Analysis of Clamping within a Fixing System

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Abstract. The complex workpiece-fixing behaviour during machining is essential for the fixture development process, especially when using innovative intelligent Piezo-electric clamping systems being very susceptible to transverse forces. Therefore, the loads acting on fixture components have been analysed and a model for predicting the reaction forces due to clamping and process loads is presented. First, a complex finite element model is used to obtain detailed information about the behaviour during the process. Second, a faster model with fewer elements is developed, validated and used for the variation of process parameters. Finally, both results are combined to an analytical model. This empiric equation allows to predict the reaction forces depending on several process parameters. The usability of this method has been exposed by modelling shape grinding of a nozzle guide vane.

Keywords: Clamping Force, Grinding, Finite Element Method, Fixture.

1 Introduction

The ability to establish and secure desired positions is significantly affecting the effectiveness of a fixture system [19]. Further on, product differentiation increases the need of highly efficient, flexible, accurate and automatic fixing systems in industry. Especially in the aerospace and automotive sector the number of low volume, high value and difficult-to-handle products is increasing[6,13,14].

Specialised fixtures only are economic within a mass production and cannot be reconfigured easily. Otherwise, the complex design and construction of modular fixtures are very time-consuming and expensive, with problems in repeatability and positioning accuracy[21,28]. Quality and precision cannot be controlled and influenced actively during the manufacturing process.

Moreover, an iterative improvement of fixture prototype designs is still common and causes high development costs[19]. At the same time the workpiece-fixture contact condition, workpiece distortion caused by cutting and clamping forces and deformation of the work holding tools still enjoy research effort[6].

As a basis of all development processes, the forces acting upon the fixing components during the manufacturing process have to be analysed. Consequently, an

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effective modelling and simulation method for the prediction of the workpiece-fixture behaviour during machining is required. It enables the possibility of fixture optimisation, too[24,23,22].

2 Finite Element Models

The finite element (FE) mesh has been developed dividing the nozzle-guide vane (NGV) into components: the blades, the outer and the inner frame (figure 1).

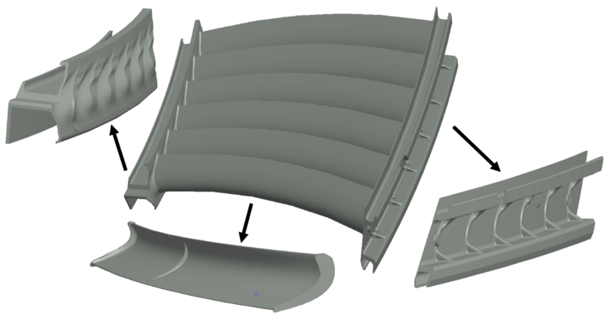


Fig. 1. Division of the NGV into three components

Simplified parametric cross section geometries and parameter optimisation lead to a simple FE-model. This inductive method of modelling has been completed by summarizing the results within an analytical model.

2.1 Complex FE-Model vs. Parametric FE-Model

Importing the geometry from CAD data, the model has been meshed using tetrahedron and hexahedron elements. As already mentioned, the part has been cut into pieces, meshed separately with the same amount and position of nodes on the contacting surfaces. This lead to a model with about 550000 elements, a mixture of eight-noded isoparametric 3D brick elements with trilinear interpolation and four-noded tetrahedral elements.

Less elements cause decreasing computation times and enlarge the capabilities of the variation of process parameters. After analysing the characteristic cross section parameters (e.g. area, second moment of inertia) of the three parts of the workpiece, suitable simplified cross section forms have been chosen (figure 2). Several curvatures have been neglected and wall thicknesses have been assumed to be constant. Moreover the blades were reasonably substituted using a simple parallelogram cross section geometry. All together 30 parameters were necessary to describe the simplified geometry of the whole workpiece.

As an important next step, the equations of the area, the centre of area and the second moment of inertia have been developed depending on the dimensions for all three cross section geometries by subdividing each cross section into simple triangles, rectangles and parallelograms (table 1).

