UKRAINIAN JOURNAL OF MECHANICAL ENGINEERING AND MATERIALS SCIENCE
Vol. 10, No. 1, 2024

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ANALYSIS OF THERMODYNAMIC, STRESS-STRAIN, AND LOADED STATES OF CHROMIUM-NICKEL ALLOY WORKPIECES USING MACHINING PROCESS SIMULATION IN ADVANTAGE SOFTWARE

Received: January 22, 2024 / Revised: February 2, 20244 / Accepted: February 9, 2024

https://doi.org/10.23939/ujmems2024.01.044

Abstract. Machining difficult-to-cut materials, which include most high-alloy chromium-nickel steels and alloys, requires optimization of cutting parameters, correct application of tool materials, cutting blade geometry, etc. The particular relevance of a scientifically based analysis in addressing these issues is due to the large costs incurred in machining products made from such materials. The possibilities of experimental research to provide correct technological recommendations are quite limited. Instead, analytical modeling is imperfect due to the complexity of formalizing dynamic processes accompanied by fast-moving power, thermodynamic, and stress-strain phenomena. An effective research mechanism is simulation modeling of the cutting process of a hard-to-machine material (including in the AdvantEdge software). The article presents an analysis of the results of simulation studies of the influence of the main parameters of machining (depth and cutting speed) on the formation of power, thermodynamic, and stress-strain (including residual) parameters formed during cutting of chromium-nickel alloy Inconel IN 718. This analysis allows us to conclude the feasibility of choosing cutting parameters to ensure the effective performance properties of products made of this material

Key words: difficult-to-cut materials; cutting; chromium-nickel alloy; stress-strain state; residual stress; thermodynamic state; AdvantEdge.

Introduction

Optimizing cutting parameters is particularly important for the efficient machining of high-alloyed heat-resistant and hard-to-machine materials, including high-chromium and nickel steels and alloys. This is because machining costs account for a large share of the total cost structure of products made from these materials, as these steels and alloys are difficult to machine. In other words, a large percentage of total costs are accounted for by tooling, energy, labor, etc. It is obvious that the correct parameters, such as cutting speed, depth of cut, machining temperature, and feed rate, can affect the economic parameters of machining, productivity of product manufacturing, tool wear rate, etc. For a scientifically based algorithm for selecting machining parameters, cutting blade geometry, correct distribution of machining allowance, formation of accuracy, roughness, and surface layer condition of the machined workpiece, it is necessary to predict the stress-strain and thermodynamic pattern of cutting a specific hard-to-machine material for the specific conditions of the product's future operation. This is implementing the function-oriented principle of process planning, an operation declared in the Industry 4.0 concept [1, 2]. The analysis of this picture allows us to make logical technological conclusions based on the peculiarities of the material flow during the shaping process.

Analysis of the influence of the structure of chromium-nickel alloys on their machinability and residual stress formation

It is known [3–5] that alloying elements such as nickel (Ni), chromium (Cr), and vanadium (V) have a significant impact on the machinability of steel by changing its structure, mechanical and physical properties. These elements can have either a positive or negative effect on machining performance, depending on their content, steel type, and type of processing. Nickel increases the strength, hardness, heat resistance as well as corrosion resistance of steel, but also reduces its weldability and machinability. An increase in the nickel content in the material being processed increases the temperature and cutting force, which leads to more intense tool wear and material deformation [3]. In addition, this material contributes to the formation of viscous chips, which can stick to the tool, forming built-up edges, which significantly degrade the quality of the machined surface. Chromium and vanadium, as alloying elements, also increase the hardness, heat resistance, and corrosion resistance of steel [4, 5]. This contributes to a more intense formation of hard carbides, which impair the machinability of steel. However, chromium also increases cutting force, tool wear, and material deformation. Vanadium improves the cutting resistance of steel because it increases the hardness and wear resistance of the tool. However, vanadium also increases cutting force, tool wear, and material deformation. High cutting temperatures can cause the diffusion of alloying elements from the surface to the interior of the material or vice versa, changing the concentration and distribution of these elements. The alloying elements can also form different phases, such as carbides, nitrides, oxides, etc., which can have different hardnesses, strengths, and machinability.

Cutting speed affects machining temperature (T), cutting force (F), tool wear (W), and surface quality (Q). As a general rule of thumb, cutting speeds should be higher for soft materials and lower for hard materials [6]. For alloy steels, cutting speeds are typically between 20 and 200 m/min, depending on the type of steel, tool type, type of machining, and other factors. Increasing the cutting speed leads to an increase in the machining temperature, which can cause changes in the structure and mechanical properties of the material, such as hardness, strength, brittleness, corrosion resistance, etc. Also, an increase in cutting speed leads to an increase in cutting force, which can cause tool wear, resulting in surface finish and material deformation. The depth of cut has the greatest impact on cutting force, tool wear, surface quality, and material deformation. Increasing the depth of cut leads to an increase in cutting force, which can cause tool wear, which in turn affects surface finish and material deformation [7]. Increasing the depth of cut can also affect the structure and mechanical properties of the material, as it increases the volume of material exposed to thermomechanical stress. Increasing the tool feed rate, on the one hand, has a positive effect on machining productivity, but, on the other hand, increases cutting forces, intensifies tool wear, and worsens surface roughness and material deformation.

An important factor in the quality of the surface layer of a machined workpiece is the formation of a residual stress zone [8]. Cutting-induced residual stresses can be the result of factors such as crystallization, and various influences, such as temperature, force, or phase transformations. These stresses are compensated for inside the object, which can lead to elastic deformations in the material. To ensure the operational properties of the surface layer of workpieces (fatigue strength, corrosion resistance, etc.), the dominant type of such stress is essential – tensile or compressive [9]. The formation of a tensile stress zone is primarily the result of high cutting temperatures. These stresses are harmful, which can cause warping, cracks, and corrosion, and useful, which increases the system's elastic limit, endurance, corrosion resistance, etc. The compressive type of residual stresses is formed as a result of a force factor that creates a hardened metal layer on the surface of the workpiece. This type of stress mainly plays a positive role in improving the operational properties of the product (primarily wear resistance) [10]. Factors contributing to embrittlement (such as the presence of volumetric stretching, temperature reduction, and a sharp increase in strain rate) usually strengthen the effect of residual stresses. On the contrary, the more elastic the material itself is, the faster and to a greater extent it can relieve residual stress.

Residual stresses can occur due to the influence of deep strains and thermodynamic processes [11]. When the outer layer of metal is heated during cutting, it tends to expand, but due to the resistance of the inner, cooler layer, this does not happen. As a result, the outer layer is subject to compression and the inner layer to tension. Intense heating can exceed the yield strength *T*, which leads to a compressive plastic deformation of the outer metal layer. During cooling, the outer layer tends to shrink to a size smaller than the original due to additional compressive plastic deformation [12]. However, the internal stress layer hinders this process, causing the inner layer to undergo compression and the outer layer to undergo tension. Thus, depending on the cutting parameters, a mechanical or thermal factor may prevail, which will determine the nature of the macro-stresses – compression or tension on the machined surface. However, this algorithm will be violated if cutting is accompanied by significant phase transformations that affect the formation of macro stresses in the surface layers by combining thermal and mechanical factors.

It is quite clear that residual stresses are interfering. That is, different factors can create such stresses of opposite signs and diversity. Additional experiments are needed to determine the dominant factor. Often, the influence of all factors is almost equivalent in terms of the magnitude of the impact on the nominal value and type of such stresses. To quickly and accurately analyze the influence of technological parameters (process structure, machining parameters, tool geometry, etc.) on the formation of the residual deformation zone, it is best to use rheological simulation models [13].

Automated rheological simulation systems can accurately determine the value of residual stresses, their depth, and distribution law. This applies to residual stresses of the thermo-deformation type I, which occur during the manufacturing process of a part and are balanced in the volume of its macro-parts or the entire workpiece. Structural-phase II residual stresses arise as a result of the phase strain of individual crystallites and grains and are equalized in the volume of the cells [11]. Stresses of the third kind are equalized in sub-micro volumes, which are small compared to the intergranular distances and are not defined as dominant in the formation of the surface layer, and therefore the influence of technological factors in this case is less significant.

