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Research Article

Investigation of the cutting force and surface profile error when free form milling

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Abstract: Machining free-form shaped surfaces is a widespread task. Aerospace, automotive, mould making and many other sectors are challenged by ever increasing demands for precision and economy. In ball-end milling, the constantly changing cutting conditions affect the shape and volume of the chip, as well as the tool load and the quality of the resulting surface. It is important to know the cutting force for a given surface characteristic, because this makes it easier to plan the machining process. The prediction of cutting forces is very important for optimising machining strategies and parameters to achieve the required accuracy. In the experiments, the forces on the tool and the surface geometric accuracy were measured by milling test surfaces of 42CrMo4 with different cutting parameters. Based on the measured values, the average cutting force was determined, the variance of the force variation was investigated and the force momentum, which takes into account the machining time. The aim of this paper is to investigate and compare the cutting force and the surface profile error of the resulting surface during finishing milling with a ball-end milling cutter.

Keywords: Free-form surface; Ball-end milling; Cutting force; Surface profile error

I. INTRODUCTION

Free-form surface milling is widely used in machine and tool manufacturing, foundry, aerospace, automotive. Their machining requires high productivity as well as high precision. There are many different aspects to be taken into account in the manufacturing process. The technological parameters of the cutting process, the tool parameters and the tool path must be defined. Productivity and accuracy must be planned within a given range of machining possibilities. Measurement options that can be used during the process should be considered to reduce the number of rejects. In addition, moulding tools are usually made of hard-to-machine alloy steels, which makes them even more difficult to produce [1][2].

The quality of the machined surface is determined by a number of parameters. The literature focuses primarily on surface roughness [3], but geometric accuracy is an equally important requirement in industry. Increasing demands are making it more and more difficult for industry to meet precision requirements. Accuracy is assessed on three criteria: (1) surface roughness, (2) geometric accuracy, (3) dimensional accuracy. Geometric tolerances defined by standards [4] are becoming increasingly important in industry, so the collection of design, measurement and manufacturing knowledge related to them is an important task [5][6][7].

The specification and verification of geometrical tolerances is a complex task, which, in addition to the interpretation of standards, has to take into account the mathematical evaluation of geometrical tolerances [8] and the number and location of sampling points. Several methods have been investigated. Examples include the B-spline curve method, a method using a fuzzy system [9][10].

Parts with free-form surfaces are milled on computer numerically controlled (CNC) machine tools using a ball-end milling tool. To achieve sufficient accuracy and productivity, machining can be divided into three main parts: roughing, intermediate machining and finishing [11]. In the first two stages, most of the excess material is removed, while in the finishing stage only a uniform thickness of material remains to be removed. Finishing is the final machining operation to produce the final part surface. It can therefore be said that this machining stage has the greatest impact on the quality of the surface.

In ball-end milling, the nature of the free-form surface means that the machining conditions are constantly changing. As well as the size of the workpiece constantly changing, the working edge length may also be constantly varying. It can be said that the machining conditions are a constantly changing system, which affects the shape and size of the chip and the cutting force.

In machining analysis, it is essential to have as accurate as possible knowledge of the cutter-workpiece engagement (CWE) [12]. CWE can be divided into three types: the first is the body modelling method based on Boolean operation [13], the second is the Z-map method based on discrete elements [14], and the third is the boundary method based on analytical or numerical calculations [15].

Machining force prediction models can help the designer to choose the right machining parameters. In machining design, CAM systems currently do not have data to predict the expected cutting forces.

This paper presents an investigation of the geometrical tolerances of free-form surfaces produced by ball-end milling and the forces involved in their manufacture.

II. Methods and Equipments

In the tests, the envelope size of the test piece was 80x80x30mm with a cylindrical surface of 45mm radius. This section is joined to a 10 mm wide horizontal plane with a radius of 10 mm. A concave (CV) and a convex (CX) part were created to compare the nature of the surfaces. The height and depth of the cylindrical part are 9.2 mm (**Fig. 1**).

