euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
www.euspen.eu

In-process measurements of strain fields during grinding

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Abstract
Production processes, such as deep rolling or grind strengthening try to manipulate the specific surface layer properties of the workpiece in a deliberate manner. For this, a comprehensive knowledge of the physical stresses during the machining is necessary. The interesting properties, like hardness and elastic modulus, are strongly influenced by plastic and elastic deformation. However, the measurement of elastic deformations in a running production process is complicated. The speckle photography method, distinguished by very short measuring times and robustness, offers the potential to meet this challenge. The measuring system presented in this paper is suitable to characterize dynamic deformations in a grind strengthening process in the sub-micrometre range. The deformation field is observed laterally in plane of the principal direction on the end face of the workpiece. The influence of out-of-plane movements on the determined deformation field can be minimized by using a high speed camera system and an interpolated subpixel resolution. The measured displacements and expansion fields allow the differentiation of elastic and plastic effects, as well as a separate consideration of the thermal influences to optimize the process parameter.

Keywords: In-process measurement, speckle photography, deformation fields, expansion fields, grinding

1. Introduction

The surface integrity, which is the surface condition of a workpiece generated by the production process, determines the functional properties of heavily loaded metal components [1]. The adjustment of the desired process parameters as well as the selection of the process depends on the available manufacturing machines and the experience of the manufacturer. Mostly, the chosen process parameters do not lead to the exact required value of the surface property, but ensure that its value lies always below or above a certain threshold. Hence, the process parameters are not optimized regarding component functionality and production costs. The surface integrity is not determined by the used process itself, but by the resulting physical loads (e.g. deformations). Here, a lack of knowledge about the existing interrelations of parameters, loads and surface characteristics exists. Thus, the dynamic measurements of loads and physical stresses during a machining process are a prerequisite for the targeted setting of specific surface layer properties. Measurement of strain and deformation fields in an ongoing production process, such as the grind strengthening, requires a robust high-speed measurement technology which is able to detect locally resolved displacements in the nanometre range. Due to the meanwhile available UHD-high-speed-camera technique the speckle photography is predestined for this task.

2. Speckle Photography

The digital speckle photography is an established procedure for tracking spatially resolved displacements respectively deformations of surface elements [2]. It is based on a speckle correlation method. Speckles inevitably arise, if a rough surface is illuminated with a coherent laser beam. When the surface is imaged with a lens, in general the speckles are so small that they cannot be resolved.

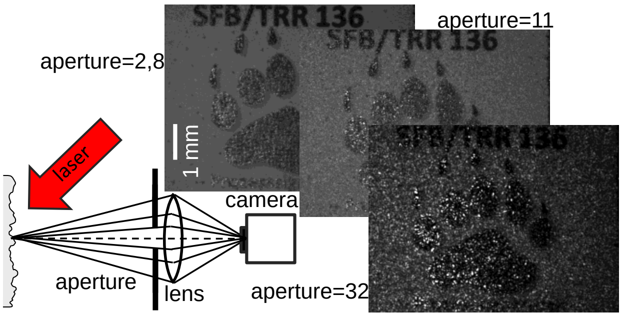

Figure 1. Formation of subjective speckle patterns.

By increasing the aperture of the objective system, the speckles are getting more distinct and bigger (Fig. 1). Each speckle can be assigned to a particular surface point and therefore, the speckles can act as local, arbitrarily small position markers with extremely high contrast.

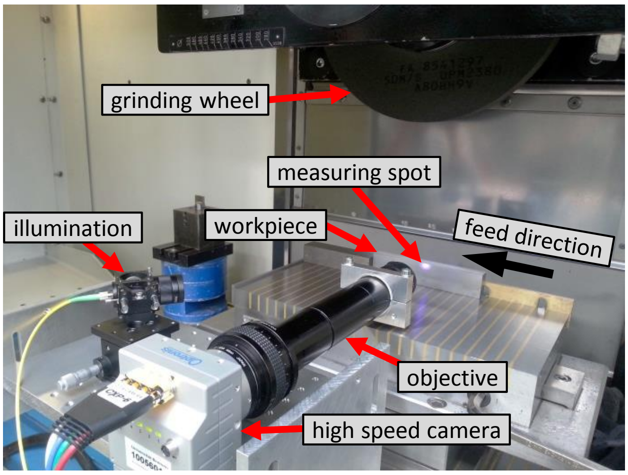

Figure 2. Grind strengthening setup including the speckle photography technique for deformation measurements.

The evaluation of the displacements can be carried out even in a post-process procedure with the help of local speckle correlation methods [3].

