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Brief note

OPTIMIZATION OF PROCESS PARAMETERS OF EDGE ROBOTIC DEBURRING WITH FORCE CONTROL

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The issues addressed in the paper present a part of the scientific research conducted within the framework of the automation of the aircraft engine part manufacturing processes. The results of the research presented in the article provided information in which tolerances while using a robotic control station with the option of force control we can make edge deburring.

Key words: edge robotic deburring, force control, robots station, 3D scanning.

1. Genesis of the problem

The issues contained in the article present a part of the research carried out within the framework of robotic manufacturing processes of aircraft engine components. The paper concerns the V2500 engine diffuser (Fig.1a). This is a turbofan engine with a high bypass ratio. It is produced by the International Aero Engines consortium, which was founded in 1983. The unit drives the V2500 aircrafts from the Airbus A320 family and the McDonnell Douglas MD-90. The engine received a certification from the FAA in 1988. The company Prat&Wittney Rzeszów SA which is part of the UTC in its operations performs technological operations involving the machining of V2500 engine diffusers' castings (Fig.1b). One of numerous technological operations is the edge deburring.

a) b)

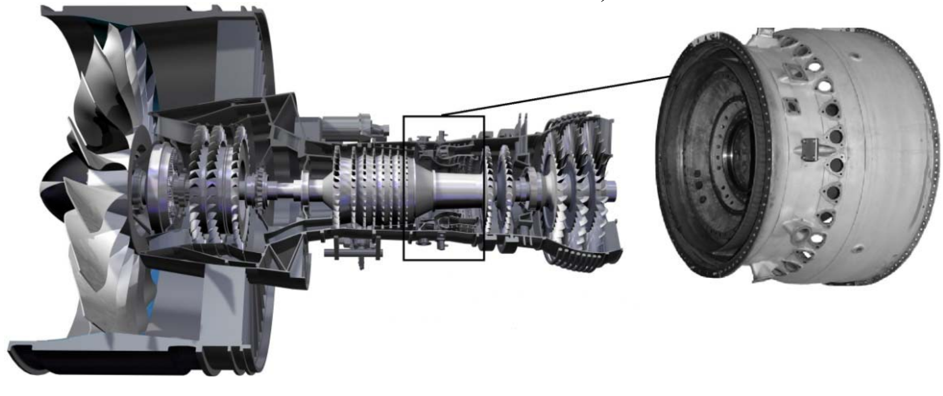

Fig.1. a) Engine model, b) exemplary jet engine diffuser.

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During the execution process of the diffuser there are a number of edge parts that require deburring which is carried out manually. Hand treatment results from the fact that there are elements of randomly variable, limited shape. This is due to precision casting technology used which is characterized by a variable geometry of the workpiece according to the accuracy of molds and the phenomenon of shrinkage during solidification. This creates a difficulty in defining a precise shape, which in turn results in the need to use manual handling (e.g. edge deburring), inability to reproducibly determine the tool path. This fact introduces a high risk of defective elements associated with the presence of the human factor (error, fatigue, stress).

The V2500 engine diffuser contains nine types of shapes to be deburred. As an example there has been chosen a triangular case shown in Fig.2. The case appearance in the row casting is shown in Fig.2a, while the case after treatment is presented in Fig.2b.

a) b)

