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Process Monitoring in Grinding Using Micromagnetic Techniques

H. K. Tönshoff, B. Karpuschewski and C. Regent

Institute for Production Engineering and Machine Tools, University of Hannover, Hannover, Germany

In production engineering, the demands on monitoring systems are steadily increasing owing to the automation of machining processes. In the past, the detection of defects was sufficient. Today, the avoidance of any defect is necessary. Therefore, monitoring systems have to be fast and reliable to guarantee zero-defect manufacturing. Most systems monitor acoustic emission (AE), power consumption or forces while machining. Thus, the quality of the workpiece is only indirectly described and the determination of workpiece quality characteristics must be made by metallographical inspections of random samples. These investigations are time-consuming and often destructive. Micromagnetic techniques make fast and non-destructive quality control of ground workpieces possible. For post-process measurements, the magnetic quantities of Barkhausen noise and field strength are used. The sensor systems have been adapted to different applications such as grinding of gears or bearing rings. In this paper the basic principle of this technique and the results of industrial implementation will be presented. A new micromagnetic analysing system will be introduced which can be used for the direct measurement of workpiece quality characteristics while machining. This system uses twelve different magnetic parameters and is a combination of the above mentioned system and an eddy current analysing system. Residual stresses, surface hardness and case hardening depth are measured in-process and can be used for process control. Furthermore, the 100% quality documentation is possible without any additional post-process measurement. In addition to the measuring principle, first results and examples of automotive applications will be shown.

Keywords: Grinding; Process monitoring

1. Introduction

Reliable and faultless manufacturing is a basic demand for processes which are used in motive power engineering in order to produce high-grade components. The spectrum of those components extends from gear shafts, guiding mechanisms and bearings to crankshafts, camshafts and gearwheels. Fine machining by means of grinding is located at the end of the manufacturing chain in which turning and milling operations as well as a heat treatment are carried out.

Because the components have a high added value up to the beginning of the final grinding treatment, thermal damage of the workpiece in grinding must be avoided by careful process monitoring. The cost-intensive grinding process offers the best possibility of manufacturing economically by an increase of output and the consequent shortening of the machining time [1,2]. A conflict resulting from those different requirements originates because of the different targets: reproducible quality by reliability of processing in opposition to economic efficiency. As a consequence, the application of process monitoring is used in order to supervise the manufacturing process and to be able to start any necessary counter measures in cases where the required quality is not achieved.

Various techniques are used to check the integrity of a ground workpiece, to monitor the process itself, or to evaluate the grinding wheel wear. In the past, a fast and quantitative inspection of the surface integrity in the production line was not possible. Today, macro- and microgeometric differences in the quality of components can be controlled easily by visual and experimental processes; corresponding systems have been available for many applications for many years [3–6] (Fig. 1). The description of the surface integrity of hard fine machined workpieces is fundamentally more complex [7–9]. Process-oriented micromagnetic surface and subsurface analysis is increasingly successful using the Barkhausen-noise signal as the characteristic quantity [10–12].

2. Micromagnetic Sensor Systems

In this paper, the principles and measuring results using different micromagnetic sensor systems in industrial applications are presented. The paper concentrates on micromagnetic systems to characterise the surface integrity of hardened workpieces. As a further development of this technique, micromagnetic in-process measurement during the grinding process will be introduced for the first time. Based on the generation of Bloch

Correspondence and offprint requests to: Professor H. K. Tönshoff, Institute for Production Engineering and Machine Tools, University of Hannover, Schlosswender Str. 5, D-30159 Hannover, Germany. E-mail: toenshoff@mail.ifw.uni-hannover.de

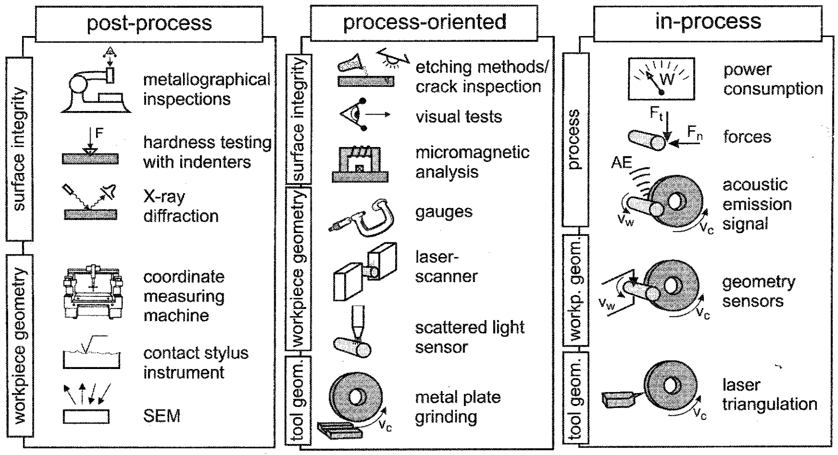

Fig. 1. Methods for quality control in grinding.

