Computer Modeling Application for Predicting of the Passing of the High-Speed Milling Machining Hardened Steel

Alexander Permyakov, Sergey Dobrotvorskiy, Ludmila Dobrovolska, Yevheniia Basova, and Maryna Ivanova(✉)

National Technical University «Kharkiv Polytechnic Institute», 2 Kyrpychova St., Kharkiv 61002, Ukraine
e.v.basova.khpi@gmail.com, ivanovamarynal@gmail.com

Abstract. A high-speed milling of hardened steels at multi-coordinate machining centers in individual and small-series production has become of special interest because of the ability to provide high-quality characteristics of products. To ensure the surface layer quality with extremely small values of residual roughness, surface microhardness, and structural phase composition, a computer-aided simulation of the high-speed milling process by computational-logical algorithms based on the finite element method was performed. The experiments with computer simulation research of high-speed milling were done for two objectives: the process of rectangular cutting and the process of oblique-angled cutting of materials. Two-dimensional and three-dimensional computer modeling was used for the research. The connection between the chip formation process, the stress–strain state of the material, and the angle of inclination of the chip-forming groove of the end mill was established. The maximum value of the energy contribution to the cutting process was offered to choose for the determination of the maximum limit cutting conditions in high-speed milling.

Keywords: Computer simulation · Finite element method · High-speed milling
Cutting conditions

1 Introduction

Nowadays, machine-building industry is characterized by an increase in the requirements for quality and accuracy of manufacturing complex surfaces parts [1]. Particularly the area of high-quality surface treatment of hardened parts is the most difficult. An urgent need for the simultaneous provision of high quality, the precision of the machined part and a reduction in its cost has arisen to ensure the competitiveness of Ukrainian products. Under the conditions of individual and small-series production development, this problem is solved due to using of the high-speed multi-axis machining centers. On such equipment, the part undergoes a complete production cycle. Particular interest and, at the same time, the complexity is represented by the surface process area of hardened steel parts on machining centers that provides production quality parameters that correspond to similar parameters after grinding.

V. Ivanov et al. (Eds.): DSMIE 2018, LNME, pp. 135–145, 2019.
https://doi.org/10.1007/978-3-319-93587-4_15

The application of existing finishing technologies in advance determines the possible change in the physical and mechanical state of the surface of the part and the formation of residual tensile stresses in it. Such phenomena negatively affect the operational properties of the machine parts. In this connection, there is a necessity to search for the new technological solutions that would ensure high quality and accuracy of processing complex surfaces of hardened steels by using the capacities of multi-axis machining centers [2]. However, the creation of such technology requires, on the one hand, the consideration of a through cycle from the design to the manufacturing of a part using CAD /CAE /CAM /CAPP systems for automated production, and on the other hand a deep understanding and study of the features of the technology and the processes in the cutting zone as well as the effect to the roughness formation and changes in the physical and mechanical state of the surface. Though, despite a large number of existing scientific works, it has not been possible to find studies that represent a systematic approach to the planning process for the development of a competitive technology for the manufacture of engineering products from hardened steels in an economically reasonable and reliable manner. Thus, we concluded that the formation of high-quality high-speed milling (HSM) of hardened parts requires an integrated approach taking into account all the stages of the through cycle from the design of accurate 3D-models to their fabrication at a machining center, including the characteristics of the fracture and surface formation processes, that is, within the CAD/CAE /CAM/CAPP systems (Fig. 1) [3–5].

