

Modeling of Deep Rolling as a Distortion Compensation Strategy during Profile Grinding

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Abstract. This paper analyzes the possibility to induce residual compressive stresses utilizing deep rolling in a long, slim steel workpiece that is profile ground and that resembles a linear guide rail. These intentionally caused residual compressive stresses at the side surfaces of the workpiece are intended to counteract the distortion due to residual stresses in the V-groove of the guide rail induced by grinding. A finite element model was prepared based on the initial state of the workpiece. The amount of respective stresses depended on the load intensity and duration of the process. The experimental data regarding the residual stress profiles due to the deep rolling process and the resulting workpiece distortion were used to validate the simulation, so that an adjustment or a calibration of the thermometallurgical and thermomechanical material data was possible. The key findings are the numerical design of appropriate strategies for the distortion potential induction, the experimental distortion results, knowledge on the mechanical treatment by deep rolling, and the successful modeling of the mechanical treatment and the process strategy.

Introduction

Grinding has been established as a typical final machining step in the production process chain of metal workpieces. One of the goals in the fabrication of profiled linear guide rails is to increase the surface quality. The challenge that engineers have to master is the avoidance of distortion during precision machining. This is also the case in linear guide rails with ground V-grooves. Due to the friction between the tool and the workpiece, the temperature is locally increased significantly during the grinding of the steel workpiece. The induced tensile residual stresses within the V-groove lead to undesirable deformations and distortions [1].

An efficient solution to this problem is the subsequent use of a deep rolling operation. In this way, compressive load stresses can be introduced in a targeted manner to achieve the desired workpiece geometry. Deep rolling is a proven process for increasing the service life of components and has an increasing importance in industry [2], but it is also a promising process for distortion compensation, as shown in several experiments [3].

Currently, no unified approach uses deep rolling as a straightening process. There is a high demand for research to determine optimal process parameters and effects of deep rolling.

Nowadays, simulations are indispensable in mechanical engineering since they considerably simplify several time-consuming and challenging tasks. The results of process simulations by Yen et al. indicate how such approaches can lead to successful models [4].

The finite element method (FEM) provides helpful tools for a detailed modeling of deep rolling. The final goal is to represent an optimized deep rolling process by adjusting the boundary conditions in the simulation. Consequently, a competitive application of this machining step will be ensured by a prediction of the distortion compensation of linear guide rails in the industrial field.

Within the scope of this work, the material and mechanical influences of deep rolling will be documented. For this purpose, a model of a linear guide rail made of AISI 4140 was created and the results were then validated based on the literature and experimental values.

Theoretical Approach

Deep rolling is classified under the forming manufacturing processes. It is defined as plastically changing the shape of a solid workpiece while keeping the mass and cohesion identical. In general, forming constitutes high productivity with short cycle times. The cost-effectiveness of this process group is noteworthy because of the large material utilization [4].

This manufacturing process is used frequently to achieve a higher mechanical load capacity. It was investigated by Klocke et al. in particular who discussed the effects of deep rolling on turbine blades [5]. These engine components are critical to the functionality of an aircraft and are in constant threat of an external object ingress. After increasing the strength by deep rolling, the blades showed increased durability, which ultimately improves safety and reduces maintenance costs.

The research work from Perenda considered the effects of deep rolling on residual stress formation of a torsion bar made of high-strength steel. It has shown that the deep rolling process both induced targeted compressive load stresses and significantly increased the hardness of the workpiece. In the scope of this work, deep rolling in the form of flat longitudinal rolling was considered as a possible distortion compensation process after profile grinding [6]. Furthermore, deep rolling stands out as a surface hardening process because not only are residual stresses induced, but surface roughness can be reduced as well [5].

The deep rolling process consists of a freely rotating ball, typically made of metal or ceramics, which is hydrostatically or mechanically pressed on a surface. To ensure continuous tool-workpiece contact and process impact, the tool is equipped with a lift to compensate for clamping errors and form deviation of the workpiece. This exhibits small plastic deformations during the process, but the effects on the strength and durability of the material are more important [7]. Selectively applied compressive load stresses resulting in an increase in workpiece deformation can thus be used to counteract the distortions caused by grinding.