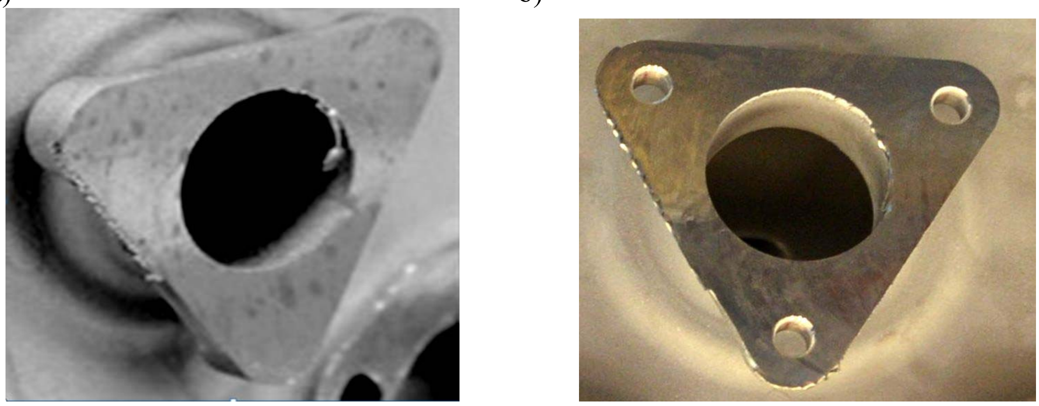

Fig.2. Fragments of the workpiece to be deburred a) raw casting. b) casting after the treatment with the edges of the parts to be deburred.

Performance parts are controlled at a few selected points by optical methods. In the vast majority, quality checks are carried out visually by an employee of quality control. The aim of quality control is the elimination of details with where there are sharp edges, notches or jam. It is obvious that the presence of the notches reduces the fatigue life of the part. The aim of the present work was the selection of parameters, the robotic process of edge deburring of the system of control forces.

2. Robotic process of edge deburring

In robotic systems solutions, there are several ways to adapt the robot trajectory in real time or on the basis of previous measurements. Adjustment of the path to changing external conditions is determined by process conditions. In the fast-changing processes of low force in tool-detail contact active tools with variable contact force are used [1, 6, 7, 8, 9]. In processes where the contact force exceeds *10* [*N*] robotic systems with control force are employed (force control) [2, 3, 5]. An alternative approach is to generate a tool path on the basis of shape measurements carried out using a laser or machine vision systems. One should not fail to pay attention to the learning systems. It is a combination of software control system forces with software recording successive digitized trajectory points. The process is divided then into the stage of the learning process and proper robot motion. Such a solution despite its precision requires a lot more time for implementation. The technological process is divided into three phases, removal of the allowance (bead), execution phase and grinding of machined surfaces. In the first stage, a dedicated tool to the support bearing is used to cut allowance.

