FINITE ELEMENT ANALYSIS OF STAINLESS STEEL AISI 420 CUTTING PROCESS TO PREDICT CUTTING FORCES AND TEMPERATURE DISTRIBUTION IN DURATOMIC-COATED CUTTING TOOL

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Abstract. The machining of stainless steel and other hard-to-machine materials in our days has become possible with the development of new cutting tools such as substrates and coating technologies. However, turning on high speeds results in high temperature and stress development at the chip-tool and workpiece-tool interfaces leading to faster tool wear, distortion of the workpiece surface finish, and increased tooling cost for processing the same amount of the parts. It is evident that the cost-effective application of this technology requires a fundamental understanding of the relationships between process variables (cutting forces, tool stresses, and temperatures developed) and performance measures (tool wear, tool life, and surface finish). Thus, modelling the high-speed machining (or HSM) process to predict process variables is an essential development to improve the cutting tool design and optimize the cutting conditions. During the process of changing cutting parameters, also the result might be different. It is possible to receive not appropriate machined surface roughness or the machining process itself (chip forming process could affect the machined result, as the cutting tool chipbreaker does not provide the recommended chip-breaking process). It is necessary to pre-define the experimental result using metal cutting simulation software. Several CAE programs are possible to be used for this process. The idea of this paper is to represent the theoretical simulation part of the research in the metal cutting process on the turning method, using Third Wave Advant Edge finite element (FEM) software. Today such methodology has become more popular. Calculation of areas of different physical dimensions using the finite element method (FEM) in the field under study requires determining the materials of the elements and their properties. First, deformation tasks determine the plastic properties – the modulus of elasticity and the Poisson coefficient. When performing 2-D analysis, it is possible to create the necessary geometry of the cutting tool in cross-section and enter all the material properties. The basic principle of analysing the finite element method is to divide the complex task into several simple ones and solve it with maximum accuracy. FEM is used for the particle formation process, temperature field, cutting force, voltage, and residual deformation distribution studies. In this paper the theoretical part of some machining process options and solving variants are given. In the practical part - the simulation result before practical experiment is represented.

Keywords: stainless steel, turning, finite element method, simulation.

Introduction

Computer simulation using the finite element method is much more economical than expensive experimental studies and allows obtaining several cutting process parameters that are inaccessible for direct measurement: machined surface roughness, machining process temperature simulation - thermal field in the tool and workpiece, stress and strain fields. Thus, simulation can be used to control the cutting process: to provide product quality parameters, for example, residual stresses of the surface layer, to predict the conditions for chip formation and tool wear, to determine the temperature and force characteristics. Finite elements have different properties that are determined by constants and options. For example, the cross-sectional area of the core GE is specified, but if a rope whose only task will be stretching is modelled, the appropriate option is selected. For non-bending flat GEs, the thickness and type of stress state can be specified: flat tensioned, flat deformed, or axially symmetrical. For flat, flexible GE and shell GE it is necessary to determine the thickness. The choice of the type, shape and size of the final element depends on the shape of the body and the type of stress-strain condition. The GE core is used to simulate the stress state of one axle in tensile (compressive) as well as shear or bending tasks. A flat two-dimensional GE, in the form of a triangular or quadrangular plate, is used to model a flat stressed or flat deformed state. A large three-dimensional GE, such as a tetrahedron, hexagon, or prism, serves to analyse the spatial stress state. GE in the form of a ring is used in the case of an axial symmetrical stress state. To calculate the curvature of the plate, the corresponding flat GE is taken, for the calculation of the shell, the GE of the shell is used, as well as a flat element with the ability to bend. In areas of the deformable body where significant stress gradients are expected, more detailed GE or larger elements should be used.

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For the calculation of areas of different physical sizes, using the finite element method in the study area, it is necessary to determine the element materials and their properties. In the deformation problems, first, the plastic properties must be determined - the modulus of elasticity and the Poisson's ratio. If plasma deformation is planned, it is necessary to determine the true deformation diagrams, which are approximated by a bilinear ate and a multilinear straight line. By performing a 2-D analysis, it is possible to create the required cross-sectional geometry of the cutting tool and enter all material properties. The basic principle of the finite element analysis is to divide the complex task into several simple ones and solve it with maximum accuracy. GEM is used for the research of the chip formation process, temperature field, distribution of cutting forces, stresses, and permanent deformations.