The material of the test parts was 42CrMo4 (1.7225; Rm = 1000 MPa), a low alloy steel, which is one of the low alloy steels containing chromium, molybdenum, manganese (**Table 1**). Toughness with high fatigue strength and good low temperature impact resistance. 42CrMo4 alloy steel is widely used for engineering applications.

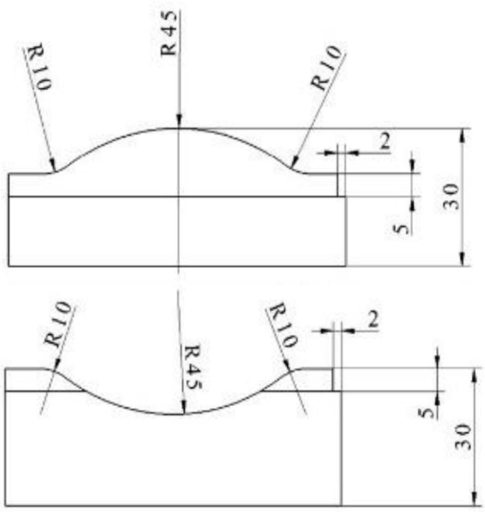

***Figure 1.** Geometry of the test surfaces*

***Table 1.** Chemical content of the 42CrMo4 steel*

C	*Si*	*Mn*	*Mo*	*S*	*Cr*	*Ni*
0.43	0.26	0.65	0.16	0.021	1.07	0.19

Machining was performed on a Mazak 410 A-II CNC machining centre. A Fraisa X7450.450 type milling tool with a diameter of 10 mm (Dc=10 mm) was used. The number of teeth was 4 (z=4). The tools were clamped with an EMUGE-FRANKEN SK40 type cold clamping fixture (PowerGrip). During machining, the coolant was applied by the flooding method (Aquamet 40, 6-8% emulsion, yield about 30 l/min).

The CNC programs were produced using CATIA v5 CAD/CAM system. During the finishing operation, the ball-end mill followed the surface parallel to the plane of **Figure 1**.

***Table 2.** Cutting parameters*

Part	*f_z [mm]*	*a_e [mm]*
1	0.08	0.35
2	0.08	0.25
3	0.16	0.15
4	0.12	0.15
5	0.08	0.15
6	0.16	0.35

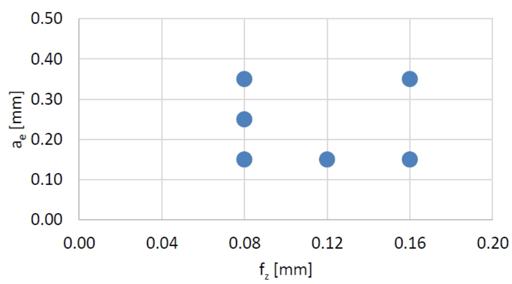

***Figure 2.** Sets of feed per tooth and width of cut*

The spindle speed was 5100 rpm, which means a nominal cutting speed of 160 m/min. The depth of cut was a_p = 0.3 mm, which was ensured by pre-finishing. The feed and width of cut were varied in 3-3 levels as shown in **Table 2** and **Fig. 2**.

The milling times for a toolpath and the machining times for a surface are shown in **Fig. 3**. For a single toolpath, the feed per tooth determines the time, but for the whole surface, the width of cut has an effect.

