DEVELOPMENT OF REVERSE ENGINEERING METHODODOLGY FOR THE PRODUCTION OF MACHINE PART

ARAVINDPRASAD SRIKANTHAN, RADOMIR MENDRICKY, PETR KELLER

Department of Manufacturing Systems and Automation

Technical University of Liberec, Liberec, Czech Republic

e-mail: aravind.prasad19@gmail.com

Engineering design is the preliminary and significant technique for manufacturing the machine parts. Conventional design methodology is the process by which desired models are transformed into real parts. Using reverse engineering concept, the real parts are transformed into models. This article deals with developing a methodology for reverse engineering of machine parts with parametric surfaces. Real part was digitized with 3D scanner and obtained digital data was processed with Geomagic DESIGN X to create 3D solid model. Numerical Codes (NC) are generated in Edgecam software by utilizing the solid model and the new part was manufactured in MAZAK INTEGREX a Computer Numerical Control (CNC) machine. Inspection procedure was performed before and after manufacturing of the new part using GOM Inspect 3D.

KEYWORDS

reverse engineering, ATOS II 400, polygonal mesh, geomagic DESIGN X, solid model, Edgecam, GOM Inspect

1 INTRODUCTION

Reverse engineering (RE) is defined as the process of reproducing the desired component by capturing its physical dimensions. Traditional engineering can be challenging in the circumstances when there is no Computer Aided Design (CAD) data exists for development of new part from available real part. In this case, RE process is the right solution for creating the CAD data and developing the documentation for manufacturing the new part. [Varady 1997] have explained the algorithm of creating geometric model of existing part having no history. To aid remanufacturing of worn parts, a RE approach was proposed [Li 2017]. Damaged real object was transformed into solid model by RE process [Sokol 2017]. Geometric reverse engineering ideology was stated for mechanical design [Anwer 2016].

RE methodology is achieved in three major steps such as data acquisition, data processing and data modelling. Data acquisition method is the primary step in RE, which acquires the data from the object of interest. Contact or noncontact measurement technology is involved to measure the target object. Hardware and software system of data acquisition devices captures data of the object and displays in the computer in form of digital data (Point cloud). Point clouds are set of 3D points representing the specific position on object's surface. The object is measured from multiple views resulting in the formation of group of points. Each point is defined by x, y, z coordinates. Data processing is the next stage in RE. Data processing is the manipulation of the digital data by computerized processing of data which is required for further analysis and data modelling. RE procedure is completed finally by data modelling to create CAD model. Solid modelling and surface modelling are major types of modelling used to create a CAD model. Professional RE software allows the user to execute data processing and data modelling. Processed data and CAD model created using software can be exported usually in STL and STEP format respectively. STL is an abbreviation for stereolithography, standard data format compatible for different applications like rapid prototyping for manufacturing prosthetic parts. Manufacturing of the machine parts with CNC using geometry of the part from STL data which is essential for NC programmer. Finite Element Analysis is computerized analysis to visualize the reaction of the target object with physical phenomenon by using its STL data. In manufacturing industry, reverse engineering is applied for reinventing the manufacturing process of the part [Wego Wang]. Intraoral scanning device is used in dental industry for obtaining the digital data of the tooth and the digital data is utilized for 3D printing of tooth fitting crowns [envisionTEC].

Main aim of the article is the development and verification of the RE method for machine part. CNC tool was chosen as the target part. The old tool holder of the CNC tool need to be replaced due to the requirement of dimensional changes. It was necessary to replace the old tool holder because the CNC tool has to be offset to 15mm from the body of the old tool holder. RE method was implemented on the CNC tool to manufacture prototype of new tool holder. RE process starts by digitizing the tool with optical 3D scanner ATOS II 400 [GOM 2012]. Digitized data of the tool was exported in STL file format. [Geomagic Design X 2016] Geomagic Design X software is important in this work for processing the STL data and extracting the design information from the data of the tool for designing 3D model of the new tool holder. 3D model was exported in STEP format. Edgecam is the Computer Aided Manufacturing (CAM) software to generate NC program from the designed 3D model [Edgecam 2017]. Prototype of new tool holder was manufactured by MAZAK INTEGREX with generated NC program. Inspection was carried out before and after manufacturing of the tool holder by GOM Inspect 3D measuring software. The developed methodology was practically experimented. Finally, the article was concluded with evaluation, attained goals, limitations and future vision of the suggested methodo.