Methodology for studying the stress-strain state of a workpiece based on rheological modeling of cutting in the AdvantEdge system

Modern engineering analysis systems that use Finite Element Analysis (FEA) allow you to determine the nominal values and type of stresses and strains in the chip formation zone, as well as to study the contact interaction of the elements of the Tool-Workpiece-Chip system. This enables an integrated calculation of the tool's stress state and an indirect assessment of its wear under various cutting conditions and parameters. Today, many different CAF (Computer Aided Forming) systems are used in mechanical engineering, both universal (ANSYS, MSC. Nastran, CosmosWorks, etc.) and specialized (QForm, LS-Dyna, AdvantEdge, DEFORM, etc.) [14]. One of the most effective systems for simulating molding processes is the AdvantEdge system. This system of rheological modeling of the cutting process implements effective methods for analyzing stress-strain and thermodynamic processes of forming on an explicit and implicit basis, Multimaterial Eulerian Hydrodynamics, computational fluid dynamics of incompressible flows, meshless Smoothed Particle Hydrodynamics (SPH) method based on the Element Free Galerkin method, etc.

The AdvantEdge offers sketch modeling, geometry export and import, changing the geometric parameters of objects and their position in spatial space, flexible mesh parameters (element size, intensity, densification, element type, etc.), automatic mesh overlay with optimization for object shapes and sizes, adding new parameters to ready-made materials from the library, creating new material and adding it to the library. The system has a simple, intuitive interface that implements a semi-automatic system for imposing links between objects with the setting of contact properties (friction force, the temperature in the contact zone, etc.). During the calculation process, full control of the calculation parameters is realized (time of the entire process, calculation step, kinetic energy in selected nodes, etc.)

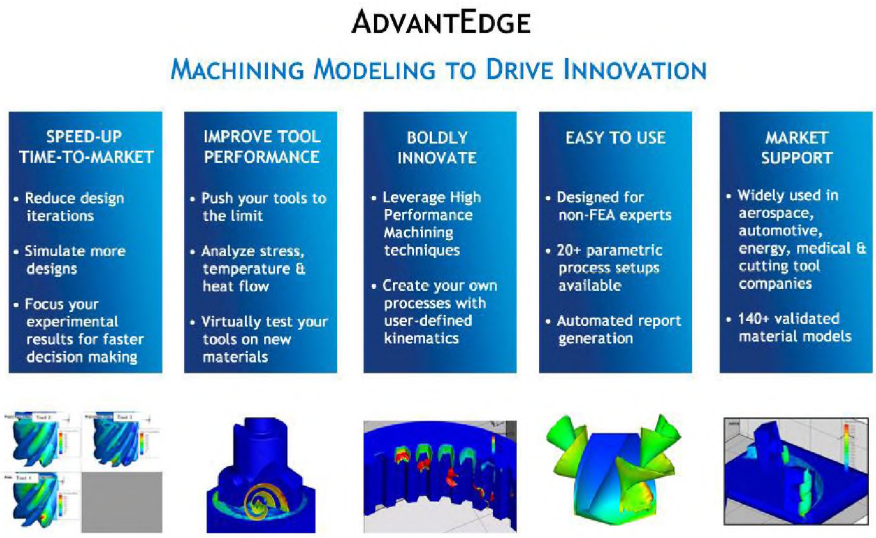


Fig. 1. The general structure of AdvantEdge [15]

In this system, flexible mesh parameters can be configured to be applied to the model. AdvantEdge can automatically impose rapidly changing boundary conditions, which provides flexibility and automated capabilities for dynamic mesh tuning (Fig. 2).

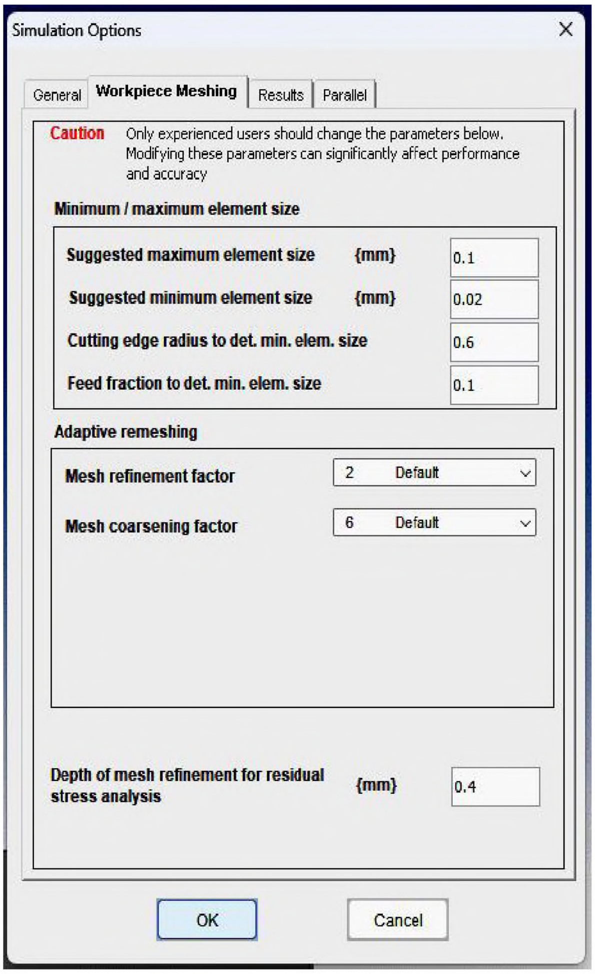


Fig. 2. The dialog box of simulation parameters

Analysis of the results of rheological modeling of the stress-strain and thermodynamic state of the workpiece in the AdvantEdge software

The object of study is a workpiece made of chromium-nickel alloy Inconel 718. The subject of the study is the effect of machining parameters (namely, cutting speed and depth of cut) on the power, stress-strain, and thermodynamic parameters of the machining process. In addition, the influence of these factors on the formation of a residual stress zone on the surface of the machined workpiece and the relaxation of these parameters deep into the workpiece was studied. It is advisable to measure these parameters in the thermal stabilization zone, i. e., in a place where the temperature has been established, which will not affect the appearance of residual stresses other than those that are already established and will not change either in sign (compression or tension) or in magnitude. The theoretical justification of the reasons for the influence of these indicators is explained above.

Study 1. Analysis of force parameters during mechanical machining of Inconel 718 chromium-nickel alloy workpieces with a change in cutting depth in the range of 0.3–2.5 mm.

Other cutting parameters (remain unchanged for different experiments):
-- STANDARD WORKPIECE --
Workpiece length = 50,0 mm
Workpiece height = 20,0 mm
Material = Inconel 718 (US)
-- STANDARD TOOL --
Tool Process Type = OBLIQUE
Rake angle = 5,0 deg
Rake length = 10,0 mm
Relief angle = 5,0 deg
Relief length = 10,0 mm
Cutting Edge Radius = 0,025 mm
Tool Material = Cubic-Boron-Nitride
Minimum Tool Element Size = 0,02 mm
Maximum Tool Element Size = 0,1 mm
Mesh Grading = 0,4
-- PROCESS --
Feed = 0,25 mm
Cutting speed = 150,0 m/min
Length of cut = 30,0 mm
-- SIMULATION --
Avg. Length of Cut Ratio = 10,0
Chip breakage = 0
Number of Cut = 1
Max. number of nodes = 72000
Max Element Size = 0,1 mm
Min Element Size = 0,02 mm
Fraction of Radius = 0,6
Fraction of Feed = 0,1
Mesh Refine = 2
Mesh Coarse = 6
Output Frame = 20

Experiment 1: Cutting depth of 0.3 mm.

A graphical visualization of the thermodynamic and force analysis of the cutting simulation process is shown in Fig. 3.