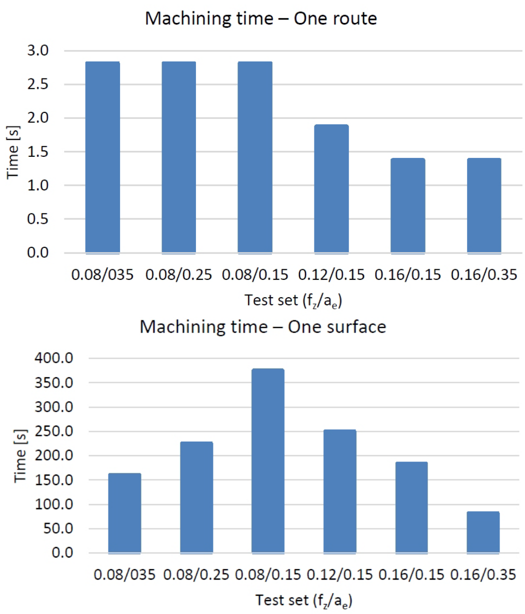

***Figure 3.** Machining time*

The cutting forces were measured using a KISTLER 5019 3-component force measuring device. The data were evaluated by the software DynoWare. The force measurements were performed at a frequency of 2000 Hz, in the down milling (D) and upmilling (U) phase. The measured values were corrected for zero offset.

As shown in **Fig. 4**, the periodical nature of the milling process and the continuous variation in milling conditions cause the force measurement values to fluctuate significantly. For processability, filtering was applied: the average values of 25 measurements were used for the evaluation. This results in a measurement frequency of 80 Hz. It means 80 points, instead of 2000 during 1 second. The effect of this is shown in **Fig. 4** in case of a 1-second long data series of the axial direction (Fz) force component of the convex test piece No.6 (f_z = 0.16; a_e = 0.35).

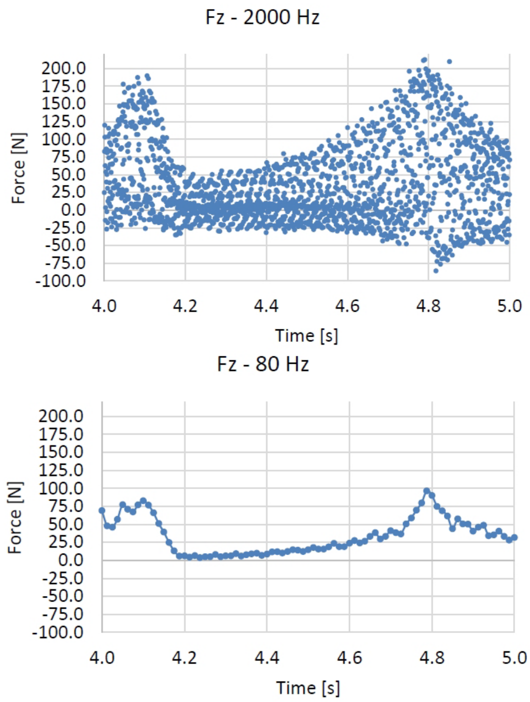

***Figure 4.** Measured and filtered Fz force component (example)*

The resultant force was calculated as the vector sum of the force components.

The surface profile tolerance is the tolerance field formed by symmetrically offsetting, which has 3 degrees of freedom (**Fig. 5**). The measured points must be located in this volume. The tolerance can be adjusted by reducing the number of degrees of freedom of the tolerance field by specifying datum.

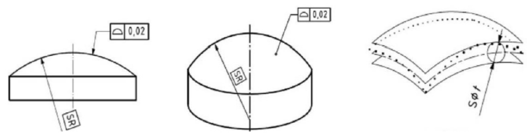

***Figure 5.** Surface profile tolerance*

Points on the surface were measured using a Mitutoyo Crysta-Plus 544 coordinate measuring machine with a 3 mm nominal diameter probe, a Renishaw TP20 touch-trigger probe. 105 points were measured on the surface along a 5x21 grid. The geometric error was evaluated based on the measured points using Evolve Smart Profile v6 software (**Fig. 6**), which is capable of comparing the