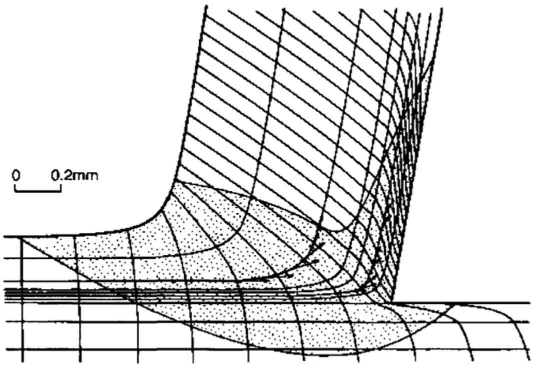


Fig. 1. **Modelling of the cutting process and division of the workpiece into elementary elements [2]**

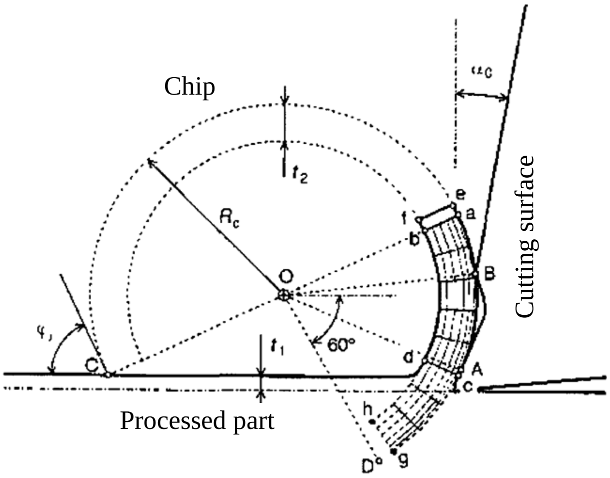


Fig. 2. **Chip formation process model:** t_1 – cutting depth, t_2 – chip thickness

Machining of stainless steels on a lathe and its features

Corrosion-resistant and stainless steel is an indispensable material for creating mechanisms, products, structures that experience high loads and aggressive environments. However, mechanical processing, including turning of stainless steels is a process that causes certain difficulties. A complete transfer of processing methods of conventional carbon steels to corrosion-resistant grades is impossible. Since this will lead to a decrease in the productivity of the process and a deterioration in the quality of the final product. The main problems in working with stainless steel are difficult chip removal, work hardening, and low cutting tool life. If earlier these obstacles were partially overcome by cutting at low speeds, today such a solution does not meet the requirements of modern industries. Therefore, engineers are constantly developing new technologies and tools that facilitate the processing of stainless steel.

If machining is performed, stainless steel will first begin to elastically deform, after which the processing of stainless steel becomes easier, as it enters the hardening stage. At this point, it can be cut only with increased effort. Ordinary steel can also survive these stages, but only high-alloyed steel has a high level of hardening.

There are several difficulties in turning stainless steels. This applies to work hardening, chip removal and tool life:

- viscosity;
- low level of thermal conductivity;
- preservation of properties;
- abrasive compounds;
- uneven hardening.

Certain difficulties during the processing of steels are caused due to the fact that steel is a rather ductile material, especially for a heat-resistant grade. That is, the chips will not break off, but will begin to curl into a long spiral.

The strength characteristics and hardness of the material remain the same even if the material is exposed to high temperatures. This is especially true for heat-resistant steel grades. It is necessary to consider the formation of work hardening, due to which the tools deteriorate rather quickly, which leads not only to damage to the cutters, but also limits the processing speed.

Stainless steel is characterized by carbide and intermetallic compounds, the size of which is microscopic. Due to their increased strength, they can be compared with an abrasive. The cutters simply begin to wear down during operation, so they need to be constantly edited and resharpened. At the time of turning steel, a lot of friction is produced, more than when working with a carbon alloy. Under the action of turning, the alloy begins to harden unevenly. If small parts are processed, it does not affect them much. However, if a shaft or large parts are being machined, this can be a problem [1-3].

Several ways to improve chip removal

Turning is a process that produces long, twisted chips that build up to make the work difficult. To remove chips from stainless steels, it is proposed to use a cutting tool with an internal coolant supply under pressure, which is especially effective for high-alloy steels. The use of such a tool provides:

- effective cooling of the cutting edge;
- chip breaking into small particles, facilitating its rapid removal from the cut zone.

