the cutting wedge (the conventional scheme) but is extended along the machined surface. Furthermore, the thickness of this zone should encompass the anticipated depth of propagation of residual stresses induced by cutting (Fig. 6).

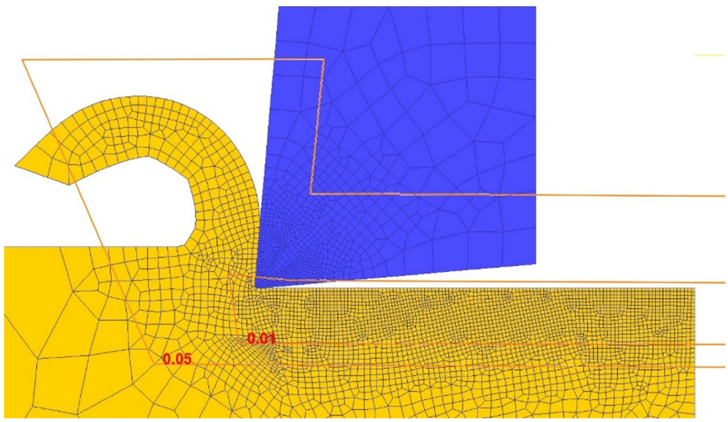


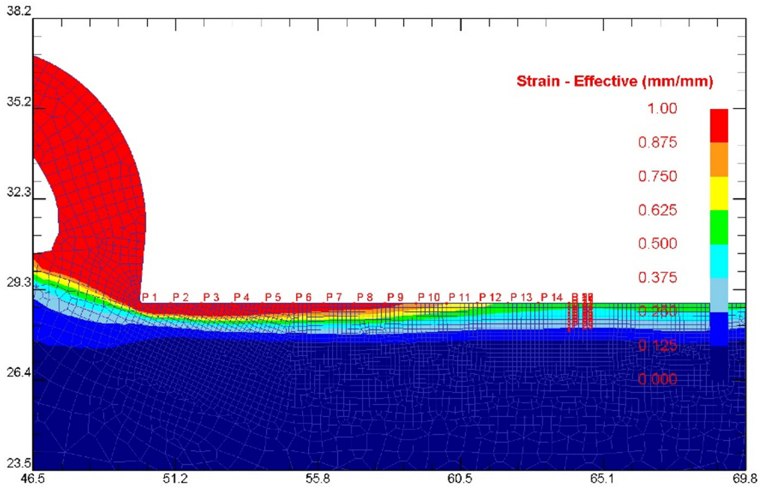
Fig. 6. Correct distribution scheme of different cell density zones for residual stress study

Another noteworthy feature is the particular distribution of reference points for the analysis of such stresses, both along the machined surface (points P1–P15) (Fig. 7a) and in the depth of residual stresses (points P15-P27) (Fig. 7b). Furthermore, the ultimate value of residual stresses must be assigned solely within the thermal stabilization zone to preclude the dynamic impact of thermal factors on the development of the tensile stress zone. This is a crucial methodological aspect that guarantees the accuracy of the final simulation results.

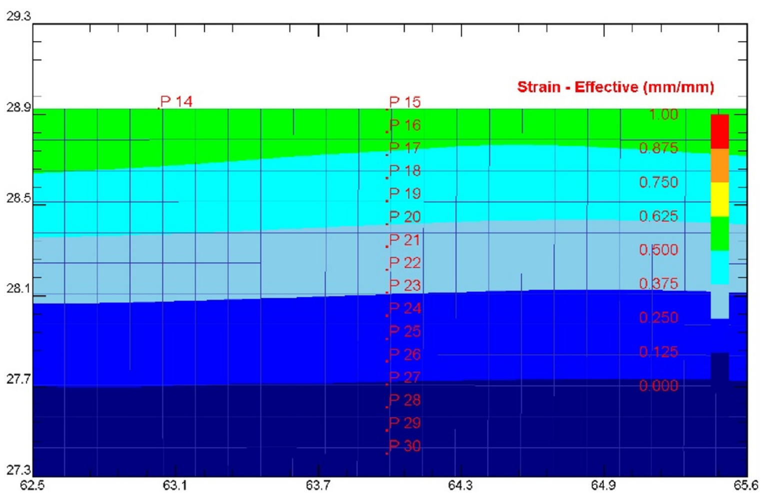
We can visually analyze the difference between the plastic and elasto-plastic stimulation patterns (Fig. 8). In the case of plastic modeling, there is no elastic recovery of the machined layer of the workpiece (Fig. 8a). Instead, for the elasto-plastic picture, such material springing can be seen in Fig. 8b. This effect will be accurately reflected in the formation of the residual stress zone.