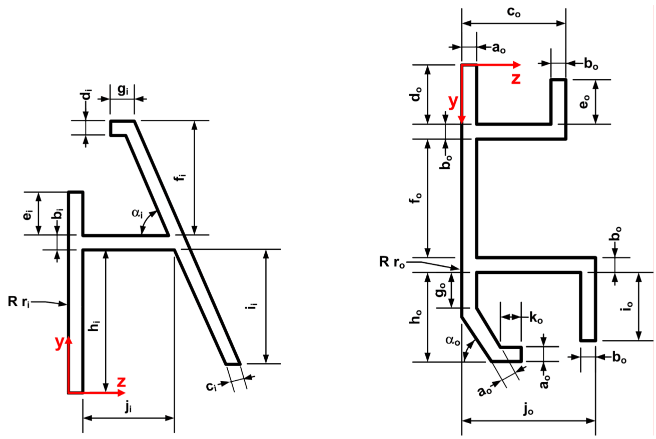


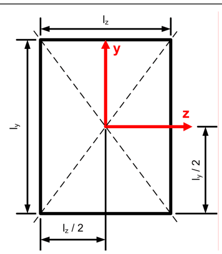
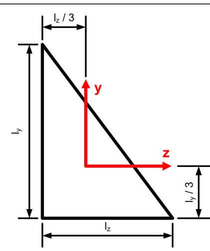
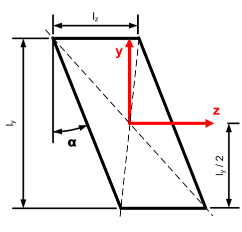
Fig. 2. Simplified cross section geometries of the inner and outer frame

The values for the whole cross section geometry have been evaluated by summation of all subareas.

$$A = \sum_k \mathrm{sgn}_k \, A_k \qquad I_{yy/zz/yz} = \sum_k \mathrm{sgn}_k \, I_{yy/zz/yz_k} \tag{1}$$

Based on the reference values from the CAD model, all geometric parameters have been optimised comparing the real part and the parametric model:

Table 1. Second moment of inertia of simple subareas

	rectangle	**triangle**	**parallelogram**
			
$\mathbf{A_k}$	$l_{y_k} l_{z_k}$	$\frac{l_{y_k} l_{z_k}}{2}$	$l_{y_k} l_{z_k}$
$\mathbf{I_{yy_k}}$	$\frac{l_{y_k} l_{z_k}^3}{12} + A_k \, (z_{s_k} - z_S)^2$	$\frac{l_{y_k} l_{z_k}^3}{36} + A_k \ (z_{s_k} - z_S)^2$	$\frac{l_{y_k} l_{z_k}}{12} \left[l_{y_k}^2 \tan^2 \alpha + l_{z_k}^2 \right] \ldots$ $+ A_k (z_{s_k} - z_S)^2$
$\mathbf{I_{zz_k}}$	$\frac{l_{y_k}^3 l_{z_k}}{12} + A_k \, (y_{s_k} - y_S)^2$	$\frac{l_{y_k}^3 l_{z_k}}{36} + A_k \, (y_{s_k} - y_S)^2$	$\frac{l_{y_k}^3 l_{z_k}}{12} + A_k \, (y_{s_k} - y_S)^2$
$\mathbf{I_{yz_k}}$	$-A_k \, (y_{s_k} - y_S)(z_{s_k} - z_S)$	$\frac{l_{y_k}^2 l_{z_k}^2}{72} - A_k (y_{s_k} - y_S)(z_{s_k} - z_S)$	$\frac{-l_{y_k}^3 l_{z_k} \tan \alpha}{12} \ldots$ $-A_k \, (y_{s_k} - y_S)(z_{s_k} - z_S)$

– the second moments of inertia related to the centre of area I_{yy}, I_{zz} and I_{yz}
– the principal moments of inertia I_1 and I_2 and their orientation φ
– the area of the cross section A

The starting values have been chosen approximating the geometry of the real part. Further on, an optimisation procedure using least square fitting has been used. A boundary condition for the inclination angle of the blades has been set.

Again, the parameters have been determined for each of the three parts separately. Considering the criteria described above, the relative error in comparison to the real part was 5% for the bounding geometries. Due to the boundary condition of the inclination angle, the relative error of the blades' principal moments of inertia was about 10%. The deviation of the blades has been considered negligible due to their small influence on the reaction forces.

Based on the estimated parameter values, the simplified FE-model has been developed in MSC.Marc.®Mentat®. Enabling fast modifications, a script for automatic mesh generation has been generated.

Finally, the parametric FE-model consists of about 17000 eight-noded 3D brick elements, which is about 3% of the amount of elements of the complex model. The similar model geometries are shown in figure 3.