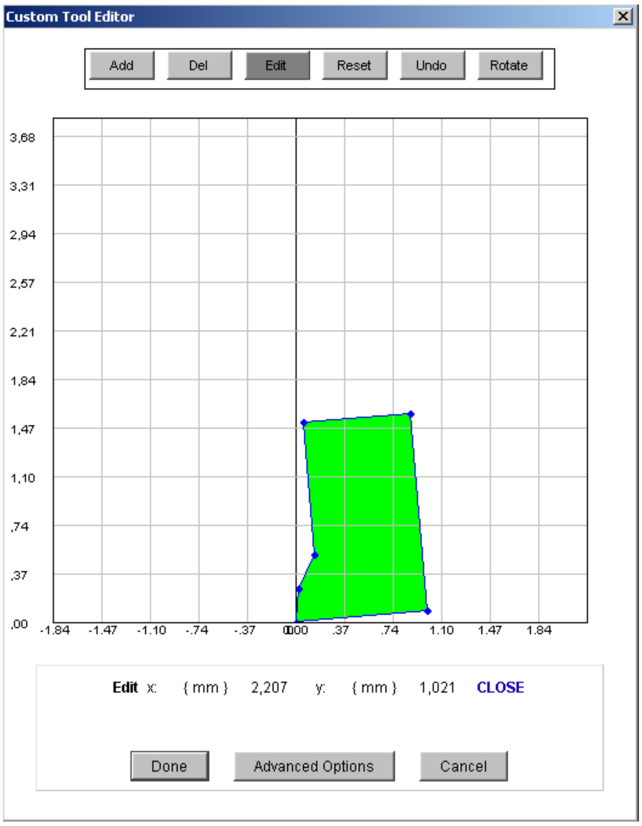
The disadvantage of this method is the high consumption of coolant. In high-precision industries and in the military industry, the most expensive and effective method is used – cooling using carbon dioxide.

An important role in the processing of stainless steel on a lathe is played by the design of the chipbreaker. Specialized tools for stainless steels should have a positive external angle that reduces self-hardening and built-up metal on the cutting edge.

Coated tools (inserts) are used to improve heat resistance and wear resistance. At the same time, CVD coatings are thicker, and they significantly increase tool life, and allow to increase cutting conditions and thus productivity. Although they are not as sharp and difficult to sharpen, PVD coatings are thinner and provide a sharp insert edge and a smooth surface. True, there is a risk of rapid wear and failure of the plate. However, PVD coatings are often used on austenitic steels. When the built-up edge formed during stainless steel machining breaks off, it can tear out some of the coating and cutting-edge particles, and thus damage the insert. The smoothness of the coating reduces the possibility of build-up, but the coating is necessary, among other things, to increase the resistance against abrasive particles of stainless steel.

Application of the finite element method for the metal cutting turning process modelling, temperature field distribution, and cutting force studies

The idea of this paper is to represent the beginning of the experimental part of the research in the metal cutting process on the turning method. The practical experiment was developed using an n-factor plan with machining parameter variations. One of the questions to study was the dry machining process, using new cutting tool geometry and coating technology called “Duratomic” [4]. As a result we studied the effect of high temperature on the tool and the resultant surface roughness R_a. But before the practical experiment it is necessary to provide simulations, to see if the result contact temperature is not out of the range. To simulate the stainless-steel cutting process before the practical experiment, a special program, Third Wave Advantedge [5], was used, based on a finite element mathematical analysis (FEM analysis). The AISI 420 stainless steel and TNMG 160412 TM-4000-MF4 Duratomic (see Figure 3) coated cutting tools were selected. In this case, the 2D geometry of the cutting insert geometry profile was created, TiN and Al2O3 coating thicknesses combination was used (which was found at the instrument manufacturer) (see Figure 4). The increase for 10% machined parameters was selected for the part’s dry machining. The machining parameters are represented in Table 1. In the simulation result, we discovered the maximal cutting temperature value in the cutting tool from 700 ºC to 1250 ºC and machined surface area (see Figure 5,6); also, the stress in the contact point and the plastic deformation of the workpiece was simulated (see Figure 7).