To ascertain the viability of employing plastic or elasto-plastic cutting models for a range of materials, a series of simulations and experiments were conducted on three materials exhibiting distinct mechanical properties: aluminum alloy Al6061, low-carbon steel AISI 1020, and nickel-chromium alloy IN718.

The aluminum alloy Al6061 (containing magnesium and silicon as its main alloying elements) is characterized by high ductility (elastic modulus 68.9 GPa) and relatively low ultimate tensile strength not greater than 150 MPa and maximum yield strength of not greater than 110 MPa. Such properties contribute to a slight



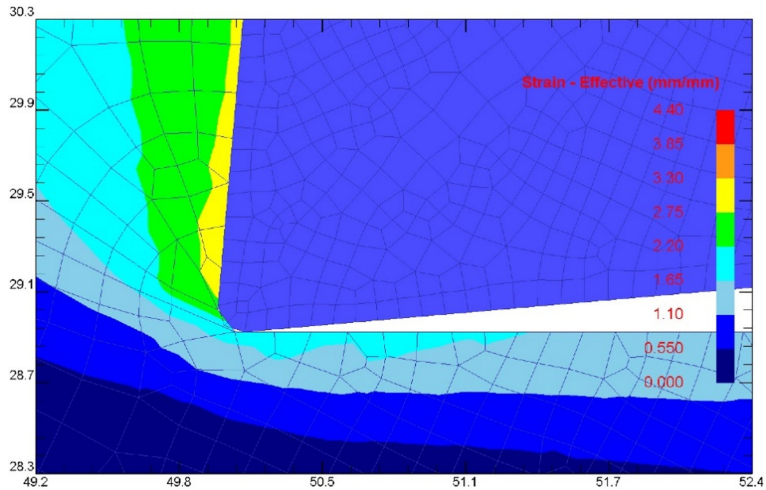
(a)



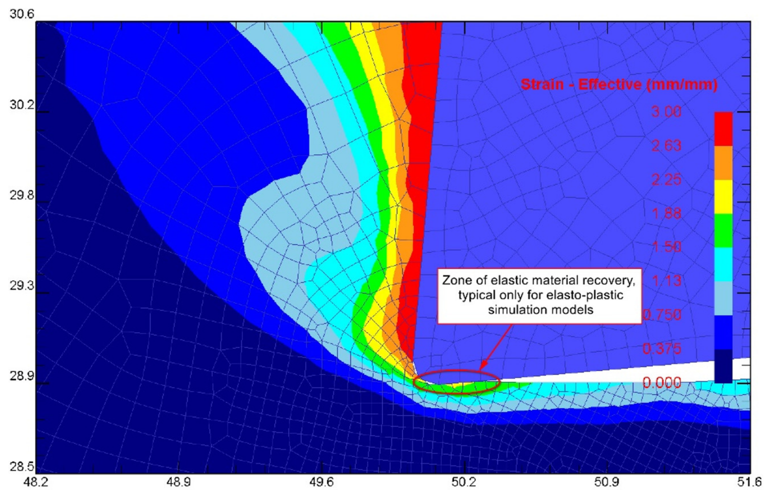
(b)

Fig. 7. Specific distribution of reference points for analyzing residual stresses, both along the machined surface (a) and in the depth of residual stresses (b)

difference in the simulation of cutting induced by residual stresses according to the plastic or elasto-plastic deformation scheme. This is confirmed by analyzing the results of such simulations shown in Fig. 9a (longitudinal studies) and Fig. 9b (depth studies). The difference between the results of the plastic and elasto-plastic patterns of residual stress formation is only 13.0% for the longitudinal stress distribution and 8.1% for the analysis of the deep distribution of such stresses. Moreover, the residual stresses for the plastic method of forming strains are higher than for the



(a)



(b)

Fig. 8. Simulation pattern of the machined workpiece layer formation in the shaping zone for the rigid-plastic (a) and elasto-plastic (b) cutting models

elasto-plastic method. This conclusion is quite logical and confirms the adequacy of the results presented by qualitative features.

The residual stresses obtained in different simulation methods exhibit a notable discrepancy when machining AISI 1020 steel, which has an elastic modulus of 190 GPa, a Brinell hardness ranging from 119 to 235, and a tensile strength of 410 to 790 MPa. For example, the difference between the results of the rigid plastic and elasto-plastic patterns of residual stress formation is 31.6% for the longitudinal stress distribution (Fig. 10a) and 57.7% for the analysis of the depth distribution of