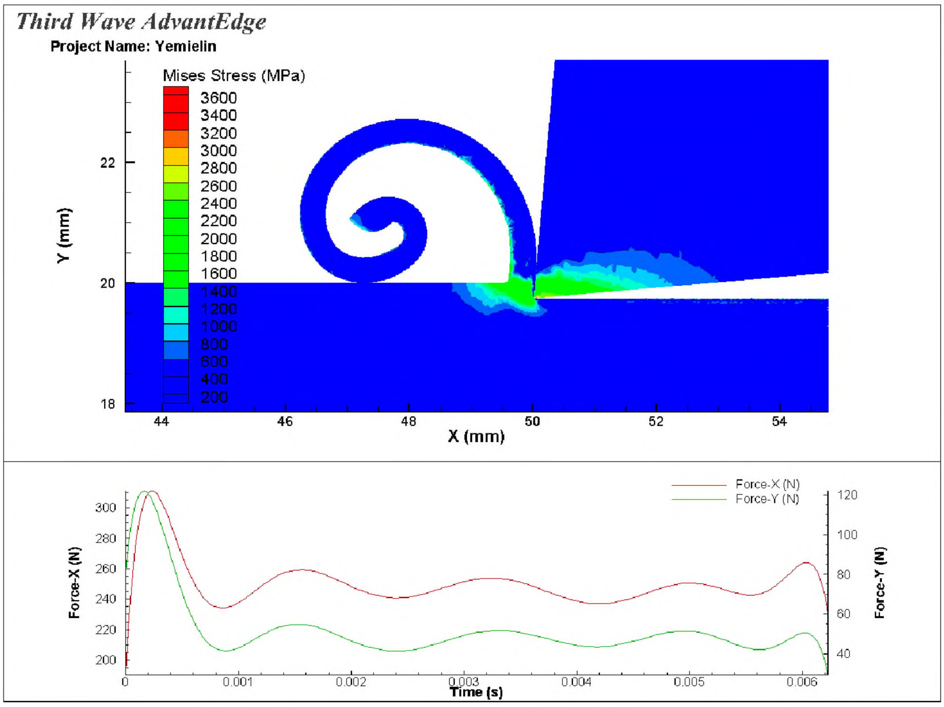


Fig. 3. Temperature distribution in the cutting zone

With a cutting depth of 0.3 mm, the cutting force is $P_\Sigma = \sqrt{P_x^2 + P_y^2} = \sqrt{248^2 + 41^2} = 251,4\ N$ (Fig. 4).

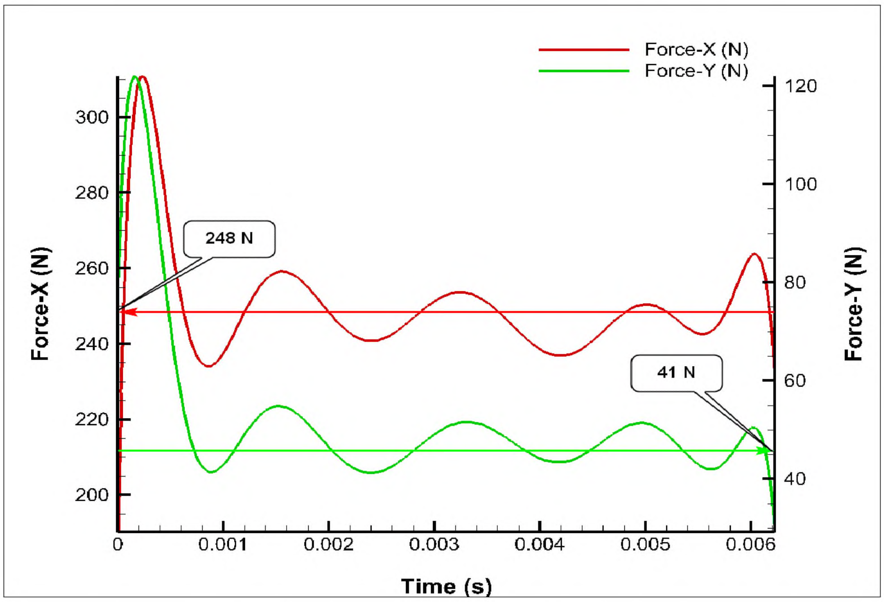


Fig. 4. Cutting force distribution graph

The cutting temperature in the forming zone is shown in Fig. 5. In the steady-state cutting mode, the maximum temperature is 1090 °C in the chip formation zone. This high temperature is due to the complex thermophysical properties of the material being machined, its high strength, and its low heat transfer coefficient. The severe thermodynamic state in the forming zone causes additional problems with the machinability of the superalloy. On the other hand, such a cutting pattern further indicates the need for a scientific approach to optimizing machining parameters, the purpose of the external process environment, the correct choice of tool material, the geometry of the cutting edge, etc.

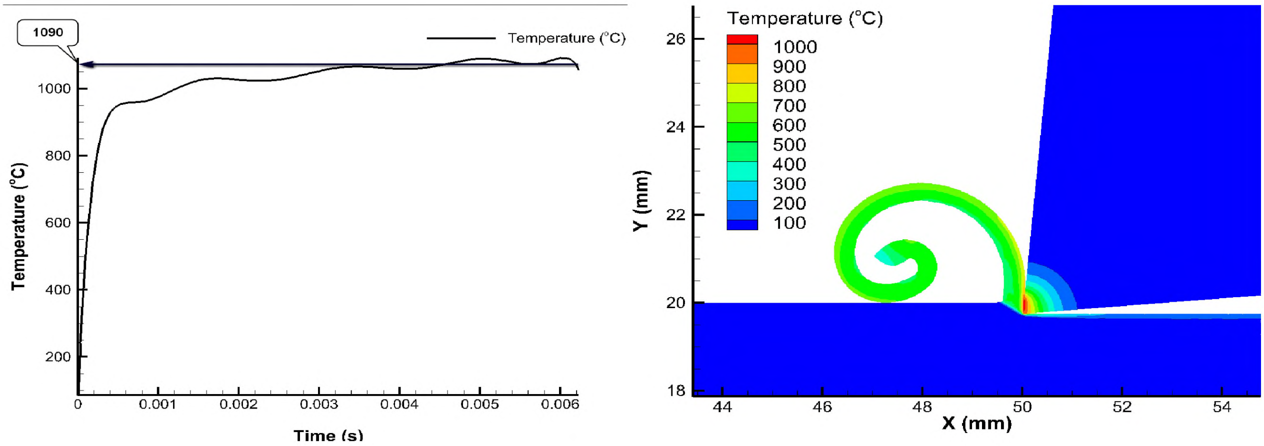


Fig. 5. Cutting temperature

The stress-strain state of the material in the cutting zone is shown in Figs. 6–7.