2 REVERSE ENGINEEING METHOD

The method initiated for RE in fig.1, commences with digitization of the CNC tool followed by processing of the digitized data (STL data) in Geomagic Design X software, generation of NC code in Edgecam software for manufacturing the new tool holder and inspection of the new tool holder's data in GOM Inspect 3D. This chapter demonstrates the equipment, software used for achieving RE and practical procedure of each stage showing the resultant images.

2.1 Digitization

The process of acquiring information of real part and converting into digital data is known as digitization. Digitization is the method for saving the digital data suitable for transferring and processing. Coordinate Measuring Machine (CMM) and robotic arm with touch probes using principles of strain gauge, optoelectronic are popular contact digitization devices. Digital data from the contact digitization device is the collection of points from real part in small or large volume.

Optical 3D scanners, laser 3Dscanners, structured light 3D scanners are noncontact digitizing devices that works on the principles such as triangulation, structured lighting, stereo vision for digitizing the real part. 3D scanners are equipment with image sensing device used for digitization of real world objects. 3D scanner collects shape and size of the real part to build 3D digital data. 3D digital data consists of geometric point cloud from the surface of the real part and each point represents the 3D position of the single point from the surface of the real part.3D scanning is rapidly growing technology in the market introducing 3D scanners for faster and cheaper digitization. It is necessary to pick the suitable method for digitization considering the cost and accuracy.
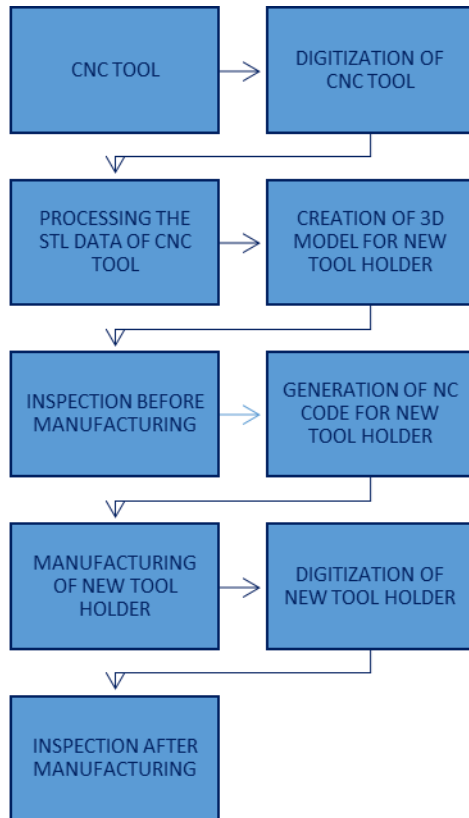

Figure 1. Schematic representation of proposed RE methodology

ATOS II 400 optical 3D scanner developed by GOM works on the principle of fringe projection. 3D Scanning of the CNC tool was performed by means of ATOS II 400 optical 3D scanner. The particular 3D scanner was selected as it was available in the university laboratory and it ensures fast acquisition of real part with high resolution. The main parts of the ATOS II 400 are projector, two cameras and control unit. Fig.2 is the image of CNC tool and it is the target part chosen for digitization. Reason for the selection of CNC tool as the target part because the holes can be precisely digitized from the CNC tool by ATOS II 400. Holes on the CNC tool are located for fixing the tool and tool holder with screws.

Control and process are handled by ATOS professional software. This software was designed to acquire 3D data and guide the operator for digitization. Calibration and adjustment of the scanner is necessary before digitization.

The mandatory steps before digitization are,

- ➢ Camera was fitted with appropriate lens.
- ➢ Selection of measurement volume 55 x 40 x 33 mm.
- ➢ Verification of measuring distance from the camera.

- ➢ Adjustment of camera angles so that projector's center point and software's camera point coincides.
- ➢ Modification of laser pointers, sensor settings, focus of projector and camera if required.