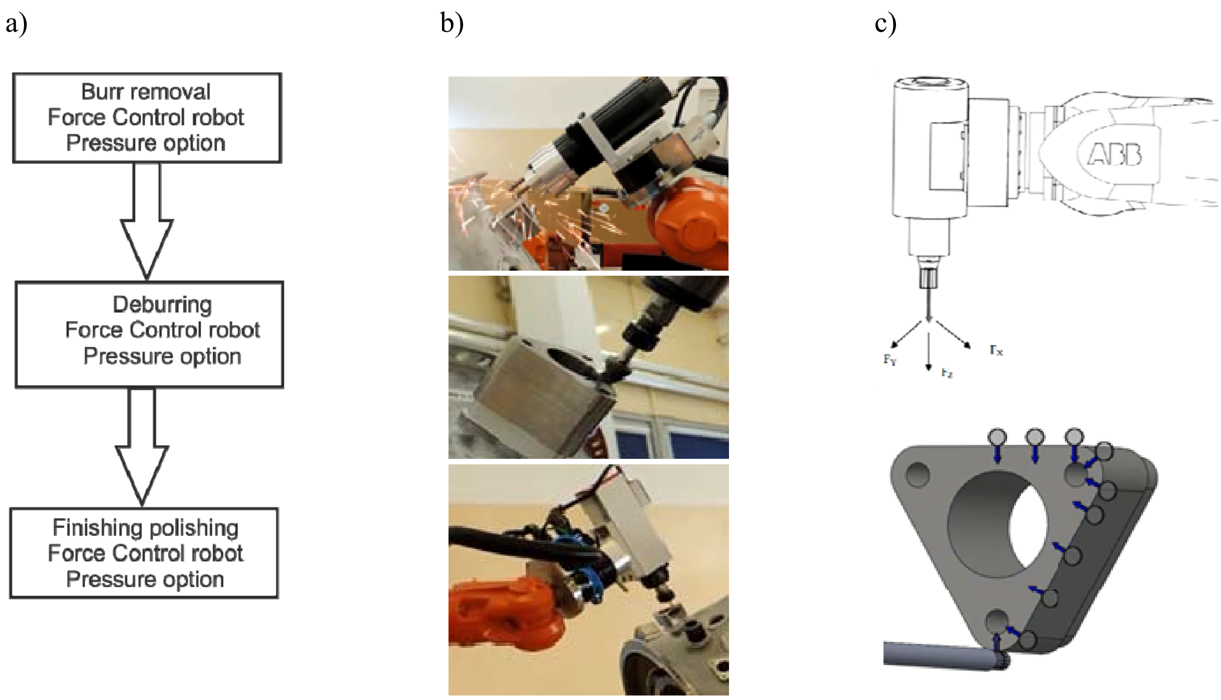

Fig.3. a) Diagram of the process, b) photos of the implementation of process stages c) the idea of tool operation with supporting bearing model.

In the next stage, edge deburring is executed with a form-tool. The third stage is polishing. All operations are carried out by a robot equipped with an option to force control. The entire process is performed by an ABB IRB140 robot and consecutive stages of processing are made possible by replacing the tools located in four-position changer.

3. Edge deburring with a robot with force control

The application of the Force Control Package in built position allows us to control the force exerted by the tool on the workpiece. Thus the position of the workpiece must be known to an accuracy of a few milimeters. Such a solution enables the robot interactions with the environment. Control strategy enables the adjustment of the movements of the robot to feedback from the force sensors in real time. The software supporting the addition of force control allows us to control the process using the strategy: FC Pressure and FC SpeedChange.

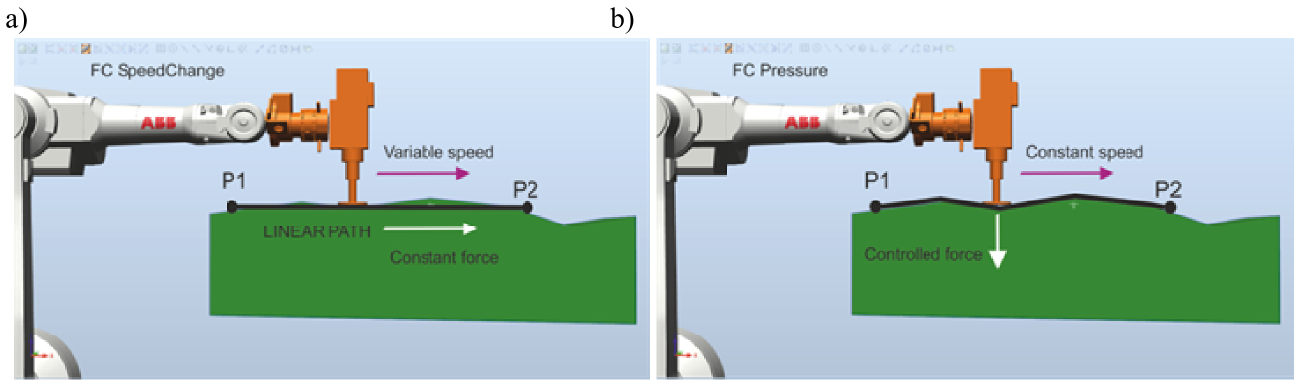

Fig.4. The principle of FC Pressure function b) the principle of FC SpeedChange function.

The FC Pressure FC option uses a feedback loop and allows polishing or grinding the cast at constant pressure of the tool on the surface of the work piece defined at a constant process speed. The idea of this solution is presented in (Fig.4a). Using this function enables the processing of the material at a constant speed and control of the force perpendicular to the work surface. The path of tool movement is adjusted to the curvature of the surface.

The FC SpeedChange (Fig.4b) allows casting deburring or removal of allowance material at a rate dependent on the occurring resistance forces. The speed of point movement of the TCP robot is reduced by the control system when the forces occurring during processing exceed the established value. This helps to avoid damage to the workpiece or the tool due to excessive stress or heat.