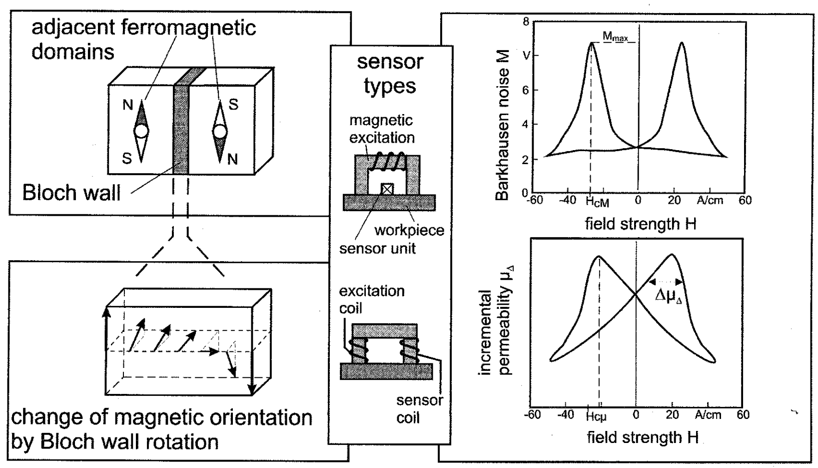

Fig. 2. Micromagnetic structure and measuring quantities.

wall motions in ferromagnetic materials, a Barkhausen-noise signal together with eddy current and micromagnetic quantities are investigated to describe the complex surface integrity after grinding. This technology can be installed as an in-process measuring system and can be used for process optimisation in grinding.

2.1 Micromagnetic Process-Oriented Measurement

Direct quality control of ground workpieces is possible with a micromagnetic analysing system. Based on the generation of Bloch wall motions in ferromagnetic materials a Barkhausen noise signal is investigated to describe the complex surface integrity after grinding [3]. White etching areas, annealing zones and tensile stresses can be separated by using different quantities. The measuring principle is based on the fact that the magnetic domain structure of ferromagnetic materials is influenced by residual stresses, hardness values and metallurgical parameters in subsurface zones. Adjacent ferromagnetic domains with different local magnetisation directions are separated by Bloch walls. An exciting magnetic field causes Bloch wall motions and rotations.

As a result, the total magnetisation of the workpiece is changing. Using a small coil of conductive wire at the surface of the workpiece, the change of the magnetisation owing to the Bloch wall movements can be registered as an electrical pulse (Fig. 2). This magnetisation is not a continuous process, rather the Bloch walls move in single sudden jumps. Barkhausen was the first to observe this phenomenon in 1919. The signal obtained by the addition of all movements is called Barkhausen noise.

The actual sensor hardware uses the parameters of Barkhausen noise and the field strength. The amplitude of the Barkhausen noise correlates to the residual stresses in the surface layers, and the coercivity to the workpiece hardness.

Figure 3 presents the results of the industrial application of this sensor system. With the increasing wear of the grinding wheel, owing to the increasing number of ground workpieces without changing the wheel, the energy in the zone of contact is significantly influenced. The increasing amount of heat penetration into the workpiece leads to an increase of residual stresses in the workpieces. The highest Barkhausen amplitudes are found for the highest workpiece numbers. All gears without thermal damage (detected by etching tests) lead to low Bark-

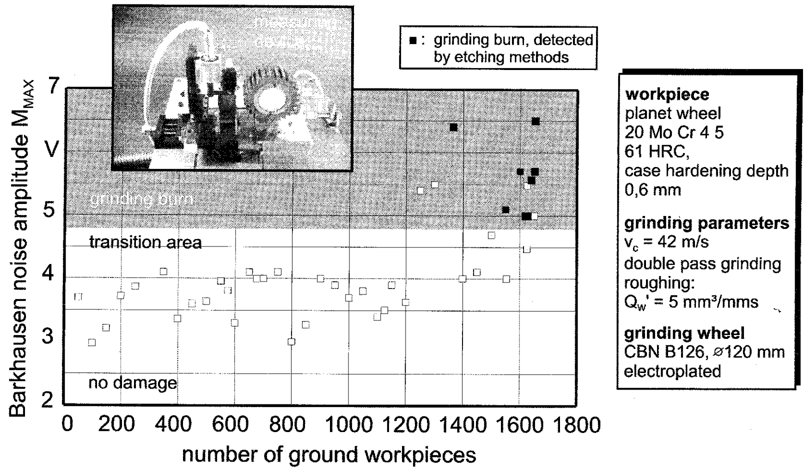

Fig. 3. Industrial application of the micromagnetic sensor system.

