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INCREASE PRODUCTIVITY OF HARD-TO-MACHINE MATERIALS BY PREVENTIVE HEATING OF THE WORKPIECE

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Abstract. The possibility of increasing productivity by increasing the cutting parameters of difficult-to-machine materials, using expensive tool materials, etc. is an extensive trend of innovative improvement and is accompanied by high costs of operations and the need to provide expensive equipment. The article argues that a more effective method of improving machining operations is the use of the workpiece Turning with Preventive Heating (TPH) method. An analysis of existing methods, advantages and disadvantages of heating the cutting zone of the workpiece for machining certain difficult-to-machine materials is presented. The stages of studying the power, thermodynamic, and stress-strain state of the workpiece resulting from the complex action of mechanical loads associated with shearing of the processed material during cutting and thermal loads created by TPH technology are recommended. Modern programs for simulation analysis of innovative cutting processes are analyzed. Arguments for the effective use of AdvantEdge software in comparison with similar alternative programs for simulating the processes of machining difficult-to-machine materials are presented. The results of studies of changes in cutting forces for different cases of preventive heating of the cutting zone of parts made of the chromium-nickel alloy Inconel 718 are presented.

Keywords: difficult-to-cut materials, cutting, turning with preventive heating, simulation, thermodynamic state, AdvantEdge.

Introduction

The widespread use of high-alloyed (including stainless) steels and heat-resistant alloys is one of the characteristic features of the development of the machinery industry. This is especially true for the production of products that operate under significant power and thermodynamic conditions, under the influence of aggressive environments, etc. These include military products, aircraft, chemical, and power engineering products. Another important operational parameter of these materials is their heat resistance, which characterizes the ability of the material to provide a given corrosion resistance under intense heating and rapid cyclic thermal relaxation. The combination of high strength and satisfactory toughness of such materials makes them difficult to cut. Machining of such materials requires the use of tool material for cutting edges with specific strength characteristics, rational cutting modes, problem-oriented selection of lubricating and cooling fluids, etc. Optimization of the structure and parameters of technological processes is of priority importance to ensure the efficiency of the technological operation of machining a product made of the given material.

Therefore, for problem-oriented correction of cutting parameters, tooling for rational separation of the machining allowance, and ensuring the specified parameters of accuracy and roughness of machined surfaces, it is necessary to analyze the causes of problems in ensuring machining performance in combination with compliance with the specified parameters of quality and roughness of machined surfaces. Moreover, based on a comparison of the physical and mechanical properties of high-alloy steel and ordinary medium-carbon steel, it can be concluded that the tensile strength, hardness, and other mechanical properties did not differ significantly [1, 2]. However, significant differences in the microstructure and corrosion resistance of these materials should be noted. In addition, the material’s specific thermal conductivity, melting point, and other thermophysical properties have a significant impact on machinability [2].

Thus, increasing the productivity of machining products made of difficult-to-machine high-alloy steels is an important task for the development of modern machine building in Ukraine. This is especially important in the context of the intensification of the military sector of the industry, and the creation and reorganization of new machinery enterprises. For example, the share of products made from heat-resistant and superhard materials is 60–70 % in the manufacture of firearms, 40–50 % for armored vehicles, and 30–40 % for aviation products.

Literature review

A significant problem with the machinability of heat-resistant steels and alloys is the combination of the high strength of the material being machined with sufficiently high ductility, which is determined by the ratio of the conditional yield strength to the tensile strength. Moreover, stainless steels are highly ductile in terms of their mechanical properties [3]. Another important indicator is the viscosity of the machined material. Moreover, increased viscosity creates problems with chip formation. This negative process causes difficulty in removing machining waste from the cutting zone, causes the formation of tool build-up, and makes it difficult to achieve precision and roughness of the machined surface [4].

The second characteristic of difficult-to-machine materials is the low thermal conductivity of the workpiece material. This feature of high-alloy steels and alloys causes high cutting temperatures and, as a result, intensive wear of the cutting tool, high cutting forces, and low machining productivity [2]. This problem can be solved by using superhard tool materials, high-performance cutting fluids, rational distribution of the machining allowance, and intensive heat removal from the cutting zone. Implementation of any of these ways leads to a significant increase in the machining cost and, as a result, a higher cost of the product.

Another feature is the formation of extremely hard intermetallic and carbide compounds under the influence of high temperatures, which, despite their microscopic size, cause intense abrasive wear on the cutting tool edge. As practice shows, the friction coefficient when machining alloy steels is an order of magnitude higher than when machining conventional carbon steels.

The high probability of loss of vibration resistance of the tool-tool system is caused by a complex pattern of chip formation. This phenomenon is due to the manifestation of the so-called adiabatic shear – the sequential formation of a zone of compression and shear of the processed material shifted in time [5]. This phenomenon causes dissonant high-frequency oscillations of the longitudinal and transverse cutting forces. These oscillations cause additional roughness of the machined surface, a reduction in machining performance, etc. Another reason for the occurrence of vibrations is that under the influence of high cutting forces, a deformation displacement of the crystal lattice occurs, which causes the formation of a rivet-surface hardening [6]. Moreover, a significant part of the tool's friction energy is converted into heat. Due to the low thermal conductivity of the material, the machined surface is heated unevenly and vibration occurs, which increases the negative effect of the above factors.

Another example of difficult-to-machine materials is chromium-nickel alloys, which are widely used in the aerospace, nuclear, military, and automotive industries. The advantages of these materials are high corrosion resistance, relatively low density, thermal stability (i. e., the ability to maintain geometric shape and size at high temperatures), etc. These alloys are characterized by low thermal conductivity, passivity concerning chemical interaction with the tool material at high machining temperatures, high hardness, low elastic modulus, etc. [7]. However, along with these advantages, chromium-nickel alloys are characterized by the presence of hard inclusions and abrasive properties, which places them in the classification group of difficult-to-machine materials [2]. The presence of a high degree of strain hardening generates a large amount of heat, which causes an increase in thermal stresses both in the tool and on the surface of the workpiece. The first of these phenomena significantly reduces tool life, and the second causes residual tensile stresses to appear on the surface of the workpiece (reduces the operating parameters of the fatigue strength of the workpiece).

