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OPTIMIZATION OF CNC FACE MILLING PROCESS OF AL-6061-T6 ALUMINUM ALLOY

In modern machining industry, the use of computer software is an integral element in the design of technological processes. This work aims to present possibilities for optimization of milling operations with the use of commercial software designed especially for that use. A face milling operation of an aluminium flange was chosen for this study. Several different optimization strategies were described and their results shown, analysed and discussed. The effect of variable radial depth of cut on cutting force values in milling processes was reflected upon. Additionally, further research involving comparison of experiment results with simulation was proposed. It was proven that correct optimization strategy can reduce machining time for the analysed face milling operation about 37% without exceeding imposed process parameter constraints.

1. INTRODUCTION

Computer aided design and manufacturing (CAD/CAM) software is a key process factor in design of technological processes. A typical approach involves modelling a finished product with the use of user preferred CAD system and importing it into CAM software environment. The next step is the generation of toolpaths and initial verification of their validity. In addition to the 3D model of the finished workpiece, parameters such as tool type, feeds, cutting speed and depth of cut need have been specified. Feed and cutting speed can be either entered manually or by the use of built-in process parameter calculators implemented in certain CAM programs. Finally, the toolpath file is transferred to the machine tool to undergo final testing. It is worth noting that the use of toolpath verification features built into CAM software does not always ensure trouble-free performance of the toolpath in machine environment. Usually, collisions between tools and workpiece are checked, allowing avoiding the damage of tool and stock, which generates relatively low costs. However, most systems do not allow for verification of collisions

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between the tool, holders and other machine parts, which can generate significant repair costs and result in production downtime. Another significant issue is the correct choice of process parameters, such as depth of cut, cutting speed and feed rate, which affect both machining time and surface quality.

Due to aforementioned reasons, it is justified to seek solutions which would allow to eliminate problems stemming from errors in generation of CNC control programs. Several engineering software systems have been developed with the aim of optimizing CNC toolpath generated in CAM systems and checking toolpath validity for collisions of tool/holder with stock or other machine tool components. One of the programs most widely used for those purposes is the VERICUT software developed by CGTech. It is designed especially to perform complex simulations of an actual machining process on a machine tool. Therefore it allows to check the validity of CNC toolpaths for the occurrence of errors such as collisions and incoherence of finished product with 3D CAD model. Another important aspect of VERICUT is the possibility of toolpath optimization in context of reducing machining time. The software analyses the input CNC toolpath, proposing changes of technological parameters in certain "critical" areas, as shown in Fig. 1.

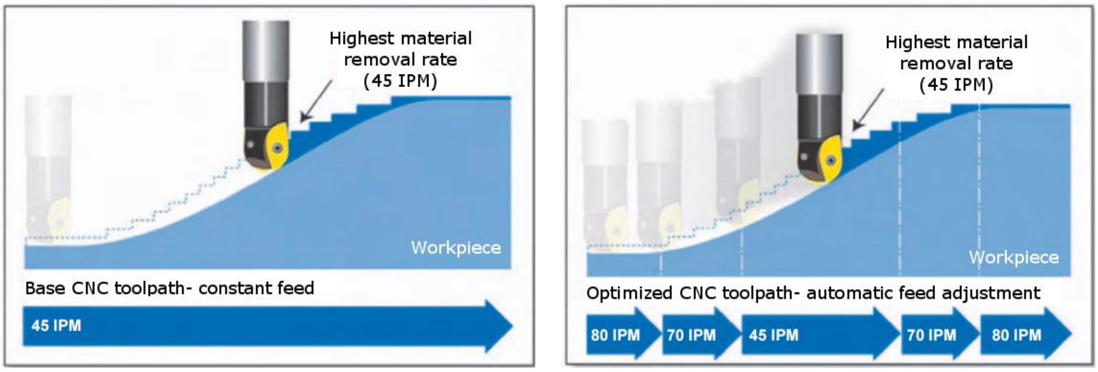

Fig. 1. Toolpath optimization in VERICUT with the assumption of constant material removal rate [1]

The optimization procedure presented above on Fig. 1 has a potential to greatly reduce machining time. The main drawback of this software is the lack of information about the impact of process parameter changes on cutting force components, spindle power and cutting zone temperature. Therefore optimization must be conducted with care not to damage the machine, tool and/or workpiece.