In the proposed solution insensitivity to acquire displacement is provided by the FC Pressure option. The use of the possibility for adapting the trajectory of the tool in real time allows the robotic insensitivity to the limited movement of machined surfaces. Assuming the maximum dispersion of the case casting shape on +/- *2* [*mm*] level, we can design an offset trajectory. The offset trajectory is specified with respect to the nominal model and its value has been adopted at doff = *3* [*mm*]. The view of the nominal trajectory is contained in Fig.5 while the offset trajectory is presented in Fig.5b.

a) b)

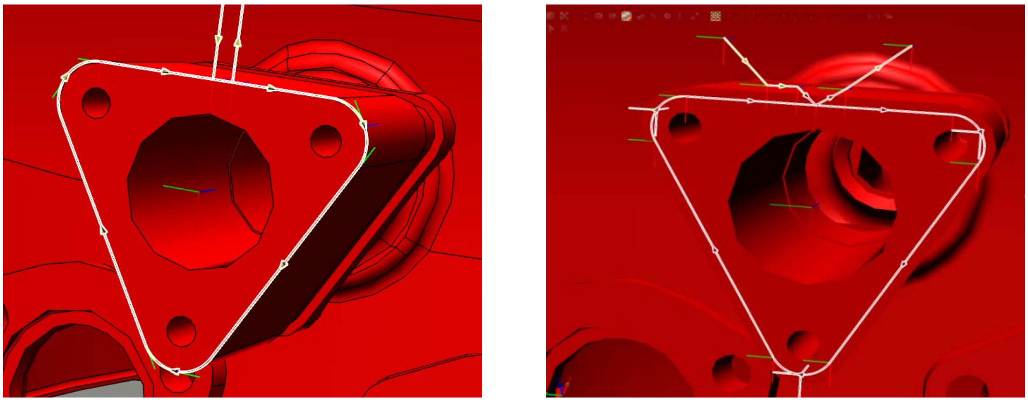

Fig.5. Model of machining process RobotStudio a) nominal trajectory, b) offset trajectory.

The use of FC Pressure addition requires the determination of several parameters such as the rate of speed change (Threshold [%]), and a rising force rate (Force Change Rate [*N/s*]), attenuation (Dumping [%]), the maximum waiting time for contact (Timeout [*s*]), the percentage of the predetermined force at which the robot starts the process (Zero Contact force [%]), the level of filtering for low pass filter (Noise level [Hz]).

A cone cutter (HFM *0307.03*.Z7) is used as a tool. The rotational speed of the tools has been adopted as *10.000rpm*. The level of filtering for the low pass filter has been determined using TEstSIgnalViewer software. The results of the selection of the filtering level are presented in Fig.6. Figure 6a presents the results of the measurement of forces in detail-tool contact in three directions corresponding to the adopted local coordinate system. Figure 6b presents a measurement of the strength after filtration.

a) b)

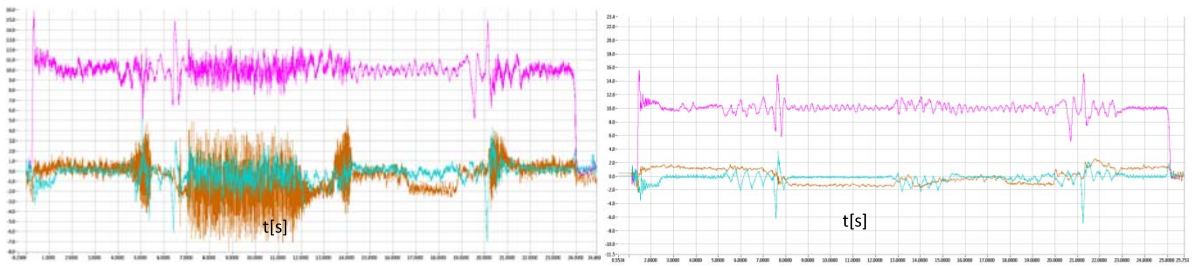

Fig.6. Values of forces on detail-tool contact a) without a filter, b) after filtration.