To be capable of modeling the deep rolling process more precisely, the effects inside the material must be mapped accurately. Before the yield point is exceeded, the AISI 4140 material behaves elastically. After that, elastoplastic effects emerge and the workpiece begins to deform. The machined area is kept constant by increasing the number of tracks to induce different distortions in a targeted manner. This has proven to be more reliable compared to varying the force used, concerning the slim workpiece geometry. By rolling along a straight track on the surface next to the V-groove (see Fig. 1) and by increasing the number of tracks, the time course must be considered in the model and thus implemented as a continuous procedure equivalent to the industrial manufacturing process.

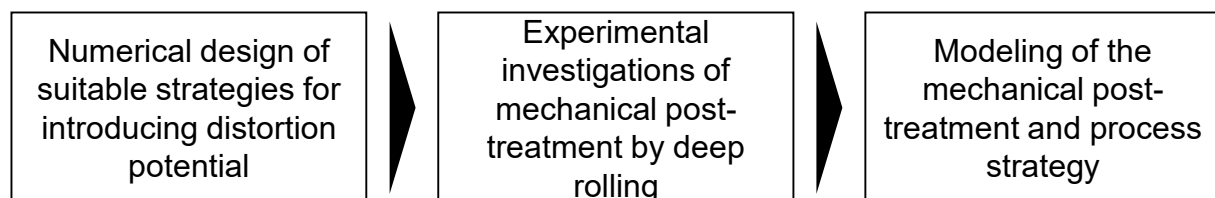


Fig. 1. The strategy of the mechanical post-treatment to analyze the compensation of the workpiece distortion due to grinding

In previous investigations of multi-stage deep rolling, Hettig et al. have shown how the internal material stresses and the resulting residual stresses can be analyzed over time [3]. If the workpiece is subdivided into several volume elements, the deep rolling tool not only has a local influence on the corresponding element directly under the tool, but also on elements farther away that were rolled over

previously or will be in the later continuous process. The lateral feed f_{dr} is also decisive. The deep rolling of the subsequent tracks results in overlaps with the material changes of the preceding tracks. If the internal material load is higher than the initial yield point, the material deforms plastically. This results in both a strain hardening and an increase in the yield strength to the level of the applied load [3].

Since the present publication is based on the potential of stress induction by deep rolling and the option to compensate for the distortion during profile grinding of linear guide rails, a suitable parameter range for this type of procedure must be estimated. Preliminary experiments and the modeling of the profile grinding process on the same workpieces have already been performed and published. Typical grinding parameters used in the industry were chosen as a reference. The tangential feed speed of the grinding wheel varied between 1,500 and 6,000 mm/min and the depth of cut was between 200 μm and 800 μm at a constant cutting speed (35 m/s). This corresponds to a grinding range in which a determinable and maximum distortion occurs, and the material is not yet damaged by grinding burn [8]. From these experiments, equivalent counteracting distortion values have been estimated for the distortions due to deep rolling that are considered here. A peak-to-valley value of approximately 0.2 mm was obtained by measuring 13 points longitudinally on the ground surface of the workpiece [8].

Fig. 2 shows a sketch of the process steps. After the grinding (1) within the V-groove, tensile residual stresses are introduced, which lead to a deformation of the workpiece after unclamping it from a magnetic clamping plate (2). A proven effective and easily reproducible way to compensate for the distortion is deep rolling (3). It introduces compressive stresses in the material on the subsurfaces next to the V-groove, which counteract the tensile residual stresses.