VERICUT has been used successfully to minimize shape errors in machining of thin-walled components [2]. The machined surface was improved by eliminating surface irregularities created by a finished workpiece manufactured with the use of the basic toolpath. VERICUT was also used to simulate surface texture in a workpiece by reducing the number of irregular machined surface textures in five-axis milling [3]. Chen et al. have used the software to improve toolpaths for manufacturing compressor impellers [4].

Another solution for optimizing CNC toolpaths is an engineering software package named Production Module 3D by Third Wave Systems, which is the developer of AdvantEdge FEM software designed for FEM simulation of cutting processes.

AdvantEdge FEM has been successfully used for metal turning simulation, showing good agreement of simulation results with experiment, as proven in the work of Nieslony et al. [5],[6]. Production Module 3D was designed especially for simulation and optimization of cutting processes. This software package allows not only to verify the correct toolpath operation and coherence of its actual technological parameters with those input in CAM software, but also for its multiple-criteria optimization. The simulation results provide the end users with plentiful information about cutting force components, spindle loads, cutting zone temperature and a number of other parameters. This kind of solution is anticipated by the machining industry, as it allows to avoid costly mistakes in design of technological processes and allows to shorten the machining time. The software can also be used for quick comparison of several different toolpath variants in accordance to a range of parameters, such as cutting force and machining times. Optimization works on the principle of increasing feedrates (in areas where values of process parameters lower than specified by the user occur) or by decreasing them (in areas where parameters are higher than specified by the user). This allows not only reducing machining time, but also increasing tool life and process stability. Experimental validation of simulation results from TWS Production Module 3D has shown a good agreement of simulation and experiment results [7]. Production Module was also used in a project by the National Center for Defense Manufacturing and Machining to reduce cutting time by up to 24% [8]. Bell Helicopter company has also used Production Module to decrease cycle times by 37% [9].

2. OPTIMIZATION OF PROCESS PARAMETERS

The depth of cut has the least effect on tool life. Increasing the depth of cut would reduce the number of machining passes need to obtain a finished workpiece, resulting in the reduction in overall cutting time. However, optimization of the account of depth of cut proves to be a challenging task, as the material is removed in several passes. Therefore the modification of depth of cut in a given pass modifies the allowance for the next passes, which could easily result in geometrical errors and incoherence of finished product with the CAD model. This is explained in Fig. 2. Modifying depth of cut also necessitates changes in

a) b)

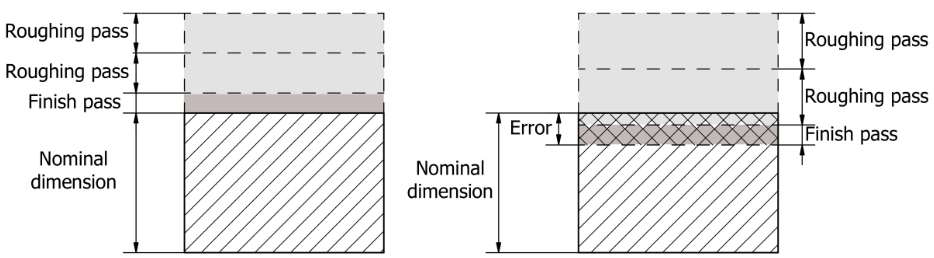

Fig. 2. Workpiece geometry error resulting from modification of depth of cut: a) original workpiece geometry, b) geometry error resulting from depth of cut optimization of roughing passes

XYZ coordinates in the G-Code, which requires its thorough modification. This would be particularly challenging for complex workpiece geometries.