All of these complexities of machining difficult-to-cut high-alloy steels and alloys encourage mechanical engineering researchers to look for alternative ways to solve the problem of ensuring sufficient accuracy and quality of machining, taking into account high productivity and at the lowest economic cost. This solution is because increasing the capacity of equipment and using high-cost processing methods and expensive tooling is an extensive way to solve the above problems.

An effective solution to the problem of high-performance machining of difficult-to-machine high-alloy steels and alloys is the so-called “hot” machining [8–10]. The basis of such an operation is the preliminary softening of the workpiece by preheating, which reduces the shear strength [8, 10]. This results in a reduction in the cutting performance of hard-to-machine materials without the need for significant energy costs, expensive tools, etc. It is particularly noteworthy that this processing method can be implemented on conventional machine tools, which does not increase the cost of the product and does not require major reorganization of the existing production. Turning with Preventive Heating (TPH) of the workpiece is commonly used to manufacture gears, roller and ball bearings, automotive components, injection pump parts, hydraulic machine components, and other products that use parts made of high-alloy materials. The effect is particularly good when turning and milling structural high-strength alloy steels of the pearlite-martensitic class, which are processed by thermal cycling in the material of the layer to be cut, which ensures the state of supercooled austenite at the time of cutting.

Preventive heating allows realizing the following advantages [11, 12]:

– the presence of intense local heating, which softens only the workpiece material in the chip formation zone, does not affect the appearance of additional residual tensile stresses, since the treated surface of the workpiece remains relatively cold and metallurgically intact;

– increased stability of the cutting tool due to reduced power and frictional loads on the cutting blade;

– cutting force is significantly reduced as a result of a decrease in the shear strength.

– energy consumption is lower;

– the intensity and speed of material removal increases, so there is a high productivity of machining;

– the surface quality is better compared to traditional methods since the forming process occurs with more plastic material in the workpiece, which eliminates the formation of a zone damaged by thermo-deformation microcracks and intercrystalline defects [11].

The analysis of the above advantages gives grounds to assert that hot turning has significant capabilities in comparison, first of all, with the technology of circular grinding. This method is the best alternative to the proposed innovative turning with preventive heating of the workpiece. Several scientists [13–15] argue that the metal removal rates (productivity) of HMW are approximately 4–6 times higher during turning than during grinding. In addition, during turning, it is possible to achieve lower microroughness in the range of Ra from 0.1 to 0.4 μm.

Given the ever-increasing restrictions and requirements associated with the implementation of the Sustainable Manufacturing concept [16], the technology of the fuel-jet lathe is more environmentally compatible, as it allows for dry cutting without the use of lubricants and coolants that seriously pollute the environment and require the use of expensive methods of disposal of these harmful products.

However, attention should be paid to some disadvantages and problems of implementing the TPH technology, namely [13–15]:

– the increased difficult-to-control temperature in the cutting zone makes it difficult to ensure the accuracy of the geometric size due to thermo-deformation "jumps" caused by the instability of the linear expansion of the workpiece;

– the need to modernize the workpiece and tool clamping mechanism requires additional tooling and measuring equipment, which significantly complicates the process of implementing such technology;

– increased production costs compared to traditional machining technology;

– complexity of using the TPH technology on CNC machines;

– the increased danger of working on the machine due to the possibility of electric shock or injury due to high temperatures in the service area of metal-cutting equipment.

In [17], scientists studied the effect of the intensity of the external heat flux and cutting modes (speed, feed, and depth of cut) on the efficiency of TPH technology. The authors note that the wear of the tool's side surface decreased by 34 % compared to conventional machining. Studies [18] have proven the effectiveness of implementing the technology of preventive heating of the titanium alloy cutting zone (only up to 300 °C) on its machinability, reducing cutting forces, increasing the stability of the cutting tool, and improving the roughness of the machined surface. However, work [19] proved that plasma heating of the cutting zone worsens tool life despite a significant reduction in cutting forces. The author explains that heat treatment does not necessarily reduce tool wear. However, at high cutting temperatures, diffusion, corrosion, and plastic deformation dominate. Depending on the materials being machined and the cutting parameters, the thermal effect on tool wear has opposite effects. Depending on the temperature, wear can be of either mechanical (abrasive) or chemical (diffusion) origin, depending on the physical and chemical properties of the materials being processed. For example, high cutting temperatures, on the one hand, reduce material stresses, but, on the other hand, activate chemical reactions between the tool and the material.

Davami and Zadshakoyan [20] studied tool temperature and surface quality during hot machining of AISI 1060 using an uncoated carbide insert. The experimental results proved that the surface roughness during hot machining was lower compared to the classical turning technology, provided that the cutting zone was cooled. The authors of [21, 22] proved that the stability of a cutting tool can be significantly increased by flame heating of the material of a pre-hardened workpiece.

Other researchers [23, 24] have concluded that TPH technology is effective for cutting chromium-nickel steels and alloys. The purpose of such studies was to analyze the chip geometry, cutting force, cutting tool wear, and operational parameters (roughness and microhardness) during the machining of the workpieces of Inconel 718, 625, and Monel-400 nickel alloys. The authors draw the following conclusions from the results of these studies:

– as a result of preventive heating, the stability of the cutting tool increased significantly. Moreover, the tool life cycle when machining Inconel 718 was shorter compared to Inconel 625 and Monel-400, which is due to the low thermal conductivity and high hardness of Inconel 718 compared to Inconel 625 and Monel-400;

– analysis of the geometric parameters of the chips obtained during the "hot" machining of the Inconel 718 workpiece showed that they are spiral, which creates problems with their crushing, unlike the straight chips formed during the machining of Inconel 625. The most convenient in terms of the conditions for removing the chopped chips from the cutting zone was the continuous segmental chip from machining Monel-400;

– the wear pattern of the cutting tool at a cutting zone heating temperature of up to 600 °C, which was used for machining Inconel 625, was notched wear, and for Inconel 718 and Monel-400, the damage was crater and diffusion type, respectively;

– the length of chip-tool contact during the machining of Inconel 718 was shorter than during machining of other chrome-nickel materials;

– the microhardness parameters of the surfaces treated under conditions of heating to 600 ℃ for all chromium-nickel alloy workpieces are 15–20 % lower than those obtained by processing the same materials under traditional cutting conditions at room temperature.