Parameters of the rate of speed change (Threshold [%]) and the percentage of the predetermined force at which the robot starts the process (Zero Contact Force [%]) are correlated with the shape of the trajectory and matched on the basis of current research practice. The parameters of force increase the rate (Force Change Rate [*N/s*]). The attenuation (Dumping [%]) has been chosen experimentally so that the beginning of the process was characterized by a lack of the recess in the performed deburring and the formed surface was characterized by smoothness. The selection of these parameters is related to the type of workpiece and the type of tool used, as well as the cutting data. Adoption of the parameters of the force control allows us to start work test to identify the process parameters such as the TCP speed and the force of detail -tool contact.

4. The selection of process parameters

Performing a series of tests and the need for a very large number of measurements motivated us to use robotic automated measuring systems. Deburring process control has been performed using a robotic station consisting of: a robot IRB1600, 3D scanner and software ATOS Professional [4]. Control measuring points in areas where the greatest inaccuracy of deburring was expected (Fig.7a) were proposed. For a triangular shape of the case twelve points of measurement selected are shown in Fig.7b.

a) b) c)

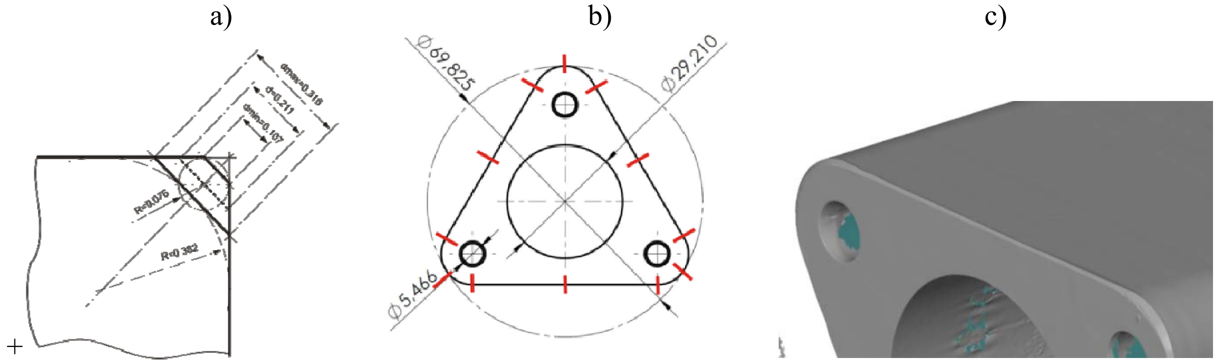

Fig.7. a) Parts which required deburring , b) the selected measurement points, c) Sample piece of 3D scan.

On the basis of imposed accuracy the nominal precision of deburring performance and limit values were specified (Fig.8). A measurement experiment based on determining the width of the implemented phase as a function of contact forces was proposed. The measurement results are summarized in a graph, which shows the value of the width of the phase carried out in the imposed limits and for which the forces of the graph has been performed (Fig.8).

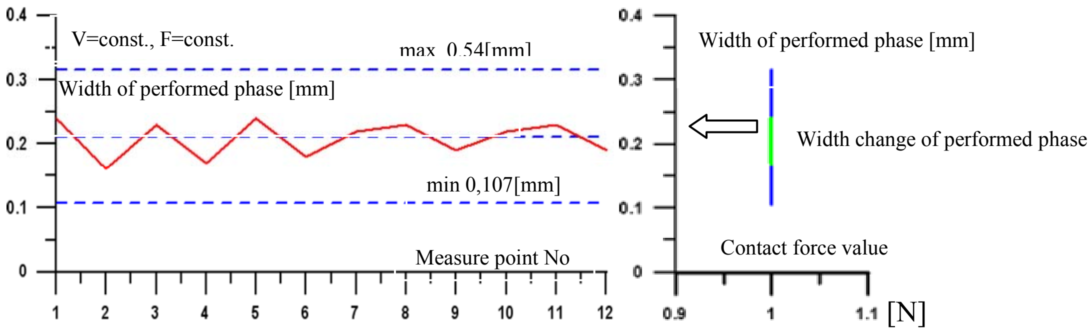

Fig.8. The concept of performed measurements.