Figure 2. CNC tool (Target part)

Preparation of target part is the main role for the operator for digitizing the target part. Suitable fixture was selected to fix the target part. Reference points are distributed according to certain rules throughout the part so that the scanner can identify the points. But in this case the reference points are placed on fixture because the target part was small. Fig.3 shows the mounted target part on fixture with reference points. Titanium powder can be applied on the target part due to its glossy surface as it is the coating for antireflection. Coating has to be completed before starting the digitization.
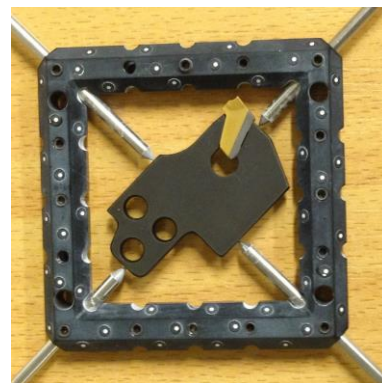

Figure 3. Reference points on fixture

Digitization steps of the target part by ATOS II 400 are as follows,

- ➢ Scanner position and optimal shutter speed are set for digitizing.
- ➢ Fixture with target part was placed on the rotating table by defining number of steps and angle of total coverage for rotation of the table.
- ➢ Scanning starts by projecting stripes of light on the target part which is displayed in the software's workspace.
- ➢ Reference points are detected by the camera to collect the data from the one side of the part and scanning was performed by turning around the part.
- ➢ Multiple scans are performed on the part and combined into single data by the ATOS professional software.
- ➢ Undesired data is removed from the scanned data to calculate polygonal mesh for exporting in STL format.

- Fig.4, fig.5, fig.6 are the images showing the digitization of the CNC tool in ATOS professional software.
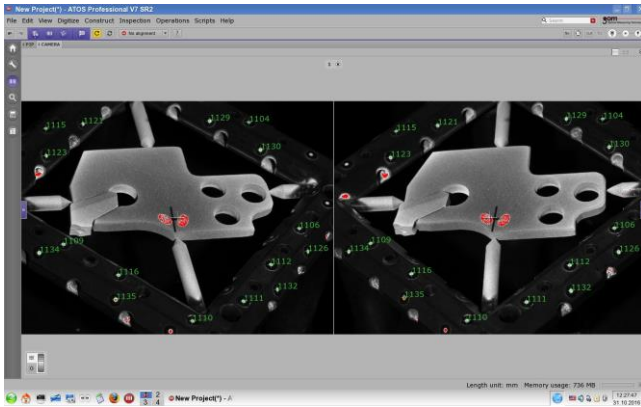

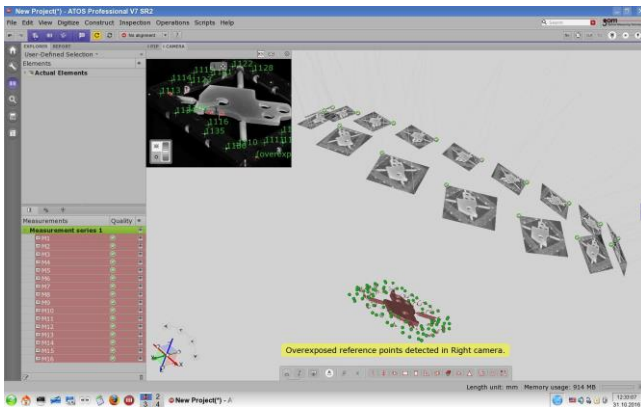**Figure 4.** Target part displayed in ATOS professional

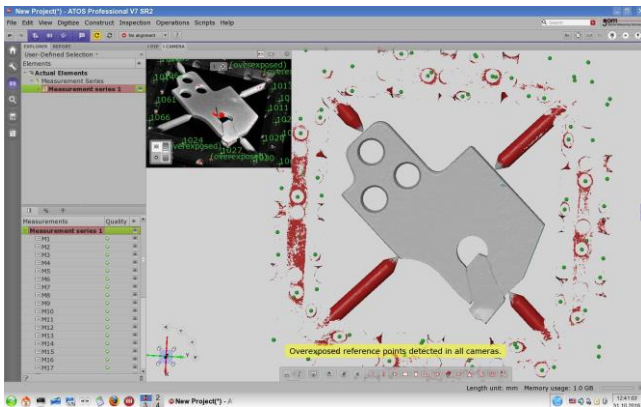
Figure 5. Combination of multiple scans

Figure 6. Elimination of fixture from scan data

2.2 Processing and modeling

Manipulation of digitized data is called processing and the transformation of processed data is known as modelling. 3D scan data obtained from the digitization is usually a raw file that is not suitable for further stages in RE. Processing the raw data file is the prime task for the RE software to create 3D model. Processing of scan data involves filtering of noise in the form of spikes, to fill the missing data and merging of multiple scan data. 3D Modeling of processed data can be completed by mesh modeling, parametric modeling and freeform modeling. Mesh modeling is to create optimized mesh from the processed data for 3D model shape analyzation. Parametric modeling is based upon the development of target object and purpose of the design. Segmentation operation splits the region into

