Journal of Machine Engineering, 2024, Vol. 24
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received*: 30 May 2024* / Accepted: *29 November 2024* / Published online: *02 December 2024*

grinding, tool,
deformation,

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ANALYSIS OF CONTACT WHEEL AND TOOL INTERACTION IN BELT GRINDING

The belt grinding process is gaining an increasing importance in the industrial sector. Due to its high flexibility regarding the range of workpiece materials and its adaptability to various, even geometrically complex workpiece shapes and designs, belt grinding has a broad field of applications. Typical application cases for this process include sealing surfaces on housing and engine parts, the production of camshafts and crankshafts as well as cylinders with high concentricity accuracy. Despite the extensive application of belt grinding in the manufacturing industry, the respective interactions between grinding belt and contact wheel of the process have not been holistically investigated. Therefore, this article focuses on the deformation of the contact wheel as well as the deformation during the interaction between the contact wheel and the grinding belt. This includes the flattening of the tool under grinding normal force F_n and deformation under centrifugal forces. The empirical data is intended to provide insights into the relationship between tool deformation and elastic effective depth of cut a_e.

1. INTRODUCTION

1.1 GRINDING WITH ELASTIC TOOLS

Elastic abrasive tools are gaining increasing relevance in the industrial environment due to high flexibility [1-3]. Particularly remarkable are abrasive tool systems within the support segment, exemplified by belt grinding. These applications can be found in the final processing of functional surfaces of cylindrical components such as camshafts and crankshafts, as well as in the machining of free form surfaces for components in steam and gas turbine construction, and also aerospace. Unlike rigidly bonded grinding wheels, where the abrasive grains are either metallic, ceramic, or resin bonded, elastic abrasive tools allow for variation in elasticity over a wide range by using synthetic bonding materials such as polyurethane, polyester, or epoxy resins. [2, 4, 5]. The elastic polymer can be used either directly as

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https://doi.org/10.36897/jme/196637

a binding system or, as is common in belt grinding, as a contact element beneath the flexible abrasive binder.

Despite the widespread industrial use, the influence of elasticity on key factors such as depth of cut, geometric deviation, and surface quality in elastic grinding processes remains largely unexplored. Process design is typically based on empirical relationships and experience [6]. The major challenge lies in describing the nonlinear material and process behaviour of the elastic tool system and its influence on the work result on the component. Due to the interaction between the stiffness of the grinding belt and the hardness of the contact wheel, there are process-specific, unexplored system superpositions. These superpositions manifest on a macroscopic level as form deviations and on a microscopic level as changes in surface roughness. The focus of the presented study is therefore on quantifying elastic process interactions between the grinding belt, the contact wheel, and the workpiece, as well as their influence on the work result depending on the grinding process parameters. The longitudinally circumferential planar belt grinding process is chosen as an industrially used process [7–9].

1.2 BELT GRINDING

The belt grinding process has a broad range of applications in industrial practice due to its great flexibility in terms of the processable material spectrum and adaptability to various, even geometrically complex workpiece shapes and forms. With high possible material removal rates as well as high surface qualities, belt grinding processes can be employed for the high-precision machining of functional surfaces concerning specified dimensional, shape, positional tolerances, and surface qualities. Belt grinding process also excel in efficiently removing burrs, surface, and edge defects as well as producing decorative surfaces according to specific requirements. In comparison to rigidly bonded grinding wheels, belt grinding systems stand out in terms of handling due to quick tool changes, providing high flexibility in adapting to the respective machining task, potential elimination of coolant usage, and relatively high safety regarding possible tool breakage [5, 10, 11]. Unlike rigidly bonded grinding wheels, belt grinding systems inherently possess increased elasticity due to the low tool system stiffness in the grinding normal force F_n direction, resulting from their construction [7]. This allows the grinding tool to adapt to the contour of the workpiece being processed over a wide range, enabling the machining of geometrically complex workpieces and can be achieved without elaborate and time-consuming tool profiling. Additionally, the flexibility of the tools allows for the economical grinding of hard-to-reach areas with small radii of curvature and easily deformable workpieces [7, 10]. In rigid grinding with bonded grinding wheels, the abrasive grains are typically multi-layered. In belt grinding, however, the abrasive grain (grinding belt) is typically single-layered, applied to a support, wrapped around at least two rotating wheels, and pressed against the workpiece in the contact area. As seen in Fig. 1. The adaptability of the grinding belt to the workpiece contour to be ground is thus significantly influenced by an elastic contact element. In contrast to grinding with bonded grinding wheels, it is generally assumed that the abrasive grains during elastic grinding can change both their orientation and their position depending on the elasticity of the tool system [12, 13].