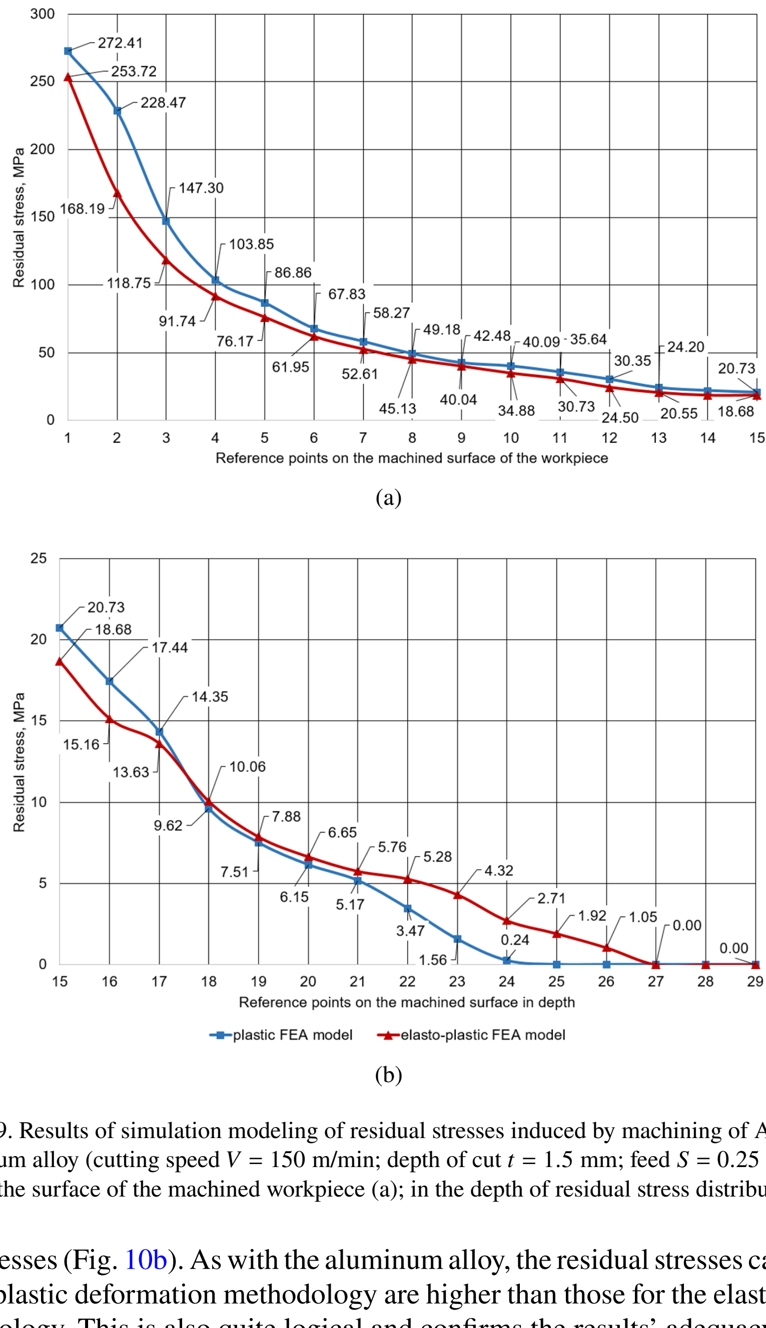
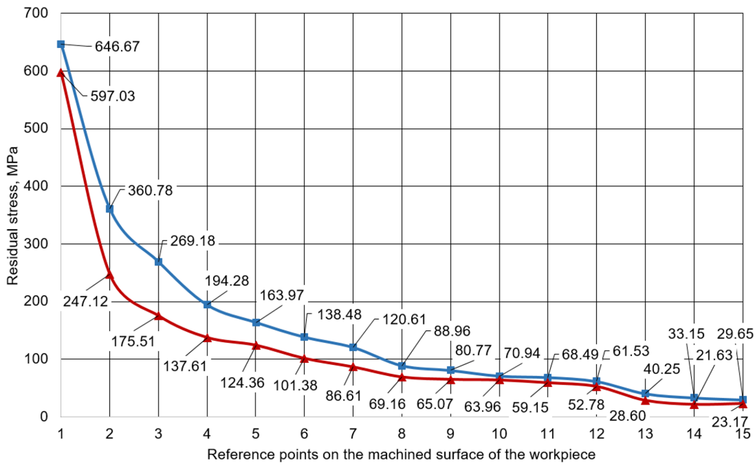


