MACHINING ERROR DETERMINATION FOR 3-AXIS MILLING OF FREE FORM SURFACES

UDC: 621.914;

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Paper received: 25.02.2015.; Paper accepted: 13.03.2015.

Abstract: *The use of free form surfaces in mechanical engineering is accelerating by functional and esthetics demands. Use of CAD/CAM software is a must because analytical description of a given surface and tool path generation. There are many methods for tool path optimization, one of them is federate scheduling which is described in this paper. The machined part which is manufactured according to optimization algorithm was measured on the optical scanner. Paper presents description of developed CAD/CAM application in Matlab software and performed experiment for determining the cutting forces in freeform surfaces machining. At the end of paper is given map of deviations determined by Matlab software for one of machined surface from point cloud obtained using optical scanner.*

Key Words: *Free form surfaces, feed rate scheduling, map of deviation.*

1. INTRODUCTION

Use of free form surfaces is present in many fields of mechanical engineering for various machine parts. Some of them are automobile, aerospace, shipbuilding and the die/mold industries. Freeform surfaces are predominantly used to improve design and/or to enhance functional requirements. The most commonly used machining procedures are 3 or 5-axis ball-end milling operations. 5-axis machining provides higher productivity and better access to all sides of the components, and eliminates the use of multiple fixtures [1]. Unlike to 5-axis machining at the 3-axis machining cutting speed is varying on the spherical part of a ball-end mill, and it is difficult to maintain valid machining parameters to achieve a satisfactory quality of the machined surface. Use of CAD/CAM systems is a must because it is needed to analytically represent the surface and, based on it, to generate an appropriate tool path.

The determination of the optimal tool path for machining of freeform surfaces requires the simultaneous fulfillment of a number of requirements, such as the amount of data that have to be stored in the machine tool control unit (MTCU), quality and accuracy of the machined surfaces, milling forces, total machining time, and the like.

Cutting forces are the main factors governing machining accuracy, surface quality, machine tool vibrations, power requirements and tool life. The ability to predict the cutting forces is useful for the design of machine tool structures and cutting tools, as well as for the control and optimization of the machining processes to achieve high accuracy and productivity [2].

The steps required to perform freeform surface machining are usually classified into roughing, semi-finishing and finishing machining operations. In rough cutting, most of the material is removed from the surface to generate an approximate shape of the surface. Shoulders left from the roughing stage by large machine tools are removed in semi-finishing to yield a continuous offset surface for finishing. In the finishing stage, the rough surface is transformed into the exact shape [3,4]. In rough cutting, as much material as possible needs to be removed in the shortest possible time, so extensive research work is devoted to this area. One of the applied methods is feedrate scheduling to maintain the cutting force at a constant value, which results in a significant reduction of the total machining time compared to the method of maintaining a constant depth of cut and feedrate [1]. The use of such an optimization method is justifiable only in rough cutting, because the depths of cut are very small in surface finishing and consequently the cutting force is small.

In addition to the above-mentioned methods multicriteria optimization methods for freeform surface machining where also developed. They include mathematical solutions that consist of the physical relationship between the mean resultant forces, cycle time and scallop heights [5].

The use of multicriteria optimization can be justified only in the case when roughing is, at the same time, the finishing operation. In cases when it is necessary to remove as much material as possible in the shortest possible time and preferably in a single-pass it is necessary to develop a machining strategy in which the roughness and tolerances are maintained within the prescribed limits, and tool breakage, and the overstepping of the cutting force limits and/or the overloading of the drive motor of the servo axis of the machine is avoided.

This paper presents a description for tool path generation based on feedrate scheduling to keep resultant cutting force at maximum limit. Paper also presents description of performed experiment for free form machining and measurement of machined surfaces on optical scanner for determining map of deviations across the surface.

Henceforth, the paper is organized as follows: An overview of the developed methods for machining of free form surfaces is presented in Section 2, followed by a description and use of developed application for the free form surface generation (CAD) and tool path generation (CAM) in Section 3. Performed experiment for determining the cutting forces in freeform surfaces machining is described in Section 4. Measurement procedure and determination of machining error are presented in Section 5. The paper concludes with a summary in Section 6.