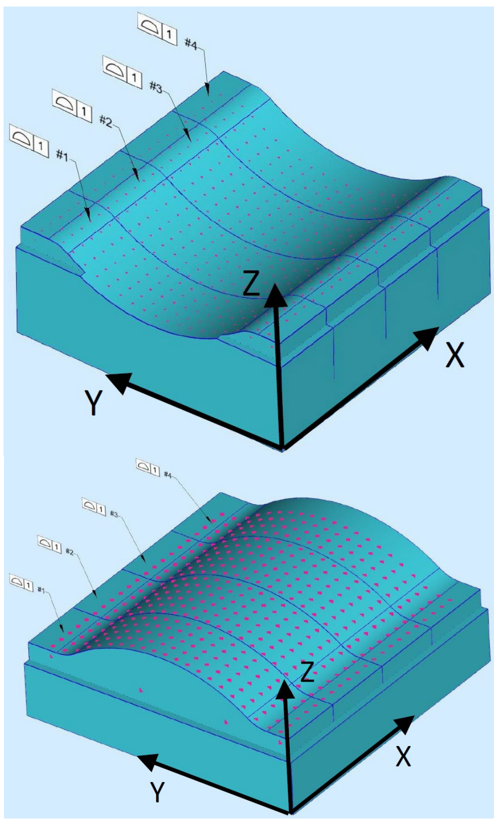

***Figure 6.** Point cloud on the surface*

measured points to a theoretical CAD model of the part under test based on a point cloud recorded by any measurement system.

III. Results

The character of the time variation of the forces during milling is described for setting No.1 (f_z=0.08; a_e=0.35). The nature of each component is similar for all settings.

Since the cutting is in the y direction, Fx, the force component in the x direction, is the passive force. Fy, the y direction component, is the force in the feed direction, and Fz, the z direction component, is the axial force in the tool axis direction. The coordinate system is indicated in the **Fig. 6.** The sum of the three force component vectors is the resultant cutting force (F). The diagrams show the variation of the forces over time for a single toolpath (**Fig. 7**).

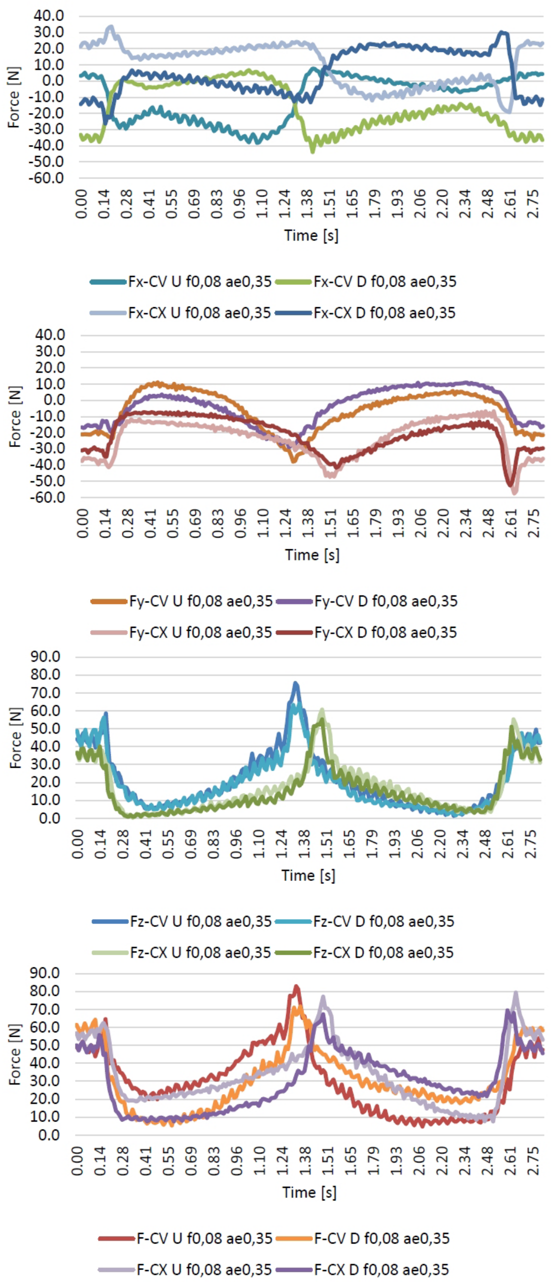

***Figure 7.** Cutting forces*

For each of these diagrams, the effect of the change in the surface area is clearly visible. The character of the force changes at the inflection point of the surfaces. The direction of the force changes for passive force (Fx), and the diagrams are nearly symmetrical for upcut (U, y+ direction feed) and downcut (D, y- direction feed) cases. The force Fx fluctuates around 0 in some sections.

