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Prediction of Residual Stresses in Components Using the Contour Method

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Abstract. During machining the accumulated bulk stresses induced by previous shape forming process steps, such as forging, casting or additive manufacturing and subsequent heat treatment, will be released and cause undesirable geometry errors on the final component. By considering the residual stresses during process planning a significant improvement in dimensional accuracy can be achieved. This paper presents experiences for prediction of residual stresses for components with complex geometries using the Contour method. Three sectioning procedures have been tested and a cutting strategi using Electric Discharge Machining with slow feed rate and cutting from two sides with final cut in the middle is proposed. Two Finite Element modelling strategies for 3D-models have been tested and a meshing strategy based on extrusion of the geometry from the cut plane is recommended. Further, a procedure to automate the Finite Element meshing of complex structures using the Alpha Shape algorithm is proposed. The ambition is to integrate this algorithm in procedures for automatization of the entire analysis.

Keywords. Residual stress prediction, machining distortions, Contour method, Complex geometries

1. Introduction

During machining the accumulated bulk stresses induced by previous shape forming process steps, such as forging, casting or additive manufacturing and subsequent hardening are released. This may cause undesirable residual deformations and geometry errors of the final component. The distortions are difficult to predict and in practice, therefore wide tolerances and several machining steps are applied to avoid reprocessing or, at worst, scrap. By considering the residual stresses during process planning a significant improvement in dimensional accuracy can be achieved and thereby save millions of Euros in scrap costs and correction procedures [1]. Thus, there is a need for industrial methods to determine and minimize those stresses and deformations. This paper suggests an industrial approach for stress analysis in practice using the Contour method. The Contour method consists of three major steps [2] where the first step is to cut a critical planar cross section of the part, the second step is to measure the spring back due to residual stress relief in the cut and the third step is to virtually push back the spring back to its initial planar shape using Finite Element Analysis. The out of plane

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residual stresses in the cut is thereby recreated in the model. The results can be used in order to calibrate process simulation models, predict the complete 3D stress field in a component [3,4] and as a tool for compensating machining distortions [5].

Section 2 describes procedures adapted to components with complex geometries for stress prediction in practice in conjunction to an industrial use case, a forged cardan joint in macro alloyed medium carbon steel, see Figure 1. Experiences concerning different cutting strategies as well as two Finite Element modelling strategies are presented. Section 3 describes a possibility for automation of data handling using a Python script where also an algorithm for automatic handling of complex geometries is proposed. Section 4 describes conclusions and suggestions of future research.

Figure 1. Forged and machined cardan joints

2. Procedures for predicting residual bulk stresses in practice

This section describes the activities used for prediction of bulk stresses in conjunction to the forged cardan joint, see Figure 2.

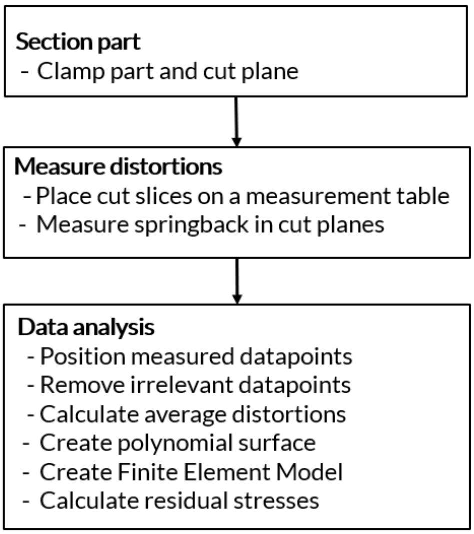

Figure 2. Procedures for prediction of bulk stresses in practice

2.1. Section the part

The first step is to section the part at the location where residual stresses is to be measured. Thus, the choice of a precision machining method that is able to cut a smooth surface along a straight line while securely clamped is crucial.