Paper [25] reports the results of a study of the life of a tool used in TPH technology for cutting a workpiece made of austenitic manganese steel. The author concluded that tool life is proportional to the workpiece temperature up to 600 °C and inversely proportional to the cutting speed. These results indicate that hot processing allows for higher cutting speeds at a given tool life. Melhaoui's research [26] also confirms the effect obtained from heating the workpiece to increase the tool life cycle. It has been proven that this technology helps to reduce the wear of the front surface of the edge by 80 % and reduce the area of craters by 60 %.

Taking into account the combination of the process of mechanical fracture of the workpiece material with the influence of the thermal softening phenomenon and, as a result, a decrease in shear stress, the most effective theoretical basis is Computational Fluid Dynamics (CFD) [27]. The main provisions of this theory involve a systematic analysis of heat transfer processes, material flow, and related phenomena, such as chemical reactions, using computer modeling. CFD is an emerging branch of engineering design that integrates the discipline of fluid mechanics/dynamics with mathematics as well as computer science, as shown in Fig. 1 [27].

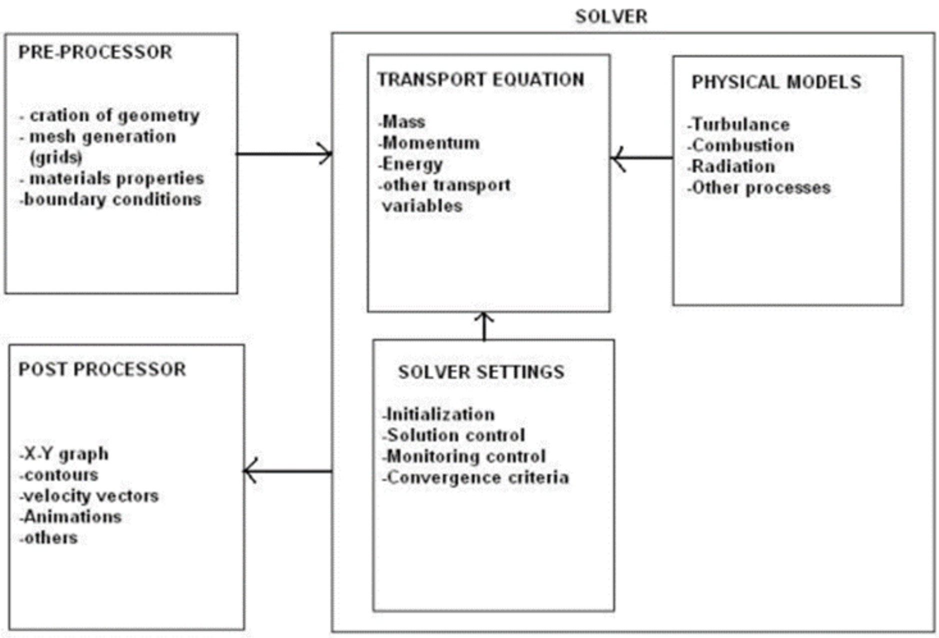

Fig. 1. The interconnectivity function of the three main elements of CFD analysis [27]

A problem-oriented analysis of the advantages and disadvantages of implementing TPH technology requires a comprehensive study of the features of the material fracture mechanism, the influence of technological indicators on the formation of parameters of accuracy, roughness, stress-strain layer of the workpiece, technical and economic analysis of innovations, etc. This article is devoted to some aspects of such research

Technological and Structural Features of Machining Workpieces with Preventive Heating of the Cutting Zone

The main difference between TPH technology is the availability of a mechanism for supplying additional heat to the cutting zone. An important stage in the design of a hot-cutting operation is the correct heating method and heating intensity for processing specific difficult-to-machine materials so as not to damage the workpiece surface and cutting tool. The heating area or zone should be as small as possible. This allows for more correct control of the heat flow, reduces additional energy costs, and localizes the area where harmful thermal deformations occur. On the other hand, the heating should not be deep enough to ensure effective softening of the material and reduce shear stress. In addition, it is known [2] that structural and phase changes occur in the workpiece material as a result of high temperature. Therefore, overheating of the cutting zone is always undesirable and should be avoided. On the other hand, insufficient heat load intensity leads to a decrease in machining performance, inefficient energy consumption, and deterioration of the machined surface quality.

In mechanical engineering, various schemes for the implementation of the TPH technology are used:

– flame heating (oxygen-acetylene, oxygen-liquefied flame) [15, 22, 28];
– induction heating [29];
– plasma heating [30];
– laser heating [31];
– electric arc heating.

Thus, this classification allows us to identify two types of heating. Plasma, laser, and flame heating are considered local heating, while induction heating and electric heating are called volumetric heating because they heat the entire workpiece, not a part or section of it. Each of these methods has its advantages and disadvantages, which will be analyzed below.

The TPH technology is best realized as a result of machining metal with a single-blade cutting tool and specifically for difficult-to-machine materials with a Rockwell “C” hardness greater than 45 (but usually in the range of 58-68 HRC). It is believed [25] that workpieces made of such materials first undergo a heat treatment process, and then turn.

The most common and quite economical method of heating the workpiece in a TPH is induction heating technology [29]. This method allows one to quickly achieve high, controlled, and stabilized temperatures. The cutting scheme is complemented by a special device that includes a semicircular enveloping inductor (Fig. 2).