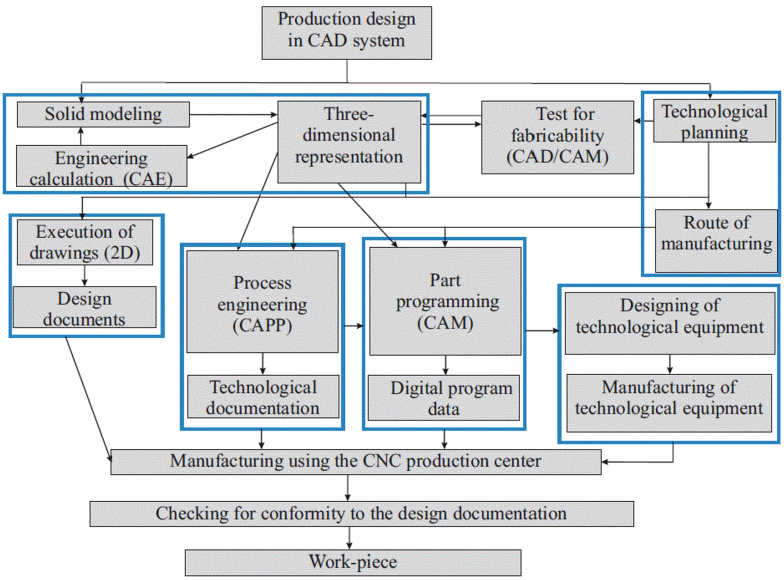

Fig. 1. End-to-end parallel workpiece manufacturing cycle.

2 Literature Review

A high-speed milling is one of the most promising methods of hardened steel surface treatment. This method allows ensuring the smoothness of the cutting tool movement and the accuracy of manufacturing complex surfaces that are not subjected to bedding-in during operation [5–7]. When planning the adoption of the high-speed milling of the surfaces of hardened steel parts, it is necessary to take into account the fact that the transformations that occur during quenching, tempering, and further heat treatment are of great technological importance. An author [8] states that hardened steel acquires good elastic properties and a relatively high viscosity. In the paper [9], fundamental differences in the treatment of hardened steel are given, namely: sawtooth chips are formed by breaking the material being processed; the chip formation process is characterized by a small material shear angle in the working plane, etc. In 1988 Professor Nakayama et al. carried out an analysis of the hardened steels treatment and identified issues that still require deep understanding and study. They are the presence of an innovative angle in the processing of brittle material and its correlation with the direction of the propagation of fracture, which from the point of view of engineering technology can ensure the integrity and durability of machine parts during the operation. It can also ensure the quality of the working surfaces. It is necessary to understand the nature of the sources of high temperature in the treatment zone of the hardened steel, its effect on the cutting process and, as a result, on the formation of the physic-mechanical characteristics of the processed material.

The basic ideas and a model of the chip formation process, proposed in the article [10], were successfully developed by the subsequent research. Studying the chip formation process [11], researchers determined that the formation of the segment chips is not a linear dynamic process. That can affect the cutting forces, the accuracy of machining and the quality of the surface. A mathematical model of the chip formation process in the treatment of hardened steels takes into account both the fracture and the plastic deformation of the thick section of the chips. That has made it possible to explain the structure of the chips.

Currently, the study of the quality characteristics of hardened steels after high-speed milling has received very little attention. Practically there is neither theoretical nor experimental research to apply the high-speed milling of the details from the hardened steels [12, 13]. For a deep insight into the phenomena occurring by the high-speed milling, a non-replaceable instrument is a finite element analysis, which allows getting fairly accurate predictions in a convenient graphical interface. Beker et al. widely adopted this method for modeling and optimization of the cutting processes [14–17]. The application of the finite element method for a three-dimensional (3D) analysis is extremely rare, although it allows obtaining a comprehensive picture of the processes and has a significant advantage in solving the complex of optimization problems.

The article purpose is to improve the quality of hardened steels part process by a computer design and simulation of the high-speed milling processes.

3 Research Methodology

According to the existing recommendations of the technology of hardened steels high-speed milling, cutting speeds of 250–600 m/min and above are required. This fact extremely limits the possibilities of using the traditional manufacturing processes. High-speed milling of the complex surfaces occurs under the conditions of localization of thermal zones and distribution of the strain–stress state of the part material. Therefore, to ensure the quality of the surface layer with extremely small values of the residual roughness, surface micro hardness, and structural phase composition, it is necessary to perform computer-aided design and simulation of the process.