Cutting speed is relatively easy to modify in CNC toolpaths, however it has the most adverse effect on tool life. The detrimental effect of increasing depth of cut and cutting speed on tool life has been shown in open literature [10].

For the aforementioned reasons, most programs work by optimizing the feedrate values, which have a less adverse effect on tool life than cutting speed. Feedrate is also much easier to modify in CNC toolpaths than depth of cut.

3. INPUT DATA OF TECHNOLOGICAL PROCESS

In accordance with the approach described in the introduction, a 3D model of the workpiece was first prepared with the use of CAD software. The finished model was then imported into the CAM program, in which the toolpath for a face milling operation was generated after essential process parameters were specified. Additionally, a 3D model of the blank was needed to simulate the material removal process in TWS Production Module 3D. The input data's used for the optimization process are presented on Table 1.

Table 1. Input data used for the optimization process

Workpiece material	Al-6061-T6 aluminum alloy hardness ~90HB tensile strength Rm=310 MPa
Tool	Kennametal KSSM 45° indexable face mill cutter with SECT1404AEFNLE inserts Tool diameter - D_1=50 mm Number of inserts - 4 Insert material - uncoated WC-Co carbide
Base process parameters	Feed per tooth - f_Z=0.075 mm Surface speed - v_c=475 m/min Depth of cut – a_p=4.5 mm

Adopted parameters are chosen from the lower end of values proposed by tool manufacturers for machined material. Therefore they leave broad possibilities of process optimization and ensure that cutting conditions for the base process are kept within the limits.

A face milling operation was generated in Mastercam X9 software by the use of "Dynamic mill" option. This option was used instead of a traditional one-way face milling approach because of workpiece geometry which contains holes and slits in the blank. Toolpath type and cutter diameter were chosen with an intent to machine the whole workpiece in a single pass, with no unnecessary entries and exits of tool into the material. A "dynamic mill" toolpath type was chosen to achieve minimum toolpath length while maintaining tool diameter dictated by the technologist. Generated toolpath, along with workpiece geometry, is shown in Fig. 3. In this paper a roughing operation will be optimized. The optimization of finish pass was not performed due to the nature of optimization method in TWS Production Module 3D, which changes feed values in the control program during optimization. The use of such method for the optimization of a finish machining operation would have an adverse effect on surface quality.

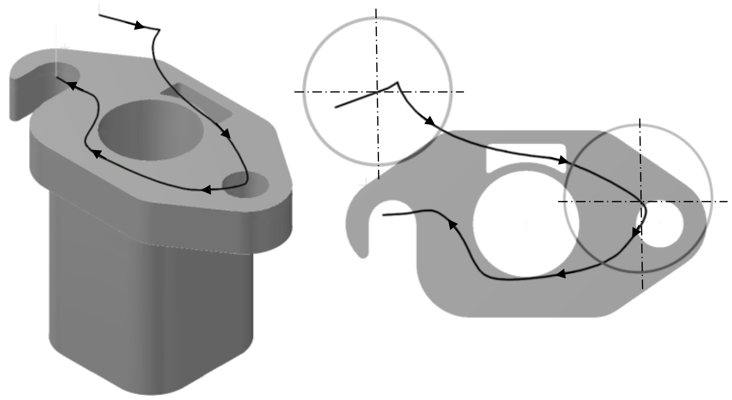

Fig. 3. View of toolpath generated in Mastercam X9 CAM software with mill position examples along the toolpath

The generated toolpath and blank model were then imported into TWS Production Module 3D. Cutting tool geometry in TWS PM3D can be defined by the use of two methods by selecting the tool type and specifying tool parameters manually or by importing a 3D model of the tool in *.STP format. In this work, the second method was used.

4. SIMULATION OF THE FACE MILLING PROCESS

After the necessary data was input, the face milling process was simulated with the use of Run Force Model command, which prompts the program to calculate process parameters, spindle loads, machining forces etc.