The graph in Fig.8 summarizes the width of performed phase with marked maximum and minimum speed point TCP robot *50*, *100*, *250*, *500*, *750*, *1000* [*mm/s*]. The chart was prepared for the forces of *3*, *4*, *5*, *6*, *7* [*N*]. The parameter values satisfying the imposed constraints resulting from the width of the phase implemented were numbered from 1 to 12, thereby a set of parameters was obtained. An example of the result of the deburring process is shown in Fig.9a.

a) b)

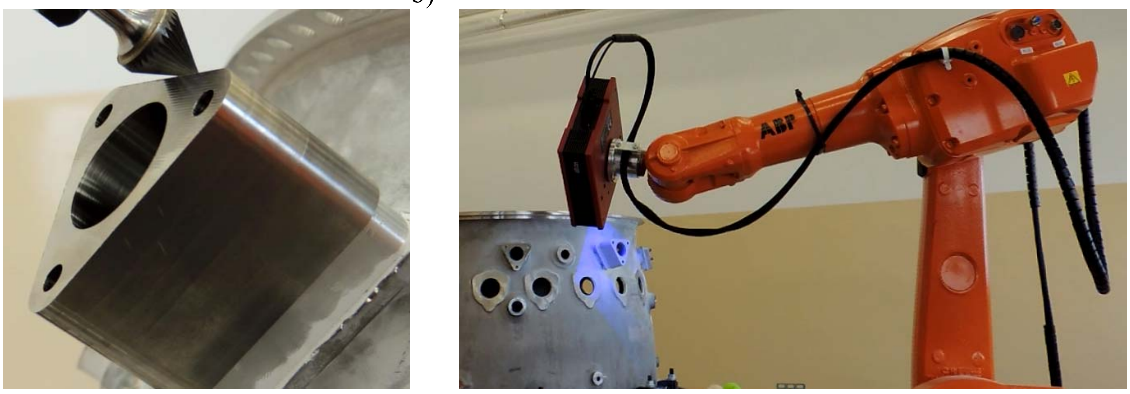

Fig.9. a) Photo of the process of the deburring performance, b) implementation of measurement 3D scanner.

360 measuring points were used to prepare the graph presented in Fig.10b. A sample measurement report for one tool-detail contact force and one set movement speed of TCP point is given in Fig.10a.

a) b)

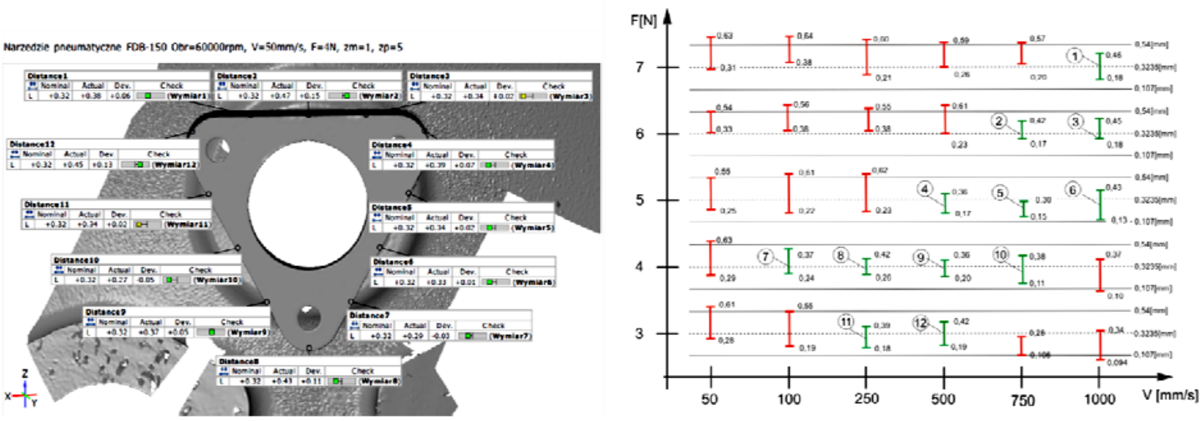

Fig.10a) Example of a measurement report, b) test results.