1.3 BELT GRINDING AS CNC PROCESS

Figure 1 depicts the setup of a continuous belt grinding process in a CNC machine. In this process, the multi-cutting-edged grinding belt pressed with the contact wheel against the workpiece. The geometrically undefined edges, under intermittent contact between the workpiece and abrasive grains, remove material from the workpiece [13].

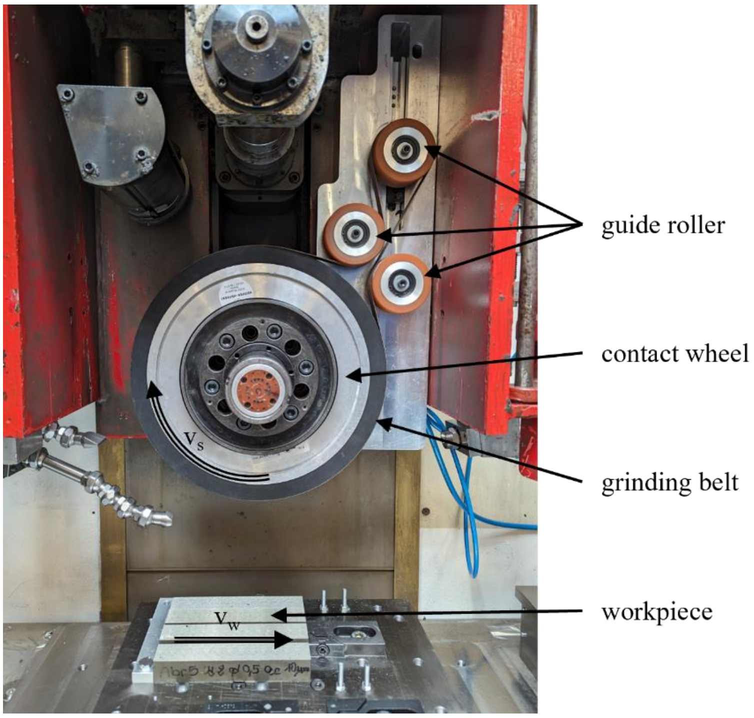

Fig. 1. CNC belt grinding

Key control parameters for the belt grinding process include the depth of cut ae, indicating how far the tool advances into the workpiece; the circumferential velocities v_s, derived from the tool's circumferential velocities vs and radius r; and the cutting speed v_c, derived from the circumferential velocities v_s and the feed rate v_w [14]. In addition to the tool and its components, the contact wheel also has a significant impact on process behaviour. Typically, the contact wheel consists of a metallic rigid core and a soft support pad coating. The support pad coating significantly influences tool deformation and can strongly affect the process by varying the Shore hardness [15].

1.4 GRINDING BELT

The typical construction of a grinding belt is shown in Fig. 2. Specifically manufactured grinding belts from HERMES SCHLEIFMITTEL GMBH, Hamburg, were used for the research. They consist of a fabric support, resin binder, and corundum abrasive grains. For the experiments, two different supports with varying stiffness, corresponding to weight class

J and *X*, were used. The other components of the grinding belt were kept constant to exclusively examine the influence of the support.