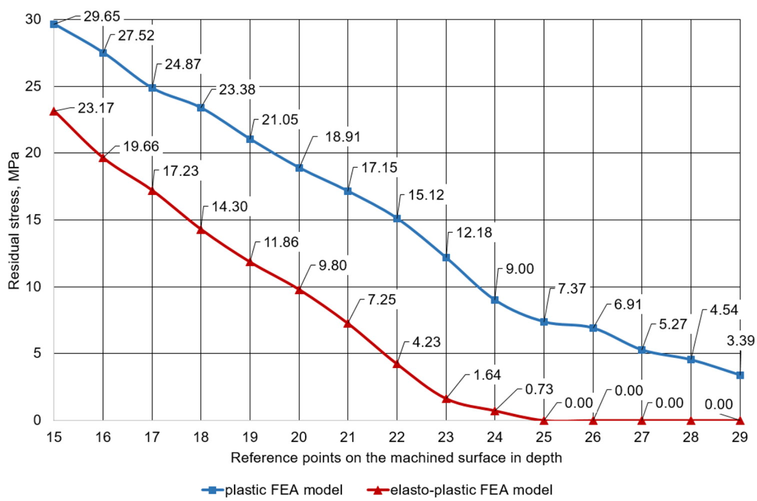
Fig. 9. Results of simulation modeling of residual stresses induced by machining of Al6061 aluminum alloy (cutting speed $V = 150$ m/min; depth of cut $t = 1.5$ mm; feed $S = 0.25$ mm/rev) along the surface of the machined workpiece (a); in the depth of residual stress distribution (b)

such stresses (Fig. 10b). As with the aluminum alloy, the residual stresses calculated for the plastic deformation methodology are higher than those for the elasto-plastic methodology. This is also quite logical and confirms the results' adequacy.

Nickel Alloy Inconel 718 (IN718) has a similar elastic modulus as carbon steel – 205 GPa. However, the mechanical characteristics of this material are significantly different: the superalloy material exhibits a minimum of 725 MPa yield strength and 1035 MPa tensile strength. Nickel and cobalt-based alloys can be difficult



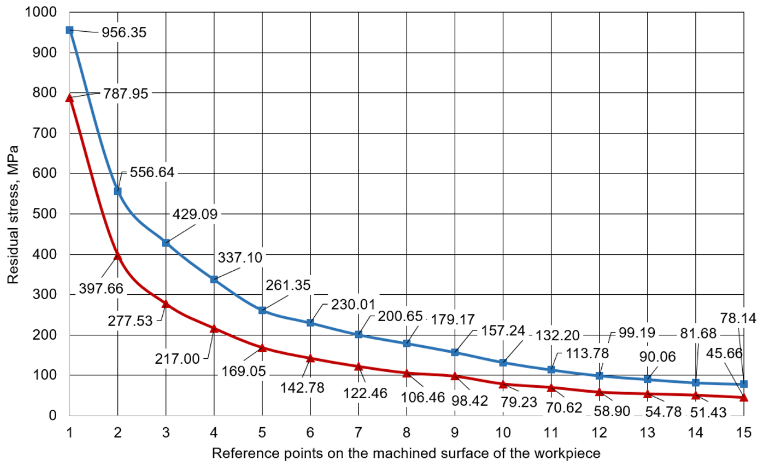
(a)



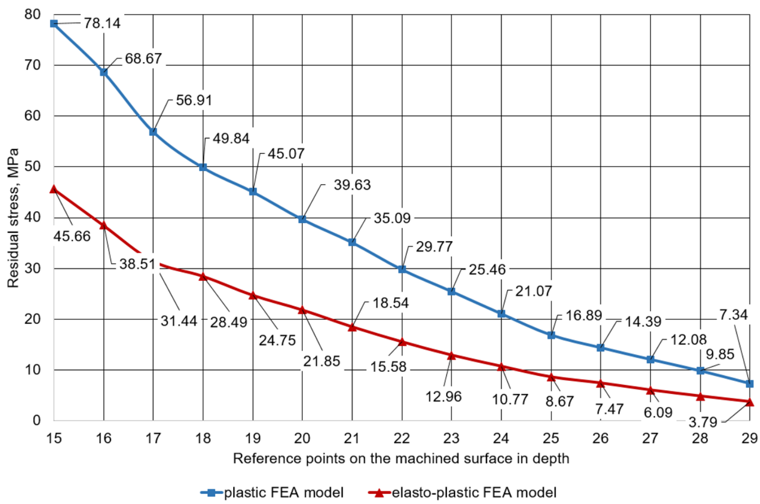
(b)

Fig. 10. Results of simulation modeling of residual stresses induced by machining of steel AISI 1020 (cutting speed V = 150 m/min; depth of cut t = 1.5 mm; feed S = 0.25 mm/rev) along the surface of the machined workpiece (a); in the depth of residual stress distribution (b)

to machine. These alloys harden rapidly, generate high heat during cutting, weld to the cutting tool surface, and exhibit high resistance to metal removal due to their high shear strengths. Therefore, the simulation results using the rigid plastic and elasto-plastic strain analysis methods significantly differ. For example, the difference betwin the results of the simulation of residual stresses by these methods is 63.8% for the longitudinal stress distribution (Fig. 11a) and 92.4% for the depth analysis of the distribution of these stresses (Fig. 11b).