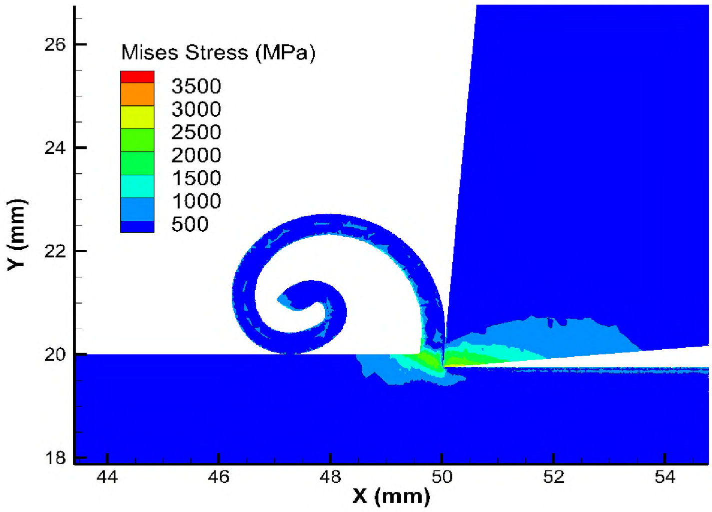


Fig. 6. Von Mises stress

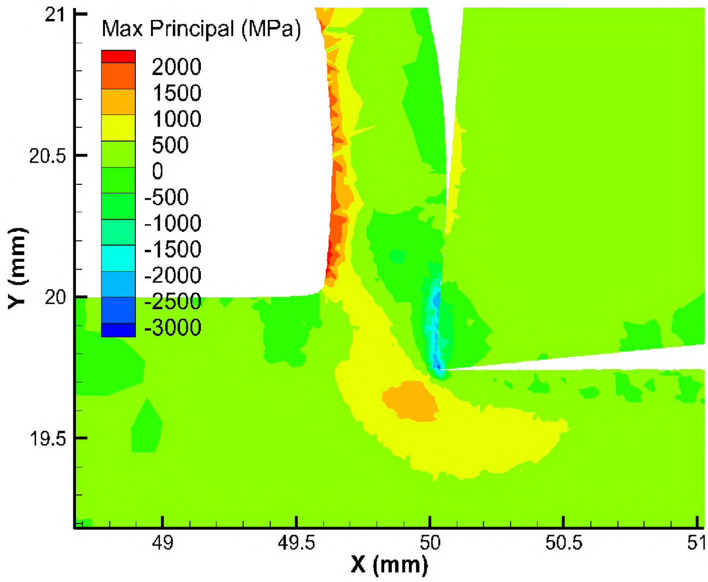


Fig. 7. Maximum principal stress

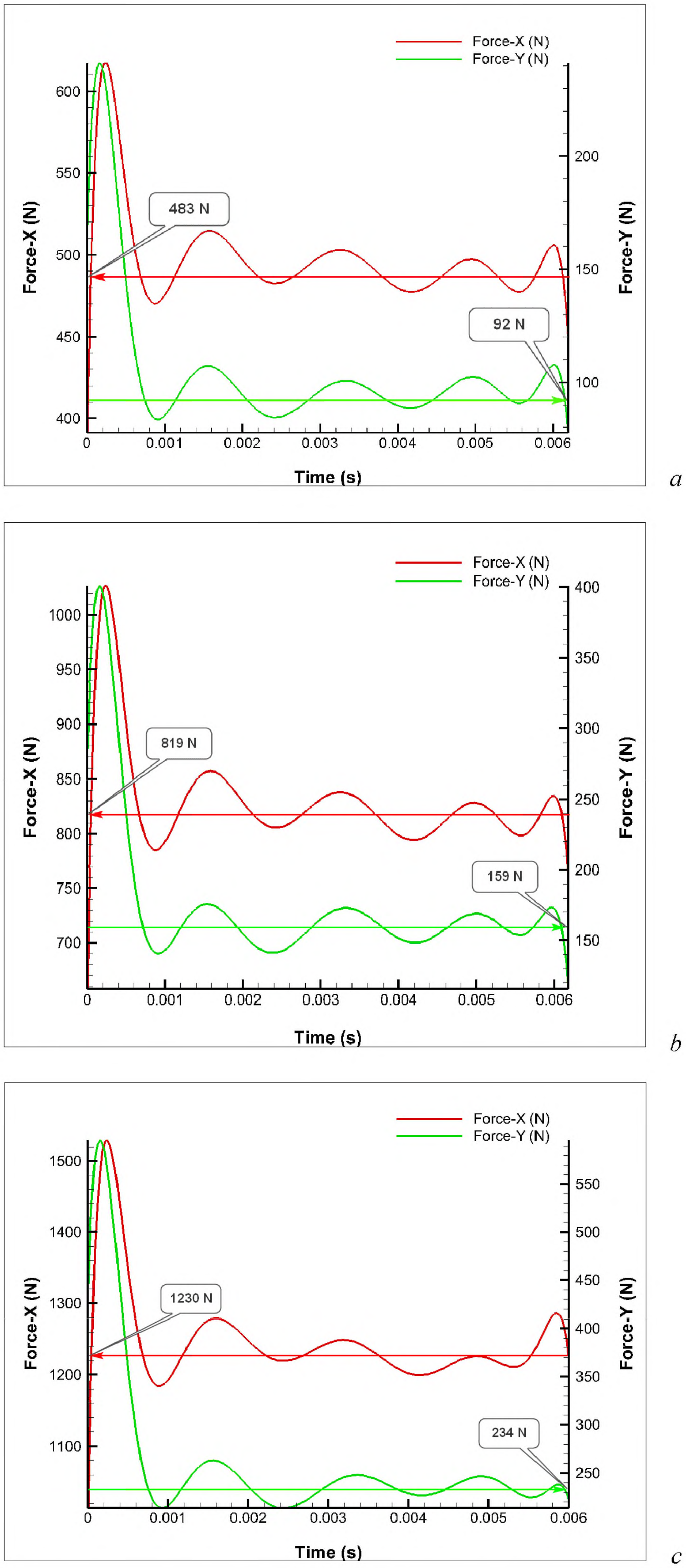
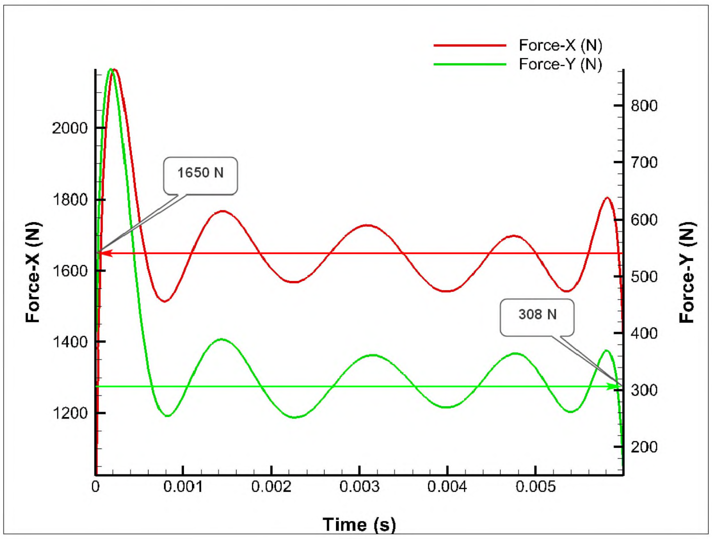


Fig. 8. Graph of cutting forces distribution



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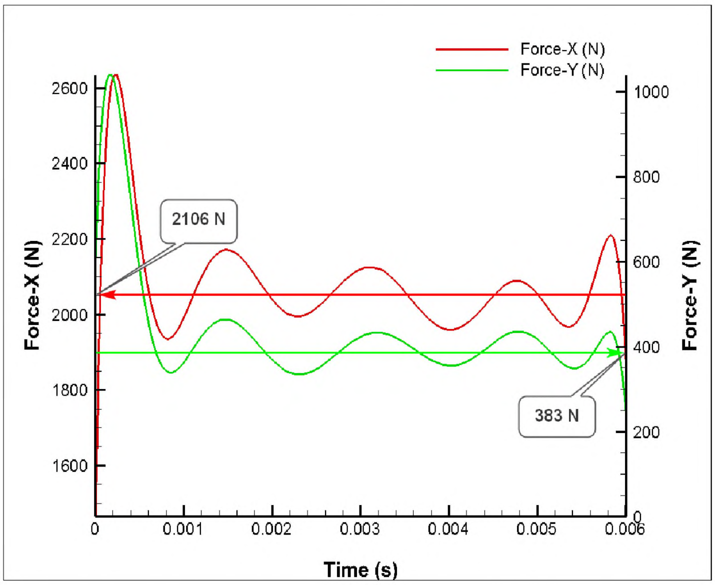


e

Fig. 8 (continuation). Graph of cutting forces distribution

The analysis of the results of such simulation showed that at a cutting depth of 0.6 mm, the cutting force is 491.68 N, which is 95.5 % more than at a cutting depth of 0.3 mm. Changing the depth of cut to t = 1.0 mm leads to a cutting force of 834.29 N. This value is 69.7 % higher than at a cutting depth of t = 0.6 mm. A further increase in the depth of cut to 1.5 mm results in an increase in the cutting force to 1252.06 N, i. e., 50 % more than at a cutting depth of t = 1 mm. At a cutting depth of 2.0 mm, the cutting force is already 1678.5 N, which is 34 % higher than the same parameter at a cutting depth of t = 1.5 mm. The largest studied value of g for a cutting depth of 2.5 mm increases the cutting force by 27.5 % more than at a cutting depth of 2 mm, i. e., to a value of 2140.54 N. The dynamics of the effect of cutting depth on the cutting force are shown in Fig. 9.