TWS Production Module 3D allows the user to obtain information about various parameters of the simulated process, such as for example: cutting forces, feeds, speeds, peak tool temperature, spindle power. It this article only tangential cutting force was analysed and optimized.

Due to the geometrical shape of the selected workpiece, radial depth of cut varied depending on tool position. Therefore, variations in values of tangential cutting force value during machining time were expected.

5. PROCESS OPTIMIZATION

After the process was simulated, face milling optimization was performed. TWS Production Module 3D has a built-in optimization feature allowing toolpath optimization in accordance to:

- user-specified value of cutting force (tangential, radial or axial),

- load per unit length,
- spindle load.

Both air-cut and in-cut toolpaths can be optimized. Feed limits for each optimization case can be specified. This feature is essential to obtaining a toolpath which can later be used on the machine without damaging its components and the tool.

As mentioned earlier, in this study the process was optimized with the use tangential force as a criterion. Three different optimization variants were established:

1) Elimination of peaks observed on tangential force graph by evening out the force value;
2) Raising the value of the tangential force to the highest value occurring in the process;
3) Raising the value of the tangential force by 25% in respect to the highest observed value.

Table 2. Tangential force values for optimization variants

Variant number	Force value, N	Feed per tooth limit, mm
1	335	0.24
2	450	
3	560	

Tangential force values from each variant were established on the basis of simulation results and shown in Table 2. Feed per tooth value was constrained in optimization criteria with respect to highest value allowed by the tool manufacturer to prevent tool damage. Only tool cutting motions in the toolpath were optimized.

6. RESULTS AND DISCUSSION

Simulation results for each optimization variant were exported from TWS Production Module 3D and processed. In the first step, the comparison of tangential force values and machining times obtained for established optimization variants, presented in Fig. 4, were analysed.

For the first optimization strategy, it can be seen on Fig. 4 that the machining time has increased slightly, by around 3%. It is also visible that the toolpath was optimized by the program so that machining starts earlier and with a constant force value. In the case of second optimization variant, machining time has decreased by approximately 23%. Force value was raised up to the highest value occurring in the base process, with accordance to input optimization criterion. As expected, biggest savings in machining time, as much as 37%, can be observed for the last strategy.

Fig. 5 presents machining times for all considered optimization variants. Irregularities in tangential force graphs can be observed for all three optimization variants. This phenomenon is related to variable radial depth of cut stemming from toolpath type and workpiece geometry.

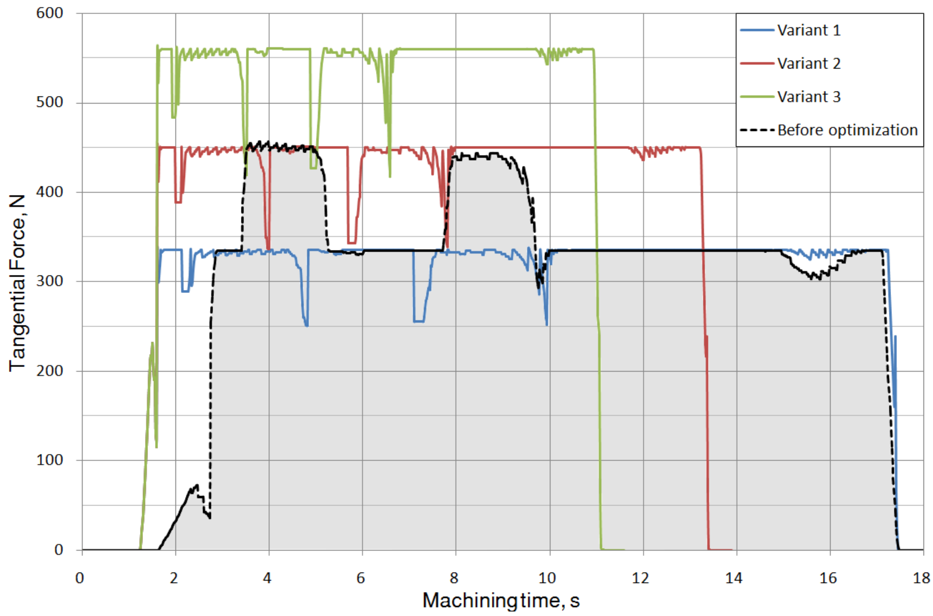

Fig. 4. Comparison of tangential force values and machining times obtained for established optimization variants