features like planes or cylinders and the intended features are extracted to create parametric features. 3D parametric model is generated by extruding or revolving the features. Features are modified by controlling the parameters. Important outcome of parametric model is to duplicate the target object and enhance the design. Freeform modeling can be defined as designing 3D surface model from the processed data. Freeform modeling is effective for designing outer surface of automobiles and consumer products. 3D model can be created by transferring the processed data to CAD software and also with RE software depending upon the availability of the software. RE software is also a CAD software but few software's are developed particularly for RE. RE software has to be selected according to the application and accessibility of user interface. Artec Studio is a professional data processing software acclaimed by the industries. Beginners in data processing can use autopilot mode for easier results in Artec Studio [Artec Studio]. Leios can be the fastest route for processing the data from the 3D scanner. Leios software is suitable for industrial and medical design [Leios]. Polyworks/Modeler is the comprehensive software that transforms digitized data into polygonal model [Polyworks Modeler]. 3DReshaper is an affordable processing software commonly used in architectural designs and cultural heritage [3DREshaper]. Geomagic design X software had the prime role in this work to process the data and create 3D model after the digitization. CAD users will be familiarized easily with this software's interface. Geomagic Design X is popular and innovative solution for designing 3D model from real world objects faster. Powerful tools of this software offers the designer sophisticated options with minimum training. Merging, aligning, optimizing and cleaning of scan data are achieved in few clicks by mesh buildup wizard. Redesign assistant option let the designer for automatic sketching, automatic region segmentation and extraction of design intent. Extrude, sweep and revolve are rendered by True hybrid modeler. Accuracy analyser can analyse deviation based on user defined tolerance between original and designed data. Processed data can be imported in several file formats compatible for other applications. The STL data of the CNC tool was processed and transformed into 3D model by Geomagic Design X software. Geomagic Design X software was utilized as it can consume the designing time than traditional surface fitting techniques [Geomagic Design X 2016]. Design of the new tool holder differs by type of data and designer's skill. The design approach followed in Geomagic Design X is parametric modelling by extracting the profiles and shapes from the scan data to design of 3D model of the new tool holder. The steps are as follows,

- The STL data of the CNC tool was imported to Geomagic Design X software. Mesh processing was skipped due to prior calculation of the mesh in ATOS professional.

- Auto segment command is the key tool for identifying the preferred region quickly from the STL data. Regions are auto segmented by recognizing the geometric features and each region is displayed in different colour for identification of particular feature.

- Manually the coordinates of the STL data are aligned to global coordinate system by align wizard tool.

- Polylines are extracted from the defined plane of the data by mesh sketch mode. Section polylines are defined as group of lines or curves from selected section of the data.

- The major polylines of the data are carefully selected to design the new tool holder. Fig.7 shows the extracted section polylines from the data of tool and major polylines are highlighted in dark blue colour. Lines and curves are drawn by fitting the major polylines from the section polyline of the data.

- The major polylines are important for drawing the 2D sketch of the new tool holder from which 3D model can be created. 2D sketch of the new tool holder can be drawn using sketch mode. Sketch mode can create or edit 2D geometries like lines, curves and splines manually on the section polylines. Fig.8 shows the final 2D sketch of the new tool holder. The old tool holder shown in fig.9 was taken as the reference to design the new tool holder.

- It was necessary to replace the old tool holder because the CNC tool needs offset to 15mm from the body of the old tool holder. Therefore, 3D model the new tool holder was designed according the dimensional requirements by offsetting the body about 15mm. Fig.17 shows the difference in the dimensional changes between old tool holder and prototype of new tool holder