Wire Electric Discharge Machining (EDM) is referred to in literature as a precise cutting method with minimal effect on residual stress in the body [6]. Other methods such as Abrasive Waterjet Cutting (AWJ) are possible and in a recent study, performed at RISE IVF, EDM and AWJ were evaluated using plane cut tests in Haines 282 test pieces. The study indicated that AWJ deteriorated the cut surface topology more compared to EDM and thus EDM was used in this study. It should be noticed that EDM conditions like cutting speed, wire feed rate, spark intensity and wire tension may introduce discontinuities such as surface waviness and local material yielding [7]. However, those cutting artefacts can be reduced to an acceptable low level by controlling some of the important EDM parameters. In this paper the influence of two different wire feed rates and EDM cutting strategies is investigated.

The Cardan joint sectioning was performed using EDM along a straight line in a Fanuc C400IA machine with a cutting wire in brass, diam 0.25 mm. This dimension is small in relation to specimen dimension and thus not considered to affect the global deformation of the kerf. The test pieces were clamped against a stiff support in the machine. In order to investigate the best clamping and EDM approach three variants of sectioning were studied, see Figure 3.

P1: EDM with normal feed and with final cut at the end
P2: EDM from two sides with normal feed rate and final cut in the middle.
P3: The same process as P2 with slower EDM feed rate.

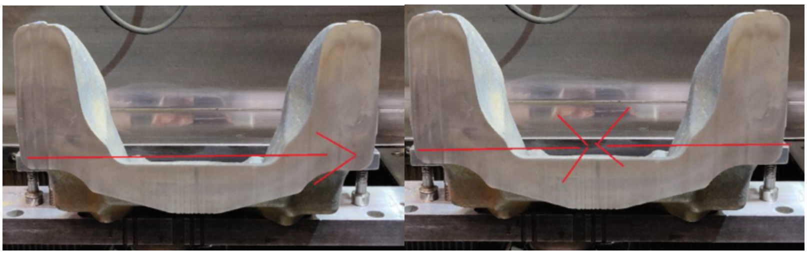

Figure 3. EDM with final cut at the end (left) and with final cut a final cut in the middle (right)

2.2. Measure distortions

The second step is to measure the geometric spring back distortions at the cut surfaces of the sectioned parts. The distortions may be measured using tactile measurements like a Coordinate Measurement Machine (CMM) or Geometrical Optical Measurement (GOM). Tactile measurement may reach an accuracy of 1 µm whereas optical measurement may reach an accuracy of 10 µm [8]. Optical measurement has advantages such as high measuring speed and in this evaluation study GOM was used. The cut parts were placed on a measurement platform and the geometry was registered as stl-models using ATOS III equipment. The point cloud of each cut surface was aligned with a plane having the normal in the global z-direction by using best fit algorithm and the out of plane z-distortions were measured, see Figure 4.

GOM was also used in order to examine the quality of the cut surface and catching EDM artefacts such as marking at the cut surfaces caused by e.g wire cut and variations in feed rate. This information about distortions coming from the cutting process itself is important in later stages when smoothing the displacement surface and deleting extraordinary vertex points as described in the following sections. For the use case GOM indicated significant higher quality of the cut surface in P3 compared to P1 and P2.

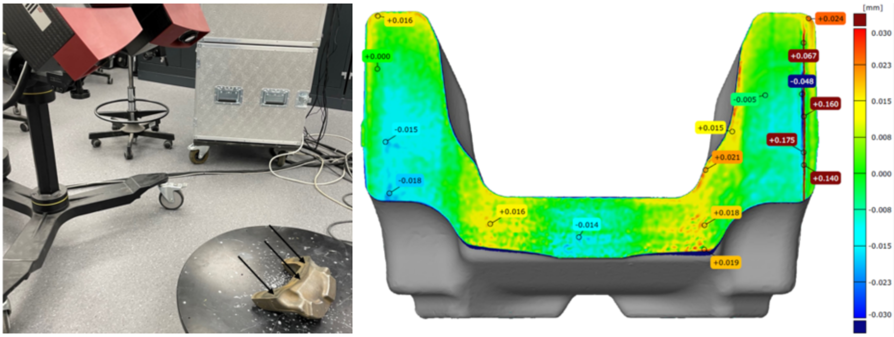

Figure 4. Measurement setup of out of plane distortions on cut section (left) and GOM measurement results from P1 cut (right)

2.3. Data analysis

In the third "Data analysis" step the measured z-distortions are used as boundary conditions in a Finite Element calculation of residual stresses FEA.