(a)



(b)

Fig. 11. Results of simulation modeling of residual stresses induced by machining of superalloy IN718 (cutting speed V = 150 m/min; depth of cut t = 1.5 mm; feed S = 0.25 mm/rev) along the surface of the machined workpiece (a); in the depth of residual stress distribution (b)

Thus, the feasibility of applying the elasto-plastic FEA cutting model instead of the classical rigid plastic model for such plastic materials as, for example, aluminum alloy is questionable. This is due to the fact that the difference between the plastic and elasto-plastic models is insignificant (within 8–10%), and the increase in the study duration (8–10 times) is high. In contrast, an entirely different situation takes place when machining sufficiently elastic materials, a typical representative of which is the IN718 alloy. In the context of simulating the machining of such a material, the discrepancy between the outcomes of plastic and elasto-plastic FEA analyses is considerable, with a range of 60–90%. For most steels, the disparity in outcomes between these approaches is also significant (30–50%). Consequently, the elasto-plastic FEA model is recommended for the use with such materials, provided that the focus is on the characteristics of the machined surface rather than on the force or stress-strain parameters of the cutting zone, tool wear, and so forth.

5. Experimental verification of theoretical research for adequacy

The principal objective of the experimental studies is to assess the mutual influence of the primary technological parameters (cutting parameters) on the formation of residual stresses and strains during the machining process. The sophisticated mathematical apparatus employed to resolve systems of differential equations and assess the convergence of FEM results entails the utilization of approximate calculation methodologies, which may potentially impact the precision of the resulting calculations. Consequently, experimental studies were conducted to ascertain the suitability of the empirical data and the simulation results. The residual stresses were determined using the acoustoelastic method, which entails modifying the velocity of ultrasonic waves in response to mechanical stresses. Rayleigh surface acoustic waves (SAW) were employed [27, 28] to determine the stresses.

Acoustic tensiometry is founded upon the phenomenon of acoustic elasticity, which is defined as a change in the propagation velocity of elastic waves as a consequence of residual stresses present in the surface layer of a given object. This concept is discussed in detail in reference [27]. Hooke's law, according to which the stress σ and strain ε are proportional, is fulfilled approximately. The dependence of the step form is more precise:

$$\sigma = C_1\,\varepsilon + C_2\,\varepsilon^2, \tag{1}$$

where C_1 is the modulus of elasticity, and C_2 is the Murnaghan's coefficient [29].

The change in the velocity of the acoustic wave (ΔV) along the object of study is proportional to the stress or strain of the machined surface layer of the workpiece:

$$\frac{\Delta V}{V} = \varepsilon\frac{C_2}{C_1} \approx \sigma\frac{C_2}{C_1^2}\,, \tag{2}$$

where V is the initiated propagation velocity of the surface acoustic wave (SAW).

$$\begin{aligned} \frac{\Delta V_1}{V_1} &= \beta_1\sigma_{11} + \beta_2\sigma_{22}\,, \\ \frac{\Delta V_2}{V_2} &= \beta_2\sigma_{11} + \beta_1\sigma_{22}\,, \end{aligned} \tag{3}$$

where V_1 and V_2 are the SAW velocities propagating in directions $1(X)$ and $2(Y)$; ΔV_1 and ΔV_2 are the changes in the corresponding velocities under the action of mechanical stresses; σ_{11}, σ_{22} are the components of the residual mechanical stress tensor; β_1, β_2 are the acoustic elastic coefficients [30].

To determine the stresses, we used Rayleigh surface acoustic waves. These waves propagate over the sample's surface in a thickness of 1–2Λ (where Λ is the SAW length). In the study, waves with a frequency of 3 MHz were used, which corresponds to Λ = 1 mm. The distance between the transducers was 15 mm. The error in determining the velocity was less than 0.05%. Under tensile strain, the speed increases, and under compressive strain, it decreases.

The principle of operation of the pulse device with oscilloscopic indication is shown in the diagram (Fig. 12). The pulse generator (5) generates short pulses with an amplitude of 35. . . 100 V, which are delivered to the excitation piezoelectric transducer (2). The ultrasonic pulse passes through the test sample (1) and after a certain time interval reaches the recording piezoelectric transducer (2), where it is converted into an electrical pulse, which is amplified by the amplifier (9) and fed to the input 10 of the ray oscilloscope (8). At a constant scan rate, the position of the pulse on the screen depends on the time of the ultrasonic pulse between the piezoelectric transducers (2) and (3), i.e., on the speed of ultrasound propagation in the test sample. The start of the oscilloscope's expectation sweep does not occur at the moment of pulse formation in block (5), but after the expiration of a time interval shorter than the time of the ultrasonic pulse between the piezoelectric transducers (Fig. 12). The time delay of the signal is realized by a special time delay unit (6), which is triggered by a pulse from the generator (5) and forms a rectangular pulse of a given duration of τ_0.