Study 2. Analysis of surface residual stresses induced during machining of Inconel 718 chromium-nickel alloy workpieces with a change in cutting depth in the range of 0.3–2.5 mm

The next stage of research is a simulation analysis of the effect of cutting depth on the formation of the induced residual stress cutting zone. Fig. 10 shows the graphical results of such studies of the cutting process of Inconel 718 alloy with a cutting depth of t = 0.3 mm (Fig. 10, *a*); t = 0.6 mm (Fig. 10, *b*), 1.0 mm (Fig. 10, *c*), 1.5 mm (Fig. 10, *d*), 2.0 mm (Fig. 10, *e*) and 2.5 mm (Fig. 10, *f*). Other parameters and cutting conditions remain unchanged for the different simulation tasks, namely: feed rate is S = 0.25 mm/PR; and cutting speed is V = 150.0 m/min.

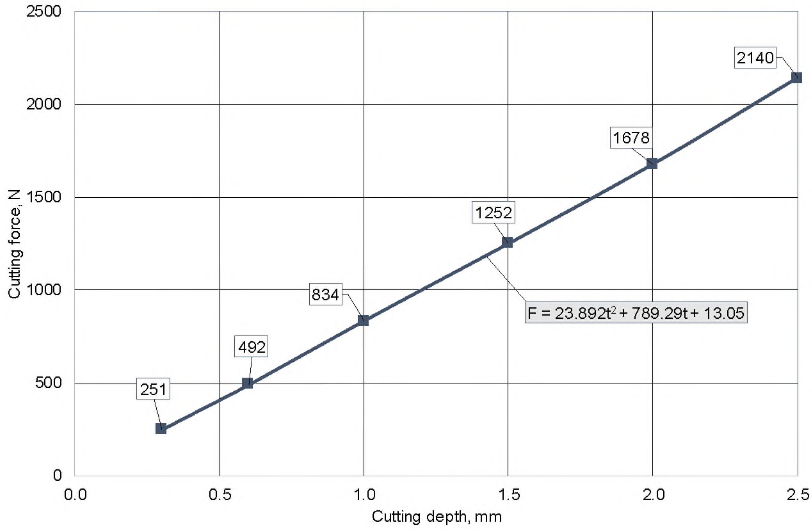
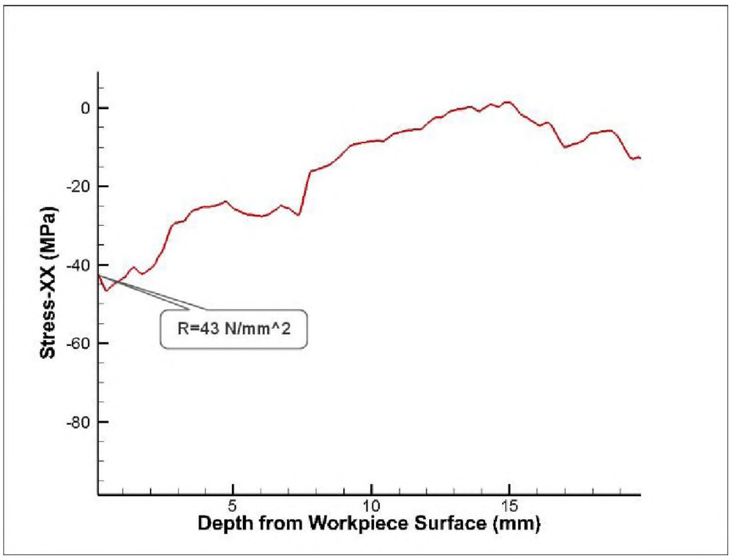


Fig. 9. Diagram of the dependence of the total cutting force on the change in the depth of cut when machining chromium-nickel alloy Inconel 718 workpieces



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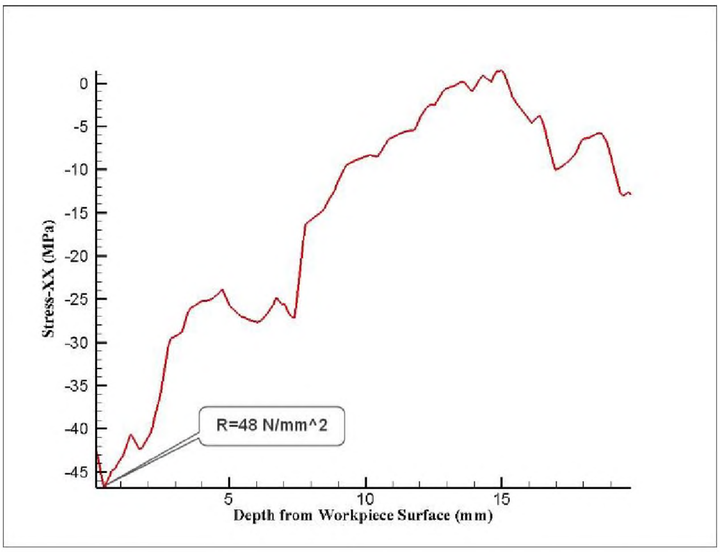

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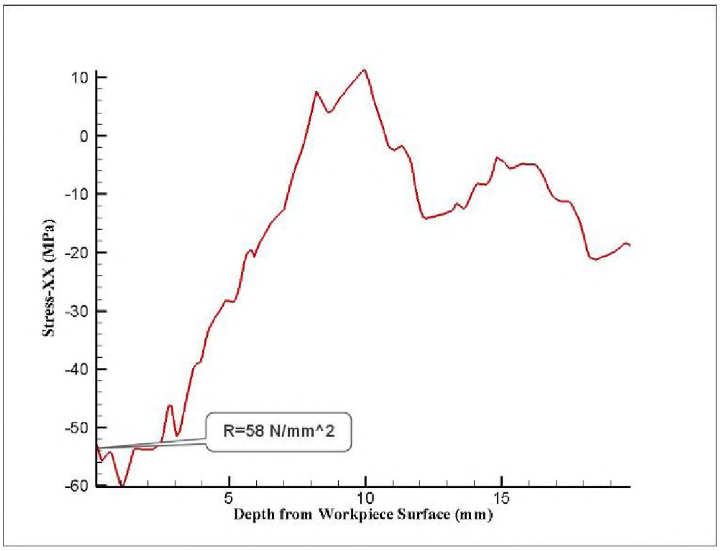
Fig. 10. Graph of residual stresses in the heat stability zone depending on the depth of cut of IN718



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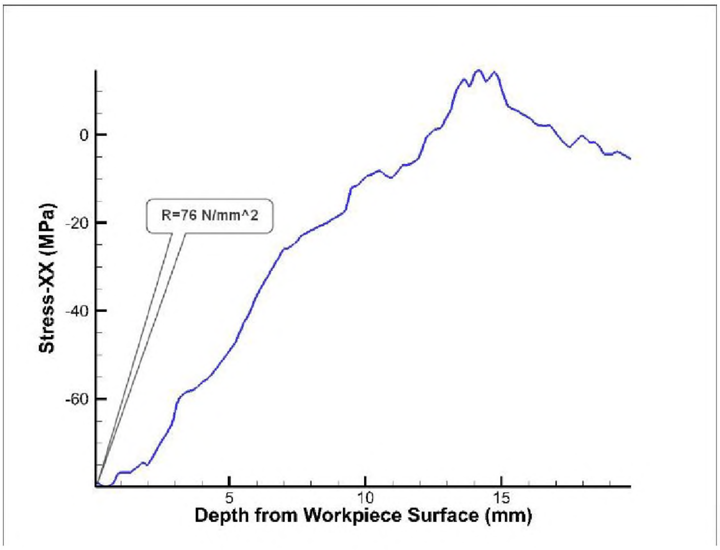