2.3.1. Position measured datapoints

In order to calculate average distortions according to section 2.3.3 the stl-models were positioned, with the cut sections aligned against each other. This was accomplished interactively with support from the LS-Dyna PrePost software, see Figure 5.

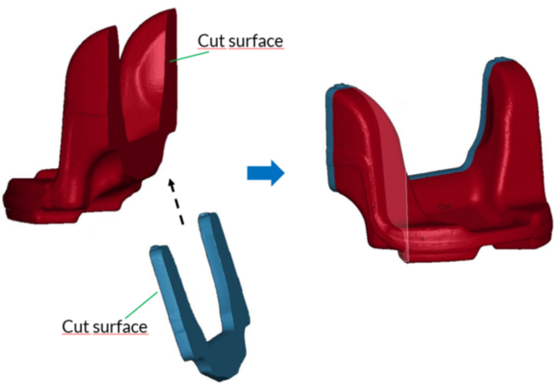

Figure 5. Manual positioning of the two stl models (blue and red) in order to align the cut surfaces

2.3.2. Remove irrelevant datapoints

The EDM cutting may cause various artefacts on the surface such as marks due to wire break or variations in the cut feed during the process. Those artefacts are registered as datapoints in the stl-files. Datapoints from edges and corners that were irrelevant for the proceeding spring back calculation were therefore removed interactively using LS-PrePost software, see Figure 6.

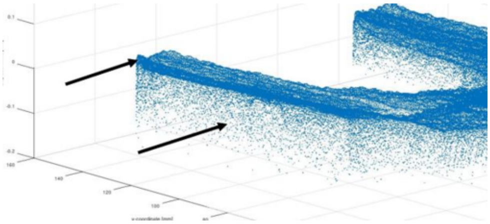

Figure 6. Removal of irrelevant datapoints from the stl models

2.3.3. Calculate average distortions

In order to improve the accuracy of the proceeding FE calculations the data points from the opposite sides of the cut were averaged, see schematic illustration in Figure 7. The calculations were performed using a Matlab script.

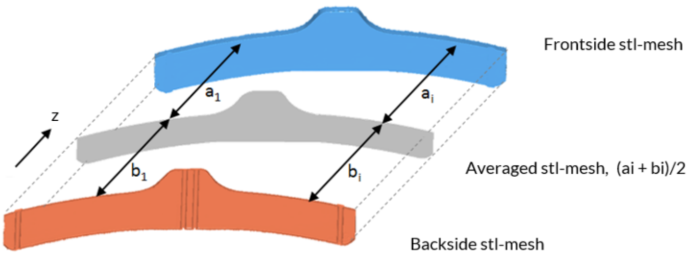

Figure 7. Calculation of average distortions

2.3.4. Create polynomial surface

A polynomial surface according to Figure 8 was created based on the calculated averaged distortion data points. The Matlab curve fitting toolbox was used to interpolate the calculated averaged datapoints points to a smooth polynomial surface. Prior to the polynomial fit the dataset was cleaned for outliers and anomalies as a consequence of EDM cutting artefacts as well as the edge effects from the optical scanning.

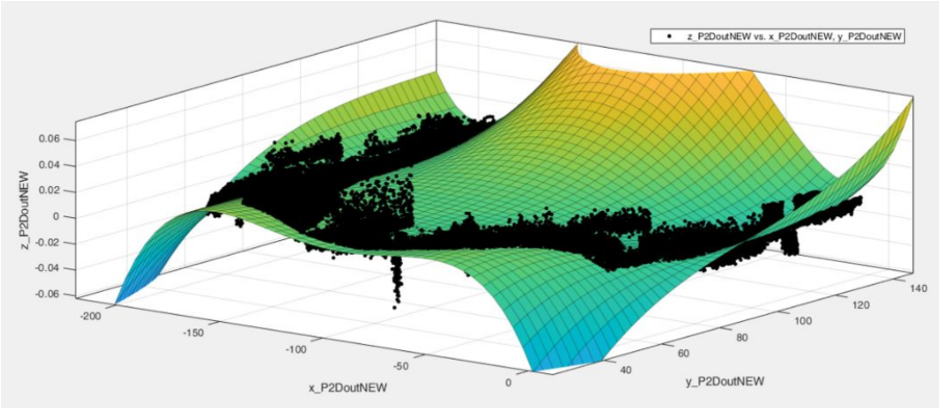

Figure 8. Polynomial surface of the cut based on averaged distortion vertex points