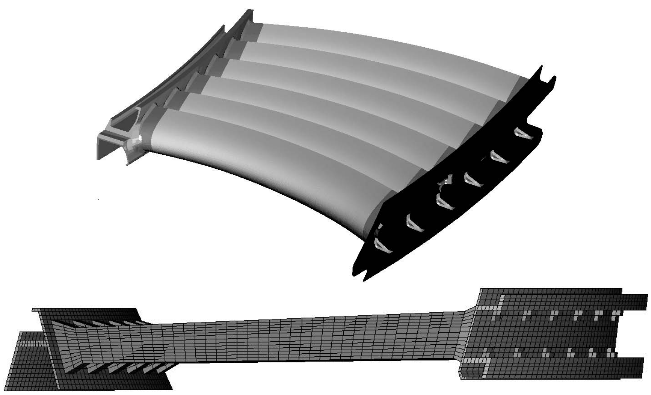


Fig. 3. Complex model vs. parametric model - geometry

2.2 Evaluation of Boundary Conditions

2.2.1 Grinding Forces

"Kinematic actions in grinding are constrained series of statistically irregular single engagements that are dependent upon the structure of the cutting area, the motion values and the geometric properties. . . . The basic models are mainly based on tests with conventional abrasives . . . . Therefore the applicability is limited to machining conditions that are usually employed in conventional grinding processes."[5] "As grinding is a very complex manufacturing process with a large number of characteristic quantities which influence each other, the reproducibility is critical."[26]

Table 2. Theoretical Models of Grinding Forces

Klocke [12]	$F'_n = \int_0^{l_g} k_p \cdot A_{cu}(l) \cdot N_{kin}(l)\ \mathrm{d}l$
Huang and Cheng [11]	$F'_n = N_t\ L_s\ p\ \overline{h}_g^2 \sin\Theta\ \tan\Theta$ $F'_t = \frac{\pi}{4}\ N_t\ L_s\ p\ \overline{h}_g^2 \sin\Theta$
Böge [3]	$F_t = k_c \cdot A = k_c \cdot a_e\ f_l\ \frac{v_{ft}}{v_c}$
Brinksmeier *et al.* [5], Tönshoff [26] Salje[20],Werner [27]	$F'_n = c_{wp} \cdot c_{gw} \cdot \left(\frac{1}{q}\right)^{e_1} \cdot a_e^{e_2} \cdot d_{eq}^{e_3}$
Decneut [7], Ono [18], Werner[27]	$F'_n = K_f \cdot \left(\frac{v_{ft}}{v_c}\right)^{2\varepsilon-1} \cdot a_e^{\varepsilon} \cdot d_{eq}^{1-\varepsilon}$

For small feed rates the grinding forces can be "resolved into three component forces, namely, normal grinding force F_n, tangential grinding force F_t and a component force acting along the direction of longitudinal feed, which is usually neglected because of its insignificance ". ... The tangential grinding force is ... much lower than the normal grinding force. "[15] Furthermore the normal grinding force caused by cooling lubricants is as high as the usual normal grinding force or even higher.[1,9] A lot of different basic models of grinding forces can be found in literature (table 2).None of the given theoretical models could be used for the evaluation of the grinding forces. All models include specific parameters depending on the workpiece material and/or machining conditions. These characteristic parameters have to be determined experimentally for each process and workpiece material. It was neither possible to measure the grinding forces nor the process parameters due to the capacity utilisation of the manufacturer.

Furthermore, the process within the this case study is unique due to shape grinding of different complex and variable grinding areas and a super-alloy workpiece. As a result, there is no corresponding literature for assuming these process

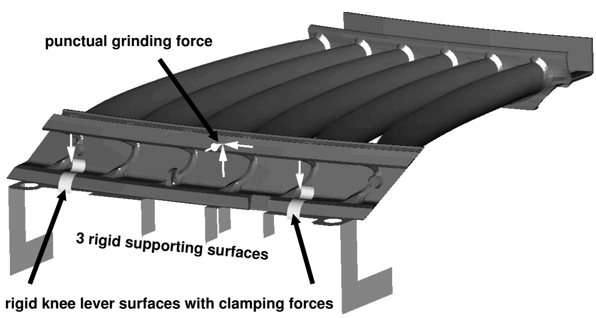


Fig. 4. Complex model with two punctual clamping forces on rigid contact surfaces and one single point load representing the grinding force

parameters. All publications either deal with simple grinding processes (e.g. face grinding) or use conventional workpiece materials.

Due to the lack of experimental data or comparable parameters for the theoretical grinding force models, an overview of corresponding projects has been carried out. Considering the major conclusions drawn by NIEWELT[17] and MEIER[16] while investigating surface grinding of Nickel based alloys similar to the material within this case study and comparing other relevant literature ([5],[8],[10],[15] and [25]), related grinding forces have been reasonably assumed for the current setup.