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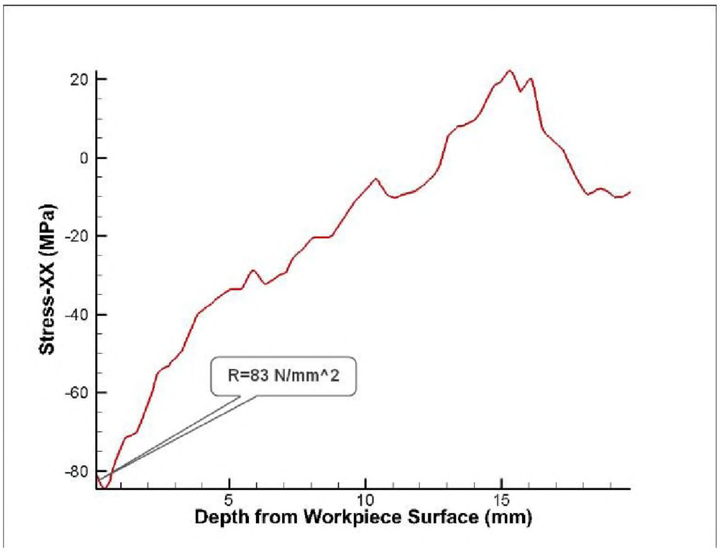

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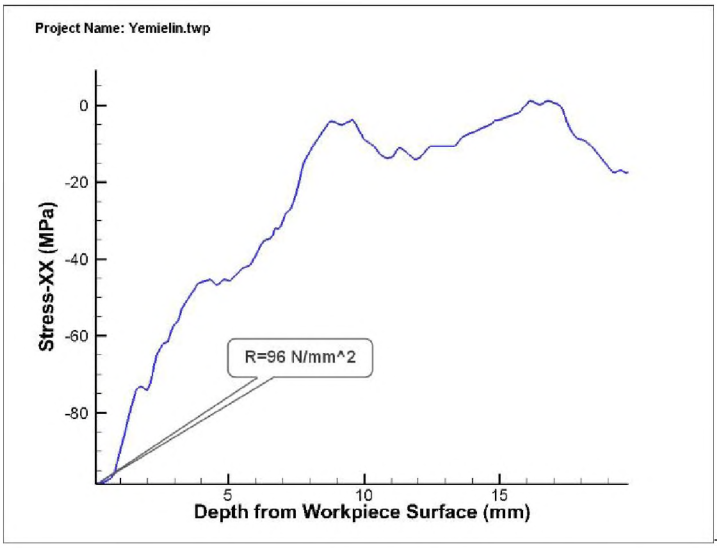
Fig. 10 (continuation). Graph of residual stresses in the heat stability zone depending on the depth of cut of IN718



f

Fig. 10 (continuation). Graph of residual stresses
n the heat stability zone depending on the depth of cut of IN718

The analysis of the simulation results showed that at a cutting depth of 0.6 mm, the residual stresses in the thermal stabilization zone are 48 N/mm^2, which is 11.6 % higher than at a cutting depth of 0.3 mm (43 N/mm^2). Changing the depth of cut to t = 1.0 mm results in a surface residual stress of 58 N/mm^2. This value is 35 % higher than at a cutting depth of t = 0.3 mm. Further increasing the depth of cut to 1.5 mm causes the residual stresses to increase to 76 N/mm^2, i. e. 77 % more than at a cutting depth of t = 0.3 mm. At a cutting depth of 2.0 mm, this value is already 83 N/mm^2, which is 93 % higher than the same parameter at a cutting depth of t = 0.3 mm. The highest value of the studied cutting depth of 2.5 mm increases the value of residual stresses by 123 % (96 N/mm^2) compared to the surface residual stress induced at a cutting depth of 0.3 mm. The dynamics of the effect of the depth of cut on the value of residual stress are shown in Fig. 11.

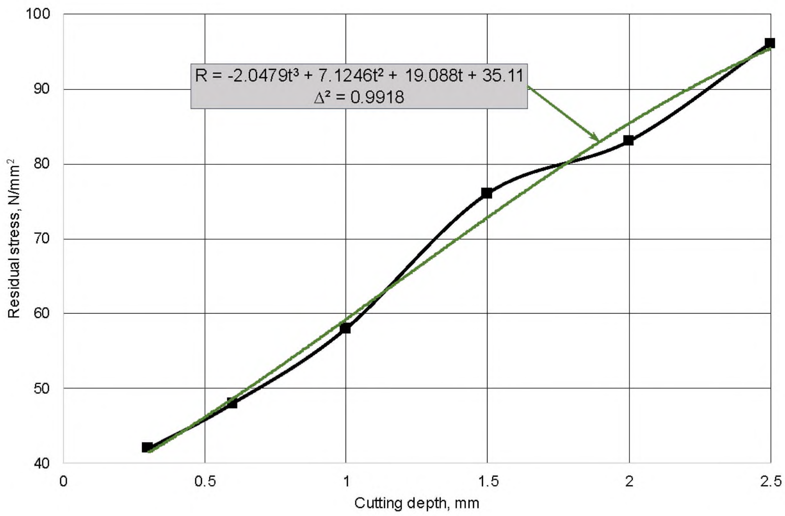


Fig. 11. Graph of residual stresses depending on the depth of cut

Study 3. Analysis of surface residual stresses induced during machining of Inconel 718 chromium-nickel alloy workpieces with a change in cutting speed in the range from 50 m/min to 300 m/min

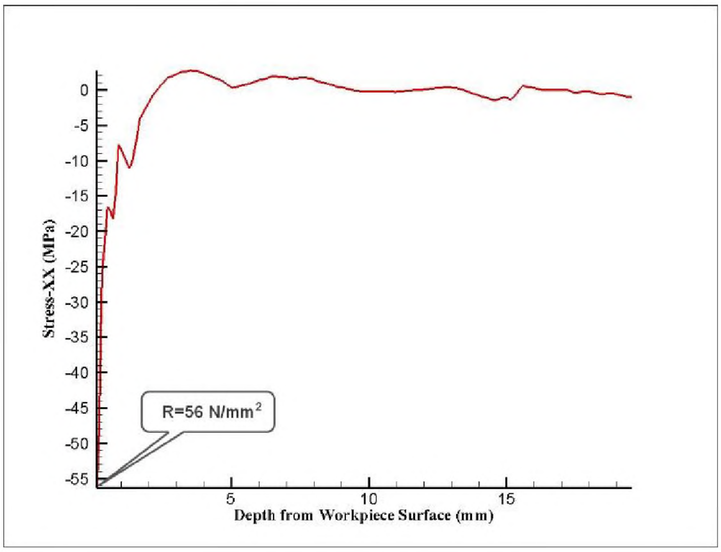
The next planned result of the study is to determine the dependence of the surface residual stress on changes in the cutting speed parameter in the range from 50 m/min to 300 m/min with other constant cutting parameters.

-- STANDARD WORKPIECE --
Workpiece length = 50,0 mm
Workpiece height = 20,0 mm
Material = Inconel 718 (US)
-- STANDARD TOOL --
Tool Process Type = OBLIQUE
Rake angle = 5,0 deg
Rake length = 10,0 mm
Relief angle = 5,0 deg
Relief length = 10,0 mm
Cutting Edge Radius = 0,025 mm
Tool Material = Cubic-Boron-Nitride
Minimum Tool Element Size = 0,02 mm
Maximum Tool Element Size = 0,1 mm
Mesh Grading = 0,4
-- PROCESS --
Feed = 0,25 mm
Cutting depth = 1,50 mm
Length of cut = 30,0 mm
-- SIMULATION --
Avg. Length of Cut Ratio = 10,0
Chip breakage = 0
Number of Cut = 1
Max. number of nodes = 72000
Max Element Size = 0,1 mm
Min Element Size = 0,02 mm
Fraction of Radius = 0,6
Fraction of Feed = 0,1
Mesh Refine = 2
Mesh Coarse = 6
Output Frame = 20

Fig. 12 shows the graphical results of such studies of the cutting process of Inconel 718 alloy at cutting speeds of V = 50 m/min (Fig. 12, *a*); V = 100 m/min (Fig. 12, *b*); V = 150 m/min (Fig. 12, *c*); V = 200 m/min (Fig. 12, *d*); V = 250 m/min (Fig. 12, *e*); V = 300 m/min (Fig. 12, *f*).