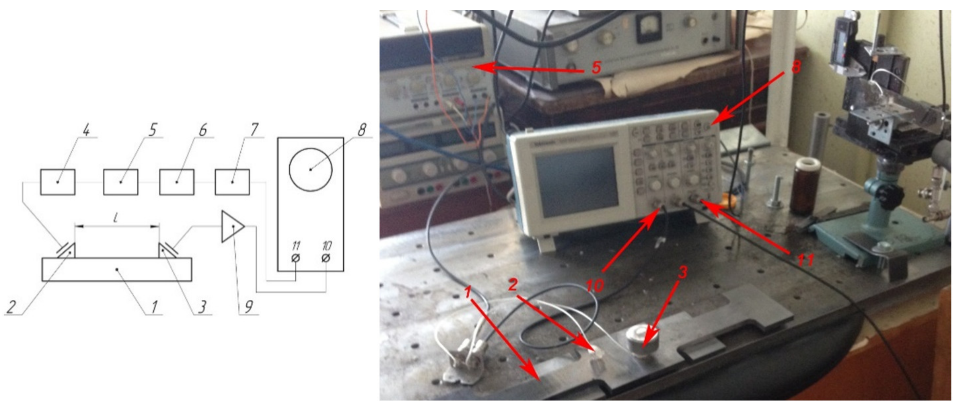


Fig. 12. Schematic diagram (a) and photo (b) of the experimental setup: 1 – test sample; 2, 3 – excitation and recording piezoelectric transducers; 4 – trigger; 5 – pulse generator; 6 – time delay unit; 7 – pulse shaper; 8 – cathode ray oscilloscope; 9 – amplifier; 10 – input and output connectors of the oscilloscope

At the end of the designated delay period, a pulse of negative polarity is generated at the triggering output of the oscilloscope (11). This pulse is then converted by the pulse shaper (7) into a positive polarity pulse, which triggers the expectation scan generator. The application of the time delay block can markedly enhance the scan speed, thus improving the measurement accuracy.

The experimental tests results allowed us to verify the simulation studies (Fig. 13).

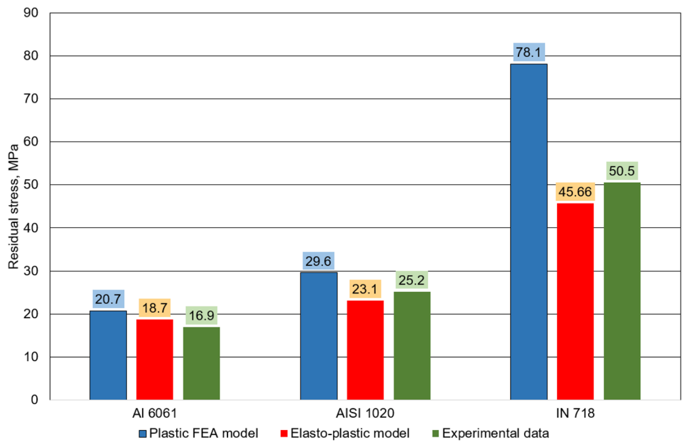


Fig. 13. Deviation of experimental data of residual stresses from the results of simulation modeling of machining

The discrepancy between the experimental data on residual stresses and the simulation modeling results in the case of machining aluminum alloy Al 6061 is 18.4% when the plastic FEA deformation model is employed and 9.6% when the elastic-plastic model is utilized. Similarly, for machining workpieces made of low-carbon steel AISI 1020, the values are 14.9% and 9.1% for the plastic and elastic-plastic FEA models, respectively. In the case of orbiting the superalloy IN 718, the data indicate a deviation of 35.5% for the plastic FEA model of strain and a deviation of only 10.6% for the elastic-plastic model. These data confirm the accuracy of the results obtained in simulation studies. However, it is recommended that residual stresses be studied using the elastic-plastic FEA model only for elastic materials.

6. Conclusions

1. The viability of employing elastic and elasto-plastic finite element analysis (FEA) cutting models in contemporary simulation software for simulating machining processes requires rigorous scientific and logical substantiation. From one perspective, the employment of an elasto-plastic model more accurately depicts the actual stress-strain processes occurring within the forming zone of the machined surface. Conversely, using such models instead of the conventional plastic deformation pattern markedly complicates the formulation of input parameters for the study, increases the calculation time by a factor of eight to ten, and is only implemented in some simulation systems.