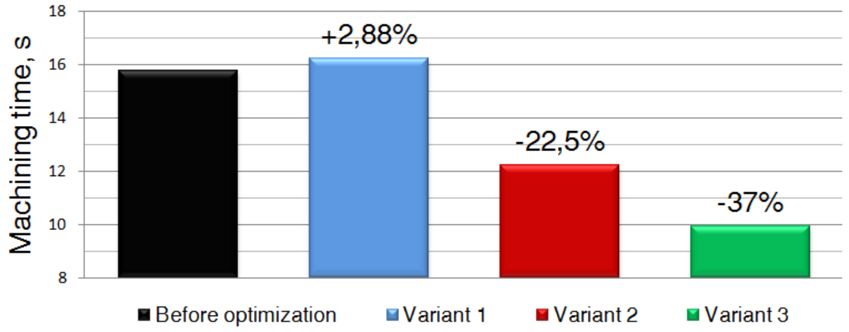

Fig. 5. Differences in machining times for established optimization variants

Changes of feed rate along the toolpath for each optimization variant are shown in Fig. 6. Part of the toolpath for which the feed rate is shown was marked with a solid line. The graphs show the method of NC toolpath optimization in TWS Production Module 3D. The software changes feed rate values to accommodate machining forces to the level specified by the user in optimization criteria. Therefore it can be inferred that the software calculates cutting forces as a function of depth of cut and feed per tooth [11].

For the first variant, smallest increases in feed per tooth values (and even some decreases) can be observed. For the second and third variants, feedrate does not exceed the limiting value specified in optimization criteria, however the increases are more significant than for the first strategy. Due to this, an increase in tool wear can be expected for the last two variants.

Table 3. Percentage of stable tool operation time for established optimization criteria

Before optimization	Variant 1	Variant 2	Variant 3
66.40%	92.80%	92.37%	92.72%

Percentage values of stable tool operation times (understood as a time of tool operation under constant cutting force) in relation to total machining times were presented in Table 3. Deviation of ±5% in cutting force value was allowed. For each optimization variant, stable tool operation time has improved by around 26%.