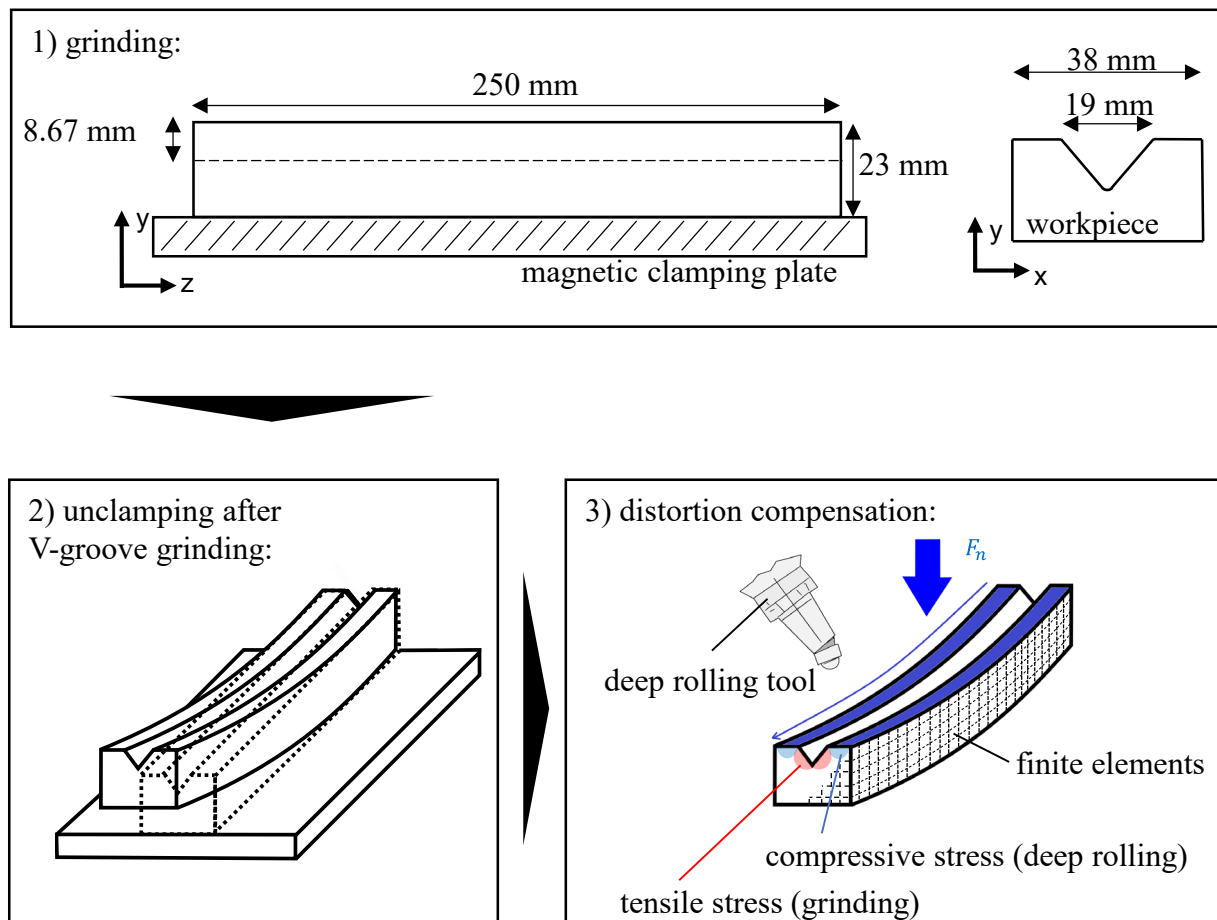


Fig. 2. The distorted workpiece after profile grinding in the V-groove with the considered mechanical compensation strategy

Experiments

Material. For the experiments described in the following, a workpiece made of AISI 4140 that is comparable to a linear guide rail was used. This workpiece was first circumferentially milled to the dimensions 23 mm \times 38 mm \times 250 mm ($h \times w \times l$). Then, a V-groove with the dimensions 8.67 mm \times 19 mm ($h \times w$) and a radius of 2 mm in the groove base was milled centered over the entire length with a stock removal of 0.6 mm. To ensure that all samples had a stress-free initial condition, they were stress-relief annealed (QT 200 C, 55 HRC) before the grinding. Table 1 shows the proportions of the alloying elements for the analyzed material.