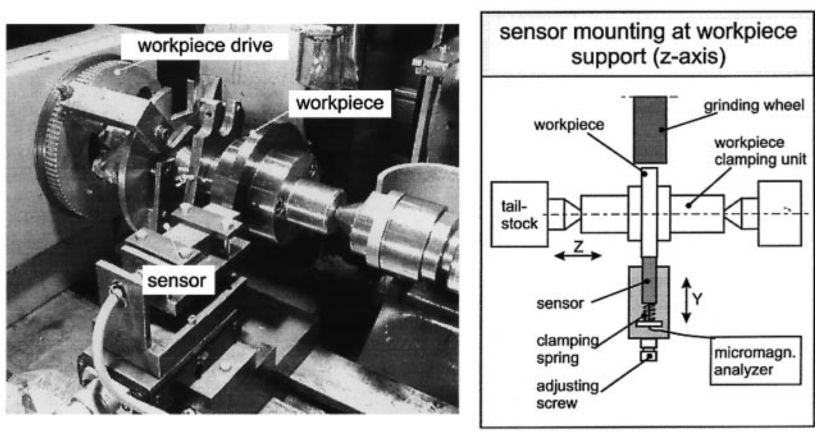

Fig. 4. Micromagnetic in-process measurement.

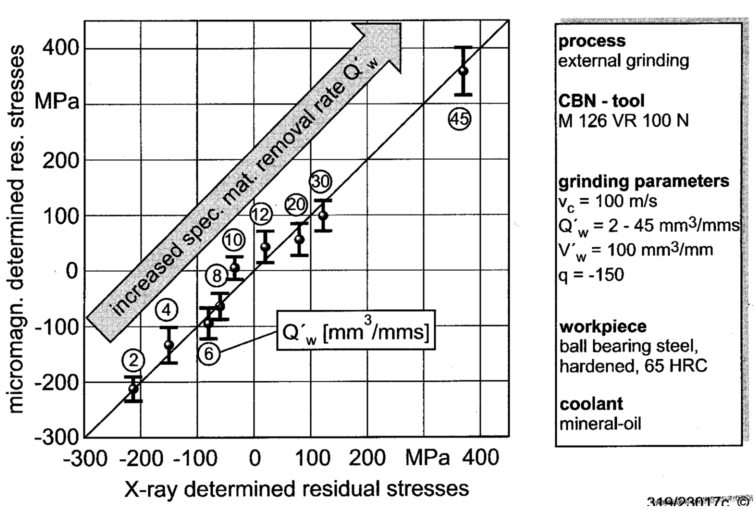

Fig. 5. Correlation of micormagnetic and X-ray determined residual stresses.

hausen amplitudes. In this investigation of the combination of grinding wheel and workpiece, a threshold of 4.3 V for the Barkhausen noise amplitude can be determined. If this threshold is not reached, thermal damage of the workpiece can be avoided. Between 4.3 and 4.7 V, a control limit can be defined. If the 4.7 V threshold is exceeded, the workpiece is undoubtedly thermally damaged and has to be rejected owing to high tensile residual stresses and likely structural changes. All workpieces which were classified as “thermally damaged” lead to high Barkhausen amplitudes. The high amplitudes occurred although the etching test did not reveal the damage.

This advantage of the Barkhausen system is caused by the depth of penetration because damage up to 20 μm beneath the surface can be detected. The etching test is limited to surface damage.

2.2 Micromagnetic In-Process Measurement

Recent investigations are concentrating on a multifrequency multisensor system to detect grinding burn, surface hardness and depth of hardness, continuously. This new system is based on an existing hardware which uses multifrequency eddy currents for non-destructive evaluation of hardness and depth of hardness. In addition, high-frequency Barkhausen noise and incremental permeability are integrated to detect grinding burn. Furthermore, a Hall probe is used to monitor the quality of measurement which is mainly influenced by the sensor to workpiece contact. The Hall probe enables the evaluation of the coercive strength and the distortion factor to be used for the detection of hardness and rehardening due to grinding burn. This multisensor system is of high efficiency for industrial use owing to its different characteristics which are independent from each other. This is quite important for extracting the effects of changes of heat treatment and the amount of austenite, on the signals. In the past, mostly these effects usually caused a failure of micromagnetic monitoring systems in production lines.

In the following sections, the first results of the application of this testing technique are shown. The testing technique was developed by *IFW* in collaboration with the *Fraunhofer Institut für Zerstörungsfreie Prüfverfahren*, Saarbrücken.