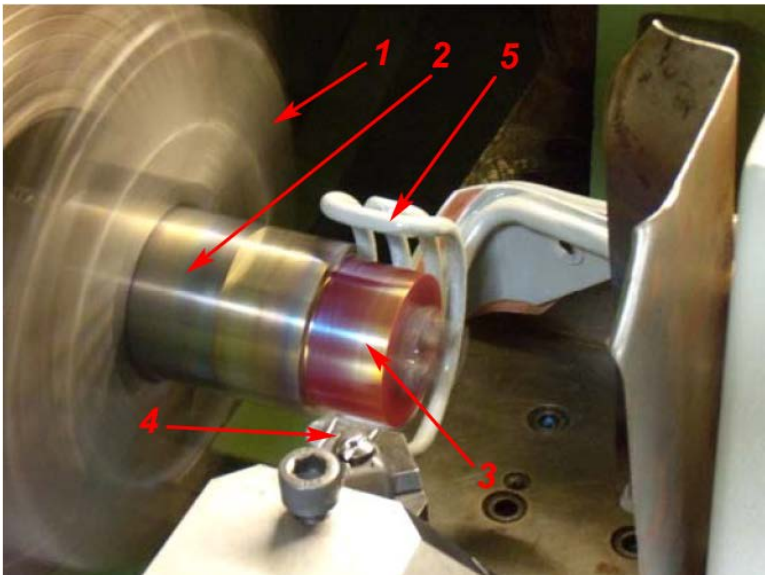

Fig. 2. An example of induction heating of a workpiece:
1 – machine spindle; 2 – workpiece; 3 – heating zone; 4 – cutting tool; 5 – inductor

Another common method of preventive heating of workpieces is plasma heating. The biggest problem in implementing this method is the volumetric effect of temperature not only on the cutting zone but also on the nearby areas of the part. This can lead to negative structural and phase changes in the surface layer of the part, burnout of alloying elements, and the appearance of residual tensile stresses. For example, during the implementation of TPH technology for machining titanium alloy, the α and β phases of this material change their structure. With subsequent rapid cooling of the surface, cracks appear, which significantly reduces the fatigue strength. Paper [32] shows the results of a study of the effect of temperature on the structure of the titanium alloy Ti-5553. At room temperature, the titanium alloy has a β metastable structure. This structure evolves into an (α + β) structure from the moment of crossing the β-transition at a temperature of about 845 °C. The mechanical and thermal stresses caused by processing cause the surface layer of the material being processed to expand. During heating with a concentrated plasma arc, the heating conditions can vary significantly depending on the power of the plasma arc and the speed of its movement relative to the workpiece. When a melting groove is formed on the cutting surface, the cross-section of the layer to be cut can be significantly reduced, which leads to a decrease in cutting forces, while the calculation of the temperature change in the layers of the layer to be cut adjacent to the surface to be treated should be carried out based on the absence of hardened structures on the surface to be machined.

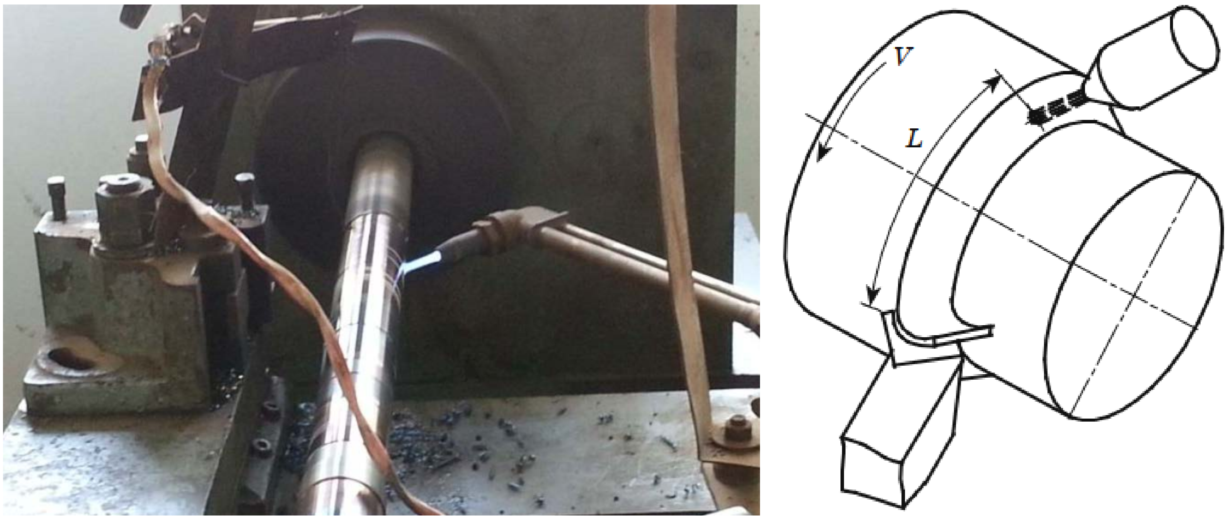

Fig. 3. Example and scheme of implementation of TPH technology using plasma heating of the cutting zone

Another effective method of preventive heating of the workpiece is the laser method [31]. The difference between this method and plasma heating is the use of a heat flux of higher density and concentration. Thus, heating occurs without any contact with the workpiece and can be easily compatible with machining. This makes it possible to raise the temperature of the titanium alloy to 1000 °C in just 2 minutes. What's more, it poses no hazards, as only the workpiece is heated and the thermal radiation remains very low. In terms of cutting force, all studies on preventive laser heating show a reduction in specific cutting force. For example, the reduction in cutting force of AISI 4130 steel as a result of using TPH technology was approximately 20 % [33].

From a technological point of view, the introduction of TPH technology can be effective in 2 main cases. First, this particular machining method can replace economically unprofitable grinding, providing high accuracy and roughness (roundness accuracy of 0.5–12 μm and/or surface roughness Rz 0.8 – Rz 7.0 μm [32]). Secondly, preventive heating can provide high productivity during the machining of hard-to-machine (including heat-resistant and complex-alloyed steels) in roughing operations. However, circular grinding is considered to be more effective for finishing operations where shape and dimensions are critical.