2. To develop a model of elastoplastic deformation of the workpiece during cutting it is necessary to significantly expand the number of description parameters. In particular, it is essential to introduce the elastic (reversible) strain and plastic (irreversible) strain tensors. In this case, to describe these parameters, taking into account their thermodynamic changes, it is necessary to set the relations that determine the relationship of these tensors with other kinematic and dynamic characteristics of the cutting model. In this case, dividing the Almanac tensor into separate tensors representing elastic and plastic deformation becomes necessary. It is recommended that the error rate of the cutting force be increased by a factor of two in comparison to the error rate of the velocity. Once the desired convergence effect has been achieved, it is advised that the force error rate be gradually reduced until the system generates the convergence above error.
3. To ascertain the viability of utilizing plastic or elasto-plastic cutting models, a series of simulation and experimental studies were conducted on the three most typical materials in terms of their mechanical properties: aluminum alloy Al6061, low-carbon steel AISI 1020, and chromium-nickel alloy IN718. It is inappropriate to apply an elasto-plastic cutting model using finite element analysis (FEA) instead of a traditional plastic model for ductile materials such as aluminum alloy. Instead, for highly elastic materials, the elastic-plastic FEA model may be an acceptable option, provided that the focus is on the characteristics of the machined surface rather than the force or stress-strain parameters of the cutting zone, tool wear, etc.
4. The intricate mathematical machinery employed to resolve the systems of differential equations and assess the convergence of the FEM outcomes entails the utilization of approximate calculation methodologies, which may potentially influence the precision of the calculated outcomes. Consequently, experimental studies were undertaken to ascertain the suitability of the actual data and simulation results. The residual stresses were determined using the acoustoelastic method, which entails modifying the velocity of ultrasonic waves in response to mechanical stresses. The results of the experimental tests enabled verification of the simulation studies. Unlike to what is observed in elastic materials, in the case of plastic materials processing the discrepancy between the experimental residual stress data and the modeling results is significant. Therefore, it is advisable to use only the elastic-plastic FE model to estimate residual stresses during the machining of elastic materials.

References

[1] J.P. Davim. *Surface Integrity in Machining*. Springer, London, 2010. doi: 10.1007/978-1-84882-874-2.

[2] V. Stupnytskyy and I. Hrytsay. Comprehensive analysis of the product's operational properties formation considering machining technology. *Archive of Mechanical Engineering*, 67(2):149–167, 2020. doi: 10.24425/ame.2020.131688.

[3] R. M'Saoubi, J.C. Outeiro, H. Chandrasekaran, O.W. Dillon Jr., and I.S. Jawahir. A review of surface integrity in machining and its impact on functional performance and life of machined products. *International Journal of Sustainable Manufacturing*, 1(1-2):203–236, Springer, 2008. doi: 10.1504/IJSM.2008.019234.

[4] V. Stupnytskyy and I. Hrytsay. Computer-aided conception for planning and researching ofthe functional-oriented manufacturing process. In: Tonkonogyi V. et al. (eds): *Advanced Manufacturing Processes*, part of the Lecture Notes in Mechanical Engineering, 309–320, 2020. doi: 10.1007/978-3-030-40724-7_32.

[5] J.M. Carbonell, J.M. Rodríguez, and E. Oñate. Modelling 3D metal cutting problems with the particle finite element method. *Computational Mechanics*, 66:603–624, 2020. doi: 10.1007/s00466-020-01867-5.

[6] C. Constantin, S.M. Crpitoru, G. Constantin, and E. Strajescu. FEM tools for cutting process modelling and simulation. *Scientific Bulletin, Series D: Mechanical Engineering*, 74(4):149–162, 2012.

[7] J.K. Rai, and P. Xirouchakis. Finite element method based machining simulation environment for analyzing part errors induced during milling of thin-walled components. *International Journal of Machine Tools and Manufacture*, 48(6):629–643, 2008. doi: 10.1016/j.ijmachtools.2007.11.004.

[8] F. Matos, T.E.F. Silva, F. Marques, D. Figueiredo, P.A.R. Rosa, and A.M.P. de Jesus. Machinability assessment of Inconel 718 turning using PCBN cutting tools. *Procedia CIRP*, 117:468–473, 2023. doi: 10.1016/j.procir.2023.03.079.

[9] C. Liu, et al. Benchmarking of several material constitutive models for tribology, wear, and other mechanical deformation simulations of Ti6Al4V. *Journal of the Mechanical Behavior of Biomedical Materials*, 97:126–137, 2019. doi: 10.1016/j.jmbbm.2019.05.013.

[10] F. Klocke. *Manufacturing Processes 1: Cutting*. Springer, Berlin, 2011. doi: 10.1007/978-3-642-11979-8.

[11] V.P. Astakhov. Metal Cutting Mechanics. CRC press, Boca Raton, 1998. doi: 10.1201/9781466571778.