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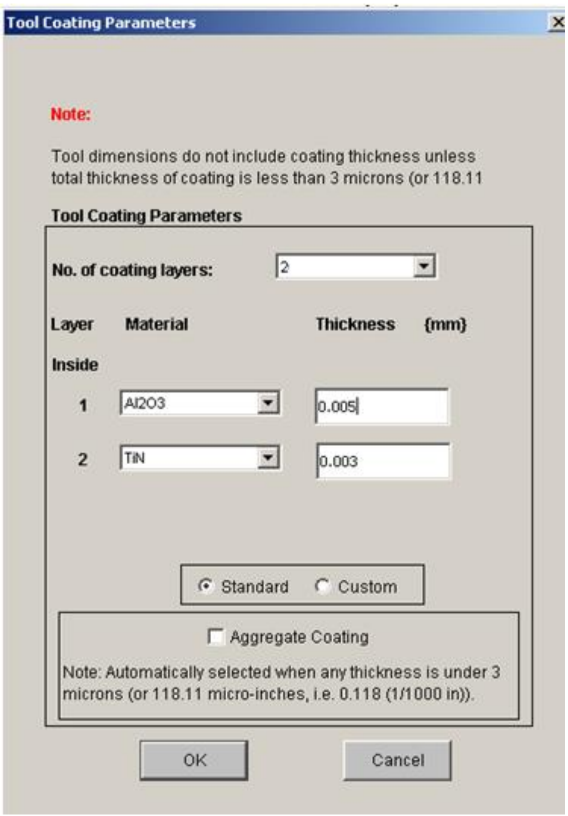

Note:

Tool dimensions do not include coating thickness unless total thickness of coating is less than 3 microns (or 118.11

Tool Coating Parameters

No. of coating layers: 2

Layer	**Material**	**Thickness (mm)**
Inside		
1	Al2O3	0.005
2	TiN	0.003

● Standard ○ Custom

☐ Aggregate Coating

Note: Automatically selected when any thickness is under 3 microns (or 118.11 micro-inches, i.e. 0.118 (1/1000 in)).

Fig. 3. **Selected MF-4 geometry development** Fig. 4. **Selected grade coating layer data**

Table 1

Simulation cutting parameter data

Machining parameter combination No.	**1**	**2**
Feeding *f*, mm·rev^{-1}	0.10	0.35
Cutting depth a_p, mm	0.5	0.5
Cutting speed, V_c, m·min^{-1}	90	150
Work area temp., °C	20	20
Machined part	AISI 420	AISI 420
Simulated temperature value, °C	700	1250

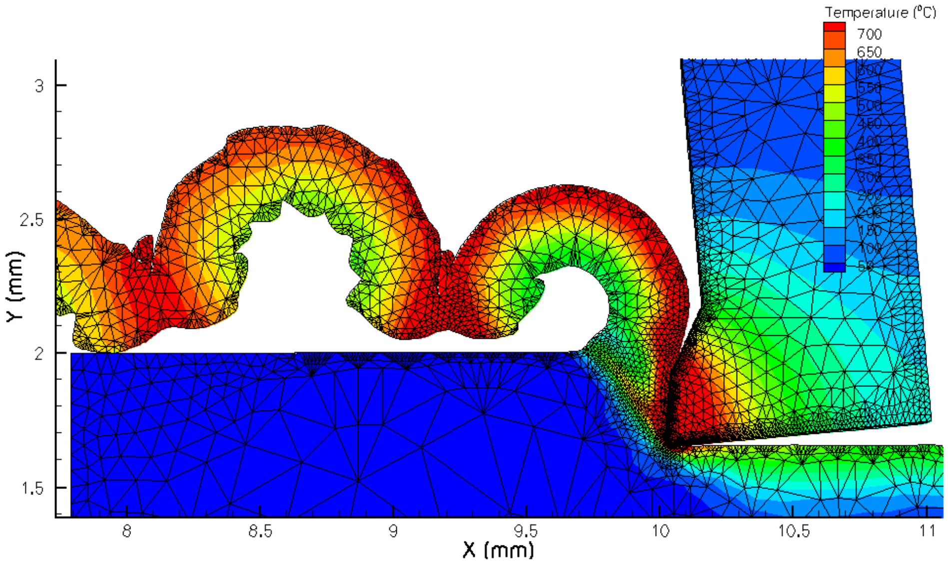

Fig. 5. **Process of chip formation and the overall view of the heat distribution field**