For the force in the feed direction (Fy), there is an extreme value of the force at the straight section, and then also near the inflection point. For axial forces (Fz), the character is similar but the variation is larger. For all three force components, a rapid decrease in force is observed as the force leaves the horizontal section, followed by a slow increase as the force approaches the inflection point. For the concave (CV) surface the maximum is just before the inflection point, for the convex (CX) surface the force maximum is slightly after.

The nature and magnitude of the resultant cutting force is determined by the axial force. The average values of the resultant forces are shown in **Fig. 8**. As can be seen, the differences are small in the case of up- and down milling, and for concave and convex surfaces. The feed rate and width of cut have a greater effect on the cutting force. The diagram also shows that the width of cut has a greater effect on the resultant force than the feed. The largest value is of course at the maximum parameters tested.

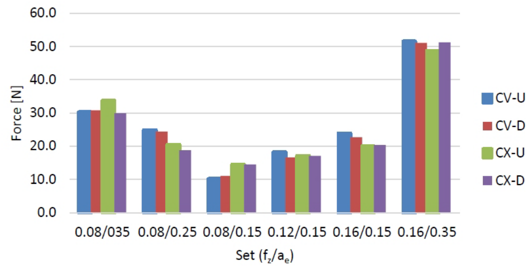

***Figure 8.** Average cutting force*

The variation in the value of the force along a path can be described by the standard deviation. As shown in **Figure 9**, it follows the trends observed for the force. The relative value of the standard deviation

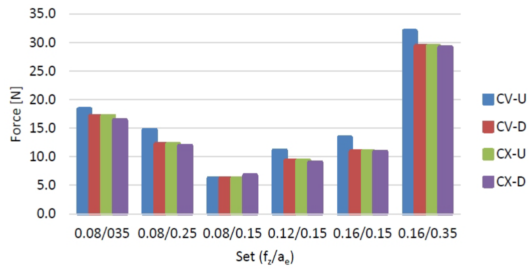

***Figure 9.** Standard deviation of the cutting force*

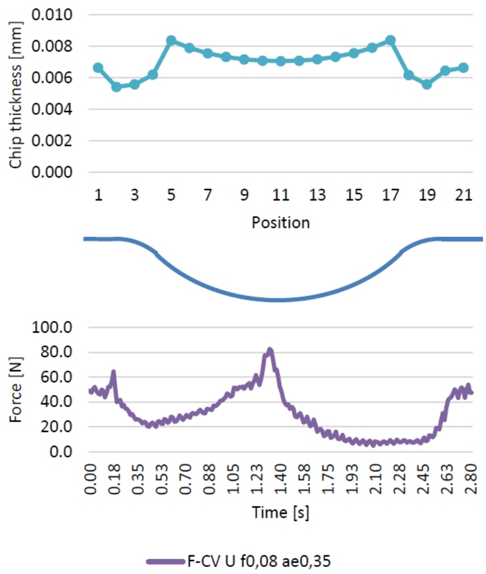

Figure 10. *Chip thickness and cutting force (CV; f_z=0.08; a_e=0.35)*

is 43-62%, indicating that there is a significant variation of the force along the toolpath.

The volume and average thickness of the uncut chips along the milling path were determined using CAD modelling [16]. The values for setting No.1 are shown in **Fig. 10** and **Fig. 11**. Comparing the change in surface area, the change in chip thickness and the change in cutting force, it can be concluded that the force value is not only affected by the chip thickness, as the increase in force in the middle part of the surface is not explained by the change in chip thickness.