[12] F. Klocke, K. Arntz, G.F. Cabral, M. Stolorz, and M. Busch. Characterization of tool wear in high-speed milling of hardened powder metallurgical steels. *Advances in Tribology*, 2011:906481, 2011. doi: 10.1155/2011/906481

[13] N. Perez. *Fracture Mechanics*. Springer, Cham, 2017, doi: 10.1007/978-3-319-24999-5_1.

[14] J.F. Besseling and E. van der Giessen. *Mathematical Modeling of Inelastic Deformation*. Chapman & Hall, 1994.

[15] J. Li, Z.Shan, and E. Ma. Elastic strain engineering for unprecedented materials properties. *MRS Bulletin*, 39(2):108–114, 2014. doi: 10.1557/mrs.2014.3.

[16] D.C.C. Lam, F. Yang, A.C.M. Chong, J. Wang, and P. Tong. Experiments and theory in strain gradient elasticity. *Journal of the Mechanics and Physics of Solids*, 51(8):1477–1508, 2003. doi: 10.1016/S0022-5096(03)00053-X.

[17] M.T. Dove. *Structure and Dynamics: An Atomic View of Materials*. Oxford University Press, Oxford, 2003.

[18] W. Herrmann. Elasto-plastic constitutive relations at large strain. In: *Shock Compression of Condensed Matter-1991 Proceedings of the American Physical Society Topical Conference*, pages 379–382, Williamsburg, Virginia, June 17–20, 1991.

[19] DEFORM v10.2. User's. Manual / Scientific Forming Technologies Corporation, 2011.

[20] L. Bai, S. Wan, G. Yi, Y. Shan, S.T. Pham, A.K. Tieu, Y. Li, and R. Wang. Temperature-mediated tribological characteristics of 40CrNiMoA steel and Inconel 718 alloy during sliding against Si3N4 counterparts. *Friction*, 9(5):1175–1197, 2020. doi: 10.1007/s40544-020-0455-3.

[21] V. Stupnytskyy and X. She. Comparative analysis of simulation results of hard-to-cut materials machining by coated cutting tools. *Journal of Mechanical Engineering – Strojnícky Časopis*, 70(2):153–166, 2020. doi: 10.2478/scjme-2020-0028.

[22] V. Stupnytskyy and I. Hrytsay. Simulation study of cutting-induced residual stress. In: *Advances in Design, Simulation and Manufacturing. DSMIE-2019. Lecture Notes in Mechanical Engineering*, Springer, Cham, pages 341–350, 2020. doi: 10.1007/978-3-030-22365-6_34.

[23] H. Kun and Y. Wenyu. Analytical modeling of residual stress formation in workpiece material due to cutting. *International Journal of Mechanical Sciences*, 114:21–34, 2016. doi: 10.1016/j.ijmecsci.2016.04.018.

[24] H. Kun, Y. Wenyu, and X. Ye. Adjustment of machining-induced residual stress based on parameter inversion. *International Journal of Mechanical Sciences*, 135:43–52, 2018. doi: 10.1016/j.ijmecsci.2017.11.014.

[25] M. Benachour, N. Benachour, and M. Benguediab. Effect of compressive residual stress generated by plastic preload on fatigue initiation of 6061 Al-alloy. *Procedia Structural Integrity*, 2:3090–3097, 2016.

[26] D. Yan, T. Wu, Y. Liu, and Y. Gao. An efficient sparse-dense matrix multiplication on a multicore system. In *2017 IEEE 17th International Conference on Communication Technology (ICCT)*, pages 1880–1883, Chengdu, China, 2017. doi: 10.1109/icct.2017.8359956.

[27] R.E. Vines, S.-I. Tamura, and J. P. Wolfe. Surface acoustic wave focusing and induced Rayleigh waves. *Physical Review Letters*, 74(14):2729–2732, 1995. doi: 10.1103/PhysRevLett.74.2729.

[28] Y. Wang et al. Acoustofluidics along inclined surfaces based on AlN/Si Rayleigh surface acoustic waves. *Sensors and Actuators A: Physical*, 306:111967, 2020. doi: 10.1016/j.sna.2020.111967.

[29] Y. Xu, Z. Yang, and L. Cao. Deflecting Rayleigh surface acoustic waves by a meta-ridge with a gradient phase shift. *Journal of Physics D: Applied Physics*, 51(17:175106, 2018. doi: 10.1088/1361-6463/aab809.

[30] V.V. Koshovyi, O.M. Mokryi, M.I. Hredil', and M. Romanyshyn. Investigation of the space distribution of the velocity of surface acoustic waves in plastically deformed steel by the laser method. *Materials Science*, 49:478–484, 2014. doi: 10.1007/s11003-014-9639-1.