Studies show that the basis of the cybernetic approach to solving the mechanical engineering problems is a system analysis. According to that the research, analysis and calculation tasks of individual technological processes, computer modeling and optimization of complex technological processes and phenomena, as well as the optimal design of technological complexes are solved in close connection with each other. e They are united by a common strategy and are subject to a single goal - the creation of a highly efficient technology production of competitive products.

The development of a high-quality products manufacturing from hardened steels by the high-speed milling requires material cost and time expenditure to find reasonable process conditions for a new material, which has unfavorable effect to the cost of production.

Computer-aided design and simulation of the process objects images under study on the computational-logical algorithms based on the finite element method were decided to use in order to determine the area of existence of the reasonable process conditions for high-speed milling of hardened steels (Fig. 2).

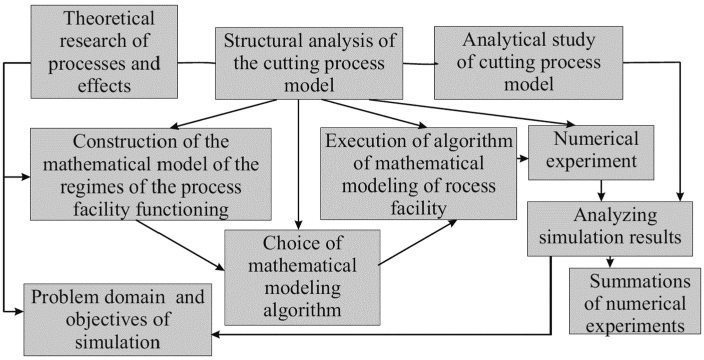

Fig. 2. Scheme of organization of computer simulation of the high-speed milling process.

Due to the computer simulation of the research HSM, the optimization and design of the real technological tasks for the manufacturing of high-quality products from hardened steel, two research objects were selected: the process of rectangular cutting and the process of oblique-angled cutting of the materials.

2D modeling of the two-component system "tool – workpiece" in DEFORM-2D (Fig. 3) was applied to analyze the rectangular cutting process.

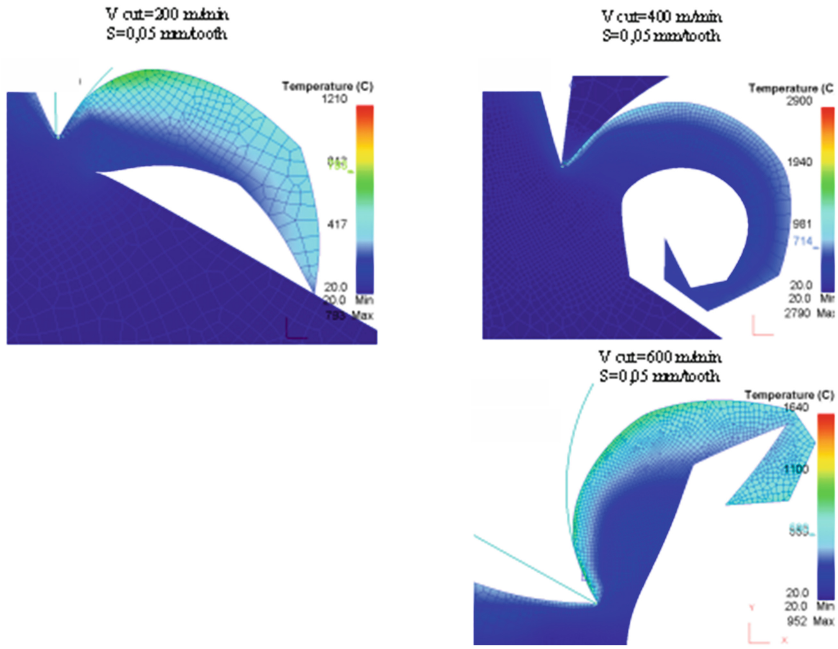

Fig. 3. 2D modeling of the process of rectangular cutting of the hardened steel (S-feed, Vcut-cutting speed).