An analysis of Fig.10b allows us to draw conclusions that there is a wide range of process parameters, namely the contact force and speed of movement of the TCP point which with the adjusted nominal speed of the tool provides edge deburring compliance with the requirements defined in the documentation. In order to select a set of these parameters to ensure the best possible implementation of the process the below-mentioned optimization procedure has been proposed.

5. Optimization of process parameters

As a result of the research 12 two-element sets of parameters (Fig.10b) were obtained ensuring the implementation of the process according to the imposed requirements. Then a two-step optimization process for selecting a suboptimal set of parameters was proposed.

In the first stage, a group of parameters was classified cumulatively in accordance with the accepted indicator of quality. As a quality indicator the sum of squared deviations relative to the nominal value was proposed, which indicates how big a mistake of deburring would be. Quality control of deburring performance is carried out in the plant on the basis of visual inspection. It may be the case that even though the size of the phase is within the imposed tolerance, it is made in such a way that we observe rapid changes in the value (the resulting surface resembles a curb, saw). Such an execution of the deburring phase would be unacceptable. In order to assess the rate of surface shape change the indicator of the maximum value of the derivative function describing the change of shape was introduced. For this purpose, the deviation from the nominal value was discretized with a set of points thus the path covered by the tool was divided into *n* points at *1* [*mm*] distance and the corresponding error value of deburring width in relation to the nominal (Fig.11) level 0 was recorded. Example of the case upper edge discretization is presented in Fig.11.

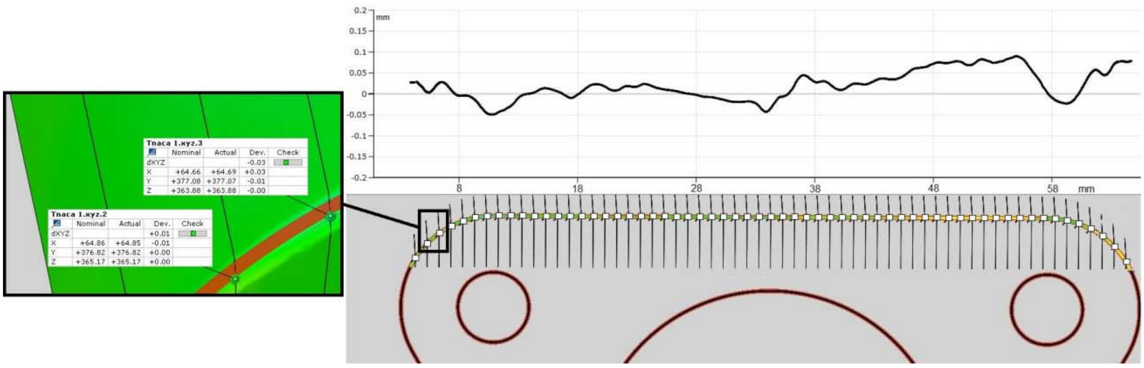

Fig.11. Chart of the accuracy of the phase as a function of the approximated points (upper part of the case measurement No. 6).

The resulting points were approximated with the spline function of the 3rd degree, using the Matlab/Simulink software. The function received was the following

$$e = F(n) \tag{5.1}$$

where: e is an error if deburring phase and n is the number of points approximating the distance covered by the tool.

Then the generated function was used to determine the proposed quality indicators for measuring from 1 to 12 in Fig.10b. The sum of the squares of deviations and the maximum absolute value of the derivative of the error function (Fig.12) were assumed as quality indicator. The indicator of the sum of squared deviations for each measurement was determined according to the relationship

$$E = \int_{0}^{N} e^{2} dn\,, \tag{5.2}$$

and the ratio of the largest absolute value of the derivative of the formula

$$\dot{e}_{\max} = \max_{n \in N}\left(\left|e_n\right|\right). \tag{5.3}$$

A summary of obtained values of indicators in the form of Fig.12b allowed a selection of process parameters from measurements No.6. Thus obtained parameters in the form of the force of tool-detail contact and the TCP point speed at a given nominal speed value of tools have been accepted as the best solution from the available set of solutions.