The predictive capability of the polynomial fit is described by e.g. R^2 recognized as the coefficient of determination. Here the adjusted R^2 varies between 0,89 to 0,94 whereas the corresponding root mean squared error, RMSE ranges from 0,003 to 0,014, see Table 1. Here the filtering of data points and removal of outliers plays a significant role.

	Adjusted R^2	RMSE
P1	0,94	0,014
P2	0,91	0,003
P3	0,89	0,004

Table 1. Capability of polynomial fit

2.3.5. Create Finite Element Model

Two Finite Element modelling options were tested and evaluated according to Figure 9. In the first approach the 2D cut section geometry was extruded whereafter a 3D Finite Element mesh was created and in the second approach a 3D mesh was created based on the CAD-model.

Nodal displacement boundary conditions at the surface mesh on the cut side were applied where the deformed shape of the polynomial surface was translated to nodal displacements. This was accomplished using a script. Also, boundary conditions for preventing rigid body motion were applied, see Figure 10.

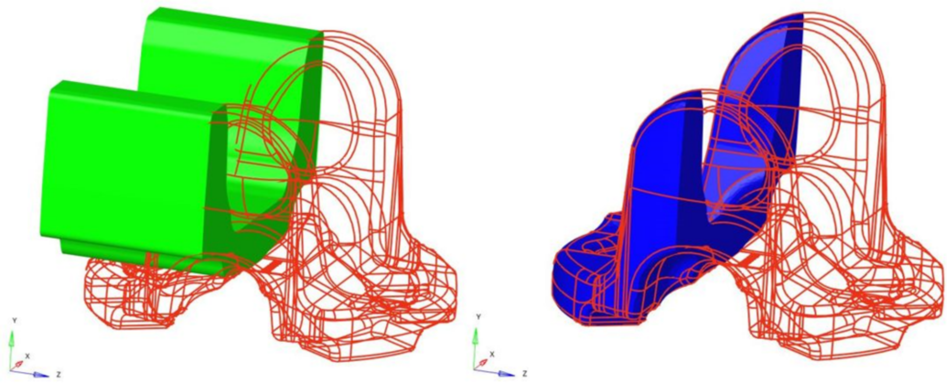

Figure 9. FE model based on extrusion of cut (left) and based on CAD-model (right)

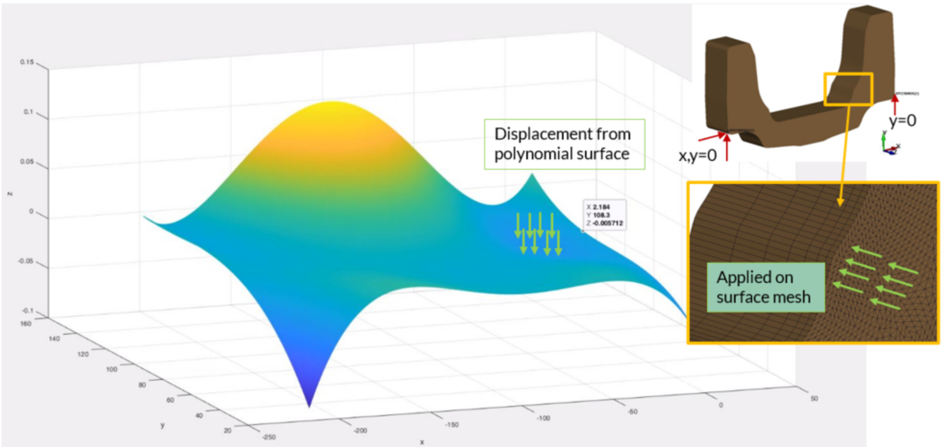

Figure 10. Boundary conditions for the Finite Element Analysis

2.3.6. Calculate residual stresses

The out of plane stresses in the cut were calculated using linear Finite Element Analysis. The aim was to evaluate how the different mesh approaches effects the residual stress results. The analysis was done using the EDM P2 cutting procedure. The calculations indicated no significant difference in the out of plane residual stress results for the two mesh approaches, see Figure 11.