Table 1. The chemical composition of the workpiece

	composition (% weight)																
material	C	Cr	Mn	P	S	Si	Mo	Ni	Al	Cu	Sn	Al	Ti	V	Nb	Fe	bal.
AISI 4140	0.400	1.030	0.820	0.014	0.020	0.240	0.180	0.130	0.013	0.180	0.010	0.013	0.011	0.003	0.002		

Methods. The results were gathered once with and once without grinding the workpiece, using the same parameter sets to investigate deep rolling as a compensation option for grinding distortions. The deep rolling process was conducted on a conventional 4-axis CNC milling machine with a 13 mm ball. An exact and constant positioning of the tool can thus be guaranteed. On both surfaces to the left and right of the V-groove, a hydrostatic deep rolling tool was used to roll off a varying number of tracks N (1, 5, 10, and 50), each with a constant rolling force F_{dr} of 4.2 kN and a constant deep rolling velocity v_{dr} of 1 m/min. This was possible by means of a hydraulic unit and a connection with reduced friction between the rotating tool and the workpiece due to the lubricant. From five tracks on, the lateral feed of the tool was also adjusted to keep the width of the processing area constant. A piezoelectric 3-component dynamometer was used to measure the force during the tests. Table 2 shows an overview of the process parameters.

Table 2. The deep rolling parameters

parameters	values
tool diameter d_b	13 mm
deep rolling force F_{dr}	4.2 kN
number of total tracks N	1, 5, 10, or 50
deep rolling velocity v_{dr}	1 m/min
lateral feed f_{dr}	varied
lubricant / bearing	5%-emulsion

Fig. 3 demonstrates the track distribution on one workpiece side of the V-groove. The aim is to increase the peak-to-valley distortion ΔPV by increasing the number of tracks. ΔPV is determined as the difference between the highest and the lowest points of the bottom sample side by measuring two rows longitudinally, each with 13 coordinate points with a distance of 20 mm. To minimize the distortion error, all tests were repeated twice with the same parameters. The mean value was then calculated from the three measured distortions.

In addition to the previously described experiments without grinding, the same deep rolling parameters were also used for a ground workpiece. For a reference distortion ($\Delta PV = 0.2$ mm) for the fixed roll experiments, a sample was selected that was machined with 700 μm depth of cut and 1,500 mm/min feed speed in the V-groove [8]. A total of twelve samples were ground. These were then rolled again three times with a varying number of tracks ($N = 1$ to 50) on each side of the V-groove.

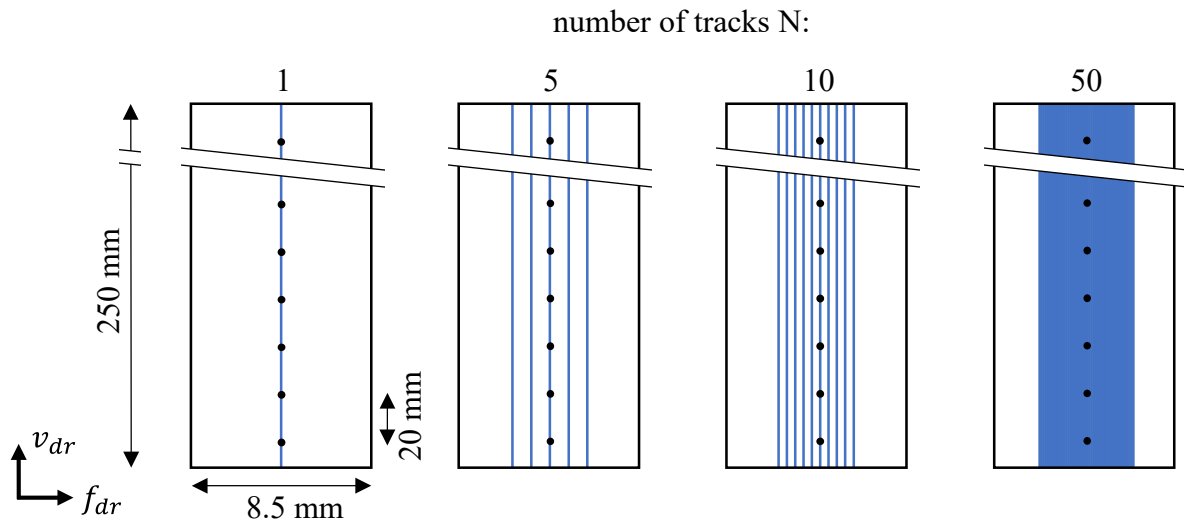


Fig. 3. The defined setup with the lateral feed direction and the number of tracks N for the deep rolling experiments on the surface of the top side next to the V-groove, as well as the distribution of the coordinate measurement points in the z -direction

Identification of mechanical parameters. The interaction of the deep rolling velocity, the normal force, and the tool diameter results in a continuous contact pressure on the workpiece [9]. The velocity v_{dr} corresponds to the relative movement between the tool and the component. This parameter is crucial in terms of productivity. The effects on the residual stress formation are negligible [10]. Accordingly, the experiments and the simulation do not aim at an optimal deep rolling velocity.