2. TOOL PATH GENERATION

The determination of the tool path is a very significant step in the process of designing the technology for complex surface machining. When the optimal tool path, aimed at achieving a satisfactory quality of the machined surface and an optimal machining time, is to be obtained, various specific constraints must be observed. For the case of rough cutting the machining time needs to be minimized, but the quality of the machined surface is not that much important. In surface finishing, in turn, care should be taken that the scallop height does not exceed the allowable deviation as prescribed by the technical documentation, but machining time does not play a significant role in the design of the machining technology. An ideal tool path should generate uniformly distributed scallops across the whole surface [6]. Smaller scallop heights than prescribed do not necessarily mean a better tool path, because the required increase in the number of tool passes increases machining time and, thereby, the cost of the part. On the other hand, a minimal machining time will be achieved when the scallop height is set to the maximal allowable measure [7].

Sculptured surfaces are most frequently represented as a bicubic Bézier, B spline or NURBS surface, which are defined and based on control points specified in Cartesian coordinates. Each point on the surface is calculated using the corresponding formulas as a function of two parameters, u and v. Specifying one parametric value enables the construction of a curve as a function of the other parameter, whereby a surface grid is generated. Three methods for complex surface machining have been developed so far, i.e., iso-parametric, iso-planar and iso-scallop.

2.1 Iso-parametric method

Iso-parametric paths have first been addressed by Loney and Ozroy [8]. The method of iso-parametric machining of complex surfaces takes advantage of the straightforward utilization of data on surface points to generate the tool path in such a way that the cutter location (CL) point is located on the surface normal vector at a distance equal to the radius of the spherical part of the ball-end mill. The disadvantage of this method is the varying scallop-height distribution on the machined surface, because keeping constant steps in parametric space leads to non-uniform steps in Cartesian space, Fig. 1. Elber and Cohen were the first to report the solution to this problem and their method was referred to as the adaptive iso-parametric method [9].

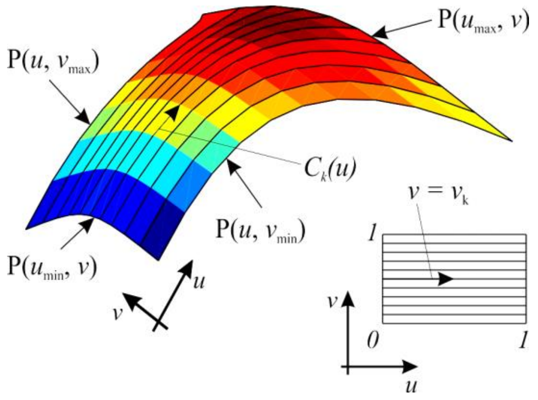

Figure 1. Isoparametric curves

2.2 Iso-planar method

In most cases the tool path in complex surface machining coincides with one of the coordinate axes of the machine tool. This has led to the development of the iso-planar method of machining, which means that the tool path is determined as an intersection of a freeform surface ($S_{u,v}$) with one of the coordinate planes of the Cartesian coordinate system. As it is difficult to determine the points of intersection between the surface and the plane, the surface should be approximated by a set of planar triangular surfaces, where every triangle is defined by the coordinates of its three vertices [10]. This method is very robust and widely used in commercial CAM systems [11]. The side step (L) in this method equals the distance between the parallel planes and is determined from the conditions defined by the maximum allowable scallop height of the machined surface (h), whereas the size of the forward step (L_{CL}) is determined from the condition of the highest allowable deviation (t), Fig. 2.

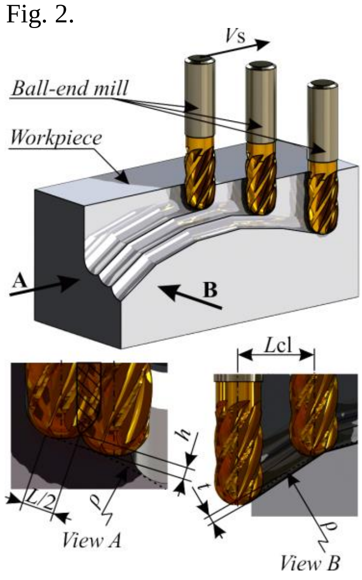

Figure 2. Side step and forward step

In this method, the adequate choice of the intersecting planes has a straightforward impact on the tool path length and, thereby, on the total machining time.