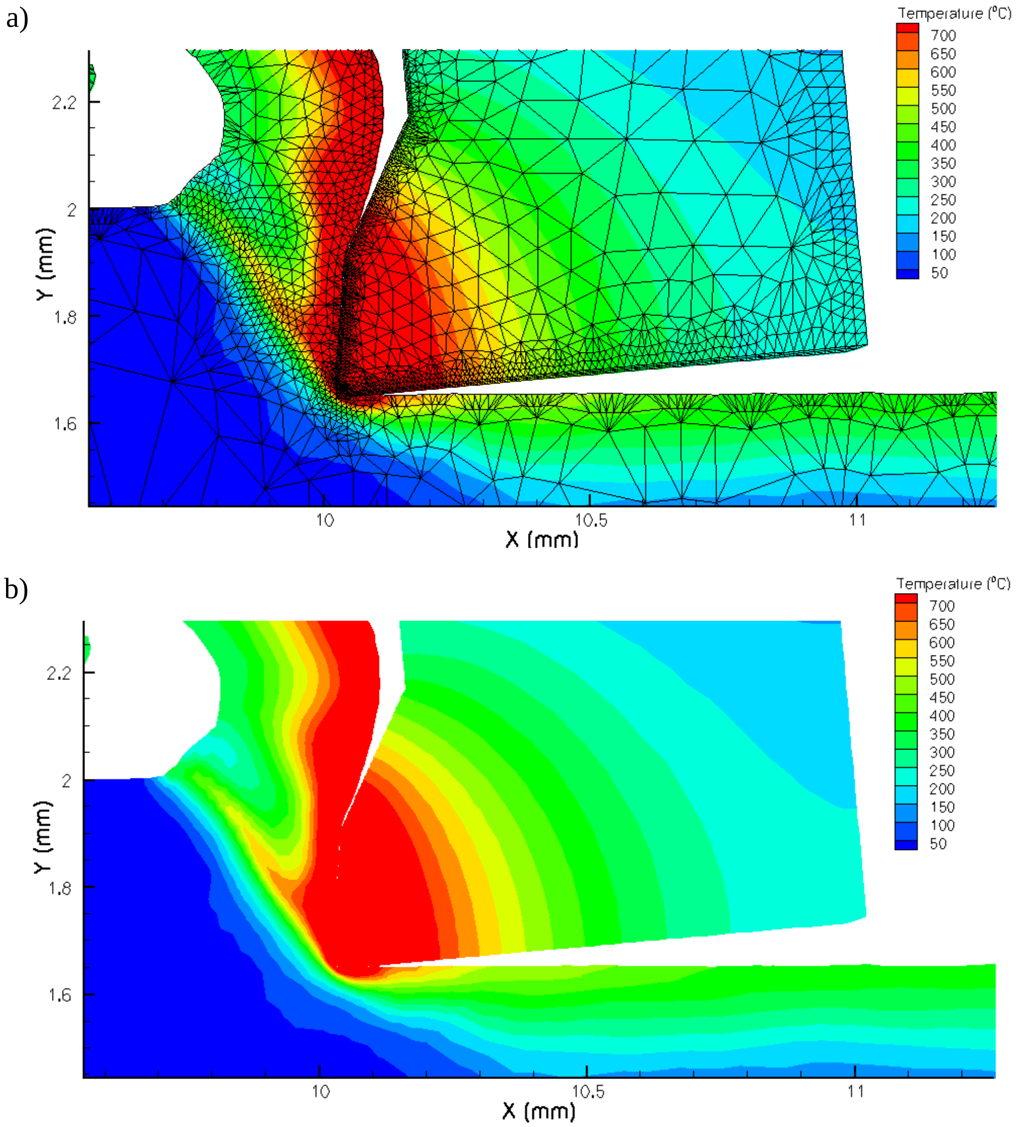

Fig. 6. **Heat distribution field modeled in the cutting process on an enlarged scale with (a) and without (b) mesh**