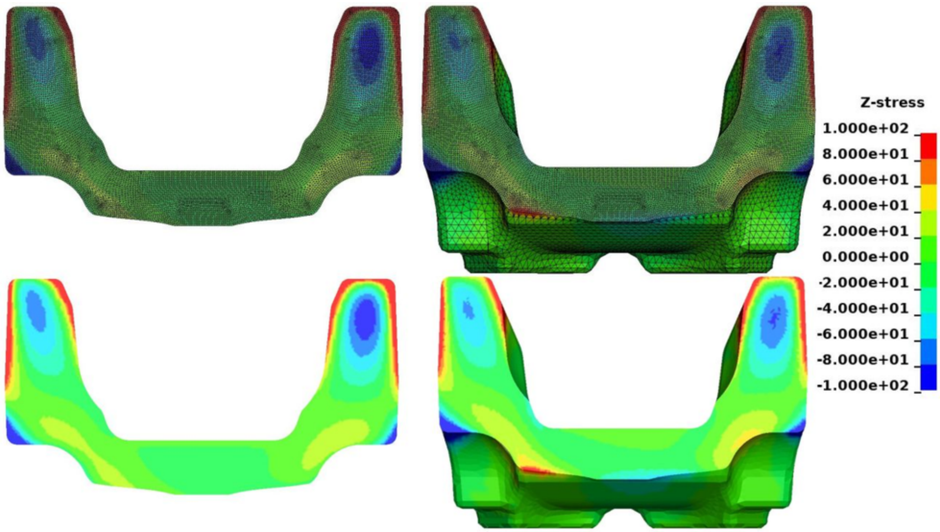

Figure 11. Out of plane stress results (z-stress) using extruded mesh (left) and Cad-model based mesh (right)

The aim was also to evaluate how different EDM procedures concerning feed rate and clamping (P1, P2 and P3) influence the residual stress results. The calculations indicated significant differences in out of planes stresses for the different strategies where P3 cutting strategy provides lower stress levels compared to P1 and P2, see Figure 12.

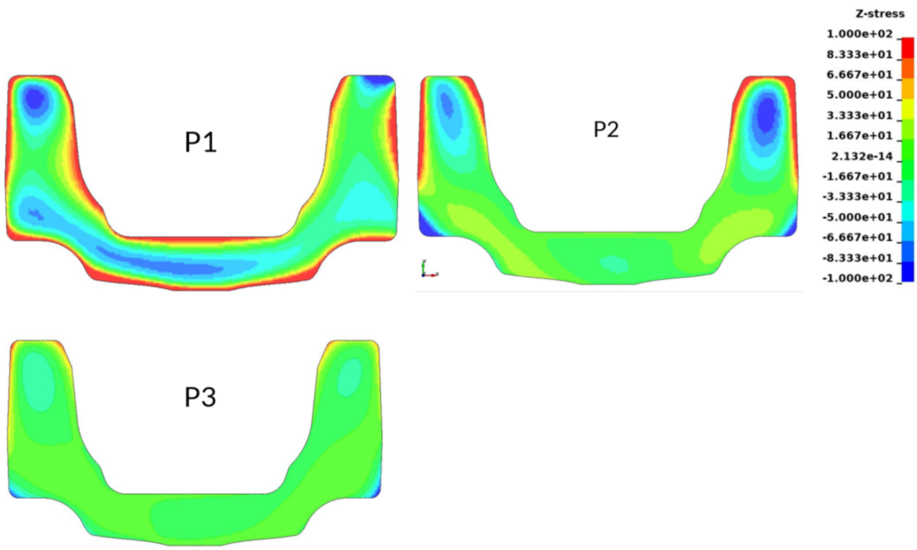

Figure 12. Out of plane stress results from P1 – P3 calculations

3. Automation of data analysis

The previous description is a summary of procedures performed in practice in connection to the test case. Efforts for automation of especially the data analysis has been done in [9] where an open-source Python script "PyCM" is described. With support from the script it is possible to align and average measured deformations from the cut surfaces, fit the averaged datapoints onto a polynomial surface, create a Finite Element mesh in 3D, apply the boundary condition and calculate stresses according to the description in Section 2. With support from the open source script it is possible to calculate stresses based on simple prismatic cut geometries. This publication suggests an extension and an algorithm for creation of Finite Element models based on complex 2D cut geometries.