2.2.1 Description of the Method and Result of Micromagnetic In-Process Measurement

In grinding tests of cylindrical surfaces, workpieces consisting of ball bearing steel were ground with a vitrified CBN-grinding wheel. Hardened rings with a hardness of 65 HRC, a diameter of 150 mm and a breadth of 10 mm were used as test workpieces. The testing was aimed at the production of different surface integrity states by varying the specific material removal rate. With a cutting speed of above 100 $m\,s^{-1}$, the material removal rate was from $Q'_w = 2\ mm^3\ mms^{-1}$ to $Q'_w = 40\ mm^3\ mms^{-1}$. Apart from micromagnetic analyses, measurements of the residual stresses on the surface and below the surface were carried out on the workpieces ground in this way.

Figure 4 shows the sensing mechanism and the measuring arrangement. Figure 5 shows the results of the in-process measurement.

The sensor is mounted on a slide which is pressed against the workpiece resiliently and so is able to compensate for the reduction of the diameter during the machining process of the workpiece. It becomes obvious that the increase of the specific material removal rate first led to a reduction of the compressive stresses, and from $Q'_w = 12\ mm^3\ mms^{-1}$ tensile stresses were measured on the surface.

The micromagnetically determined residual stresses were produced from the twelve different measuring parameters of the sensor system by step-by-step regression. A square onset has been chosen which diminishes the number of the influencing variables by steps and, as a final result, determines a polynomial which only includes the most important, dominant values. From the residual stress which has been determined by X-ray measurement, the coefficients of the polynomial can be defined; the correlation is shown in Fig. 5.

For this reason, it is possible to evaluate the residual stress directly from the micromagnetic quantities which exists on the surface up to a correlation of 95%.

2.2.2 Advantages of Micromagnetic In-Process Measurement

This new method of examination enables the grinding process to be designed, adapted and optimised. In comparison with other methods of examination, the main advantage consists of the known relationship of the parameters used with the surface integrity of the ground workpiece. Therefore, the correlation relates to the main target of the fabrication which is faultlessly ground surface and consequently durability and functionality of the component.

As shown in Fig. 6, the machining costs are determined by the time which is needed for measuring and machining. In conventional machining, a component has an inspection before grinding and a final inspection after grinding. Manufacturing with in-process micromagnetic testing means that no additional time for measurement is needed, except for a sampling test for geometry. Furthermore, all important workpiece quality characteristics such as residual stresses (influenced by grinding burn), the hardness and the case depth can be determined while machining. This may lead in the near future to a dramatic reduction of measuring time. The estimated reduction of production costs is up to 20%.

3. Summary

Thermal damage in grinding has a great influence on the quality and thus on the reliability of heavy components. In the recent past, different sensor systems for the detection and avoidance of grinding burn have been developed. This paper describes two micromagnetic sensor concepts which have been investigated in the grinding of hardened steel.

A micromagnetic analysing system based on the Barkhausen noise effect can be used for monitoring ground workpieces. An increasing Barkhausen signal indicates increasing thermal damage of the workpiece. It is possible to determine control- and tolerance-limits for chosen tool/workpiece combinations.

Current research work is concentrating on a multisensor concept to detect grinding burn, surface hardness and depth of

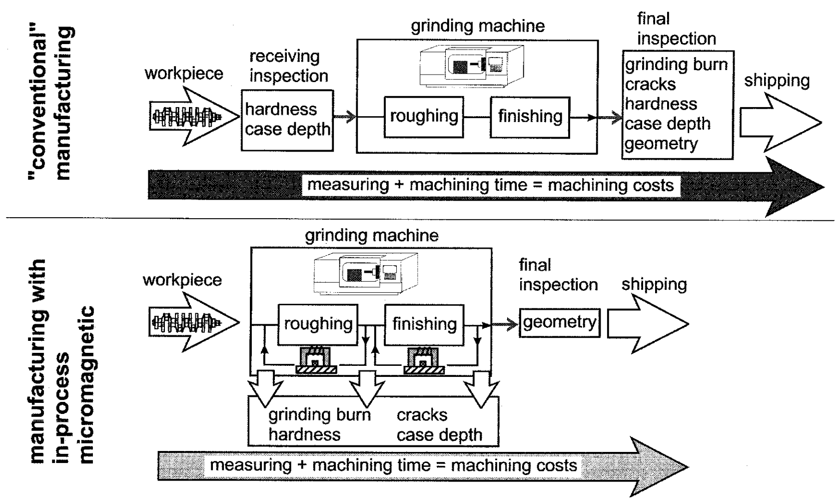

Fig. 6. Advantages of micromagnetic in-process measurement.

hardness continuously. By an effective suppression of disturbance variables, this concept enables the in-process use/application in the working area of the grinding machine. The measurement takes place during machining. A direct correlation between the X-ray measured residual stress and the micromagnetic parameter measurement results may be proved.

A polynomial can be determined by a regression account from which it is possible to evaluate the residual stresses in the surface by means of the micromagnetic parameters. In the future, new possibilities will result from this method, concerning the design, optimisation and control of the grinding processes.

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