Both of the above-mentioned methods lead, in only a very small number of cases, to a uniform distribution of scallop heights on the machined surface. When there are parallel plane-surface intersections, and the parallel planes are eqidistant, unnecessary large scallop heights may be realized in some places on the machined surface, whereas, at other places, they may be very small.

2.3 Iso-scallop method

To obtain a uniform scallop height distribution across the machined surface, a novel machining method, called the iso-scallop method, has been introduced [12, 13]. The method of iso-scallop machining is an improved iso-parametric and iso-planar method. To define the tool path that respects the condition of uniform scallop height, subsequent tool paths must be defined based on the known preceding paths and the condition that the curve representing the scallop peaks between two tool passes is common for both passes. This principle implies that the known iso-scallop surface is an edge intersection curve of the tool envelope surface and the iso-scallop surface, Fig. 3.

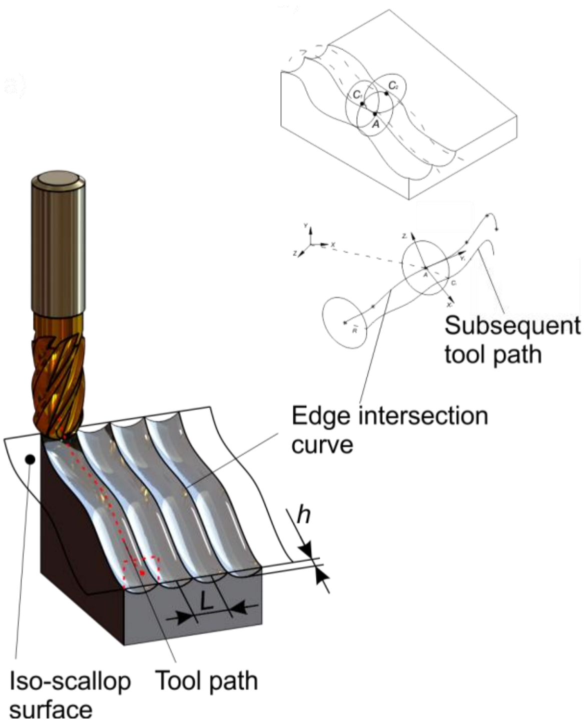

Figure 3. Iso-scallop model

The iso-scallop tool paths do not lead to redundancy and multiple machining passes over the same part surface are unnecessary. This implies that a shorter path is obtained in this way, i.e., workpiece machining is performed for a shorter time as compared to NC machining with iso-parametric or iso-planar tool paths [14].

3. DESCRIPTION OF DEVELOPED APPLICATION

Using the Matlab software it was developed CAD/CAM application for 3D modelling of free form surfaces. Beside the manual input of coordinates for control points, Fig. 4 it is also possible to load STL (STereoLithography) files of free form surfaces generated in one of commercial CAD sotware package.

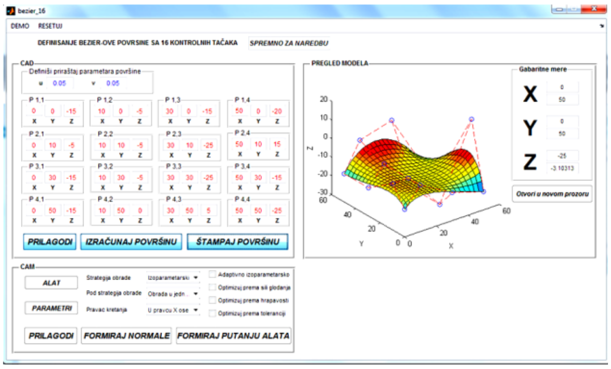

Figure 4. Form of developed application for manual design of Bezier surface

Developed CAM module of application allow tool path generation according to iso-parametric and iso-planar method. For both methods it is implemented condition for scallop height and max allowed deviation. For any of mentioned strategies is it possible to choose one of three sub strategies showed in Fig. 5. It also possible to choose direction of cut (along to X or Y axis of machine).