The analysis of the results of this simulation showed that at a cutting speed of 100 m/min, the residual stresses in the thermal stabilization zone are 66 N/mm^2, which is 18 % higher than at a cutting speed of 50 m/min (56 N/mm^2). When the cutting speed is increased to 150 m/min, the value of surface residual stresses is already 75 N/mm^2. This value is 34 % higher than at a cutting speed of 50 m/min. A further increase in the cutting speed to 200 m/min results in an increase in residual stresses to 105 N/mm^2, which is 88 % higher than at a cutting speed of 50 m/min. At a cutting speed of 250 m/min, this figure is already 116 N/mm^2, which is 107 % higher than the same parameter at a cutting speed of 50 m/min. The highest value of the studied cutting speed of 300 m/min increases the value of residual stresses by 127 % (up to 153 N/mm^2) compared to the surface residual stress induced at a cutting speed of 50 m/min. The dynamics of the effect of cutting speed on the value of residual stress are shown in Fig. 13.

The main reason for such a significant increase in residual stresses when cutting a chromium-nickel alloy, depending on the machining speed, is, of course, the high temperature in the cutting zone



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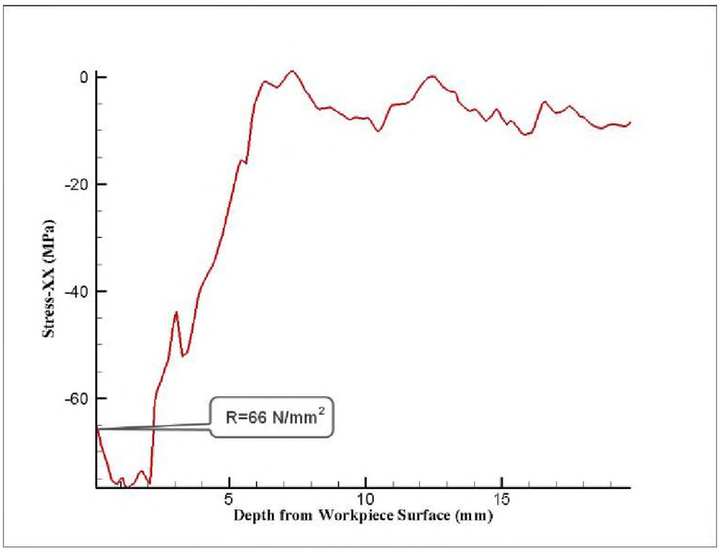

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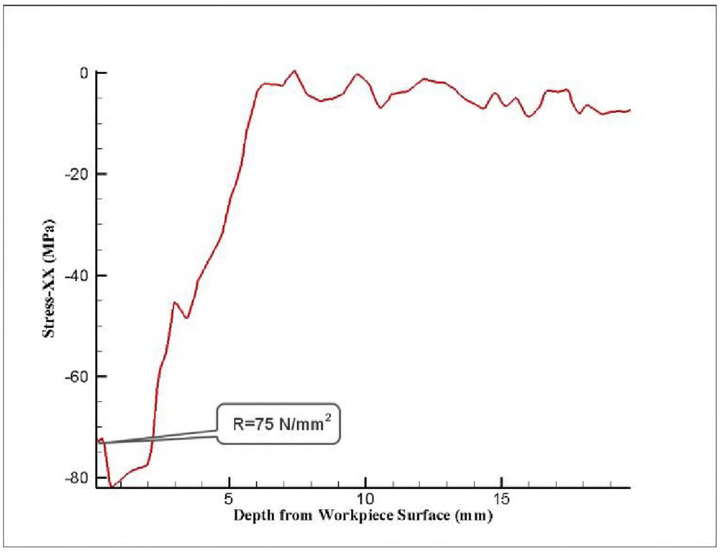

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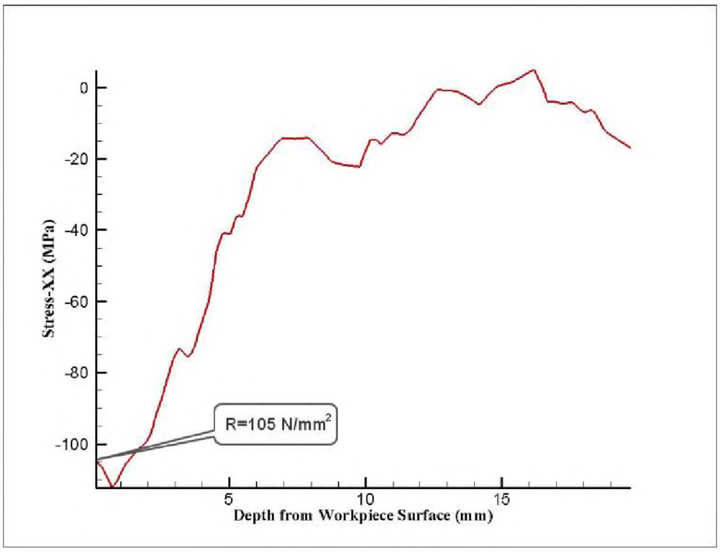
Fig. 12. Graph of residual stresses in the heat stability zone at different cutting speeds of IN718



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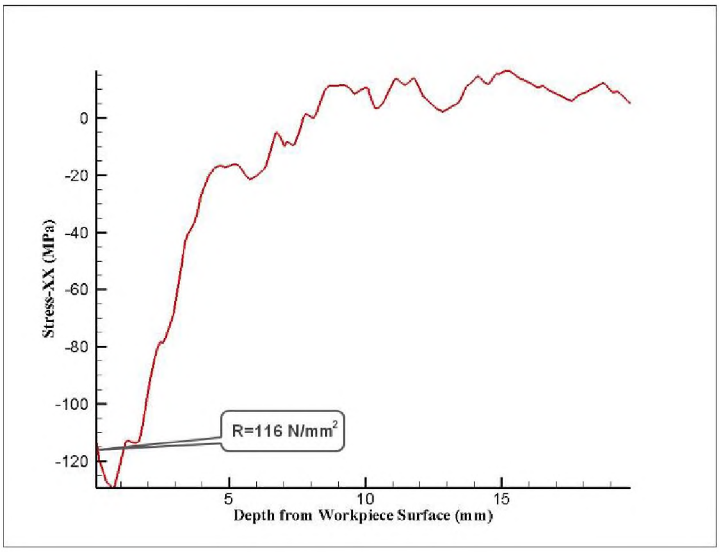

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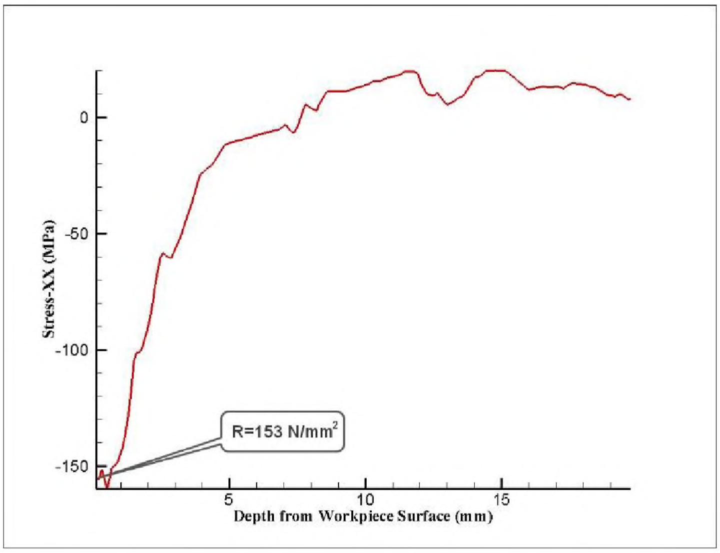

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Fig. 12 (continuation). Graph of residual stresses in the heat stability zone at different cutting speeds of IN718