F_{dr} describes the normal force by which the tool is pressed on the component surface. It has to be high enough so that the surface of the tightly rolled material plastically deforms [7]. The higher the values are, the greater and deeper the stress formation is [10]. The surface strength is equally increased with a high normal force.

The effect of various ball diameters is one of the issues examined in the research of Meyer et al. Higher residual stresses and strengths can be expected when larger balls are pressed on the material [11]. This parameter was kept constant for the sake of comparability.

Modeling

This paper presents a finite element (FE) model for predicting workpiece distortions during deep rolling, and thus extends the grinding model from previous research [8]. In the following, the structure and the results of this model are described.

If a ball is pressed against a flat surface with a normal force, there is an interaction between the two objects. If the bodies are rigid, the contact is a theoretical point contact. Since in reality the ball and the workpiece can be deformed, the objects are flattened. The so-called Hertzian pressure has a parabolic distribution and its highest value is exactly below the theoretical contact point. This purely elastic model predicts also the corresponding contact radius. Due to the plasticity of the steel workpiece, which is the basis for the distortion considered here, limitations of the Hertzian model had to be considered. The calculation area changes in the plastic case to a rectangular cuboid, whereby a corresponding simplification was made in the boundary definition since the focus was especially on the calibration of the workpiece model concerning the distortion. The force source F_{dr} was based on a defined exponential function to represent the pressure area of the Hertzian compression with the central load maximum based on the assumptions of Spinu et al. [12]. Therefore, within this contact radius 85 % of the load was set to approximate the pressure area of the rectangular cuboid. This allowed the necessary increase of the contact radius as well as the flattening of the load profile compared to the Hertzian pressure due to plasticity. An integral describes the total load per area p_{max} .

The displacement field was calculated under the assumption of linear elasticity, whereas the defined material parameters for AISI 4140 allowed the plasticity to be mapped. The different load levels during a step-by-step roller contact described by Spinu et al. were neglected because of the constant pressure and the uniform deep rolling velocity v_{dr} [12]. The feed motion was approximated by a transient linear load activation. A modification of the contact region together with adjustments of the load distribution in the simulation counted in the relationship between the normal and frictional stress over the tool surface, friction characteristics at the tool-workpiece interface and the roller velocity. The transient change of the local load, according to the track definitions, was imported as an interpolation of defined start and end points on a spreadsheet.

The workpiece geometry was defined regarding the symmetry and with the corresponding material parameters of AISI 4140. The clamping was performed by means of a fixed bearing with a given displacement direction on the bottom side. Furthermore, there was a selected area for the boundary load on the surface next to the V-groove. After defining these basic boundary conditions, the transient and steady-state studies of the FE simulation were defined. This started first with the modeling of the local transient load application by the tool. For this, the spreadsheets with the defined interpolated paths were called first. The number of tracks defined not only the track progressions but also the time parameters of the studies. After completion, the change of the predefined displacements due to the unclamping from the entire bottom side to individual corner points of the workpiece was performed via a steady-state study. Thus, it was possible to allow a shift on the xz-plane (1) during the deep rolling (Fig. 4). In the simulation model this is defined as a prescribed displacement. It could be assumed that the performance of the design was quite sensitive to variations in the time-varying load distribution. Here, it was important to consider the network definitions described below to obtain a model that was robust enough for load variations. By subsequently changing these boundary conditions along the y-direction (2), the peak-to-valley distortions due to the simulated applied compressive load stresses could be visualized.