An important factor in the implementation of TPH technology is the logical problem-oriented choice of a tool. Moreover, in this case, attention should be paid to both its geometry and the choice of tool material [21, 25]. The most suitable tool materials for the implementation of the TPH technology are cermets and cubic boron nitride (CBN). Additional requirements for the material of the cutting blade are heat resistance, high current conductivity (in the case of using electrocontact heating of the cutting zone), and sufficient strength for machining high-strength material in complex thermodynamic conditions. Moreover, CBN is the material of choice because it eliminates the need for grinding. The main advantages of this material are a significant reduction in production costs, increased machining performance, and improved quality of the processed products

Simulation of the Cutting Process with Preventive Heating of the Workpiece in the AdvantEdge

Modern methods of innovative research in mechanical engineering involve a comprehensive analysis of thermodynamic, stress-strain, and load parameters of machining using analytical and simulation modeling. As a rule, such studies precede experimental research. The reason for this sequence is that:

– first, experiments are time-consuming and costly;

– secondly, during experimental studies, it is difficult or impossible to comprehensively assess all the physical and mechanical factors that form a complex picture of cutting, and the results of simulation modeling can provide a systematic analysis of all the most important cutting parameters;

– thirdly, some important machining parameters are so transient and dynamic that their material fixation is practically impossible;

– fourth, 2D or 3D modeling of the cutting zone allows to observation the development of the stress-strain and thermodynamic cutting pattern “in the depths” of the workpiece, which is impossible to realize in experimental conditions;

– fifth, simulation modeling can be used to observe the formation of a zone of residual stress and strain parameters of the machined layer of the workpiece, which is extremely difficult to implement in the production conditions of the experiment.

Therefore, the following research plan is a more effective algorithm for studying innovative cutting processes.

1. The purpose and objectives of the research are formulated, and the variation limits and boundary conditions of the research are determined.

2. A simulation model is developed, all input parameters are determined, and force, thermodynamic, and stress-strain parameters are calculated in one of the problem-oriented software products (DEFORM 2/3D, AdvantEdge, LSDyna, or ABAQUS).

3. A comprehensive analysis of certain indicators is carried out and a qualitative cutting picture is formed.

4. Tasks for experimental research are formulated.

5. Special equipment is manufactured and research is ongoing.

6. The results of simulation studies and experiments are compared and the simulation models (fracture criteria, deformation models, etc.) are adjusted following the actual test results.

7. Simulation studies are repeatedly performed and correlated with the results of the experiment.

Only such a procedure for applying the mathematical apparatus and real indicators can be considered effective and hope for a high level of adequacy of analytical and simulation modeling. An effective specialized software product for simulation modeling of fuel dispenser technology is AdvantEdge software.

The unsteady three-dimensional heat conduction equation described in partial derivatives for the case of 2D modeling used in this program has the following content:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{q(x,y,t)}{\lambda} = \frac{1}{\alpha_T} \cdot \frac{\partial T}{\partial t} \tag{1}$$

where λ is the thermal conductivity coefficient; T is the temperature; αT is the thermal conductivity coefficient, q is the heat flux; x and y are the Cartesian coordinates of discrete points of the 2D finite element model; t is time

This equation is subject to the following boundary conditions in the region exposed to the environment:

$$-\lambda \frac{\partial \mathrm{T}}{\partial \mathrm{t}} = k\left(T - T_E\right) \tag{2}$$

where k – is the heat transfer coefficient.

The problem-oriented advantages of AdvantEdge™ over other similar cutting process modeling software (Deform 2/3D, ABAQUS, LSDyna [34]) are due to some features of the chosen system, namely:

– AdvantEdge (a product of Third Wave Systems Co.) is designed exclusively for simulating cutting processes, unlike the above programs, which are universal. This feature of AdvantEdge ensures high efficiency and simplicity of input data for simulation, allows the use of simplified problem-solving algorithms for generating degenerate meshes in FEM systems (which creates great difficulties for the full functioning of Deform and LSDyna software).

– This system allows you to set the initial temperature in the molding zone simply and efficiently. In the other programs mentioned above, it is also possible to program this state of the workpiece, but it is a complicated procedure. An example of setting the “initial temperature” parameter is shown in Fig. 4.

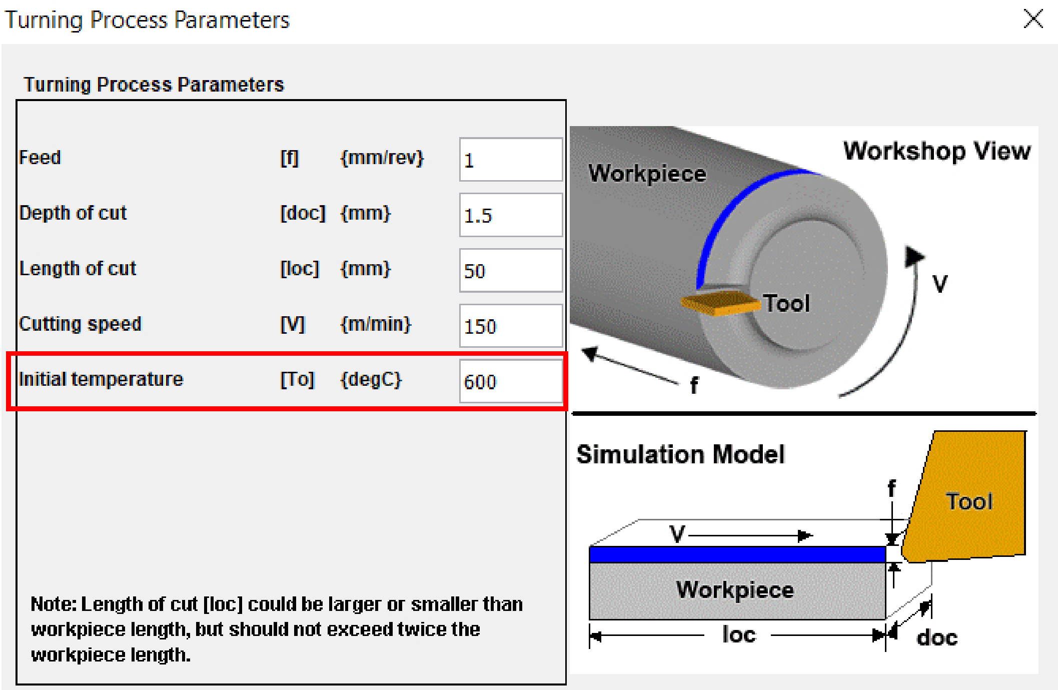

Fig. 4. The process of setting the input process parameters, including the initial temperature of the workpiece in the cutting zone (highlighted in red)

– AdvantEdge™ allows the use of previously created tool meshes in cutting simulations. This enables saving a significant amount of time in tool mesh creation. This tool reuse capability is particularly useful when performing DOE analyses using the same tool multiple times. Based on the data available at https://thirdwavesys.com/advantedge-v7-8-release, reuse of STEP tool meshes can save up to 90 % of the time spent on mesh construction each time the tool is used for a new simulation (Fig. 5).