3.1. New algorithm for analysis of complex geometries.

Point clouds obtained from the GOM scanning of surfaces are unstructured and hence a geometric outline for generating a mesh for finite element analysis, i.e. generation of a mesh for hexa- and tetra elements in the point cloud, is necessary. The outline of the point cloud is a series of connecting line segments that envelops the points. To do this, the outline, of the point cloud need to be constructed and often, for simpler geometries, a convex hull or a Delaunay triangulation algorithm, based on convex hull assumption, is often used. However, often the outline of a point cloud includes points from features like holes and fillets etc. that can only be captured by a concave hull.

Three approaches are proposed to generate the concave hull of unstructured set of points as a point cloud: Alpha shape [10] Ball pivoting [11], and Poisson surface reconstruction [12]. Due to its versatility and robustness, the Alpha shape approach is used in this case study and implemented in Matlab using a function called "Boundary". The function gives the indices of the set of points that envelopes all the points in the point cloud by employing a restrictive parameter alpha, to select the points on the concave hull.

$$p = boundary(x, y, z) \tag{1}$$

where p is the indices of the points on the boundary, (x,y,z), the points in the point cloud.

This Matlab function is wrapped and implemented in Python to integrate it to the complete the series of functions need for the analysis, i.e., functions that loads and transforms input data, filter the data, register the point clouds with reference data set, surface generation, meshing and finally post processing. Figure 13 below illustrates the outline generated from a point cloud of the case work piece.

4. Conclusions and future research

This paper presents a detailed methodology for industrial use of the Contour method for components with complex geometries including cutting, measurement of geometric distortions and data analysis procedures. The paper shows the importance of selecting a cutting process with low feed rate together with a firm clamping. Further, the paper

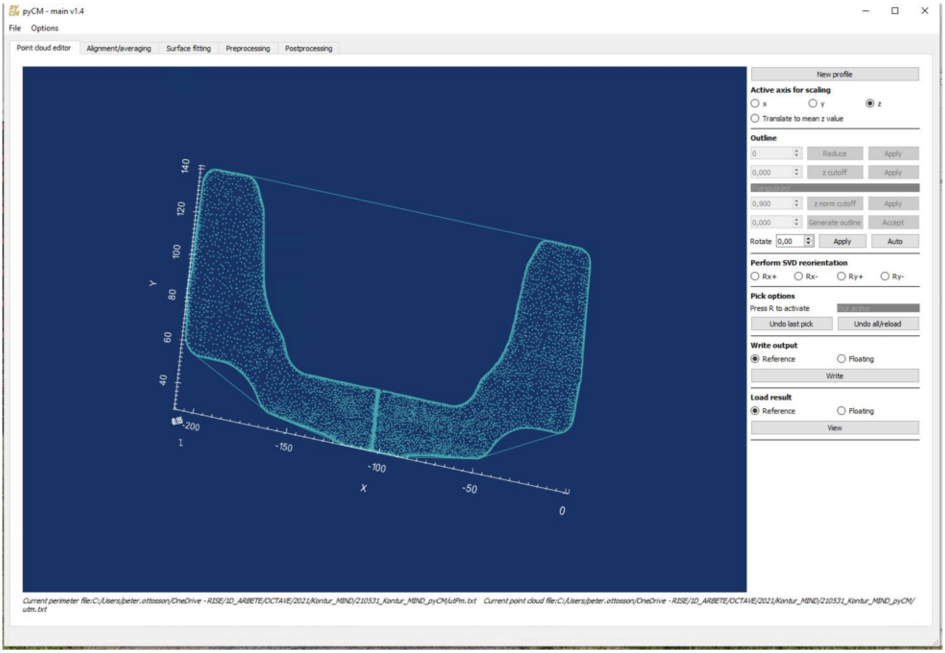

Figure 13. Outline visualized in PyCM generated from a point cloud using Alpha Shape Algorithm