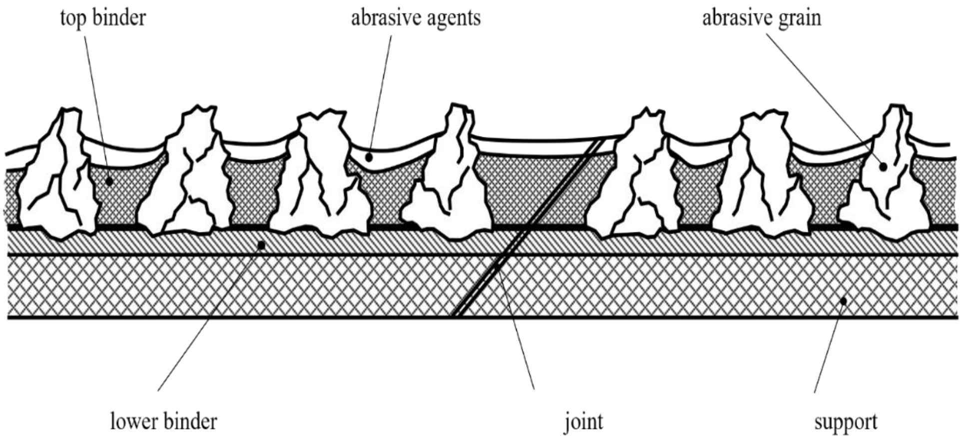

Fig. 2. Structure of a grinding belt

Various materials are used for the support, depending on the expected thermal and mechanical loads. These include paper, fabric, vulcanized fiber, or combinations thereof. Paper has the lowest strength values and is therefore mainly used in hand-guided manufacturing operations and woodworking. Woven supports are used in grinding processes with higher mechanical loads, with polyester fabrics exhibiting the highest tensile strength values.

The bond between the abrasive support and the abrasive grains is established by the binder, which also supports the individual abrasive grains. It consists of two layers: the lower binder and the top binder. Binders such as animal hide glue and synthetic resins are used. Synthetic resins offer higher strength and heat resistance.

The type and application of the abrasive grain are also crucial. Corundum and silicon carbide are almost exclusively used as abrasive grains, while diamond or cBN may also be used for fine finishing. The coating technique, either mechanical or electrostatic dispersion, influences the performance of the grinding belts. This is because the orientation of the abrasive grains or the application of specialized coatings, such as island patterns, can lead to targeted changes in productivity and surface quality [16].

2. DEFORMATION EXPERIMENTS OF THE TOOL SYSTEM

2.1 PRESSURE TESTING OF THE TOOL SYSTEM WITH VARYING CONTACT WHEEL HARDNESS AND WORKPIECE ENGAGEMENT

To identify the explicit influences and interactions of grinding belt and contact wheel on the overall deformation behaviour will be investigated, with the tool system not engaged in the grinding process. The aim of this investigation is to develop and quantify outcome parameters describing the deformation behaviour, in order to identify potential correlations between the applied testing methods and the technological grinding process.

First, for the investigation, three contact wheels with different hardness, specifically 40, 60, and 80 °Shore, were used. Initially, the depth of cut a_e of the of a contact wheels with a width of b_s = 20 mm was tested at different normal forces F_n using the tensile-compression testing machine type Z150 from ZWICK & ROELL AG, Ulm. Two loading cases were considered. In the first case, the tool is narrower than the workpiece. For this, the force measurement platform was pressed against the contact wheel with its full width. In the second case, the tool is wider than the workpiece. Therefore, a force measurement platform with a width of $b_{s,eff}$ = 15 mm was pressed against the contact wheel. The investigation aims to determine the influences of different Shore hardness levels, as well as the impact of whether the tool engages over its full width or only partially. The results of the investigation are shown in Fig. 3. All experiments were conducted five times, and the average values were presented.