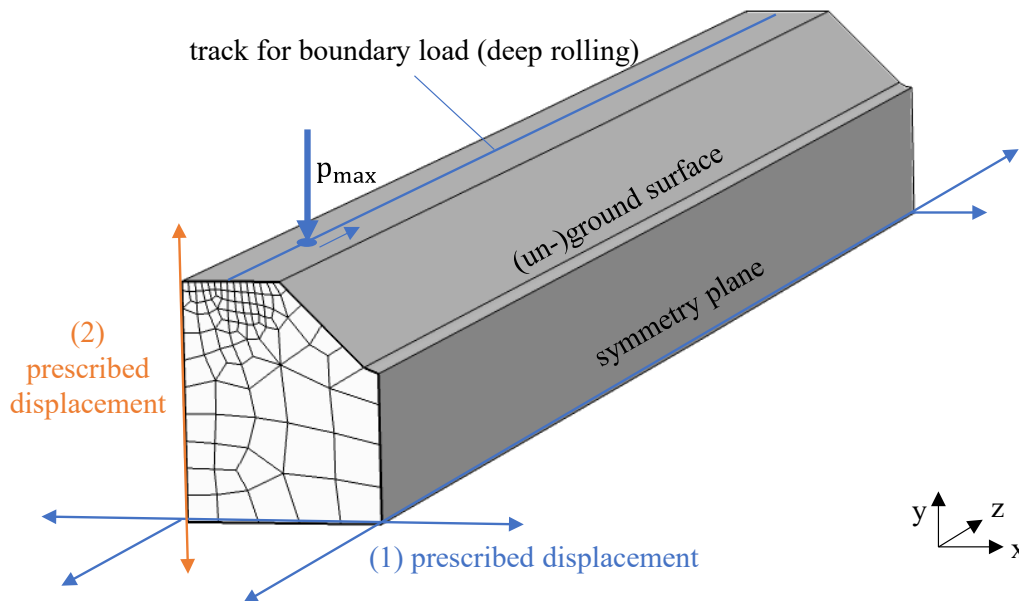


Fig. 4. The geometry of the workpiece and applied boundary conditions for the finite element simulation

Mesh. The meshing of the geometry was specifically designed for the application of a load on the upper surfaces of the workpiece. An optimization of the results requires finer meshing due to the small contact area between the tool and the workpiece in Hertzian pressing. For this purpose, the model geometry was divided into two areas: one with a transient load and one with an optimal performance. The interfaces of the optimization and the solid mechanics can thus be combined. The cross-section, a quad mesh, was defined with a strong refinement towards the rolling side and with a

coarser mesh towards the restrained side. This two-dimensional definition was then extruded to obtain the 3D-model.

Results and Discussion

In the following, the results of the experiments are presented and compared with the simulated distortions based on the previous definitions. For this purpose, the analysis of the unground workpieces was conducted first. Subsequently, the distortion findings of the rolled workpieces, which were deformed due to the residual tensile stresses introduced during grinding, will be analyzed.

Workpiece distortion due to deep rolling. Fig. 5 shows the measured peak-to-valley distortions ΔPV for the number of rolling tracks N equal to 1, 5, 10, and 50. The applied compressive load stresses cause the workpiece to bend in the negative y-direction. While the workpiece still reveals a relatively small distortion of -0.023 mm when the workpiece surface is traversed in a single track, one of -0.093 mm is already evident when five tracks are rolled. With a further increase of N in the same machining area, that is, with a reduction of the lateral tool feed, the workpiece distortions increase to -0.115 mm for ten rolling tracks. A comparison with the distortions obtained in the simulations also shows a close match. There was a stronger increase up to $N = 10$, and then a smaller increase in distortion at $N = 50$. The simulation results were always within the measurement accuracy and within the variance from the three test samples.