– The AdvantEdge™ software has an extensive library of machining materials and solid-state tool models (13 turning and 6 grooving inserts already separated into elements using the intelligent mashing system) from Sandvik Coromant, which greatly simplifies the process of setting input data (Fig. 6).

Processes	First case meshing time (min)	Imported tool mesh case time (min)	Improvement
Solid Endmill 1 (Chip breaker)	239	39.96	6x
Solid Endmill 2 (Standard 4 Flute)	93.46	3.6	25x
Skiving (Custom process)	37.65	1.12	33x
Tapping	15.02	8.2	2x
Indexable Drilling	4.28	2.48	2x

Fig. 5. AdvantEdge™ Tool Mesh Import

Fig. 6. Solid-state models of Sandvik Inserts

The process of creating a cutting model includes the following steps.

Stage 1. Formation of the workpiece model. At this stage, the dimensions of the workpiece are set, the machined material is selected, and the workpiece model is mashed into finite elements (Fig. 7, 8).

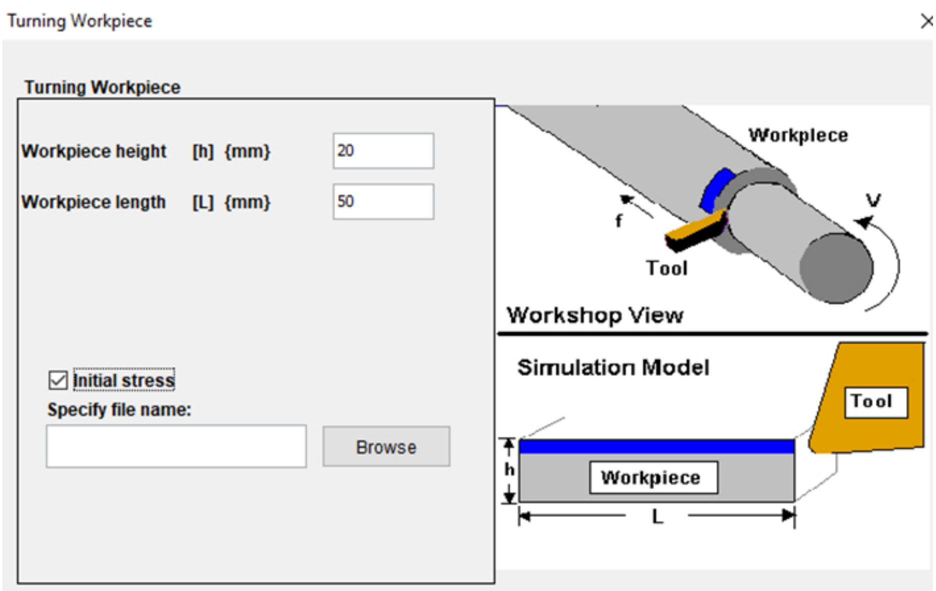

Fig. 7. Formalized representation of the workpiece model in the AdvantEdge software

It is proposed to use the chromium-nickel alloy Inconel 718 (ISO 15156-3 (NACE MR 0175)) as the material under study. The chemical composition and mechanical characteristics of this material are shown in Fig. 8). Inconel 718 is a dispersion-hardening alloy of nickel, chromium, and iron-containing niobium and molybdenum. It has high impact strength and corrosion resistance. In718 has high strength at high temperatures up to 700 °C (1290 °F) and is a difficult-to-cut material.

Stage 2. Formation of the cutting tool model.

This stage involves setting the tool geometry (Fig. 8), selecting the tool material, and mashing the blade into finite elements (Fig. 9).