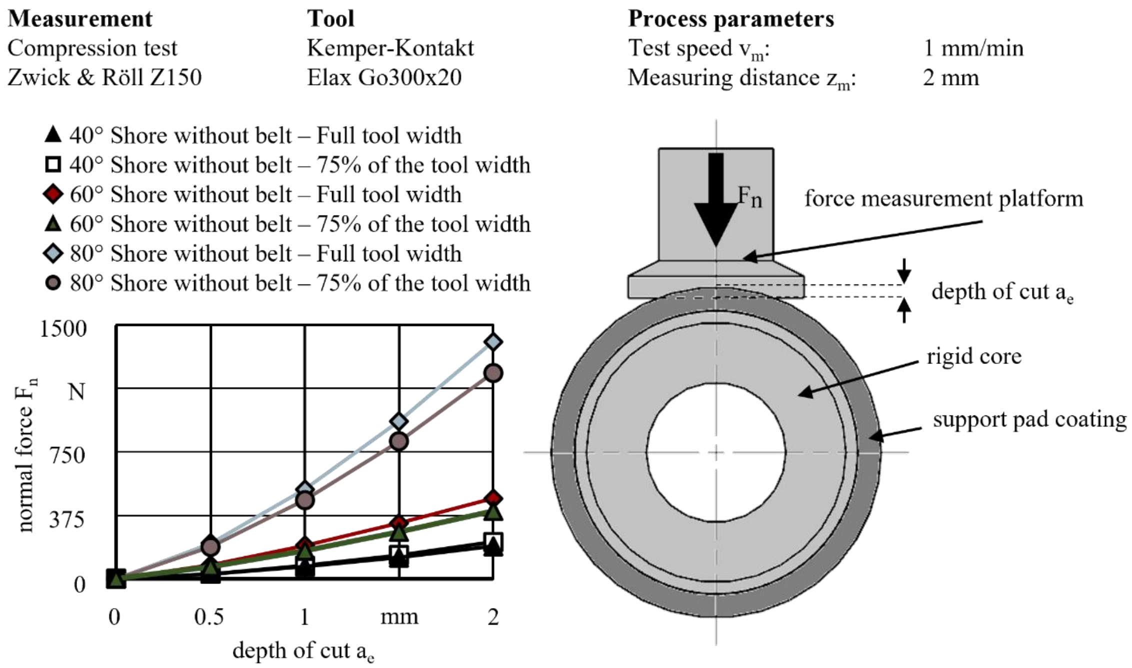

Fig. 3. Tool deformation at static force without grinding belt

A nonlinear relationship is evident between the input parameter depth of cut a_e and the output parameter normal force F_n. This is because the flattening of the tool causes more material from the support pad coating to be engaged. The results also show that the hardness of the contact wheel significantly influences the normal force F_n at constant approach. With increasing Shore hardness, the normal force F_n increases significantly. The relationship between Shore hardness and normal force F_n is non-linear as well. The increase in normal force F_n with higher Shore hardness of the support pad coating can be attributed to the reduced deformation of harder materials. The nonlinear relationship between Shore hardness and normal force F_n is also due to the complex interactions between the material properties of the support pad coating and the elastic deformations influenced by factors such as material compression. In loading case 2, the normal force F_n decreases 11.5% to 15.8% compared to loading case 1, with no apparent correlation to contact wheel hardness. the normal force F_n is only slightly reduced because the tool wraps around the edges of the force measurement platform. This causes areas of the tool beyond the width of the platform to exert pressure on it, even without direct contact. In the next step, the contact wheels with grinding belts were investigated as a tool system. For this, the tool system was pressed against the measurement platform until a depth of cut of a_e = 2 mm was achieved. Contact wheel with Shore hardness of 40° and 80° were examined, as well as both load cases and grinding belts with a soft support of the weight class *J* and stiff support of the weight class *X*. The results are shown in Fig. 4.