- Closed profiles are extruded to create solid model and hole feature is used make holes in the solid model. Fillet features are applied to edges to finish the solid model. Final 3D model of the new tool holder in fig.10 was exported in STEP format.
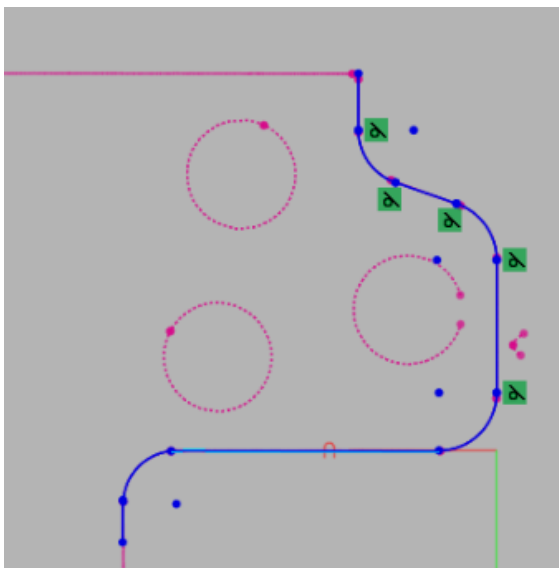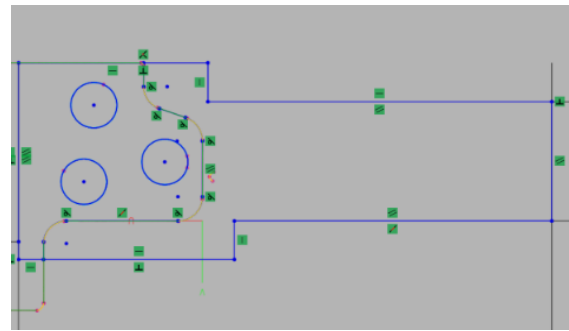

Figure 8. 2D Sketch of new tool holder

Figure 9. Old tool holder

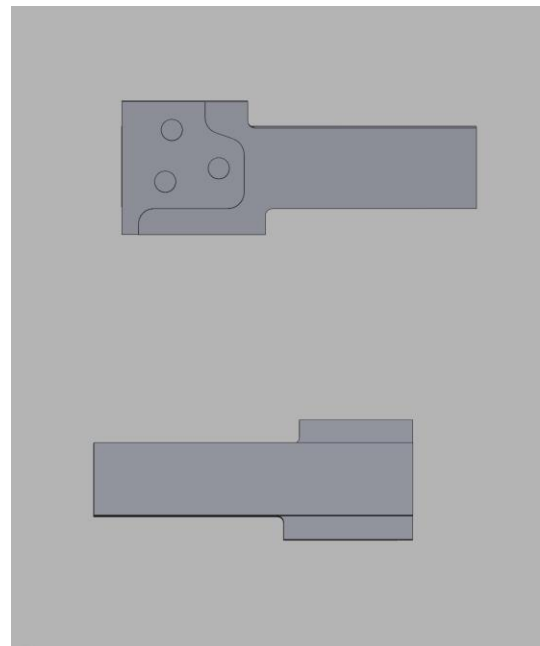**Figure 10.** 3D model of new tool holder

Figure 7. Fitting of major section polylines

2.3 Manufacturing

Conversion of raw material to finished product by various technologies for example CNC machining, additive technology is known as manufacturing. CAD software is the prime way for modelling. CAM software is effective for manufacturing the model in CNC machine. The combination of CAD and CAM can transfer information from design stage to manufacture stage. In CAD/CAM software the data developed in CAD is processed by CAM which generates tool path for manufacturing the required part. CAM is the central software for generating the tool path and NC program from the data for manufacturing the part. Data transferred to the CAM software is usually STEP data for generation NC program but NC program can also be generated directly from STL data in CAM software's namely MeshCAM and VisualCAM. MeshCAM is simple CAM software to work with STL data. Toolpath is generated from STL data using minimum

inputs. MeshCAM users are in every field from jewellers to aerospace [MeshCAM]. VisualCAM is complete CNC programming software package by Mechsoft used in general machining, wood working, molds, dies and tooling. VisualCAM package is benefited by aerospace, automotive, production, architecture because of its valued price. Sugiyama Industries utilized VisualCAM package in production of steel dies by programming advanced toolpath algorithm with VisualCAM for machining the die [VisualCAM]. Edgecam software is the leading CAM application for developing machining strategies and generating NC program from the 3D model. Edgecam offers solution for 4 and 5 axis milling. Edgecam's advanced machining cycle provides optimized tool path control and higher machining efficiency for manufacturing industries [Edgecam 2017]. After the inspection of STL data of the CNC tool and STEP data of the new tool holder in GOM Inspect (Detail explanation in subchapter 2.4.1). The STEP data of the new tool holder was transferred to Edgecam software for the generation machine tool path and NC program. The sequence used in the Edgecam software are as follows,