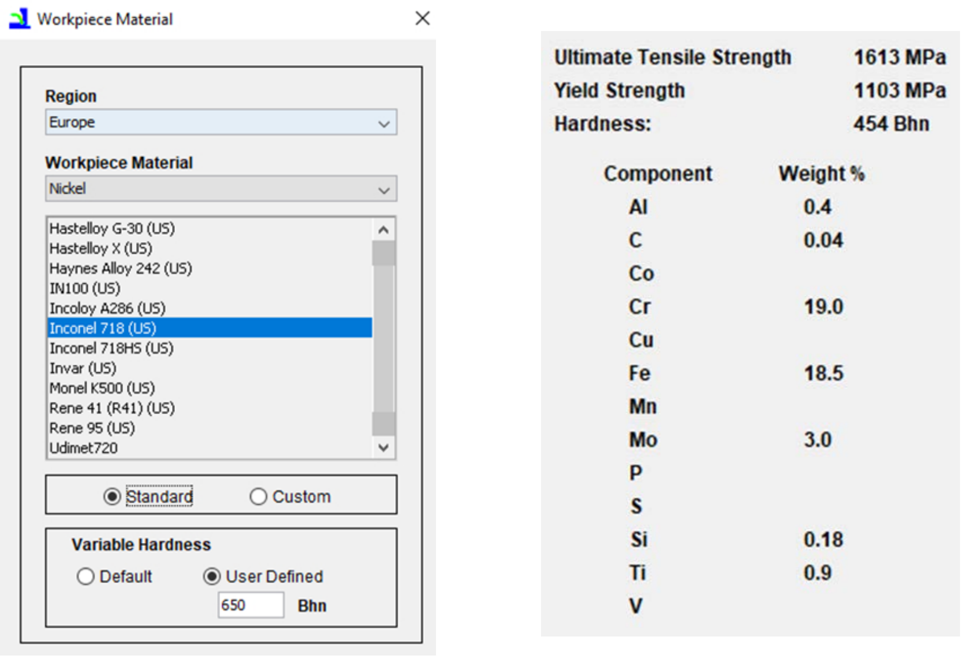

Fig. 8. Selecting the workpiece material in AdvantEdge

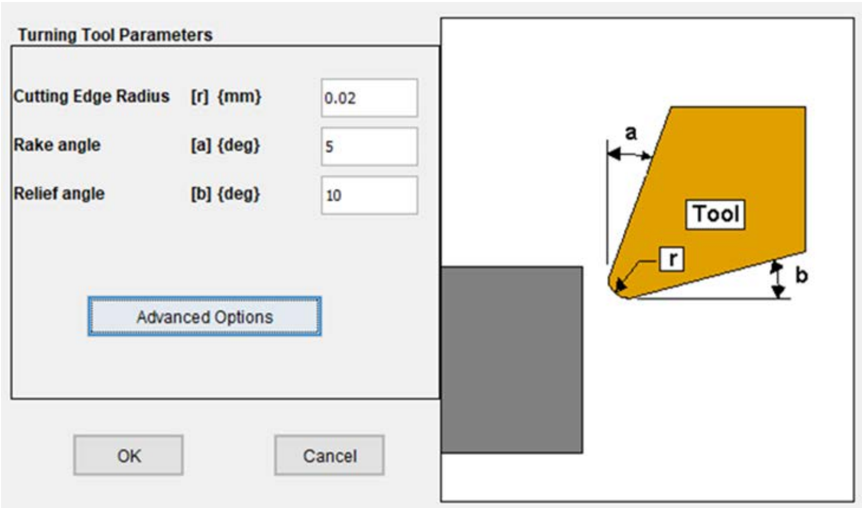

Fig. 9. Formalized representation of the cutting tool model in the AdvantEdge

The change in the size of Mesh Tool Elements from the minimum size (0.02 mm) to the maximum size (0.4 mm) is because a higher density of FEA meshes is required in the chip formation zone, where the highest force and thermodynamic loads are applied (Fig. 9). In other (lower priority for study) areas of the tool, a high mesh density is not required, as it only leads to a significant increase in simulation time, but does not contain research value.

Stage 3. Formation of a database of cutting process parameters.

At this stage, the main machining parameters are set (Fig. 4), namely: feed rate (set constant for all model experiments *f* = 0.1 mm/rev); cutting speed (set constant *V* = 150 m/min); depth of cut (set constant doc = 1.5 mm). In addition, for different experiments, the initial temperature in the cutting zone T0 is added in the range from 20 ℃to 700 ℃.

Stage 4. Simulation modeling of the cutting process.

During this stage, the cutting process is simulated and a database of the load, thermal, and stress-strain states of the workpiece and tool in the part-forming zone is created. As shown above, the cutting conditions, materials, and geometry of the workpiece and tool remain constant, except for the change in the initial temperature in the cutting zone T0 in the cutting zone: 20 ℃, 100 ℃, 200 ℃, 400 ℃, 600 ℃, and 700 ℃. The simulation results obtained in the AdvantEdge™ program are processed using the Tecplot 360 software package. The software is designed for engineering graphing with a wide range of 2D and 3D tools, the formation of a database of the stress-strain and thermodynamic state of the workpiece during machining with an edge tool, and is equipped with a user-friendly interface for visualizing research results and transferring data to statistical data analysis packages. An example of the graphical interpretation of the study results is shown in Fig. 11.

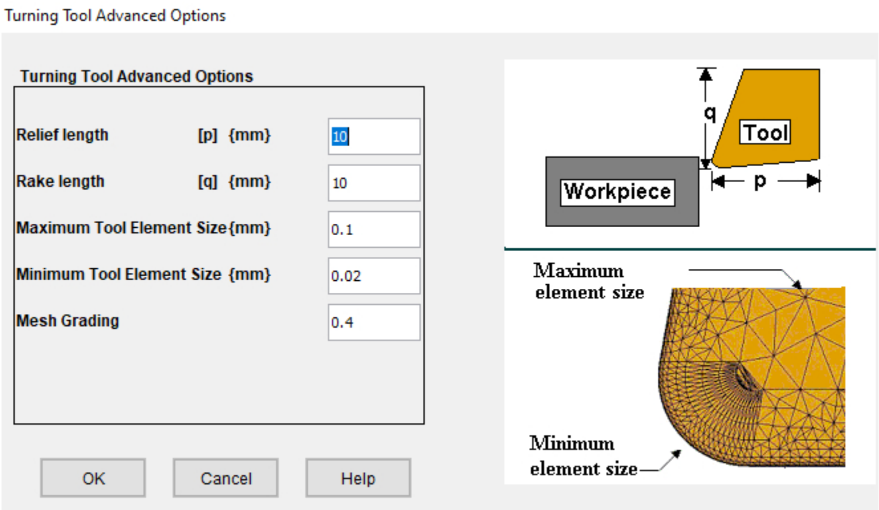

Fig. 10. Mashing the cutting tool model into elements with different densities in AdvantEdge™ software

Stage 5. Statistical analysis of the results of simulation studies.

The database generated at the modeling stage is subject to statistical analysis in the EXCEL program. The graphical relation of the cutting forces of Inconel 718 chromium-nickel alloy under the following cutting parameters: feed rate *f* = 0.1 mm/rev, cutting speed *V* = 150 m/min, cutting depth doc = 1.5 mm on the initial temperature in the cutting zone T0 is shown in Fig. 11

The analysis of these graphs proved that TPH technology can be an effective way to increase the efficiency of machining hard-to-machine materials (for example, Inconel 718). Moreover, we can conditionally distinguish 3 zones of influence of the initial temperature on the reduction of cutting force. Zone 1 (marked in yellow) is limited by the heating temperature of the cutting zone to 200 °C. A slight effect on the cutting force characterizes this zone. For example, when machining Inconel 718, the cutting force is reduced by only 4.4 %. Zone 2 (marked in blue on the graph – Fig. 11) is in the range of 200–500 ℃ and is characterized by a moderate thermal effect on the cutting force. During machining, the cutting force decreases by 17.6 %. Zone 3 (marked in pink on the graph – Fig. 11) is the zone of intense influence of the initial temperature on the cutting force. This zone starts at approximately 500 °C. At a cutting zone heating temperature of 700 °C, the reduction in cutting force is 37.5 %. This figure is very high and needs to be verified by a full-scale experiment