In DEFORM, the stresses and deformations that are used in stress–strain curves are shown as effective stresses and effective deformations. The processor uses the following effective stress and strain equations:

$$\bar{\sigma} = \frac{1}{2} \cdot \sqrt{\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + \left(\sigma_z - \sigma_x\right)^2 + 6 \cdot \left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)}, \quad (1)$$

$$\bar{\varepsilon} = \frac{\sqrt{2}}{3} \cdot \sqrt{\left(\varepsilon_x - \varepsilon_y\right)^2 + \left(\varepsilon_y - \varepsilon_z\right)^2 + \left(\varepsilon_z - \varepsilon_x\right)^2}, \quad (2)$$

where σ - the normal mechanical stress applied to the unit area of the cross section, normal to the cross section (Pa), ε - active deformations used by program solvers in stress-deformed curves.

In the plastic deformation processes, essentially all of the deformation energy converts into heat, and this causes the irreversibility of the processes. The only reversible energy that is restored is the energy caused by the elastic deformation. According to the fact that the elastic deformation energy is small, we can assume that the reversible energy equals approximate zero. Thus, the specific thermal energy can be presented as:

$$Q_p = \frac{1}{J} \cdot \int_{\bar{t}_1}^{\bar{t}_2} \bar{\sigma} \cdot d\bar{\varepsilon}, \quad (3)$$

where *J*—the amount of specific heat per unit time during the plastic deformation.

At very high deformation rates, provided that there are no thermal losses, the adiabatic temperature can be calculated as follows

$$T = T_0 + \frac{Q_p}{c \cdot p}, \quad (4)$$

where T_0—the initial temperature, °C; *c*—specific thermal capacity; *p*—specific material weight.

4 Results

Understanding the mathematical processes taking place in the selected CAE system, the search for the area of existence of the reasonable cutting conditions was carried out by numerical experiments with changeable cutting speed (m/min), tool feed (mm/tooth) and cutting depth (mm). The experimental analysis was performed on constructing the model by an updated Lagrangian, which uses the method of automatic reconstruction of the grid. This allowed to ensure continuous reconstruction of the grid and to exclude the use of the separation criterion in the process of chip formation.

The chosen model of the manufacturing process simulation allows in case of distorted elements to trigger automatically the generation of a new grid that divides the contact boundaries, connects adequate internal nodes, smoothes the elements, and then interpolates the stresses and deformations for the new grid. As a result of numerical calculations, it was possible to establish lower limits of technological conditions for the transition from conventional to high-speed cutting. It is determined that the transition from conventional cutting to high-speed cutting is characterized by an increase in the time shift between the deformation wave and the temperature wave taking place in the material destruction zone by 10^{-7}–10^{-8} s [5].

The analysis of the influence of various technological factors on the qualitative changes in the plastically deformed layer of the material showed that there is a direct correlation between the chip formation and the stress–strain state of the material depending on the slope of the chip-shaped groove of the tool. This fact has been confirmed by a number of numerical calculations with diverse variants of changes of the cutting tool 3D models.

Simulation of the oblique-angled cutting was carried out in the DEFORM-3D modeling system (Fig. 4). The boundary conditions were the heat exchange between the tool, the material and the external environment.

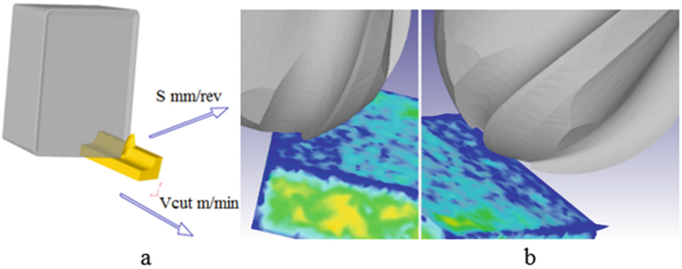

Fig. 4. 3D modeling of the rectangular cutting of the hardened steel process (a) and the oblique-angled cutting of the hardened steel process (b).