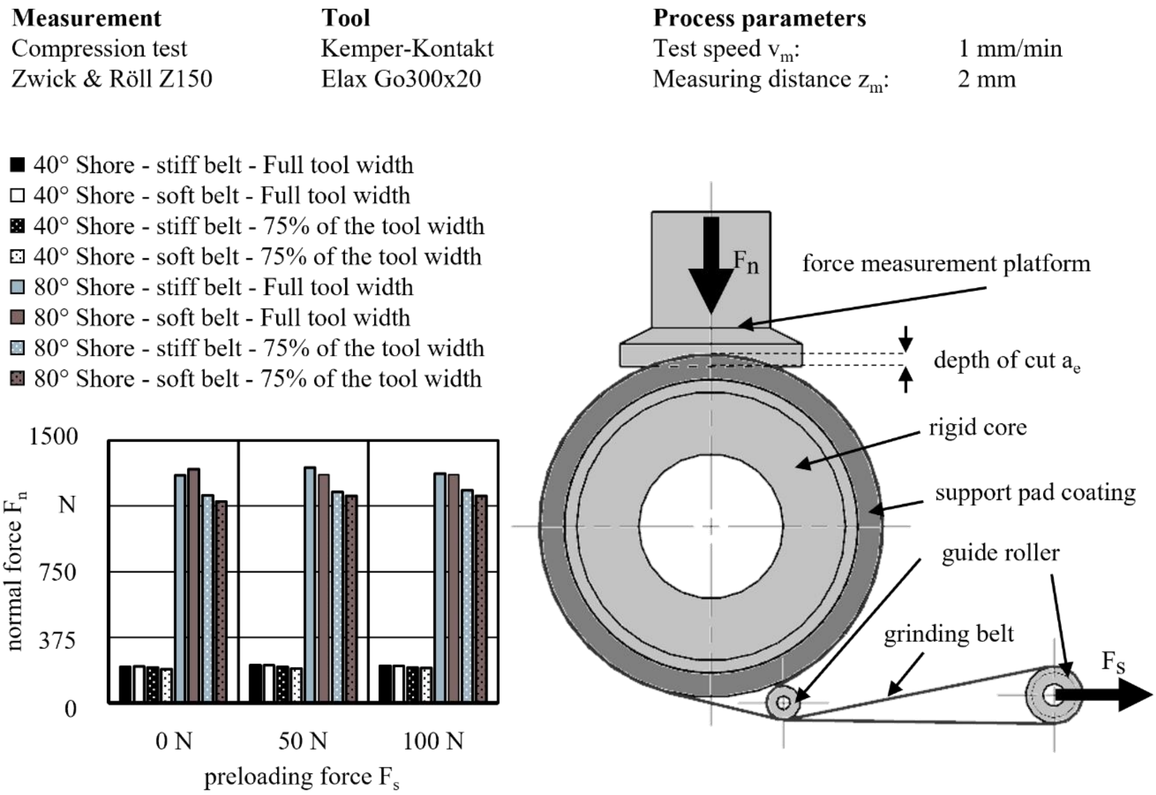

Fig. 4. Tool deformation at static force with grinding belt

A comparison is made between the two loading cases with different preload forces F_s using both hard and soft contact wheels, as well as two grinding belt configurations. Aside from contact wheel hardness, the variables exhibit minor impacts on the normal force F_n. At a preload force F_s = 0 N, the grinding belt with a soft support causes an increase of 1.5% of the normal force F_n compared to the grinding belt with hard support, while at F_s = 50 N, a decrease of 2% of the normal force F_n is applied with the soft support compared to the hard support. At F_s = 100 N, the normal forces F_n for both supports are approximately identical. This observation holds true only in the first loading case. In the second loading case, the preload force F_s has no significant impact. The significance of preload force F_s in maintaining stable grinding performance and mitigating problems such as uneven force distribution is further elaborated in the work of Douglas Jensen, offering complementary insights to the observed experimental results [17].

The depth of cut a_e is an important factor to influence the material removal rate Q_w. The effective material removal rate $Q_{w,eff}$ is approximately constant during the process. However, this is only the case if the contact wheel's support pad coating has a sufficiently high hardness. A support pad that is too soft deforms under increasing forces, opens the grinding gap, and causes a decrease in the material removal rate due to the resulting reduction in the depth of cut a_e. Conversely, a support pad that is too hard can lead to a shortened tool life. This can be attributed to excessive grain axial cutting forces f_a and their correlation with the normal force F_a. Furthermore, a harder contact wheel presses the abrasive grain further into the workpiece, creating an increase in chip volume. This deteriorates the surface roughness. Depending on the grinding belt and workpiece material, the appropriate contact wheel hardness must be selected [16].

Additionally, pressure distribution was examined for the two loading cases, see Fig. 5. The contact wheel with an 80 °Shore hard support pad coating was investigated with depth of cut of a_e = 1 mm. Pressure-sensitive film Prescale from Fujifilm Europe GmbH, Ratingen, was used for measurement. The pressure-sensitive film changes color depending on the pressure distribution. Thereby, the color intensity increases with increased pressure. Fig. 5a illustrates loading case 1 with an approximately homogeneous pressure distribution, showing only a slight increase in pressure at the edges of the contact surface. In contrast, loading case 2, Fig. 5b, exhibits significantly elevated pressure at the edges, leading to increased edge wear and consequently higher form deviations.