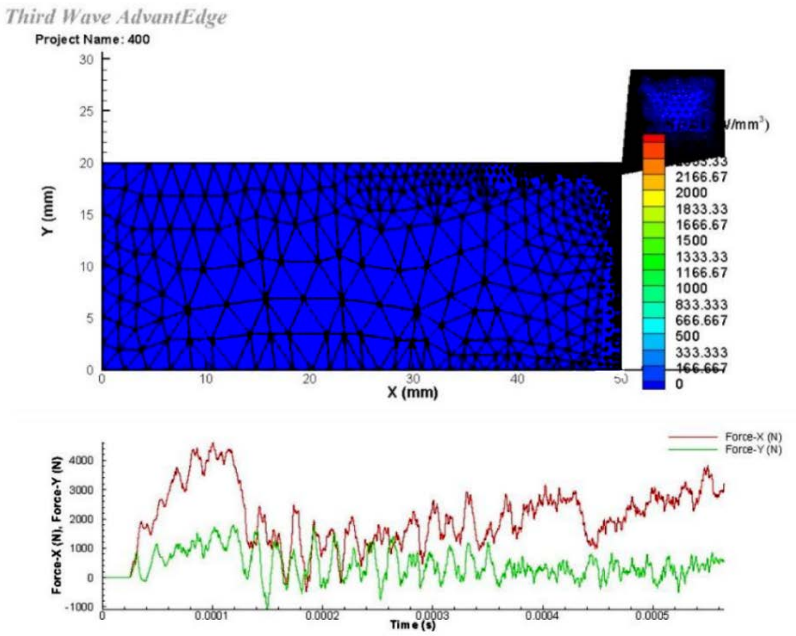

Fig. 11. The result of the simulation of the cutting process in the Tecplot 360 system

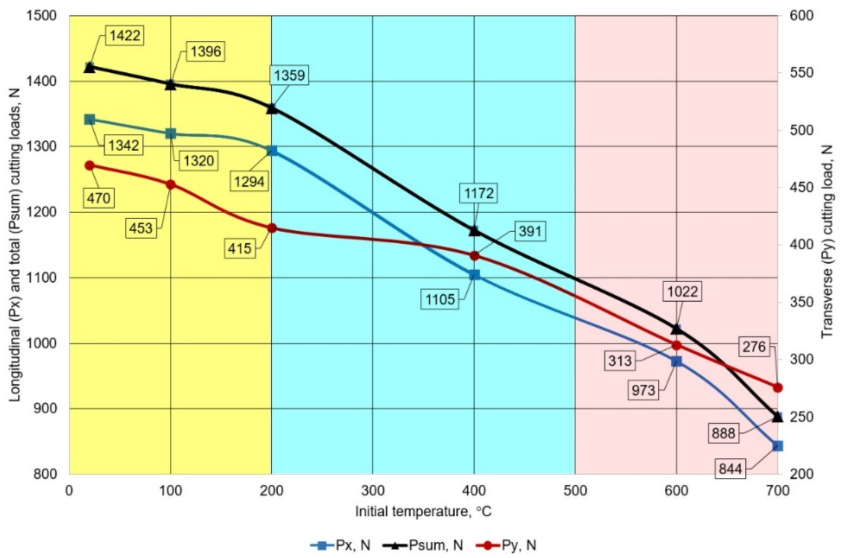

Fig. 12. Graphical relationship of cutting force of chromium-nickel alloy Inconel 718 with the initial temperature in the cutting zone T0

Conclusions

1. The problem of increasing the efficiency of machining hard-to-machine materials (heat-resistant and stainless steels and alloys, high-alloy steels with a high content of tungsten, molybdenum, chromium, etc.) is extremely relevant for Ukraine, given the need for rapid restoration of the military and defense engineering complex. Opportunities to increase labor productivity by increasing cutting modes, using expensive tool materials, etc. are an extensive area of innovative improvement and are accompanied by high labor costs and the need to provide expensive equipment. A more effective method of improving

machining operations is to use the Turning with Preventive Heating (TPH) method of the workpiece. This technology is characterized by the low cost of innovative equipment modernization, the ability to use universal tooling and the high efficiency of implementation results.

2. Technological and structural features of machining workpieces with preventive heating of the cutting zone provide for a mechanism for supplying additional heat to the cutting zone. An important stage in the design of the “hot cutting” process is the correct heating method and heating intensity for processing specific hard-to-machine materials so as not to damage the workpiece surface and cutting tool. Moreover, the heating area or zone should be as small as possible, which allows for more correct control of the heat flow, reduces additional energy costs, and localizes the area of harmful thermal deformation. On the other hand, the heating should not be deep enough to ensure effective material softening and reduce shear stress.

3. An important stage in the preparatory work for the implementation of the TPH technology is the study of the force, thermodynamic, and stress-strain state of the workpiece arising from the complex action of mechanical loads associated with the displacement of the processed material during cutting and thermal loads generated by the HFR technology. This is necessary because the thermal effect on the workpiece in the forming zone creates some problems that can harm the condition of the surface layer of the processed product (e. g., residual tensile stresses, surface defects, and burnout of alloying elements). Such changes can hurt the subsequent operational properties of the machined part. The most effective research method is simulation modeling of the cutting process. A preliminary analysis of existing machining simulation programs showed that the most convenient program is AdvantEdge^{TM}.

4. The analysis of the results of the simulation of the cutting process of a workpiece of chromium-nickel alloy Inconel 718 under the following cutting parameters: feed rate – 0.1 mm/rev, cutting speed – 150 m/min, cutting depth – 1.5 mm proved that HF technology can be an effective tool for improving the efficiency of machining hard-to-machine materials. Moreover, we can conditionally distinguish 3 zones of influence of the initial temperature on reducing the cutting force. Zone 1 is limited by the heating temperature of the cutting zone to 200 °C and is characterized by a slight effect on the cutting force (the cutting force is reduced by only 4.4 %). Zone 2 is in the range of 200–500 °C and is characterized by a medium thermal effect on the cutting force (cutting force is reduced by 17.6 %). Zone 3 is the zone of intense influence of the initial temperature on the cutting force. This zone begins at approximately 500 °C (a reduction of 37.5 % in cutting force). However, this data requires additional verification using a full-scale experiment.

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