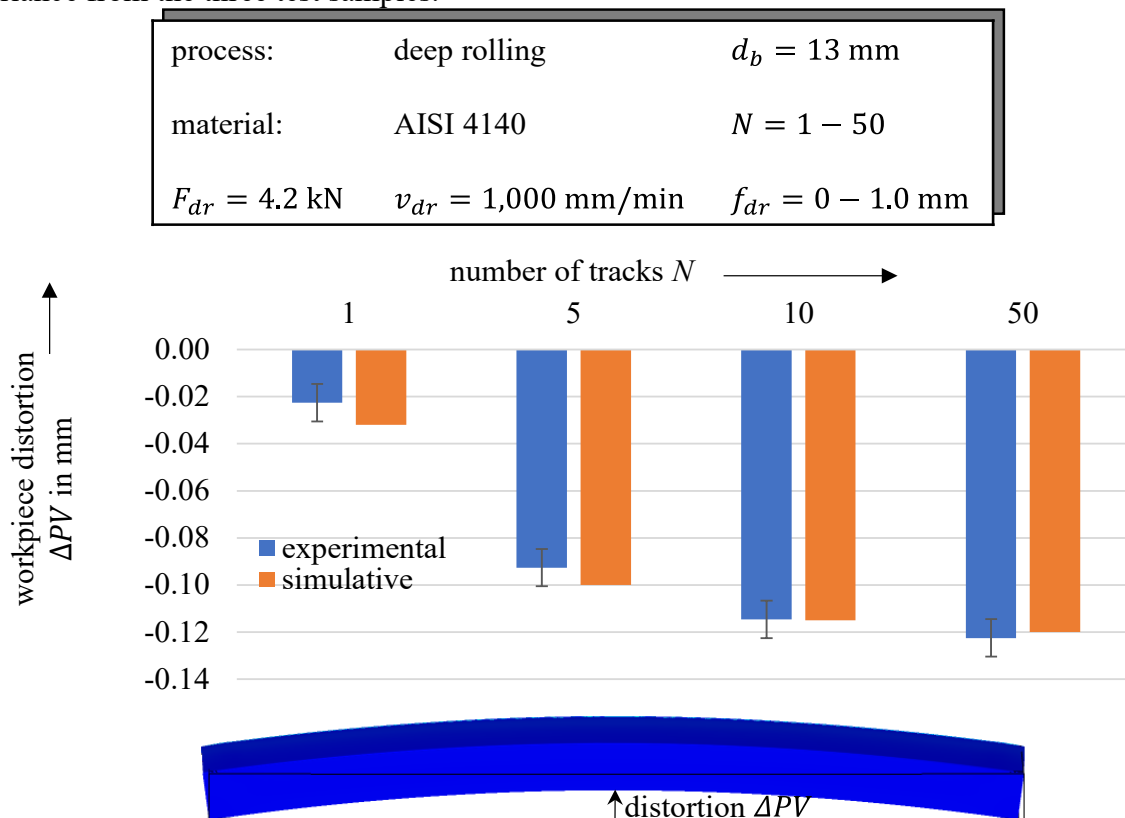


Fig. 5. The experimental and simulated peak-to-valley distortions in the y-direction of deep rolled workpieces with the number of tracks $N = 1, 5, 10$, and 50

Compensation effect of deep rolling on ground workpieces. To evaluate the possibilities of deep rolling as a mechanical compensation process for workpiece distortions during grinding and to assess the FE simulation as a predictive model, the tests were also repeated using ground workpieces. Previously, the reference sample was defined with a grinding distortion of $\Delta PV = 0.2 \text{ mm}$. Fig. 6 first shows the distortion of the ground workpiece that was not rolled ($N = 0$) for a direct comparison. Next to this, the distortions for the ground and rolled workpieces are again plotted in the order of the previous figure. The single-track test showed a reduction of the initial distortion by 0.006 mm. Despite the large difference between $N = 1$ and 5 in the experiments for the unground samples, there

were hardly any other differences. The large standard deviation was remarkable, and it was due to just one outlier of the three samples with 0.275 mm distortion. The other two workpieces had respective ΔPV values of 0.117 mm and 0.121 mm, which would be more in line with the expected counter-distortion. From $N = 10$ onwards, the distortions changed only very little. At $N = 50$, the peak-to-valley value was 0.099 mm. In order to be able to use the simulations from previous research, which predicted the grinding distortion through FE models, the reference distortion of 0.2 mm was used as the initial condition in the solid rolling model [8]. It can be seen that the simulation is promising as a choice for an overall model of the distortion prediction. Only at $N = 50$ did the distortion value deviate a little bit from the error range. For later industrial applications for the correction of linear guide rails, such a high number of rolling steps with a barely variable distortion would not be economical concerning the values at $N = 5$ and 10 due to higher time consumption and tool wear. Another factor is that the reference distortion of 0.2 mm selected here corresponds to a very high value, which should define the upper limit of grinding distortions [8].