Two possibilities of load application have been tested. First, the forces have been applied on a solid contact body representing the grinding wheel geometry and touching the deformable workpiece, which is moving along the grinded area. Due to the discretization of the workpiece geometry and the small displacement compared to the grinding wheel diameter, the contact area is restricted to two nodes. Based on these results, the grinding forces have been modeled as equidistant static point loads on the grinded areas (figure 4). This reduces the computation time by avoiding the iteration processes of the contact algorithms.

It should be pointed out that all point loads are singularities in the FE-model causing higher deformations and stresses than the real process. These peaks are limited to a small area surrounding the point load, thought the main focal points - reaction forces on the clamping mechanism - are not affected.

2.2.2 Fixture-Workpiece-Contact

Currently, knee levers are used for clamping of the workpiece. Based on the given tightening torque of the screws, the estimation of the clamping forces, using BÖGE's approach of the screw preload force [4] and the law of the lever, lead to clamping forces. To avoid plastic deformation due to the clamping forces, the contact stress is limited to the yield tensile strength. Thus the maximum clamping force has been ascertained with the help of the HERTZian contact equations [2].

Within the FE-models, the surrounding surfaces of the fixture are represented by rigid contact bodies surfaces (figure 4). The clamping normal forces F_{cnf} have been applied to one single node per knee lever. This node has been coupled to the surface representing the rigid contact body. Furthermore, the node displacement in both horizontal directions has been fixed to withstand the transverse contact forces. Finally, the supporting areas are simply fixed by displacement boundary conditions.

2.2.3 Heat Effects

Grinding is a process with a significant thermal load upon the workpiece. Furthermore, different fixing principles (e.g. piezoelectric actuators) have a very high thermal sensitivity. Nevertheless, the heat conductivity of the workpiece was not taken into account due to the small heat affected zone and the cooling lubricants flooding the workpiece during the grinding process. Though, the influence on the fixing points has been neglected as well as the thermal expansion of the workpiece.

3 Simulation Results

3.1 Verification of the Parametric Model

The parametric model has been verified by comparing two types of simulation results. First, single point loads have been applied on the workpiece fixed by displacement boundary conditions, neglecting contact problems, friction and fixture stiffness. The maximum total displacements close to the loaded nodes have been compared (figure 5). The results are corresponding for all applied loads except the first and the last increment. This inaccuracy is caused by the replacement of the blade geometry with a simple parallelogram and its influence upon the stiffness on the connected frames. Except the outer load locations, the relative error is less than 2.5%.

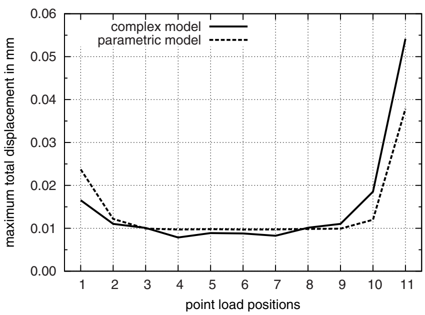


Fig. 5. Maximum total displacement at point load position

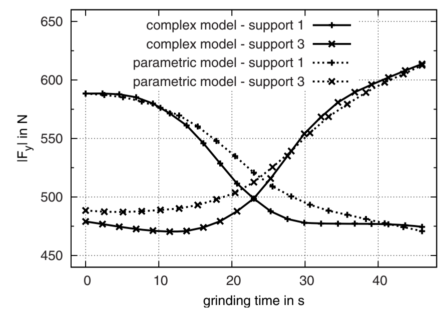


Fig. 6. Normal reaction forces on supporting surface

Secondly, fixture-workpiece-contact has been considered, too, evaluating the reaction forces acting on the knee levers due to the grinding loads. In general, the forces show the same curve paths with similar absolute values. The normal forces acting on the knee levers remain constant throughout the whole process in both models. In contrast, the transverse forces on the knee levers as well as all force components acting on the supporting surfaces show a time dependency.

As an example, the reaction forces on the supporting areas one and three during load case five have been compared (figure 6). The curve progression for the results of both models are similar in most cases but not equal. For all loadcases and fixture components the approximation of the contact normal forces is almost accurate. It is possible to show tendencies of the transverse forces with the help of the parametric model but not exact values.

3.2 Parameter Variation

The main influencing parameters on the reaction forces are the coefficient of static friction, the grinding forces and the clamping forces. These parameters have been varied using the parametric model.