shows the importance of a structural removement of irrelevant datapoints caused by e.g. artefacts during cutting. Two different modelling strategies has been evaluated where the results from an extruded FE-mesh, based on the extrusion of the 2D cut geometry, was compared to a model that was meshed based on the 3D Cad geometry. The calculations indicate no major difference in the residual stress results and hence the extruded mesh procedure is recommended due to modelling simplicity and due to possibilities to integrate the meshing strategy in an automation procedure of the data analysis using tools like the PyCM script. A possibility to automate the data analysis for complex geometries using the Alpha shape algorithm is presented. Future research is suggested concerning:

- *Cutting:* Further evaluation of AWJ as a cutting process is recommended.
- *Polynomial surface*: An investigation how to improve the quality of polynomial surfaces for complex geometries is recommended.
- *Alpha shape algorithm:* Further development and integration of the Alpha shape algorithm into an automation process is recommended.
- *Quantitative validation:* The Finite Element calculations were done for qualitative evaluation of different cutting and modelling options. Thus, it is recommended to further validate the residual stress levels using e.g. Neutron Diffraction technique.
- *Improving accuracy:* Several factors, such as cutting artefacts, measurement uncertainty, polynomial surface accuracy and Finite Element modelling influence the accuracy of the results. This paper has investigated how EDM cutting strategies, data analysis and meshing approaches influence uncertainties. A more comprehensive overall investigation concerning uncertainties in displacements and modelling is recommended as a future research area.

- *Machining application:* Develop methods and tools for prediction of residual stresses and distortions to be used in process planning and process control. Such a tool will enable to ensure to set the optimum operation conditions for a given machining task and appropriate compensations when stress induced distortions are observed or predicted.

5. Acknowledgements

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References

[1] Chatelain, Lalonde, Tahan, "A Comparison of the Distortion of Machined Parts Resulting From Residual Stresses Within Workpieces", Recent Advances in Manufacturing Engineering, ISBN: 978-1-61804-031-J2
[2] Johnsson, "Residual stress measurements using the Contour method", PhD thesis, University of Manchester School of materials, Manchester UK, 2008
[3] Werke, Wretland, Ottosson, Holmberg, Machens, "Geometric distortion analysis using a combination of the contour method and machining simulation", 51st CIRP conference of Manufacturing Systems, 2018, Stockholm
[4] DeWald, Hill, "Multi-Axial Contour Method for Mapping Residual Stresses in Continuously Processed Bodies", Experimental Mechanics (2006) 46: 473–490
[5] Werke, Hossain, Semere, Wretland, "Machining distortion analysis of aerospace components using the Contour method", Aerospace Technology Congress, October 2019, Stockholm.
[6] Prime, Dewald, "The Contour Method" Chapter 5 in Practical Residual Stress Measurement Methods, pp. 109-138, Wiley-Blackwell, Las Alamos, 2001.
[7] Hosseinzadeh, Kowal, Bouchard "Towards good practice guidelines for the contour method of residual stress measurement" The Journal of Engineering, Vol. 2014, Iss. 8, pp. 453–468
[8] www.gom.com/en/topics/tactile-and-optical-measurement-technology
[9] Roy, Stoyanov, Moat, Withers, "pyCM: An open-source computational framework for residual stress analysis employing the Contour Method", Elsevier, 2020
[10] Edelsbrunner, Kirkpatrick, Seidel "On the shape of a set of points in the plane, IEEE Transactions on Information Theory", 29 (4): pp 551–559, 1983
[11] Bernardini, Mittleman, Rushmeier, Silva, Taubin, "The ball-pivoting algorithm for surface reconstruction", IEEE transactions on visualization and computer graphics, 5(4), pp 349-359, 1999
[12] Kazhdan, Bolitho, Hoppe, "Poisson surface reconstruction", Eurographics, 2006.