Implemented algorithm [17] for cutting force prediction is one of the aditional possibility of developed CAM module. It is possible to run simulation of milling process for ball-end mill and given combination of tool and workpiece material. Prediction of cutting force is performed according to current axial and radial depth of cut determined based on known workpiece and free form surface geometry. According to that the developed application generates tool paths for which the cutting force is maintained at a constant value by varying the feedrate in the specified range, e.g., from 0.015-0.13 mm/tooth for a cutting speed of 40 m/min. In the case that the value of the feedrate reaches the minimum allowable value, and the cutting force value is higher than the maximum allowable, a notification is received that the surface cannot be machined using the specified machining parameters, and, as a consequence, machining should be done in several passes.

It was used bicubic Bezier surface for demonstration of developed application. For tool path was used iso-parametric method with one way direction cut sub strategy, Fig. 5a. A part of generated NC code is presented in Table 1 where can be observed change of feedrade for each CL point.

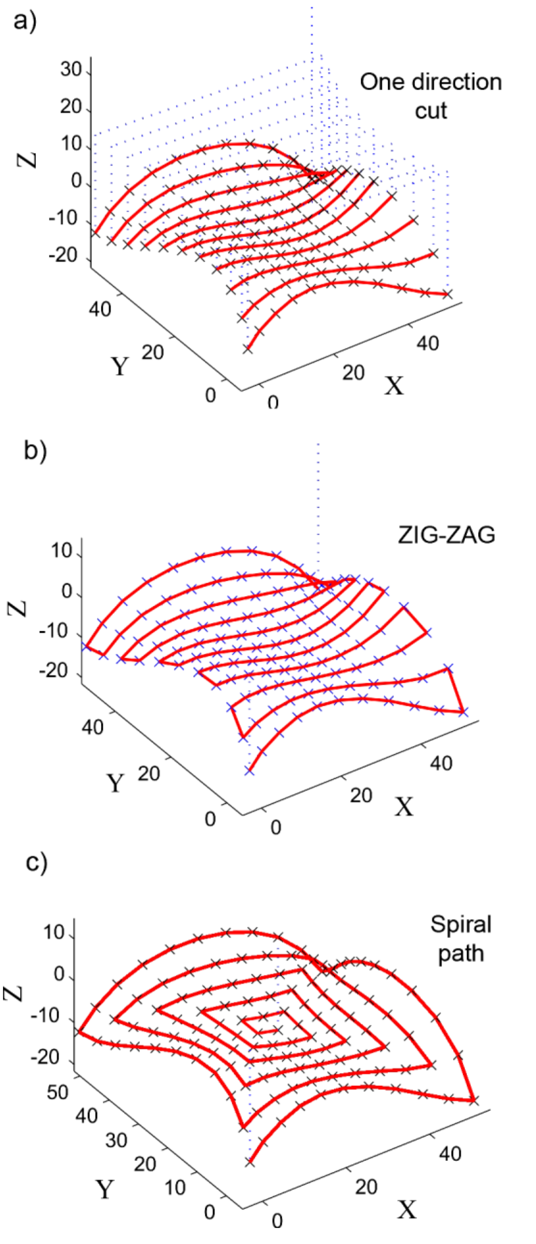

Figure 5. Developed machining strategies

Table 1. A part of generated NC code

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...
G01 X-0.281 Y10.851 Z-0.231 F140
G01 X 1.686 Y10.915 Z-0.154 F130
G01 X 4.066 Y10.988 Z-0.333 F125
G01 X 6.363 Y11.066 Z-0.726 F120
G01 X 8.619 Y11.143 Z-1.257 F113
G01 X10.868 Y11.215 Z-1.875
G01 X13.129 Y11.281 Z-2.539 F 97
G01 X15.411 Y11.338 Z-3.212 F 82
G01 X17.714 Y11.383 Z-3.861
G01 X20.037 Y11.415 Z-4.454 F 72
G01 X22.372 Y11.430 Z-4.959
G01 X24.712 Y11.425 Z-5.348 F 63
G01 X27.050 Y11.395 Z-5.594
G01 X29.382 Y11.339 Z-5.674
G01 X31.706 Y11.254 Z-5.567
...
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4. EXPERIMENT

After the generation of NC code, the next step was to machined free form surface according to generated tool path. It was used AlMg4.5Mn workpiece material with two dimensions, 50x50x50 mm and 70x70x50 mm. Machining was performed with a high-speed cutting steel (NSSE 8% Co) ball-end mill with a 12 mm in diameter with 2 teeth and a helix angle of 30^0 on a horizontal machining centre ILR HMC500/40. Max allowed scallop height was set at 0.6 mm because this machining was regarded as rought machining.