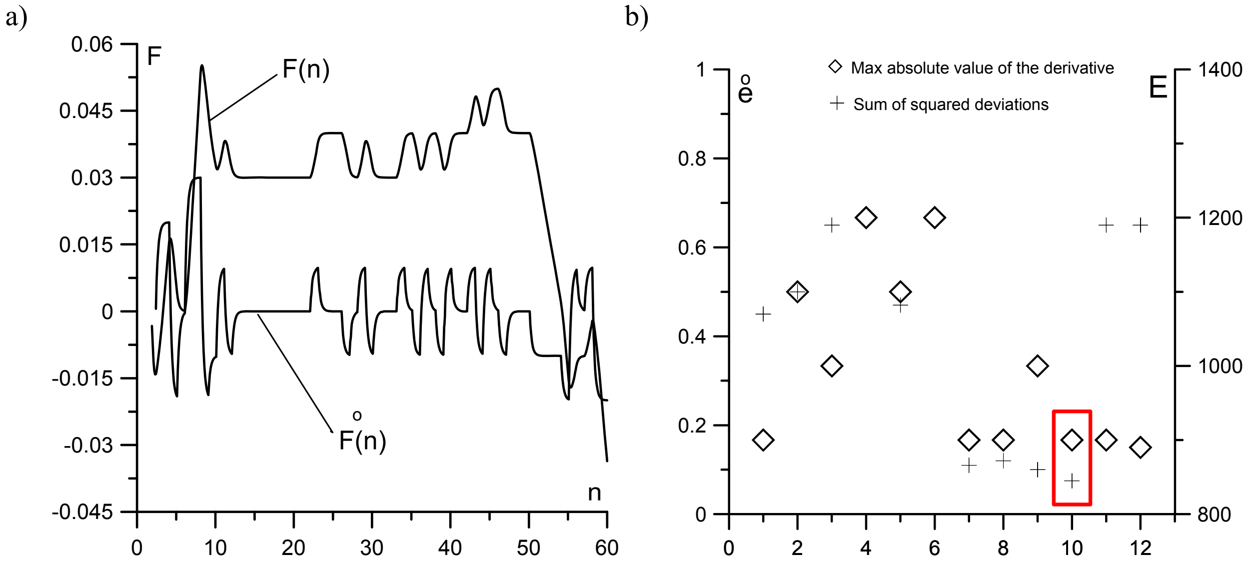

Fig.12. a) The changes in the value and accuracy of execution and its derivative for measurement No.6, b) a summary of quality indicators.

6. Conclusions

The results of research presented in the article provided information in which tolerances while using a robotic control station with the option of force control we can make edge deburring. It should be noted that the results relate to the Iconel 718 material and tools and are not universal. The authors propose a procedure for conducting studies allowing a selection of suboptimal process parameters. In the present case, the speed of movement of the characteristic point and the force of contact detail-tool.

The proposed optimization procedure made it possible to indicate a set of process parameters ensuring compliance with the requirements defined in the documentation. The proposed solution is of engineering nature and it is not a classic search for extreme function from the point of view of two adopted criteria (quality indicators). The advantage is the simplicity of the proposed solution ensuring the improvement of deburring quality, which from the point of view of industrial application is very important. To sum up, the best values are the tool speed *12000* [*r/min*], the force of the contact *4* [*N*], the speed of movement of the tool (point TCP) *750* [*mm/s*]. The authors in the framework of this research have developed a robotic processing station, the use of which ensures the implementation of edge deburring operations of variable shape. The resulting solution in the form of a robotic machining technology has been implemented in production plants of Prat&Wittney S.A. in Rzeszow.

Nomenclature

E – sum of squared deviations
e – error deburring phase
$\dot{e}$ – derivative error deburring phase
$\dot{e}_{\max}$ – max value derivative error deburring phase
N – max amount of points approximating the distance covered by the tool
n – number of points approximating the distance covered by the tool

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