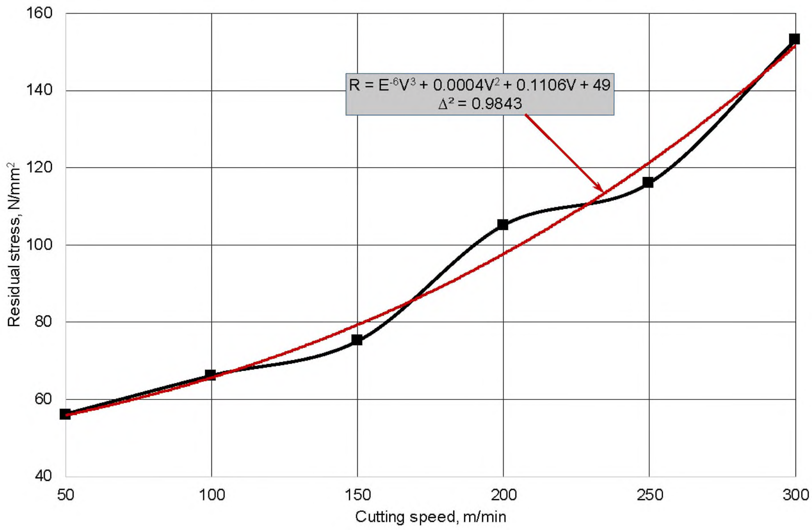

Fig. 13. Graph of dependence of surface residual stresses on cutting speed

Study 4. Analysis of the thermodynamic state of the machined material in the forming zone during machining of Inconel 718 chromium-nickel alloy workpieces with a change in cutting speed in the range from 50 m/min to 300 m/min

Fig. 14 shows the graphical results of such studies of the cutting process of Inconel 718 alloy at cutting speeds of V = 50 m/min (Fig. 14, *a*); V = 100 m/min (Fig. 14, *b*); V = 150 m/min (Fig. 14, *c*); V = 200 m/min (Fig. 14, *d*); V = 250 m/min (Fig. 14, *e*); V = 300 m/min (Fig. 14, *f*).

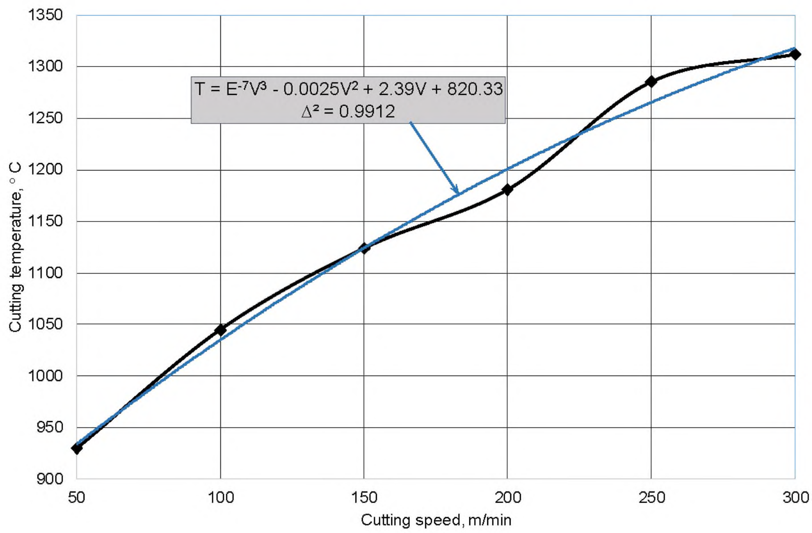

Fig. 14. Graph of cutting temperature dependence on cutting speed

The analysis of the results of the simulation study of the thermodynamic state of Inconel 718 chromium-nickel alloy workpieces showed that at a cutting speed of 100 m/min, the temperature in the cutting zone is 1045 °C, which is 13 % higher than at a cutting speed of 50 m/min (930 °C). When the cutting speed is increased to 150 m/min, the temperature reaches 1124 °C. This value is 21 % higher than at a cutting speed of 50 m/min. A further increase in the cutting speed to 200 m/min causes the temperature to rise to 1181 °C, which is 27 % higher than at a cutting speed of 50 m/min. At a cutting speed of 250 m/min, this indicator is already 1285 °C, which is 38 % higher than the same parameter at a cutting speed of 50 m/min. The highest value of the studied cutting speed of 300 m/min increases the temperature value by 41 % (up to 1312 °C) compared to the temperature in the forming zone at a 50 m/min cutting speed

Conclusions

1. For a scientifically based algorithm for determining machining parameters, cutting edge geometry, correct distribution of machining allowance, formation of accuracy, roughness, and surface layer condition of the machined workpiece, it is necessary to provide a stress-strain and thermodynamic picture of cutting a specific hard-to-machine material for specific conditions of future product operation. Analyzing this picture allows us to make logical technological conclusions based on the peculiarities of material flow during the forming process. An effective method for analyzing the parameters of the thermodynamic, stress-strain, and force state of workpieces is the use of simulation modeling of the machining process in the AdvantEdge software.

2. The analysis of the results of simulating the power parameters during the machining of chromium-nickel alloy Inconel 718 workpieces with a change in the depth of cut showed that at a cutting depth of 0.6 mm, the cutting force is 491.68 N, which is 95.5 % more than at a cutting depth of 0.3 mm. Changing the depth of cut to t = 1.0 mm leads to a cutting force of 834.29 N. This value is 69.7 % higher than at a cutting depth of t = 0.6 mm. A further increase in the depth of cut to 1.5 mm results in an increase in the cutting force to 1252.06 N, i. e., 50 % more than at a cutting depth of t = 1 mm. At a cutting depth of 2.0 mm, the cutting force is already 1678.5 N, which is 34 % higher than the same parameter at a cutting depth of t = 1.5 mm. The highest studied value of d for a cutting depth of 2.5 mm increases the cutting force by 27.5 % more than at a cutting depth of 2 mm, i. e. to a value of 2140.54 N.

3. Analysis of surface residual stresses induced during machining of Inconel 718 chromium-nickel alloy blanks with a change in cutting depth showed that at a cutting depth of 0.6 mm, the residual stresses in the heat stabilization zone are 48 N/mm^2, which is 11.6 % higher than at a cutting depth of 0.3 mm (43 N/mm^2). Changing the depth of cut to t = 1.0 mm results in a surface residual stress of 58 N/mm^2. This value is 3 % higher than at a cutting depth of t = 0.3 mm. Further increasing the depth of cut to 1.5 mm causes the residual stresses to increase to 76 N/mm^2, i. e. 77 % more than at a cutting depth of t = 0.3 mm. At a cutting depth of 2.0 mm, this figure is already 83 N/mm^2, which is 93 % higher than the same parameter at a cutting depth of t = 0.3 mm. The highest studied value of the cutting depth of 2.5 mm increases the value of residual stresses by 123 % (96 N/mm^2) compared to the surface residual stress induced at a cutting depth of 0.3 mm.

4. Analysis of the surface residual stresses that varied with the change in cutting speed showed that at a cutting speed of 100 m/min, the residual stresses in the thermal stabilization zone are 66 N/mm^2, which is 18 % higher than at a cutting speed of 50 m/min (56 N/mm^2). When the cutting speed is increased to 150 m/min, the surface residual stresses are 75 N/mm^2. This value is 34 % higher than at a cutting speed of 50 m/min. An increase in the cutting speed to 200 m/min results in an increase in residual stresses to 105 N/mm^2, i. e. 88 % more than at a cutting speed of 50 m/min. At a cutting speed of 250 m/min, this indicator is already 116 N/mm^2, which is 107 % higher than the same parameter at a cutting speed of 50 m/min. The highest value of the studied cutting speed of 300 m/min increases the value of residual stresses by 127 % (up to 153 N/mm^2) compared to the surface residual stress induced at a cutting speed of 50 m/min.

5. An analysis of the thermodynamic state of the processed material in the forming zone during machining of Inconel 718 chromium-nickel alloy workpieces with a change in cutting speed showed that at a cutting speed of 100 m/min, the temperature in the cutting zone is 1045 °C, which is 13 % higher than at a cutting speed of 50 m/min (930 °C). When the cutting speed is increased to 150 m/min, the temperature reaches 1124 °C. This value is 21 % higher than at a cutting speed of 50 m/min. A further increase in the cutting speed to 200 m/min results in a temperature increase of 1181 °C, which is 27 % higher than at a cutting speed of 50 m/min. At a cutting speed of 250 m/min, this value is already 1285 °C, which is 38 % higher than the same parameter at a cutting speed of 50 m/min. The highest value of the studied cutting speed of 300 m/min increases the temperature value by 41 % (up to 1312 °C) compared to the temperature in the forming zone at a 50 m/min cutting speed.

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