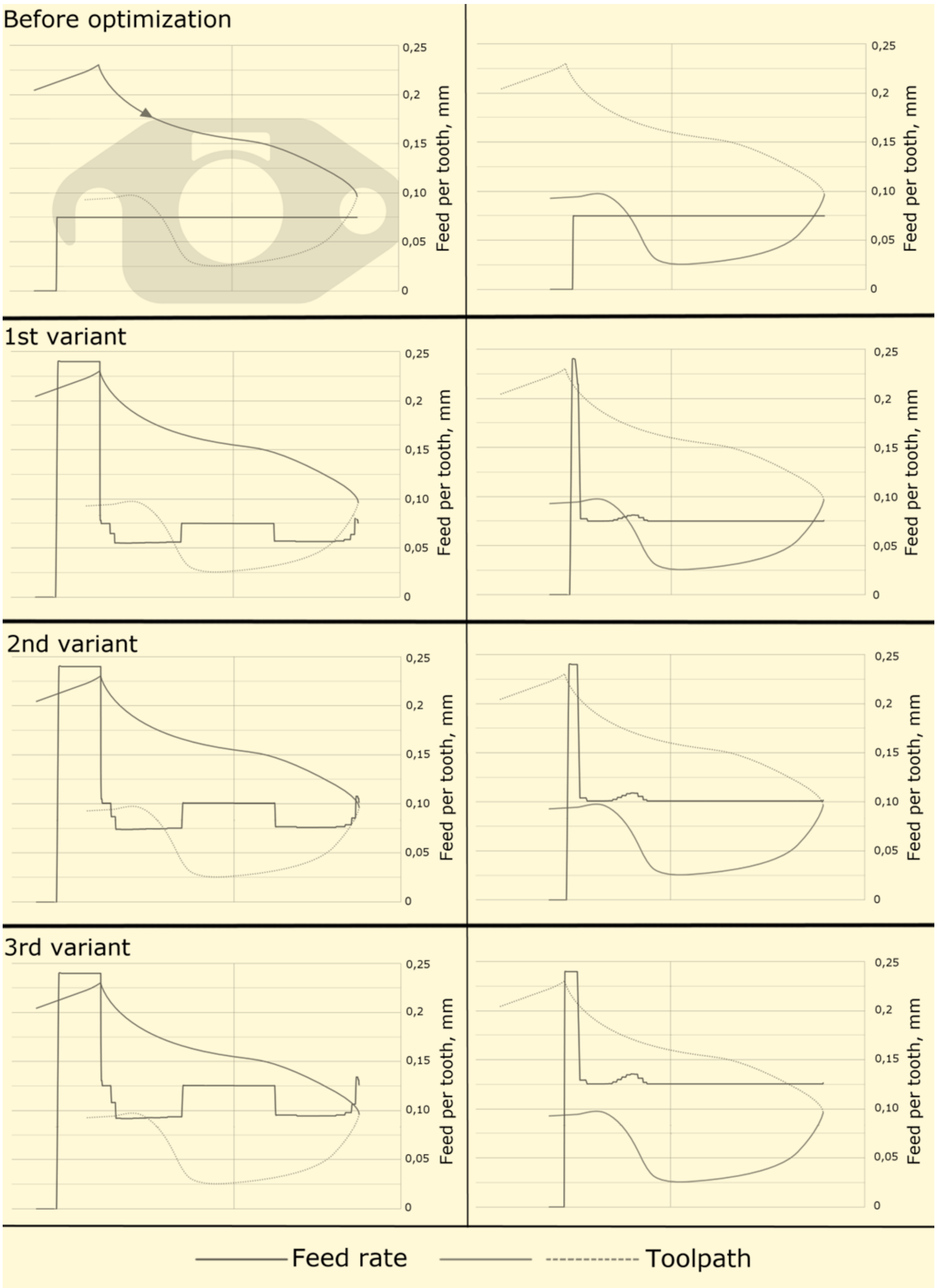

Fig. 6. Feedrate changes in function of tool position defined as position along toolpath

7. CONCLUSIONS

Based on the performed simulations and analysis of their results, following conclusions have been reported:

- With the correct choice of optimization strategy, savings in machining time for the analysed face milling operation as big as 37% can be obtained without exceeding imposed process parameter constraints.
- Optimization strategy presented in variant 2 results in time savings of about 22% without increases in cutting force values in comparison to highest force values already extant in base process.
- Feedrate variations were observed for optimized toolpaths. While feed per tooth values did not exceed the imposed constraints, feedrate fluctuations are significant (namely by as much as 336%, from 0.055 mm/tooth to 0.24 mm/tooth as seen in Fig. 6 and can result in increased tool wear.
- Not all irregularities in cutting force value could be eliminated, as they are related to workpiece geometry and toolpath type. However the machining time at which the tool works under constant load, despite the variable depth of cut, has increased significantly, by approximately 26% for each optimization strategy.

The presented software is a user-friendly, low-cost alternative to costly and time consuming experimental tests and allows to avoid issues stemming from errors in NC toolpath design. To evaluate the usefulness of presented software in practical applications and validity of simulation results, the authors are planning to conduct experimental tests of cutting forces for milling operations and compare experiment and simulation results.

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