- The STEP file of the new tool holder was loaded to the Edgecam.
- Shape and size of the of the stock was defined. Stock is the material displayed in Edgecam simulator from which the final part can be machined.
- Feature finder in Edgecam identifies the shape feature. Shapes are identified from the particular plane of the model for machining.
- Predefined tools can be accessed from toolstore database in Edgecam. Mazak database was chosen as toolstore because the new tool holder was manufactured by MAZAK machine.
- Machining sequence can be developed by switching to manufacturing mode. Machining operations are finalized after defining certain parameters for each operation and selecting the features.
- Turret should be moved to tool change position every time to choose appropriate tool for machining operation.
- Turning was the first machining operation created by choosing the turning tool from the toolstore. Feedrate and Speed is defined. Start point and end point are specified by selecting the desired feature.
- Milling was the next operation. Face milling, flat land finishing and profiling are achieved with milling tool.
- Tool path for face milling, flat land finishing was created by defining the Feedrate, Speed, Clearance, Level, Depth, Cutincrement and selecting the feature.
- Boundaries are set. Start and end point are specified for profiling operation.
- Holes are selected to define plunge feed, speed and clearance for drilling operation.
- Parting off was the final operation performed to remove the final part from the excess stock material.
- Machining sequence is simulated in Edgecam simulator. Simulator provides visual machining of the operations created, check collision of tool path with the stock to avoid the damage of the tool and comparison of machined part with original part.
- NC program was generated with Generate NC icon after simulation.

The generated NC program was saved in flash disk. The program was fed to MAZAK INTEGREX 100-IV. YAMAZAKI MAZAK COOPERATION from japan is the producer of this machine. They are also leading manufacturers of machine tools, multitasking centres and CNC machining centres. The new tool holder was manufactured using aluminium material. Aluminium material was used because the manufactured new tool holder was a prototype model. Fig.11 displays the simulation of machining operation for manufacturing the new tool holder from the stock material in the fixture and fig.12 is the prototype of new tool holder.
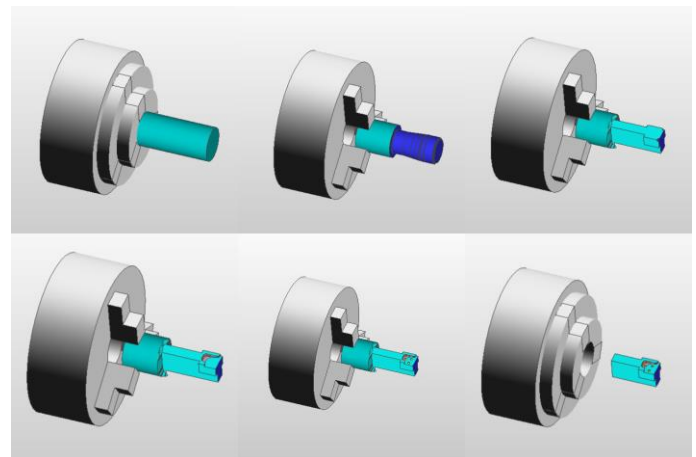

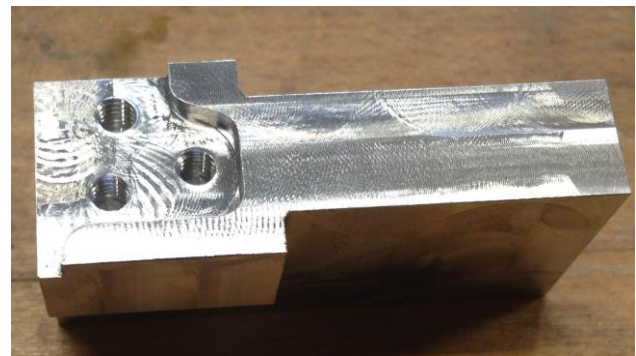**Figure 11.** Simulation of machining operation in Edgecam

Figure 12. Prototype of new tool holder

2.4 *Inspection*

Inspection involves in measuring the manufactured part and verify the dimensions of the part to meet the required standards. GOM Inspect software was used for inspection. GOM Inspect is the advanced inspection software to inspect the data from CAD software. Data from the digitizing device can be inspected in GOM Inspect software as it supports several data formats. Optimization of polygonal mesh, Geometrical dimensions and tolerance analysis, comparison of the nominal data and actual data to acquire colour map deviation are different kinds of functions available for the user. GOM Inspect is the special inspection tool for quality control, product development and production [GOM 2012]. Inspection procedure that has been carried out in GOM Inspect before and after manufacturing of the new tool holder and the results of inspection are discussed in this section.