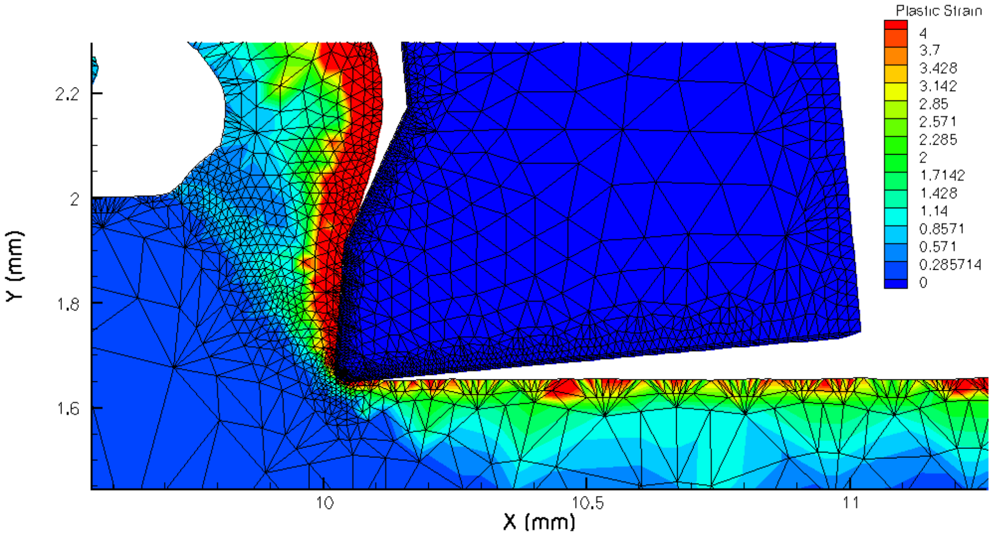

Fig. 7. **Distribution of plastic deformations modeled during the cutting process**

Firstly, the chip forming process was simulated to get information about possible chip forms in our metal cutting experiment. It is known that because of the high amount of alloy element chip control in machining, stainless steel is one of the problems to be solved. The cutting process cutting forces distribution values in the machined part and the cutting tool were received for the further theoretical study (see Figures 8 and 9). As further practical experiments showed us, all simulation results completely correspond to the practical ones.

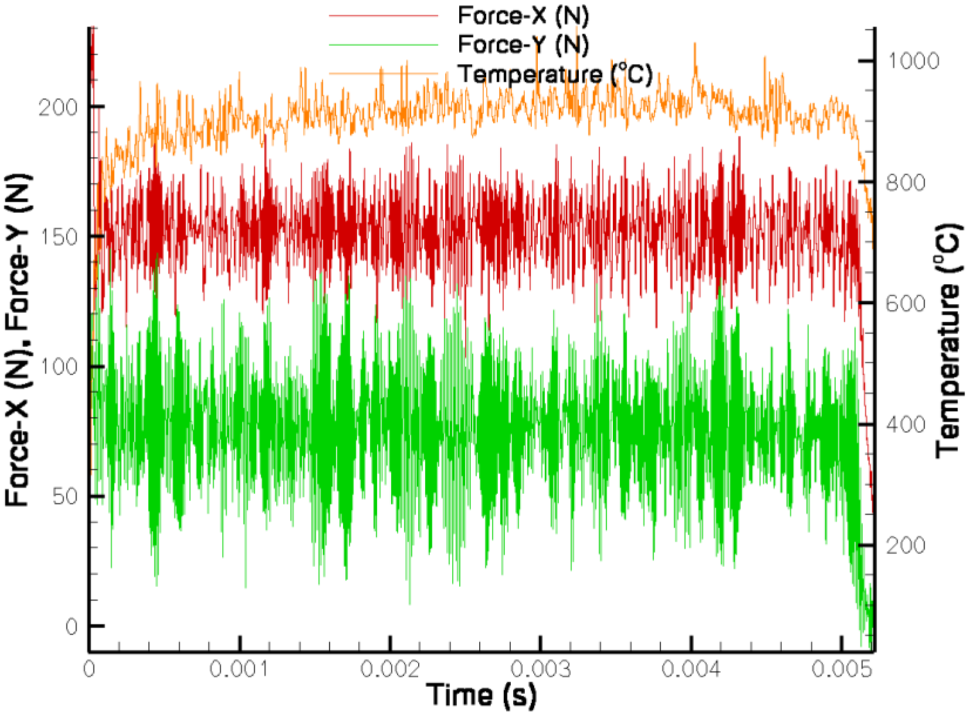

Fig. 8. **Cutting force and temperature values for the 1st parameter combination**