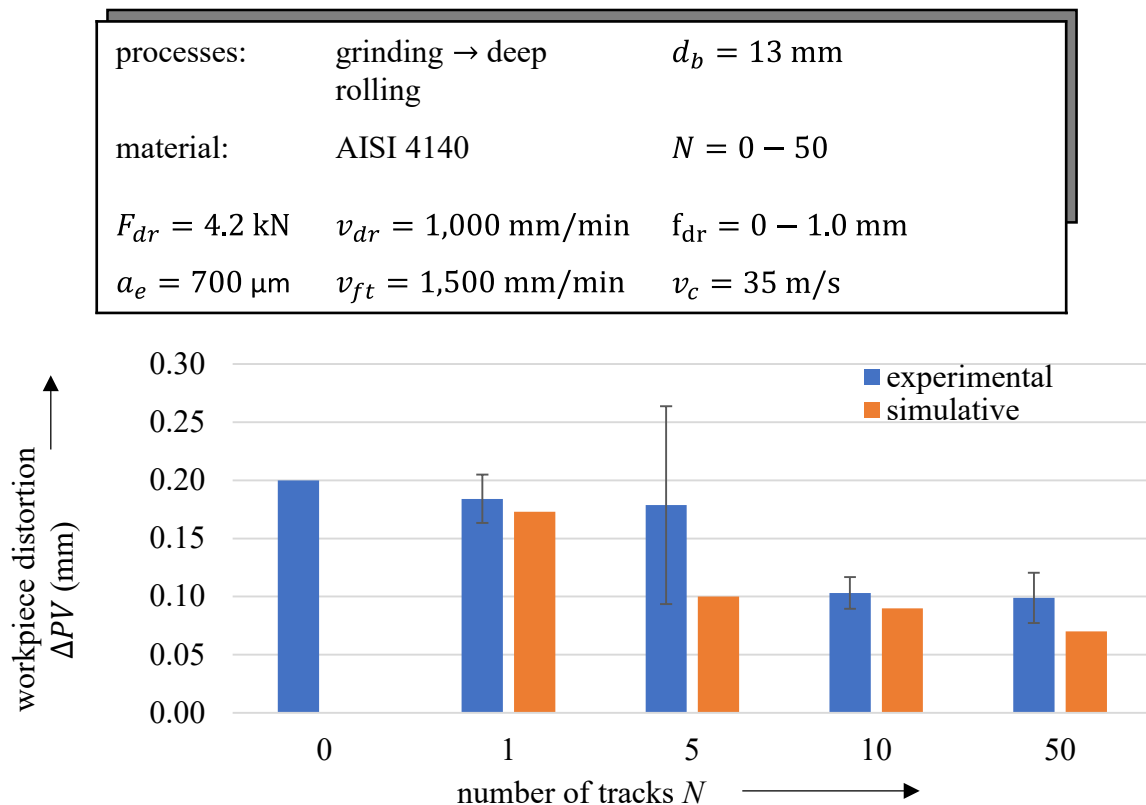


Fig. 6. The experimental and simulated peak-to-valley distortions in the y-direction of the deep rolled ground workpieces ($a_e = 700$ μ m and $v_{ft} = 1,500$ mm/min) with the number of tracks $N = 1, 5, 10$, and 50 in comparison with the reference sample ($N = 0$)

Conclusions

In this paper, deep rolling was investigated as a machining option to compensate for the distortion of V-grooved workpieces similar to linear guide rails in grinding processes. The results were used to develop and validate a finite element model. For this purpose, stress-free workpieces made of AISI 4140 were machined on the two surfaces adjacent to the V-groove with track numbers between 1 and 50 per side using a deep rolling tool. The distortion results were then adjusted using an implemented simulation model. Boundary conditions corresponding to the process were selected for this purpose. In addition, a reference distortion of a ground sample in the maximum range was then selected from previous research to repeat the deep rolling tests and to match their results with the simulations. Promising outcomes were obtained in both cases. Future research will extend the experimental scope

to refine the model and then complement it with possible thermal distortion compensation methods such as lasering.

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