Due to realizing the multi-criterion optimization of the high-speed milling process and ranking its technological parameters, the sufficiently accurate forecasts of the physical and physical-mechanical characteristics of the high-speed material destruction was obtained [5]. Analyzing the results of the experimental computer simulation data of the high-speed milling process, it becomes possible to state that the maximum processing conditions, where cutting conditions can be assigned, are between maximum energy contribution to the process of material destruction and the amount of energy contribution to the cutting process that corresponds the moment of material inertial flow.

Thus to achieve the estimated purpose of the maximum limit processing condition, it is necessary to use the maximum value of the energy contribution to the cutting process.

The disrupted layer depth of the material test sample was estimated by the results of visualization of the material deformation distribution and the graphic representation of their distribution in high-speed milling process. The acquired results were considered to define the process condition range of high-speed milling (Figs. 5, 6, 7, 8, 9).

Computer simulation results of rectangular and oblique cutting show that the temperatures for the oblique cutting are much lower than for the rectangular cutting. In this case, rectangular cutting is accompanied by phase transformations. These facts allow to state, that oblique high-speed milling will avoid the drawbacks of materials during processing and the appearance of unfavorable structural characteristics in the disturbed-deformed layer (Figs. 5, 6, 7, 8, 9).

From the mechanical engineering point of view, this makes it possible to ensure a stable dislocation nature of the damaged material accumulation, during manufacturing as well as operation processes products. The result can be adopted as a wear resistance criterion of treated surfaces.

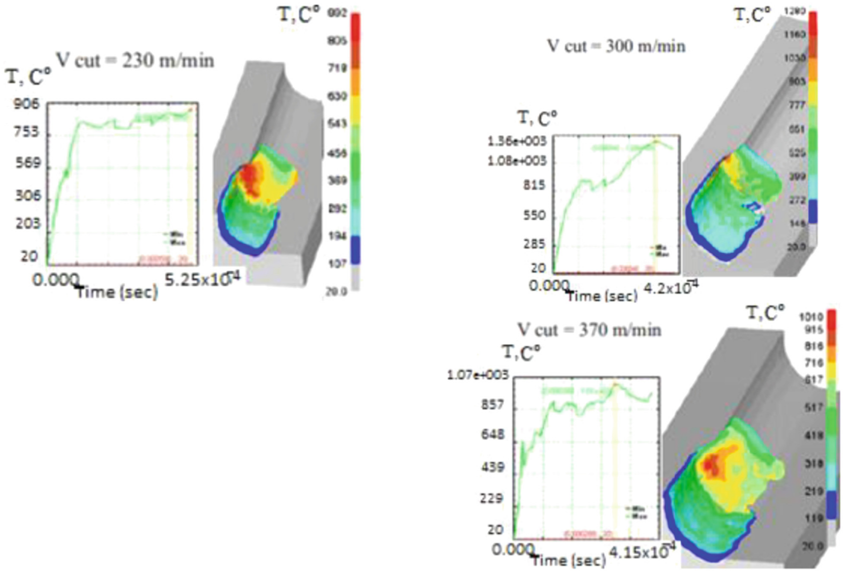

Fig. 5. Dependence of the temperature in the zone of orthogonal cutting on the processing time at different process speeds (S = 0.15 mm/rev).

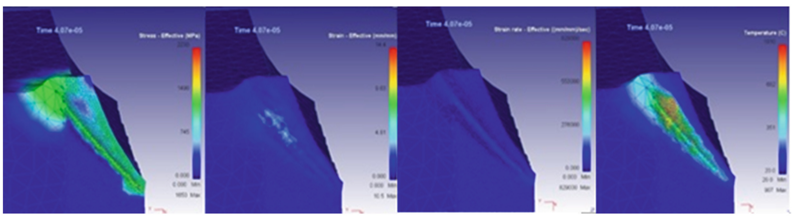

Fig. 6. Window postprocessor with the image of the diagrams (an angle of inclination of the helical line 35°).