The increase in force is due to changes in the machining conditions. The tip (cross edge) of the tool is also at work on the surface sections close to the horizontal. However, here the cutting speed is close to 0 due to the small diameter and the chip separation is limited due to the edge design. Consequently, as the chips separate, the elastic and plastic deformation of the material increases, which is reflected in an increase in the force acting on the tool.

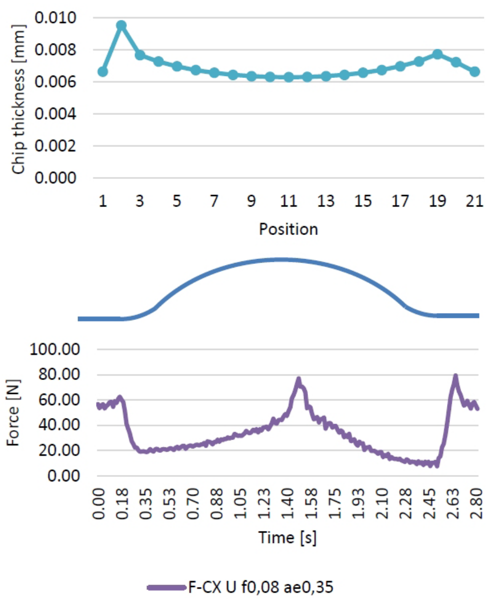

Figure 11. *Chip thickness and cutting force (CX; f_z=0.08; a_e=0.35)*

Machining times vary for each setting (**Fig. 3**). The effect is shown by the force momentum, which is actually the area under the force-time function. The force momentum is a suitable tool for comparing force values measured under varying machining conditions.

The force momentum value takes into account both the magnitude and variation of the force and the duration of the machining operation. **Fig. 12** shows the values for a toolpath. As the feed rate is reduced (setting No.1-2-5), the value decreases. Then, the increase in force caused by increasing the width of cut (setting No.5-4-3) is compensated by a shorter milling time. In the last setting with maximum values (No.6), the high force values are compensated by the very short milling time, so that the force momentum value is lower than in the case of setting No.1.

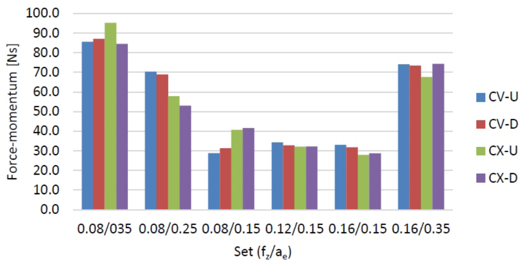

Figure 12. *Force momentum for one tool path*

Calculating the force momentum value for the entire surface, the upmilling and downmilling path sections must be considered simultaneously. The values (**Fig. 13**) are higher for the No.1 setting. For settings No.2 and No.5, the values determined for the concave and convex surfaces are significantly different. For settings 5-3-4-6, essentially identical values are obtained.

The surface profile error of each surface is shown in **Fig. 14**, ranging from 0.06 mm to 0.14 mm. As

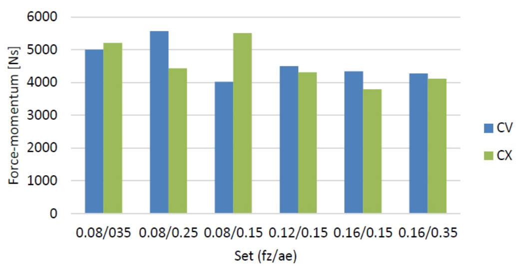

Figure 13. *Force momentum on the surface*

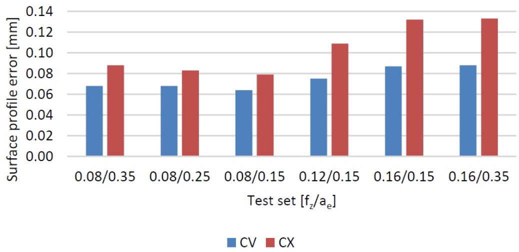

Figure 14. *Surface profile error*

can be seen, the error of the convex surfaces is larger, even though no large difference in the average values of the resultant force was observed. While for the cutting forces, the width of cut shows a larger effect, the geometric error increased to a larger scale with increasing feed rate and the width of cut has minimal effect. This may be due to the different change of the force components along the toolpath, which requires further investigation.