The friction coefficient has been reasonably assumed to be $\mu = 0.2$. Considering other surface finishes ($\mu = 0.4$) and coated supporting surfaces ($\mu = 0.05$), the friction coefficient has been varied. The normal forces acting on both knee levers remain constant throughout the whole process, due to the direction of the acting grinding forces. The transverse preload forces on both knee levers due to the clamping loads show a linear dependency on the static coefficient of friction. Equally, the time dependent force components caused by the grinding process are rising. Figure 7 shows the force paths for the transverse forces. It is reasonably assumed that the amplitude of the reaction forces caused by the clamping loads is linear dependent on the friction coefficient.

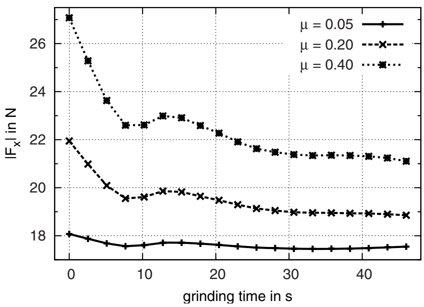


Fig. 7. Variation of friction coefficient

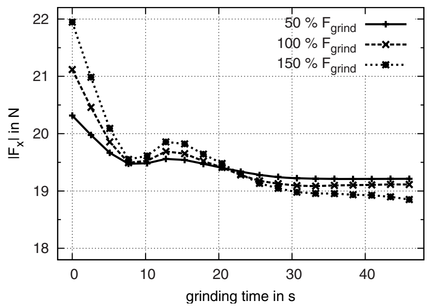


Fig. 8. Variation of grinding forces

In addition, simulations have been done with 50% and 150% of the assumed grinding forces. Again, the normal forces remain stable whereas the transverse forces acting on both knee levers (figure 8) are varying. The amplitude of the dynamic force component is linear dependent on the grinding forces. Lastly, the clamping force has been decreased 25% three times (figure 9).

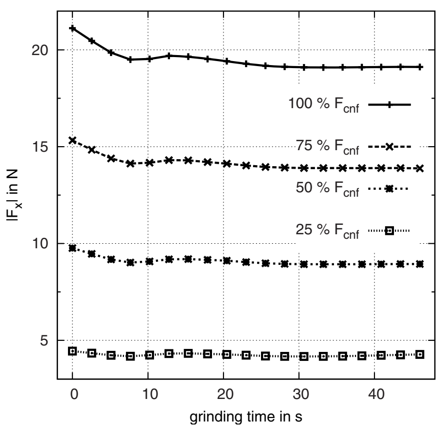


Fig. 9. Variation of clamping forces: transverse force on knee lever

Predictably, the static share of the reaction forces is linear dependent on the clamping forces. Decreasing clamping forces cause decreasing reaction forces in all directions naturally. The amplitude of the dynamic transverse reaction forces caused by the grinding process is also changing, dependent on the clamping forces. This dependency is reasonably assumed to be linear. The combination of both effects leads to a non-linear dependency of the transverse reaction forces on the clamping preloads.

4 Analytical Model

An analytical model has been developed exemplary for the transverse force in x-direction being applied on one knee lever. To ensure the accuracy of the model, it is based on one curve path taken from the complex model. Furthermore, the results of the parameter variation with the parametric model have been used to consider the dependencies on grinding load, clamping forces and the coefficient of static friction (figure 10).

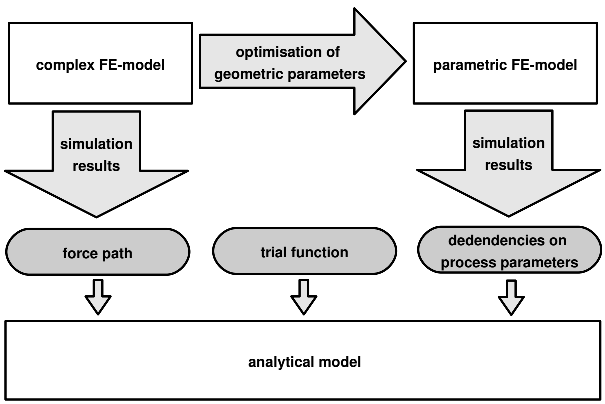


Fig. 10. Development of the analytical model

The total reaction force F_x has been divided due to its causes - clamping preloads $F_{x_{preload}}$ and grinding forces $F_{x_{grind}}$ (figure 11).

$$F_x(t) = F_{x_{preload}} + F_{x_{grind}}(t) \tag{2}$$

The reaction forces due to the grinding loads are evaluated by eliminating the constant preload force component. Moreover, this curve has been approximated by a sine function, leading to the basic form of the empirical model (figure 12):

$$F_x(t) \approx F_{x_{preload}} + a \cdot \sin(b \cdot t + c) + d \tag{3}$$

All four parameters within the approximation function are determined with a curve fitting procedure. The preload force has been taken from simulation results.