The experimental setup for the determination of the cutting forces in freeform surface machining is shown in Fig. 6. With installation of the inductive linear measuring element it is enabled to get the cutting force data as a function of displacement of worktable of machine tool (in this case in X axis direction). For identifying the cutting force it was used two component dynamometer with strain gauges.

Signals of the two perpendicular components of the cutting force and measurement element enter three amplifiers KWS3082A, HBM Co., where their conditioning is performed. From the amplifiers, signals enter the system for data acquisition that consists of NI Compact DAQ USB cDAQ-9174 with a NI9215 module for analog input: ±10 V, 16-bit with 4 channels and 100 ks/s/ch. The measurement results were analysed in LabVIEW software.

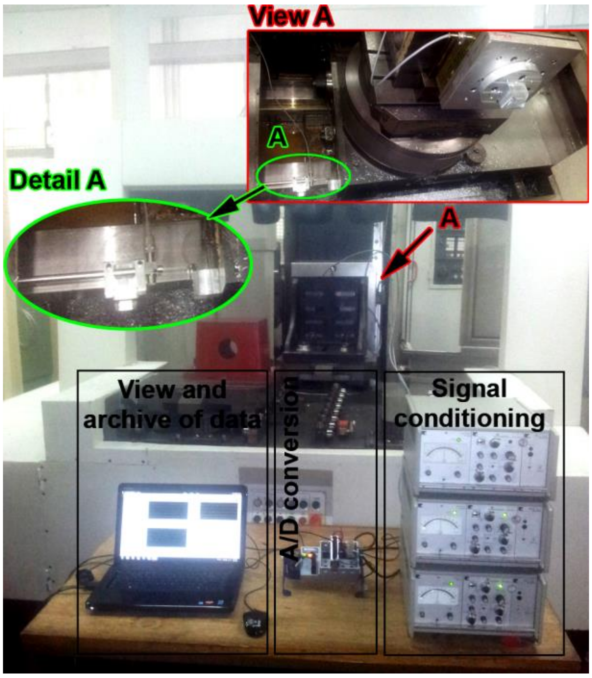

Figure 6. Experimental setup for determining the cutting forces in freeform surfaces machining

Using the Matlab software it was processed experimental data and it was obtained records of cutting force as a function of displacement of worktable of machine tool. The measured value of cutting force in the plane perpendicular to the toll axis as a function of X displacement of machine tool for one pass is shown in Fig. 7.

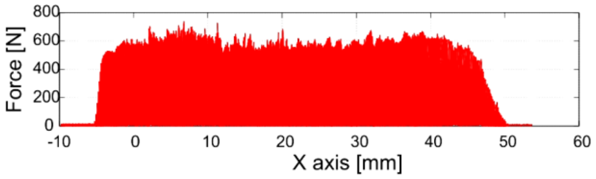

Figure 7. The resultant cutting force in the plane perpendicular to the tool axis for one pass

Based on the experimental result it can be concluded that the way for tool path generation with developed application is applicable for free form surface machining with feedrate scheduling. Based on Fig. 7 it is noticeable that the value of the resultant cutting force (F_{xy}) was kept at the specified value of 600N with allowed deviation.

5. MEASUREMENT OF MACHINED SURFACE

The scanning with measuring arm and optical scanner of machined part was performed for verification of the accuracy of tool path generation with developed application. The representation of scanning of machined surface is shown in Fig. 8.

Figure 8. Measurment of machined surface

For scanning of machined part was used ROMER ABSOLUTE ARM (7330SI) with technical specifications: point repeatability of ±0.075mm, probing volumetric accuracy of ±0.100mm and scanning system accuracy of 0.119mm. The machined part and obtained point cloud after scanning are shown in Figure 9.