2.4.1 *Inspection before manufacturing*

The STL data of the tool obtained from digitization in ATOS II 400 scanner and the 3D model of the new tool holder designed in Geomagic Design X was compared to check deviations before manufacturing. The nominal data (new tool holder) and actual data (tool) are imported to GOM Inspect. Alignment functions in the software aligns the nominal and actual data. Local Best fit was created by selecting the region from the actual data.

From the nominal data, the region on which the nominal data is in contact with the actual data was selected. The selected region on the nominal data is important region for the inspection because the nominal data was created by extracting the required polylines from the of actual data (fig.7).
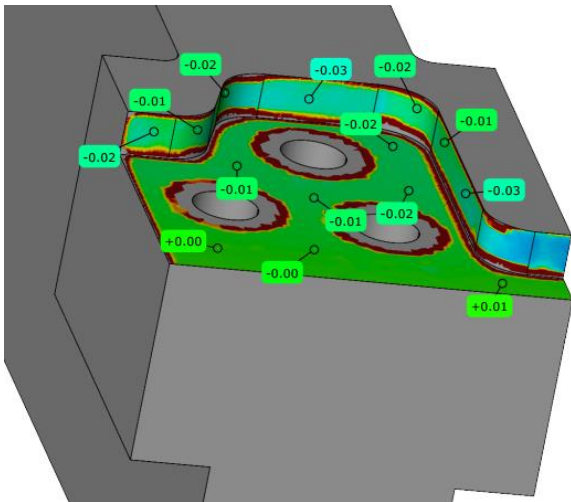

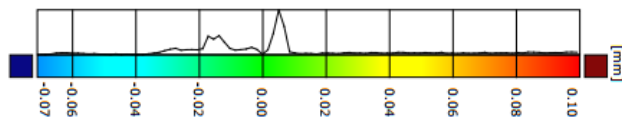**Figure 13.** Colour map deviation on nominal data before manufacturing

Figure 14. Histogram of deviation on nominal data

Colour map will be displayed on the selected region of nominal data with the surface comparison option. Colour map deviation is shown fig.13. Deviation labels and histograms can be generated by GOM Inspect for documentation and verification. Deviations are considered only in the important region that was selected for the surface comparison. In fig.14, the deviation results ranges from -0.03 to +0.01. There are positive errors in the nominal data at contact region of the tool but errors are minimum for proceeding the inspection.

Concentricity was checked for the holes to verify the deviations between median points of actual data and nominal data. The concentricity deviations are 0.12mm, 0.09mm and 0.08mm between actual data and nominal data for the 3 holes. Concentricity errors are also minimum. Therefore, the STEP data was taken further for generation of NC program to manufacture the prototype of new tool holder.

2.4.2 Inspection after manufacturing

The prototype of new tool holder was inspected after manufacturing in MAZAK machine. Digitization procedure followed in the chapter 2.1 was repeated again. ATOS II 400 scanner was used to digitize the prototype of new tool holder to acquire STL data (actual data). The 3D model of new tool holder (nominal data) from Geomagic design X and actual data are compared to check deviations. Same procedure as stated in subchapter 2.1.4 for inspection was followed in GOM Inspect. The important region on which the tool is in contact with the tool holder was concentrated again from the actual data for the surface comparison. Concentricity of the holes are checked to verify the median points of actual and nominal data, the results of deviations are 0.08, 0.10, 0.11. Maximum deviation of +0.26mm occurred in the contact region of the actual data. The colour map deviation on the actual data is shown in fig.15. The maximum deviation was spotted at the corners of the actual data and it is due to improper generation of the machining path in Edgecam software. Machining path has to be optimized to reduce the errors. Finally, the tool was fixed with the prototype of new tool holder with suitable screws for checking the functionality (fig.16). Fig.17 shows the old tool holder and prototype of new tool holder with CNC tool.
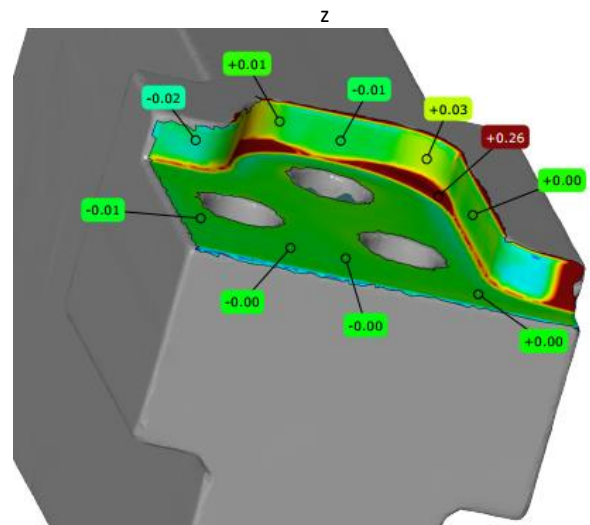

