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# *In-situ* magnetic inspection of the part fixture and the residual stress in micromilled hot-work tool steel

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ABSTRACT

A magnetic method for the *in-situ* inspection of the combined effects of both, clamping force (CF) and the distribution of the surface residual stress (RS) on a face milled workpiece are presented. FE simulations have been conducted and evaluated, illustrating the impact of clamping on the workpiece surface deflection and thus, the machining accuracy. Furthermore, magnetic Barkhausen noise (MBN) signals were acquired on a hot-work tool steel workpiece after three different milling procedures: Face milling, one pass of micro-milling and 38 passes of micro-milling. Finally, the MBN signal on the unclamped workpiece was obtained. The MBN signal energy $MBN_{energy}$ presented the highest values with the probe oriented in the pick (clamping) direction for all stages of milling process where the CF was applied. After unclamping the workpiece, the higher value of the $MBN_{energy}$ was obtained with the probe oriented in feed direction of the milling processes revealing the true effect of the RS. These results were in agreement with the literature and confirmed by numerical simulations and X-ray diffraction based residual stress measurements.

## 1. Introduction

The clamping force (CF) and the surface residual stresses (RS) are significant impact factors in milling processes [1,2]. The CF is in general applied to prevent workpiece motion, while workpiece deflection is relegated to a secondary place [2].

While clamping forces elastically deflects the workpiece [2], the cutting tool leave plastically deformed regions on milled surface, inducing an in-depth hook-like profile of RS which depends principally on the radial depth of cut, the feed, the cutting speed and the shear angle in the chip formation as the most influent cutting parameters [1,5]. Surface RS was measured at the surface and in several depths below the surface in a nondestructive manner after a calibration method using target values simultaneously like the hardness and the residual stress [3,4].

The *in-situ* monitoring of the manufacturing process promotes a fast diagnosing tool to assure part quality on shop floor. The magnetic Barkhausen noise (MBN) shows promise application to process monitoring [6–8].

On the other side, micro-milling of hardened steels is getting more attention from researchers as a potential method to replace electrical discharge machining (EDM) [9]. The main advantages are the higher material removal rate and better dimensional accuracy as well as a clearer understanding of the process itself. However, the industrial application of micro-milling is still dependent of more knowledge and understanding of several mechanisms involved in the process, such as tool wear and resulting surface quality. During machining of materials that are difficult to cut, the unpredictable tool life and premature failure may become a major issue since it raises manufacturing costs and results in lower-quality outputs [10–12].

For these reasons, investigations have been conducted involving *in-situ* inspection of the deflection of the hot-work tool steel workpiece due to clamping force and the behavior of the RS induced in the surface due to the micro-milling cutting process by determining the magnetic Barkhausen noise (MBN).

## 2. Experimental and simulation methodologies

The workpiece was a rectangular prism with a width of w = 42.55 mm, a length of l = 57.40 mm and a height of h = 10.70 mm. The workpiece material is a standard composition of an AISI type H13 hot-work tool steel (see Table 1).

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**Table 1**
Chemical composition of H13 tool steel.

| C | Si | Mn | Cr | Mo | V |
|---|---|---|---|---|---|
| 0.40 | 1.00 | 0.35 | 5.20 | 1.50 | 0.90 |

**Table 2**
Parameters of milling conditions.

| Stages | Tool diameter d [mm] | Feed rate f [mm/min] | Feed per tooth fz [μm] | Cutting depth ap [μm] |
|---|---|---|---|---|
| **S1**: Face milling | 8 | 96 | 20 | 100 |
| **S2**: One pass of micro-milling | 0.4 | 454.5 | 5 | 15 |
| **S3**: 38 passes of micro-milling | 0.4 | 454.5 | 5 | 15 |
| **S4**: Workpiece unclamped | The same as **S3** | | | |

The cutting experiments were conducted on the ultra-precision machining center KERN Evo, KERN Microtechnik Gmbh, Eschenlohe, Germany.

The milling procedures were divided into three stages. In the first stage, the workpiece was face milled with the objective to flatten the surface and prepare it for micro-milling. The second stage included a single pass of micro-milling at the center of the work piece using an end milling tool with a diameter of d = 0.4 mm. In the third stage, 19 passes of micro-milling were conducted at each side of the first pass. In a final stage the workpiece was unclamped. The parameters of the four stages are described in Table 2.

The characteristics of the milled and micromilled surfaces can be seen in Fig. 1. In that figure the directions of the clamping forces, the pick and feed directions as well as the micro-milled channels are highlighted.

### 2.1. Magnetic Barkhausen noise

Ferromagnetic materials present microscopically localized regions in which material behaves as a magnet. Those regions are called magnetic domains [13–15] and its size, distribution and border (domain wall) characteristics arise from the minimization of the total magnetic energy [13–15]. Those domains and domains walls are influenced by material microstructure and its states of stress. When an alternated magnetic field is applied to the material, the domain walls move lowering the total magnetic energy of the system, then in this movement the domain walls interact with defects and stress fields producing the Barkhausen noise signal. This signal can be properly measured with a coil placed at the surface of the sample and between the poles of the electromagnet [13–15], as shown in Fig. 2.