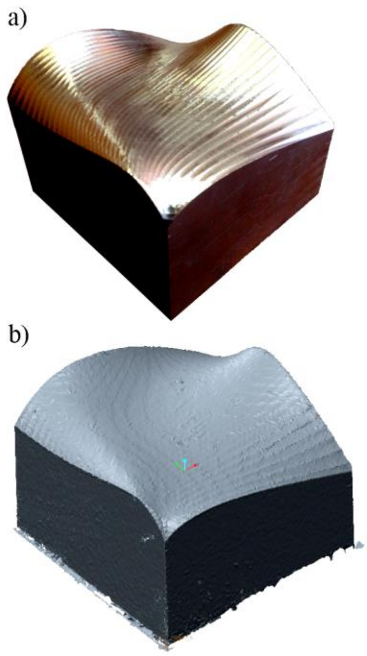

Figure 9. Machined part (a) and point cloud (b)

At each measurement point, the local deviation from the CAD model (nominal surface) is determined in the direction normal to the model [18], as shown in Fig. 10.

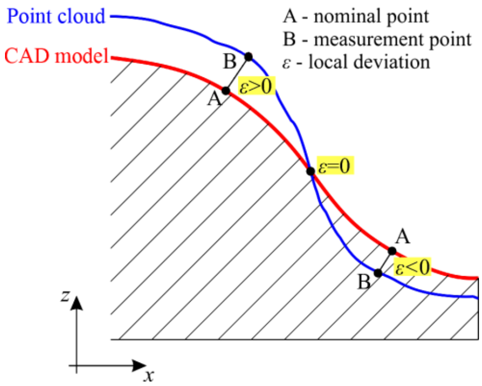

Figure 10. Local deviation at a measurement point

In measurements based on the CAD model, the values of these deviations are determined by developed code in MatLab software. If data are virtually fitted to the CAD model, deviations of surface location and orientation are separated, and then measurement data represent surface irregularities [19]. The obtained map of deviations for one of machined surfaces is shown in Figure 11.

With the analysis of data from Fig. 11 is is observed that the machining error (deviation) was in imputed tolerances given with the basic machining parameters at the start of tool path generation.

The existence of larger deviation is explained with the fact that the clamping of workpiece to the machine worktable was performed via dynamometer which is elastic element itself.

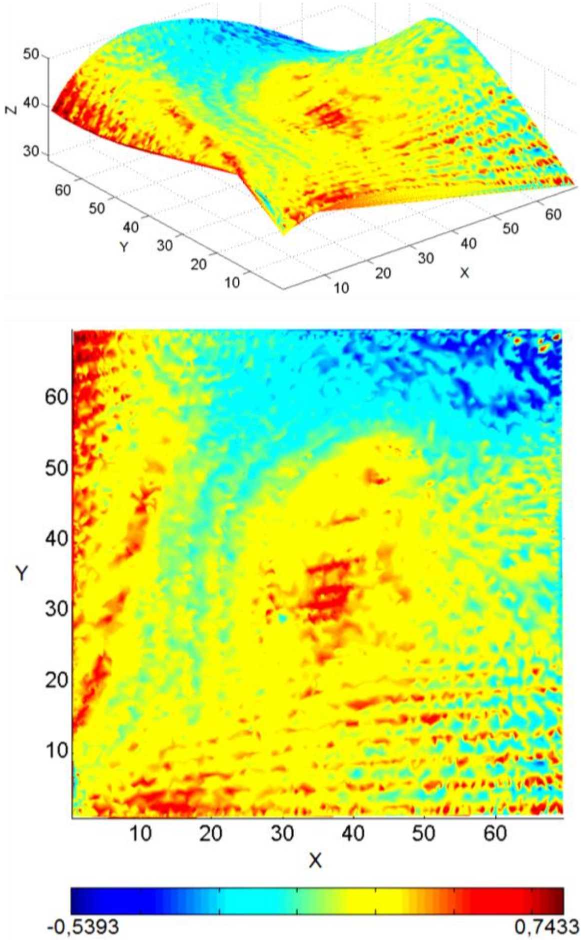

Figure 11. Map of deviations

6. CONCLUSION

The paper presents description of developed machining strategies for free form machining and the developed CAD/CAM application. It was performed machining of several parts with free form surface according to generated NC code with developed application. It was used feedrate scheduling strategy for machining.

It was experimentally verified that the cutting force was kept at the value (defined at the start of manufacturing process) with allowed deviation of 10%. Map of deviation was determined with the analysis of point cloud obtained with scanning of machined part. The clamping of workpiece to the machine worktable via dynamometer which is elastic element itself was caused the existence of larger deviation at certain places where was big axial depth of cut. Also the accuracy of measuring arm causes the value of deviation which was included in total machining error.

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