Mechanical surface modification using cutting inserts

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Introduction

Mechanical surface modification processes are applied to create highly functional workpiece surface layer states. The possible surface layer states may render superb resistance against wear and fretting, which can hardly be ensured with the same material by other manufacturing processes. A wide range of different mechanical surface modification processes exist [1]. These are generally sorted by tool type and tool contact situation. The two main groups are those with guided and those with unguided tools. The processes using guided tools are separated in those with continuous and those with periodic contacts. In this work, a new process is presented with a guided tool and periodic contact. Similar processes will be the focus of the following brief technological description.

Mechanical surface modification processes with guided tools and periodic contacts are part of the group of processes denominated “Machine Hammer Peening” (MHP) [1]. Hammer peening processes use a ball- or pin-shaped tool to apply plastic deformation to the surface layer of the workpiece, thus changing surface layer states to increase workpiece performance [1]. MHP-processes with periodic contacts are realized with different commercially available systems. These systems can be classified by their force generating system. Pneumatic processes (P-MHP) use pneumatics to generate the necessary impulse for mechanical surface modification [2]. Sonotrode and direct sonotrode driven systems are the most numerous in type [1]. One example is the Ultrasonic Impact Treatment (UIT) devolved by [3], which can be both, sonotrode and direct sonotrode driven [1]. Electromagnetic Machine Hammer Peening (MHP) uses the Lorenz force induced by a fluctuating electrical current to create the necessary kinematic and associated forces [4]. The relatively new Piezopeening [5] offers high flexibility of process parameters (within limits regarding hammer frequency and stroke) through piezoelectric actuators. The resulting beneficial surface layer states include the surface roughness [6], work hardening of the surface layer [7], and induction of compressive residual stresses [8].

Currently most methods for mechanical surface modification like burnishing or machine hammer peening (MHP) of high performance components entail an additional step for the process chain. While there are a number of attempts to shorten process times through hybrid processes (like [9] [10]), a true integration of surface modification into machining operations has not been attempted yet.

Objectives

In this work the foundation of a true integration of mechanical surface modification and machining by dual use of the cutting insert as tool for the cutting and the hammering process is presented. This fusion of processes would require a rapid movement of the cutting insert performing a hammering motion without inhibiting the cutting process. Although it may seem, that something similar can be achieved through classical vibration assisted machining (VAM), this is definitely not the case. Approaches to include a tool movement perpendicular to the workpiece surface and direction of cut into vibration assisted machining lead to an elliptical motion of the cutting insert. This motion proved to be beneficial for the machining process [11] and can be used for surface texturing [12]. But the effective relative velocity between cutting insert and workpiece ensures the process to be firmly rooted in cutting rather than hammering of the workpiece. Since creating a setup suitable to address this issue is a big challenge it is prudent to begin by establishing the general feasibility of the process. The first priority is therefore proving that cutting inserts can be used to induce surface layer states similar to those achieved by MHP-processes. The presented work addresses this validation of mechanical surface treatment using cutting inserts regarding topography, residual stresses and work hardening through an experimental analogy.

Methodology

A correspondence experiment for surface modification by hammering with cutting inserts was set up on a high precision 5-axis micro-milling machine from Kugler GmbH. The kinematics were implemented in CNC code analogous to an idealized hammering motion (not meandering, but in straight lines) using the machines µm-accuracy and the fastest speed of the linear axes. The surface modification was executed line-by-line applying each setup to an area of 10x10 mm. Cutting inserts type P8TN-6028833 WKM by Walter Tools were used on a regular tool-holder (one tool edge for each experiment). These cutting inserts feature a nose radius of 0.4 mm and a cutting edge radius of 40 µm. Flat specimens (4x20x80 mm) of AISI 4140QT were clamped magnetically and face milled directly before applying the surface modification. Face milling was conducted with the same parameters for all specimens in order to ensure comparable initial surface states.

When comparing different MHP processes, the process parameters have to be considered carefully. The parameters for the experiments conducted for this work were calculated in analogy to an existing comparison of MHP processes to ensure comparability [13]. The overlap of indentation is critical for the resulting surface layer states, thus it is necessary to calculate similar overlaps when using different tool geometries like cutting inserts. Overlap can be calculated using the area (or diameter) of indentation, stepover distance and distance of indentation as per Fig. 1. (left). While this calculation is rather simple, the resulting overlap is dependent on the direction of analysis (transverse or longitudinal to the line of work) as is demonstrated in Fig. 2. (right). The direction dependent parameter is not suitable for a comparison of processes considering the effective total overlap on a hammered surface. To compare process results for the whole surface, the spatial overlap is better albeit more complicated to calculate. The non-spherical volume of displaced material by a cutting insert further complicates this matter. Therefore, the process parameters were chosen considering transverse and longitudinal percentage overlap as per Table 1.