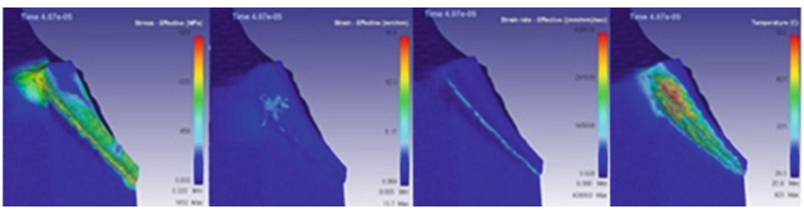

Fig. 7. Window postprocessor with the image of the diagrams (an angle of inclination of the helical line 40°).

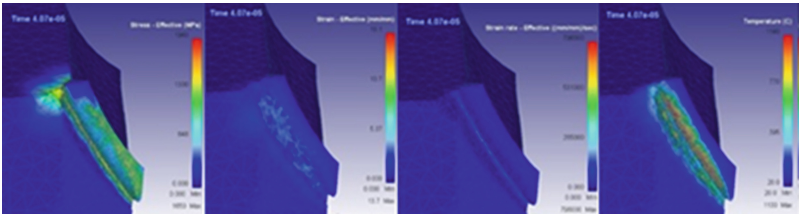

Fig. 8. Window postprocessor with the image of the diagrams (an angle of inclination of the helical line 45°).

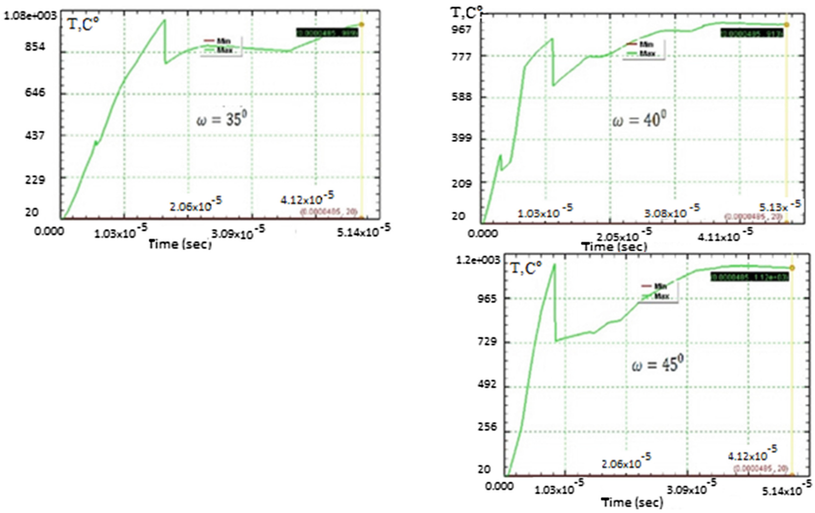

Fig. 9. Graphs of temperature versus time.

5 Conclusions

1. Computer modeling of different engineering processes is an integral stage in the manufacturing of quality products. Computer modeling allows reproducing the cutting process with a high degree of isomorphism and obtaining sufficiently accurate predicted results of processes and phenomena. In addition, it has been determined that computer simulation of the high-speed milling process is sufficient for determining the technological conditions of processing the part at the stage of planning the production process, eliminating the stages of cutting conditions development in the manufacturing environments and reducing the cost of production.
2. Computer simulation of HSM allowed defining the fact that the maximum processing conditions, where cutting conditions can be assigned, are between maximum energy contribution to the process of material destruction and the amount of

energy contribution to the cutting process that corresponds to the moment of inertial flow of material.

3. A comparison of the results of computer modeling of rectangular and oblique-angled cutting showed that it is possible to avoid the drawbacks of materials and unfavorable structural characteristics in the disturbed-deformed layer with the oblique-angled cutting.

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