The parameters b and c are influencing period and phase shift of the function but are not dependent on the clamping loads, the grinding forces or the friction coefficient. Once determined for one force path, they remain stable.

Scaling is done by the parameters a and d. Referring to the results of section 3.2, the amplitude a of the sine approximation is linear dependent on the grinding

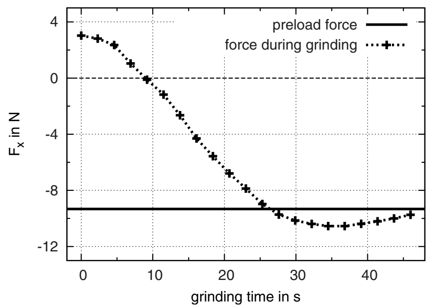


Fig. 11. Reaction forces on a knee lever caused by preload and grinding forces

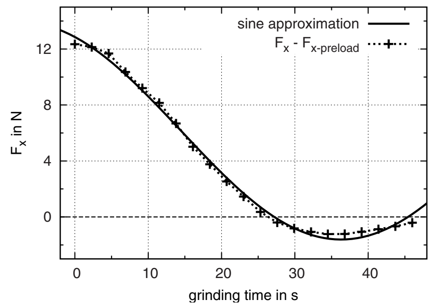


Fig. 12. Time dependent reaction force due to grinding loads and its sine approximation

forces as well as on the clamping forces and on the friction coefficient. Moreover the same dependencies have been assumed for the vertical shift d. Lastly, a, d and the preload forces are again linear dependent on the static coefficient of friction.

To predict the reaction forces due to changing process parameters, one exact reference force path (measured or taken from the simulation results with the complex model) has been scaled. Scaling factors referring to clamping forces, grinding loads and friction coefficient of the reference curve (indexed with *ref*) are introduced.

$$k_{clamp}\left(F_{cnf}\right)=\frac{F_{cnf}}{F_{cnf_{ref}}}\quad k_{grind}\left(F_{grind}\right)=\frac{F_{grind}}{F_{grind_{ref}}}\quad k_{frict}\left(\mu\right)=\frac{\mu}{\mu_{ref}}\quad (4)$$

A combination of the basic model (3) and the scaling factors (4) leads to the final analytical model:

$$F_x\left(F_{cnf},F_{grind},\mu,t\right)=k_{clamp}\left(F_{cnf}\right)\cdot k_{frict}\left(\mu\right)\cdot\ldots \quad (5)$$
$$\left\{F_{x_{preload}}+k_{grind}\left(F_{grind}\right)\cdot\left[a\cdot\sin\left(b\cdot t+c\right)+d\right]\right\}$$

5 Summary and Outlook

Using different FE-models, a method is presented which allows to predict the reaction forces depending on different grinding parameters. A complex FE-model with a huge number of elements has been created followed by a parametric model with similar mechanical properties but less elements. Therefore, the cross sections have been simplified with optimised geometric parameters based on the second moments of inertia.

The results of the complex model provided detailed information of the workpiece-fixture behaviour during the process. An analysis of the influencing process parameters has been carried out with the fast but less accurate parametric model resulting in scaling factors. Combining the accurate force path, the scaling factors and a sine trial function, an analytical model has been developed. It provides the opportunity to forecast the reaction forces within a certain range of grinding parameters.

The usability of the method has been exposed by forecasting the transverse reaction forces acting on knee levers fixing a NGV during shape grinding.

Nevertheless, further investigations need to be carried out on this field. The most important pending issue is the validation of the complex FE-model with experimentally measured values. In addition, the complex model can be improved using time dependent grinding force profiles from ongoing research activities to get information about the dynamic behaviour of the workpiece-fixture system. Spring-damper elements can be used to consider the deformable behaviour of the fixture components. Moreover, the fast parametric model can be combined with optimisation algorithms to improve the locations of the fixture components and to minimise clamping forces. Lastly, the analytical model in combination with control software/hardware facilitates real time process simulation for possibly active clamping components.

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