3. Experimental setup for the grind strengthening process

Figure 2 illustrates the experimental measurement setup of the first, not quite realistic process of “dry” grind strengthening (without cooling). The grinding wheel is approaching from the right with a feed rate of 0.5 metres per minute, a cutting speed of 40 metres per second and an infeed rate of 200 µm. The high speed camera observed the displacements of the material perpendicular to the tool movement on the end face of the workpiece. Workpiece and camera system are firmly interconnected via a magnetic chuck. A collimated laser with a wavelength of 405 nm illuminates the measuring spot diameter of about 10 mm with a Gaussian beam profile and thereby generates the speckle pattern.
With the UHD camera chip (4080 * 3072 pixels), a sub-pixel interpolation [4, 5] between the speckles and a full frame rate of 167 Hz, local surface displacements in each pixel of less than 20 nm can be detected. The lateral spatial resolution is defined by the pixel dimensions, which for the measuring spot of 10 mm * 7.5 mm are 2.5 µm in both directions.
Due to the tough environments of the dry working process (Fig. 3), a special pre-calculation algorithm is necessary, eliminating the flying sparks in the pictures. Achieving a good resolution requires the setting of the smallest possible average speckle size to about 2-5 pixels [3]. The sparks, moving rapidly through the picture, unfortunately destroy the measuring effect. However, since they have a much larger diameter (> 10 pixels) they can be recognized in the evaluation window and the displacement caused by it can be ignored.
The measuring system, which consists of the camera and the illumination optics, is sensitive to damage by the tough environmental conditions in the working area (sparks etc.). Therefore, it is encased in a metal housing for protection. A glass window in the observation direction allows the view of the measured object.

Figure 3. Field-testing under tough environments with strong flying sparks.

4. Measurements in the grind strengthening process

Figure 4 shows an excerpt from a time series, recorded during the grind strengthening process. The upper part represents the real image of the rotating grinding wheel, at the bottom half the surface displacements on the end face are calculated. The picture shows the moment, at which the contact point of the grinding wheel, approaching from the right, is just passing the left side of the picture. The slight deformations (<1 µm) at the bottom of the picture up to 200 µm below the surface are purely dynamic in nature and disappear when the grinding wheel is leaving the image section.
Since the dry grinding is not a realistic grind strengthening process, strong heat influences arise at the processed surface. The large thermal shifts of above 4 µm in the centre of the image diminish after a few seconds. Remaining minimal plastic deformations in the near surface region actually cannot be detected with the large spatial resolution of 2.5 µm.

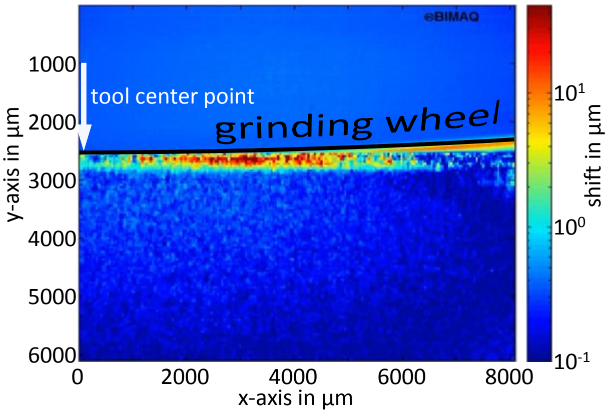

Figure 4. Measured absolute values of local displacements in a grind strengthening process.

However, reduced measurement spots lead to corresponding higher spatial resolutions and therefore, depending on the selected subpixel interpolation, displacements in the one digit nanometre range can be calculated. The evaluation of the captured time series delivers the temporal course of the deformation for all surface areas. Hence, the load and unload periods of these areas can be identified from which the plastic and elastic portions of the deformations can be derived [5].

5. Conclusion

It was shown that speckle photography is suitable for characterising spatially resolved displacements and stresses occurring in a running production process, even under tough conditions. Depending on the size of the measuring spot, local resolutions down to the one digit nanometre range can be achieved. Furthermore, it is possible to separate the plastic and the elastic deformations during the manufacturing process. In future, the derived stresses could be an important feature to answer open scientific questions in different manufacturing processes and to get a better understanding of these processes.

6. Acknowledgements

The authors gratefully acknowledge the German Research Foundation (DFG) for the financial support of project C04 “In situ measurement of mechanical and thermal material stresses” within the Transregional Collaborative Research Center SFB/TRR136 "Process Signatures". They also thank Mr. Ewald Kohls for his assistance during the measurement campaign.

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