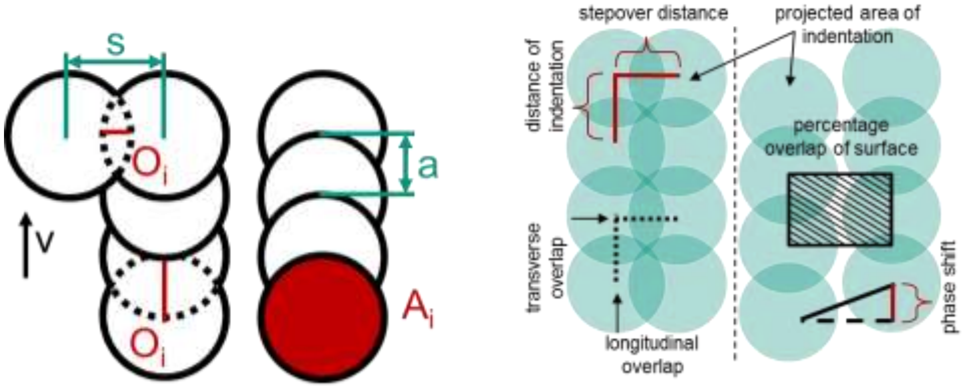

Figure 1: left: overlap of indentation O_i, projected area of indentation A_i, distance of indentation a, and stepover distance s; right: clarification of the difference between transverse, longitudinal, and percentage overlap.

Table 1: Experimental process parameters for experiments on the micro-milling machine.

Exp.	Stroke h in mm	Stepover distance s in µm	Distance of indentation a in µm	Overlap (longitudinal) $O_{i\%,long}$ in %	Overlap (transverse $O_{i\%,trans}$ in %
1	0,02	4,8	12	598	1443
2	0,02	4,8	3,9	1796	1443
3	0,02	0,8	8	848	8660
4	0,02	48	69	100	144
5	0,04	48	80	100	144
6	0,02	48	93	75	144
7	0,02	48	138	50	144
8	0,02	48	276	25	144

Parameters for experiments 1 to 3 correspond to the reference parameter set for piezo peening while the tool radius of the cutting insert is significantly smaller (40 µm) than the spherical piezo peening tool (8 mm). A small radius leads to very small stepover distances when aiming for the same overlap. Small stepover distances are a challenge to realize in a productive machining operation as feed needs to be very low or frequency very high. A stepover distance of 48 µm was chosen for experiments 4 to 8. Experiments 4 and 5 feature different strokes with the same resulting overlap. Since the overlap is dependent on the area of indentation, this results in larger distance of indentation for experiment 5. To analyze the possibility to apply specific surface topographies, experiments 6 to 8 featured longitudinal overlaps smaller than 100%. All experiments were set up without phase shifts between two lines indentations.

The resulting topographies were analyzed optically with a confocal light microscope type Nanofocus µsurf. Subsequently the roughness R_z was taken transverse and longitudinal to the feed direction. Whenever possible the profiles were put into valleys and not across single outliers. Furthermore, the specimens were analyzed for transversal and longitudinal residual stresses as well as work hardening (full width at half maximum, FWHM).

Results and analysis

The optical analysis of the resulting topographies is shown in Fig. 2 for all experiments. Three distinct surface orientations can be observed: orientation in working direction (see Fig.2: 1 and 2), orientation orthogonal to the working direction (see Fig.2: 4 to 8), and no dominant orientation in the case of experiment 3 with an extreme transversal overlap (see Fig.2: 3). It is notable, that the resulting surfaces of experiments 1 and 2 are both oriented in the working direction, even though the relation of transverse and longitudinal overlap is different. The different strokes of experiments 4 (20 µm) and 5 (40 µm) clearly influence the cleanliness of the resulting surface. A larger stroke (experiment 5) leads to a higher number of adhering material particles on the surface and a less uniform surface in total. With decreasing longitudinal overlap (experiments 6 to 8), the left over original surface increases, until the milled surface is clearly visible between rows of indentations (experiment 8).