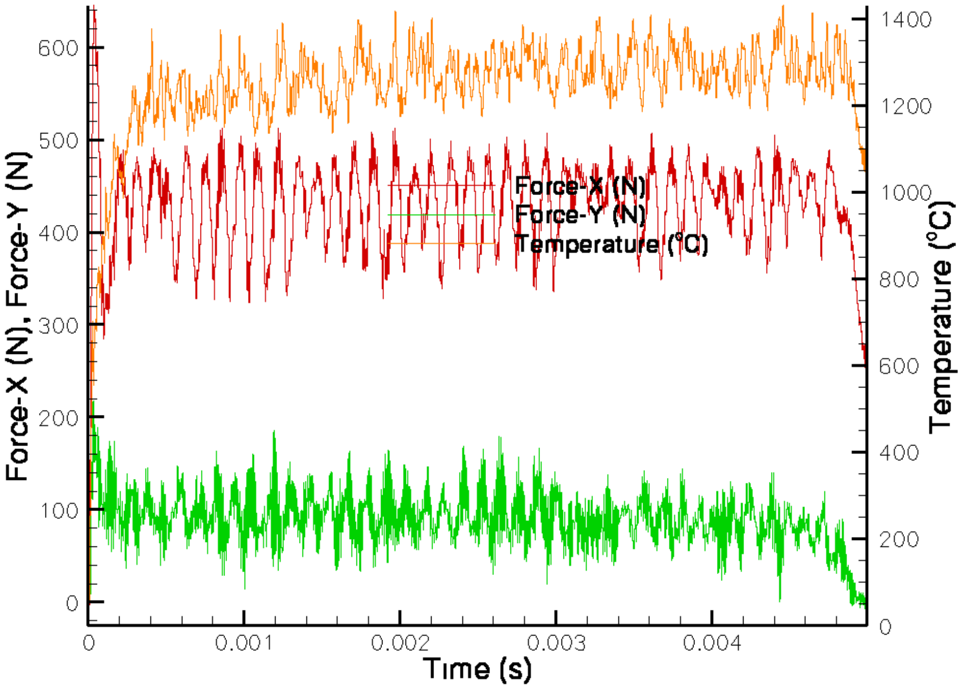

Fig. 9. **Cutting force and temperature values for the 2nd parameter combination**

Conclusions

1. Modeling of the metal cutting process using the Third Wave Advantedge program display plastic deformation and fracture of the material makes it possible to obtain the stress and strain fields of the material being processed and the tool, the thermal field of the chip and the workpiece. The results obtained are in good agreement with the data known in the literature, and later- obtained experimentally, and do not contradict the traditional provisions of the theory of cutting. The proposed modeling technique makes it possible to study the stress-strain and thermal state of the cutting process, the conditions of chip formation, and to predict the quality parameters of the surface layer. Further improvement of the modeling technique will be aimed at working out various technological cutting conditions.
2. As a result of a detailed review of the stainless steel turning process, it was found necessary to conduct in-depth studies of the stainless steel processing process.
3. Using the finite element method, as well as new research programs, the usefulness of the program “Third Wave Advantedge” required for the simulation of the metal cutting process was substantiated.
4. The methodology of selection of cutting tools is substantiated, which allows to perform experiments with different cutting speeds and feeds ensuring a stable cutting process: constant cutting force, temperature in the allowable range, chip formation and breaking process, as well as a stable treated surface roughness profile (R_a).
5. The obtained experimental results provide an opportunity for cutting tool manufacturers, such as Seco Tools AB (Sweden), in cooperation with Duroc Machine Tools (Latvia), to use them in the further development of cutting tools.
6. During the cutting process, studies using variations with combinations of cutting angles were analyzed and modulated, while allowing an increase in cutting forces to be predicted, causing greater vibration, reducing the roughness of the treated surface, and reducing the service life of the cutting tools.
7. The modulated results could be applied in a modern automated manufacturing process using artificial intelligence, or Industry 4.0, to obtain the specified quality details using the developed mathematical models and the adaptive process of metal cutting based on the cutting forces monitoring.

Author contributions

Conceptualization, Viktors Gutakovskis; methodology, Viktors Gutakovskis and Anita Avišāne; software, Natālija Mozga; writing – review and editing, Anita Avišāne and Viktors Gutakovskis. All authors have read and agreed to the published version of the manuscript.

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