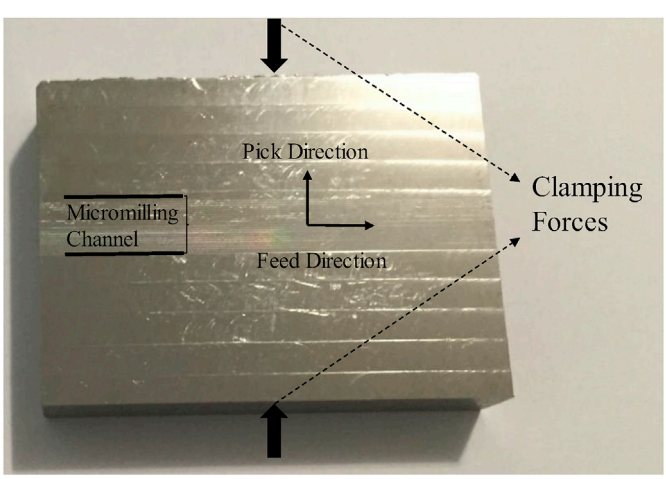


**Fig. 1.** Milled piece with the micromilled channel highlighted.

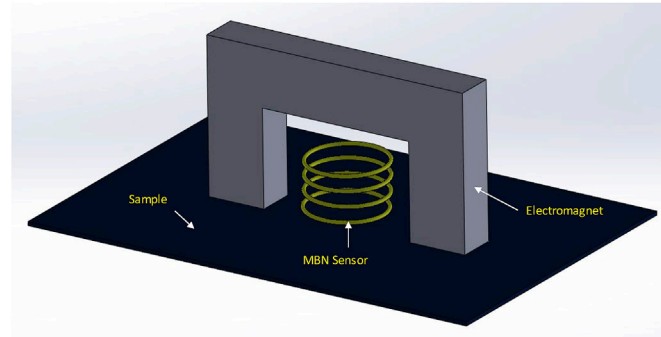


**Fig. 2.** Simplified layout of a MBN probe.

Magnetic Barkhausen noise and stress were investigated in steel, the increase of compressive stress shows a decrease on MBN signal, however increasing tensile stress increases the MBN signal [16].

3MA is an acronym for Micromagnetic, Multiparameter, Microstructure and stress Analysis. This approach combines different micro- and electromagnetic measuring quantities and uses regression analyses or pattern recognition algorithms for the quantitative determination of material properties. For example, the 3MA approach was used for a successful *in-situ* monitoring of the grinding process. A further application of this methodology is the online determination of yield strength and parameters characterizing the deep drawing process of cold rolled steel strips [4,17,18].

These Barkhausen signals were acquired with the professional equipment Rollscan-250, American Stresstech Technologies, Inc., Pittsburgh, USA, as can be seen in Fig. 3. The frequency of the alternated magnetic field applied determines the depth of penetration into the material of the magnetic field and influences the attenuation of MBN [7]. For the tests an alternated magnetic field with a frequency f = 10 Hz and a voltage of U = 1.2 V was used.

The MBN signals were acquired at the sampling frequency fs = 250 kHz with a resolution of 16 bits using the data acquisition system NI-sbRIO- 9632, National Instruments Corporation, Austin, USA. At each point, a total of 20 MBN signals were acquired with the purpose of eliminating fluctuation. The value analysed was the MBN signal energy $MBN_{energy}$ was measured on the workpiece in feed and perpendicular to

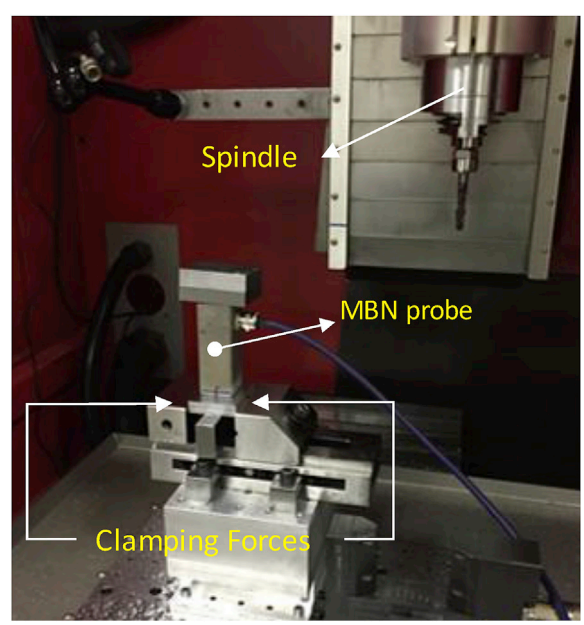


**Fig. 3.** *In-situ* magnetic inspection of the part fixture.

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