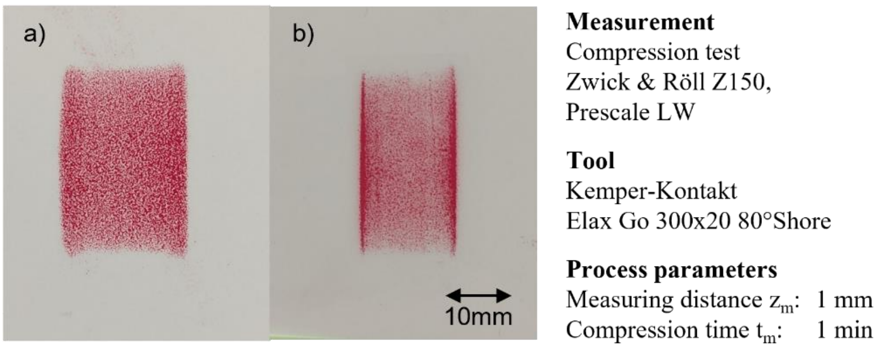

Fig. 5. Difference of pressure distribution. a) full tool width, b) 75% tool width

2.2 CENTRIFUGAL FORCE TEST WITH VARYING CONTACT WHEEL HARDNESS

Centrifugal force has a pronounced influence on the performance of elastic abrasive tools [4]. Depending on the stiffness of the tool system, profile deformations in the radial direction were captured using a 2D laser triangulator, specifically the scanCONTROL 3060 50 model from MICRO-EPSILON MESSTECHNIK GMBH & CO. KG, Ortenburg, with a resolution of η_z = 1 µm in the z-direction and a measurement range of z = 30 mm in the x-direction. The principle of pure point triangulation is extended to two dimensions by focusing the laser onto a line instead of a point. After analysing the profiles, the profile deformation of various contact wheel hardnesses were compared based on single measurements under centrifugal force and static measurements, Fig. 6.