Figure 15. Colour map deviation on actual data after manufacturing

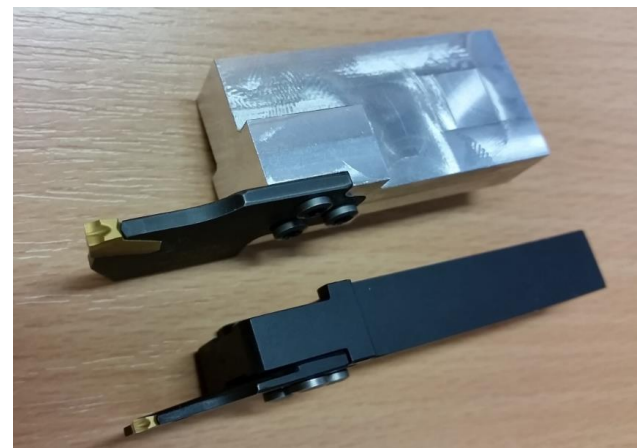**Figure 16.** Prototype of new tool holder with CNC tool

Figure 17. CNC tool with old tool holder and with prototype of new tool holder

3   CONCLUSIONS

Development of RE methodology for the machine part was the absolute goal of this work. CNC tool was selected as the target part for implementing the RE methodology. Digitization of the target part, processing of digital data, 3D modelling of the processed digital data, manufacturing and inspection of the final part are the practical task achieved in this work.

CNC tool was the target part for designing and manufacturing the prototype of new tool holder because the available old tool holder is not the better solution to be chosen as target part for digitization in this work. The holes in the old tool holder as got M4 threads which may lead to poor quality of scan data. The outer shape of the CNC tool and old tool holder are same which does not change the shape of the scan data but holes are better to scan from the tool. Better quality of scan data was the foremost reason to prefer the CNC tool for digitization. This work was performed in the Technical University of Liberec, therefore the selection of particular hardware and software in this work was based on the availability of advanced laboratory facilities from the university. While processing the STL data in RE software, imperfection occurred in manual positioning of the coordinate system of the data. It affected the machining path generation in CAM software and shown errors in the inspection software. The prototype of new tool holder was manufactured by Mazak CNC machine with aluminium material. Material was not the significant thing in this work because the final part was a prototype. However, the main aim of this work was to develop and verify the RE method for machine part with parametric surface which was proved by taking a CNC tool as practical application.

In this work stated RE methodology was applied to a simple part to create a new design. The selected target part was very simple therefore implementing the RE technique can be expensive in this case. The proposed RE methodology in this article can be a benchmark for product development lifecycle. This RE methodology can also provide solution for creating a new design from the existing machine parts based on designer's innovation. The CNC tool can be digitized, processed and modelled for manufacturing the new tool holder by applying this stated RE methodology using other compatible hardware and software.

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CONTACTS:

Ing. Aravindprasad Srikanthan

Technical University of Liberec

Faculty of Mechanical Engineering

Department of Manufacturing Systems and Automation

Studentska 2, 461 17 Liberec 1, Czech Republic

e-mail: aravind.prasad19@gmail.com

Ing. Radomir Mendricky, Ph.D.

Ing. Petr Keller,Ph.D.

Technical University of Liberec

Faculty of Mechanical Engineering

Department of Manufacturing Systems and Automation

Studentska 2, 461 17 Liberec 1, Czech Republic

Tel.: +420 485 353 356; +420 485 353 359

e-mail: radomir.mendricky@tul.cz ; petr.keller@tul.cz

www.ksa.tul.cz