The surface profile error indicates the thickness of a defect band, but the deviation varies along the surface. **Fig. 15** and **Fig. 16** show the deviation within the surface profile tolerance for surfaces with setting No.1. These deviations follow well the evolution of the cutting force. At the horizontal start and end sections and at the centre of the surface, where the maximum value of the force was measured (**Fig. 7**), the surface deviation is the largest in the positive direction. At the through radius, where the force decreases, the surface shows a large negative deviation.

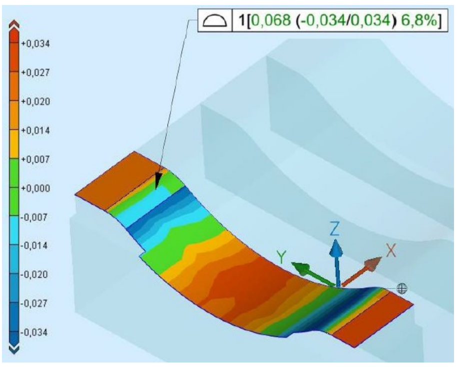

Figure 15. *Surface profile error map (CV; f_z=0.08; a_e=0.35)*

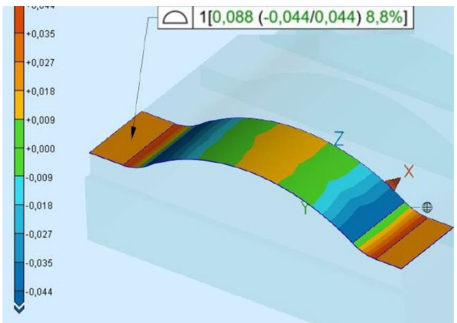

Figure 16. *Surface profile error map (CX; f_z=0.08; a_e=0.35)*

IV. Conclusion

When machining free-form surfaces with ball-end milling, a CAM system must be used to create a toolpath that ensures dimensional and shape accuracy of the surface and the correct surface roughness. The combination of these requirements is only possible by selecting the right motion strategy, tool geometry and cutting parameters.

In the present study, the cutting forces and surface geometric accuracy of 42CrMo4 test parts were measured at different feed per tooth and width of cut (side step) parameters.

Based on the measurement data, it can be concluded that

- the cutting force varies greatly during the machining process;
- the geometric accuracy of the milled surface follows the change in cutting force, but the feed and the width of cut have different effect,
- the force momentum can be used to effectively compare the effect of changes in force and machining time caused by machining parameters;
- the change in force is determined not only by the change in the cross-section of the chip, but also by the conditions of the section of the tool that is actually working;
- when the tip of the tool is involved in the machining operation (surfaces close to horizontal), the cutting force increases significantly, the form deviation increases;

Based on the results obtained, it can be concluded that for the smooth milling of free-form surfaces with a spherical tool, a milling strategy should be chosen in which the tip of the tool is not involved in the machining process in order to reduce the cutting force and the shape deviation.

When determining the cutting force by calculation, the position of the working section of the tool must be taken into account in addition to the chip cross-section, as this also has a significant effect on the cutting force.

Further research could investigate the effect of tool design on cutting forces and deflection, for example for different numbers of teeth.

Author Contributions

Varga B.: Conceptualization, Experiments, Force and chip analysis, Writing.

Mikó B.: GPS analysis, Writing, Review and editing. Supervision.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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