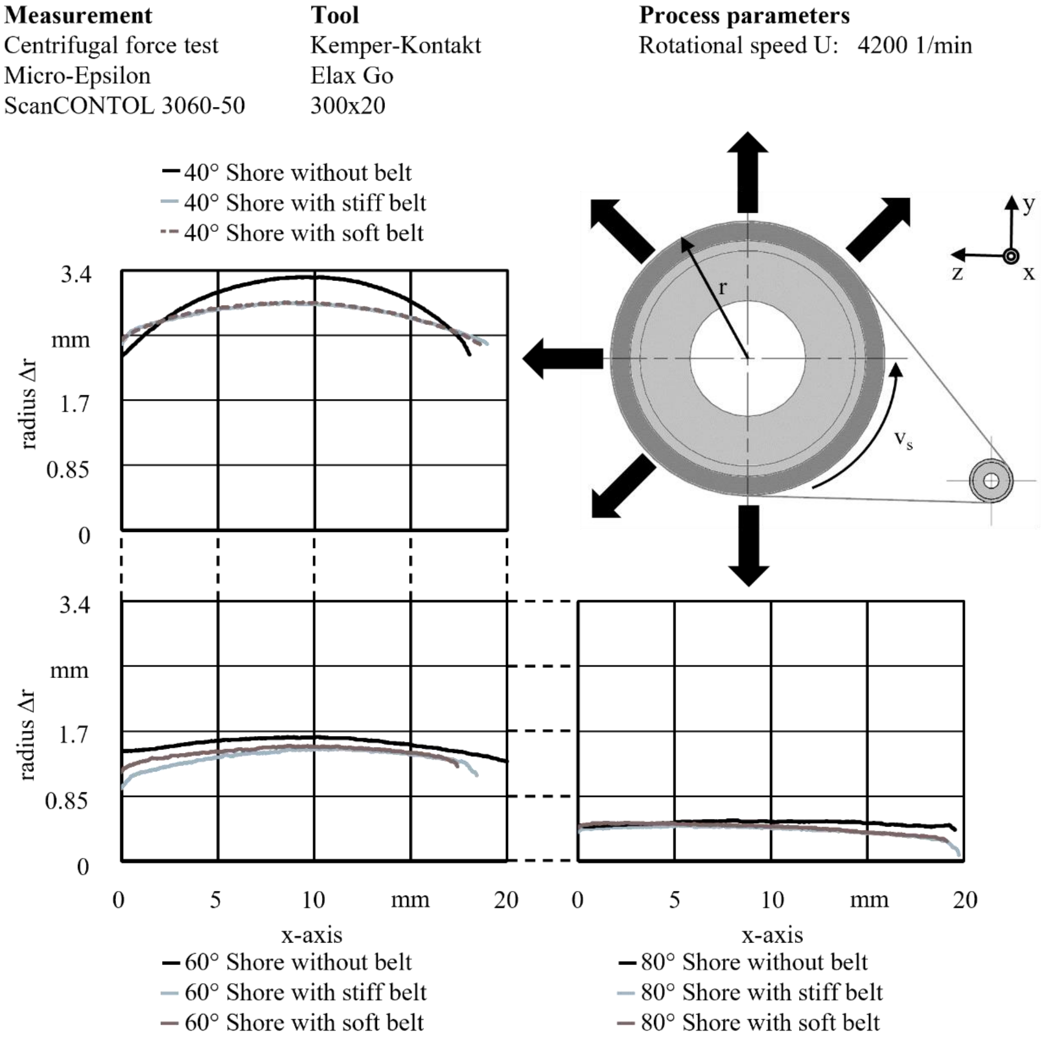

Fig. 6. Tool deformation at centrifugal force

The results demonstrate a non-linear relationship between the maximum radius expansion Δr_{max} and contact wheel hardness. The maximum radius expansion Δr_{max} is 3.31 mm for the soft contact wheel (40°Shore) without a grinding belt, 1.62 mm for the medium hardness (60°Shore), and 0.54 mm for the hard contact wheel (80°Shore). Additionally, a significant influence of grinding belts is observed with the contact wheel having a 40 Shore support pad coating. Both the curvature and maximum radius are noticeably reduced with the use of grinding belts. The impact is less pronounced with higher hardness contact wheels, and the influence of grinding belt support stiffness was not significant in the experiments. These findings highlight a clear connection between contact wheel hardness, deformation, and the effect of grinding belts on curvature and maximum radius, particularly evident with soft contact wheels equipped with a 40°Shore support pad coating.

The expansion, determined by centrifugal force along with the counteracting normal force and the material tension resulting from deformation, is referred to as the depth of cut a_e. Additionally, due to the curved deformation, it can be assumed that the centrifugal forces induce a varying distribution across the width of the grain normal cutting force f_n. This would lead to greater chip formation in the center of the tool, resulting in shape deviations, uneven surface quality, uneven tool wear, and deviation in workpiece shape.

3. CONCLUSION AND SUMMARY

In these investigations, the relationships between contact wheel hardness, deformation, and the influence of abrasive belts on tool system behavior were examined. To identify potential correlations between different testing methods and the grinding process, aiming to anticipate the influences of deformation behavior on the grinding process, experimental investigations were conducted. A significant finding was that a contact wheel with a 40 Shore hardness exhibited a maximum radius expansion of $\Delta r_{max} = 3.31$ mm, compared to $\Delta r_{max} = 0.54$ mm for a wheel with 80 °Shore hardness under centrifugal force. The results of the static and centrifugal force studies reveal a nonlinear relationship between contact wheel hardness and deformation, as well as an impact of the abrasive belt on tool system behavior, particularly with soft contact wheels. The experiments did not show a significant influence of abrasive belt support hardness on the results. At a preload force $F_s = 50$ N, softer grinding belts increased the normal force F_n by 1.5 %, whereas at $F_s = 100$ N, the normal forces for both belt types were nearly identical. The two examined loading scenarios exhibited an interesting, intermittent phenomenon with increasing preload force F_s. Furthermore, the normal force F_n was influenced regardless of contact wheel hardness. In the loading cases, the transition from full-width to partial-width engagement caused a reduction of normal force F_n by 11.5% to 15.8%, independent of contact wheel hardness.

In further investigation, controlled grinding experiments will be conducted, whereby the input parameters are the same as in the experiments already conducted, but at different circumferential velocities v_s. To describe the influence of the elastic behavior deformation of the tool system while grinding, the parameter elastic effective approach $a_{e,eff}$, maximum workpiece form deviation f_{max}, grinding contact area A_k, and surface roughness are measured. Using this data along with previously collected information, an empirical process model will be developed. The insights from this process model will serve as the basis for a 3D simulation based on a penetration model. To conclude the research, grinding experiments will be conducted under different parameters to validate the simulation and verify the results. This iterative approach aims to develop a comprehensive understanding of belt grinding processes and enhance the predictability through simulation techniques.

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