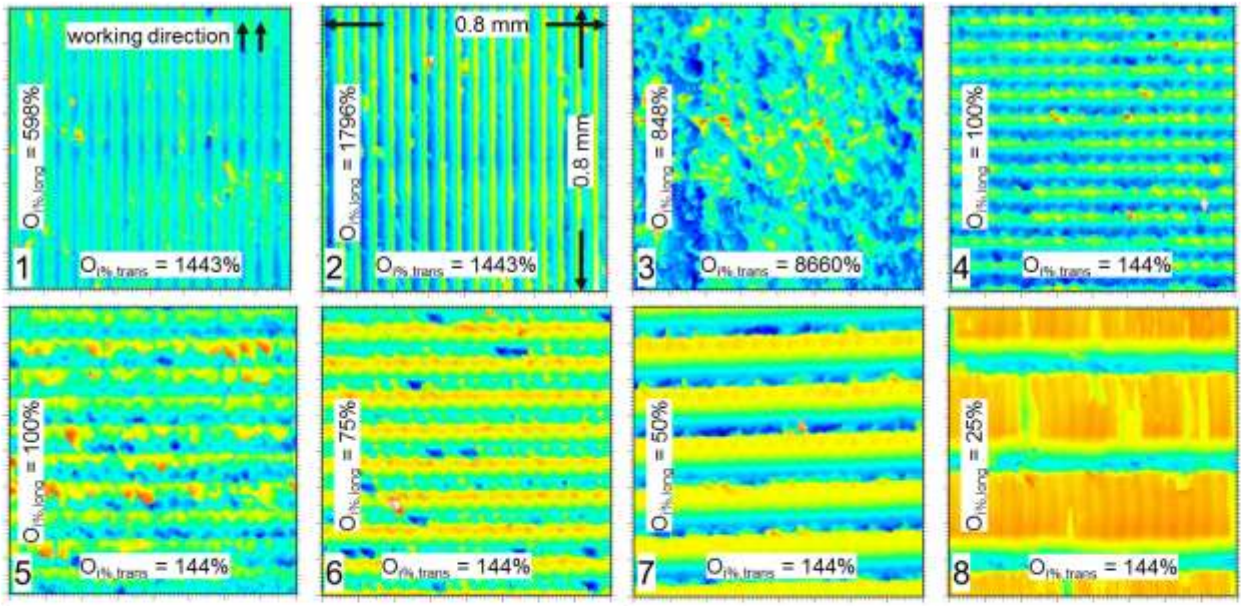

Figure 2: Topography of all specimens with corresponding transverse and longitudinal overlap.

The analyses of the resulting roughness R_z are shown in Fig.3 (left) for all experiments in transverse and longitudinal direction as well as the micro-milled reference surface. Most specimens show a reduced roughness after surface modification by the cutting insert. This is especially true for the transverse direction measured in the valley of indentation. Usual surface roughness after mechanical surface treatments falls into the range of R_z 9.5 µm down to 0.5 µm [13]. Tasked with creating samples of minimal surface roughness other MHP processes achieve a roughness of 2 µm and below. The resulting roughness of surface modification using a cutting insert is therefore within the range of conventional MHP processes, albeit with a higher residual roughness – probably due to the small tool radius. Fig. 3 middle and right shows the profile of specimen 8 as an example. The depth of the indentations after relaxation is 10 µm, about half of the stroke.

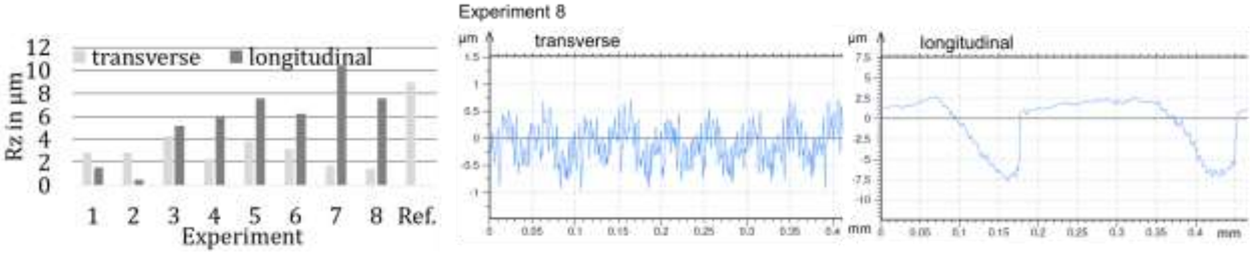

Figure 3: left: Resulting roughness Rz transverse and longitudinal for all specimens and the reference; middle and right: transverse and longitudinal profile of experiment 8.

Specimens from experiments 4 to 8 were analyzed regarding work hardening and residual stresses. Experiments 1 to 3 were not considered, as the parameters used are not feasible for machining operations. Fig. 4 shows residual stresses of the measured surfaces in longitudinal and transverse direction, including the reference surface. The reference (0 ± 4 MPa) was measured in 200 µm depth to avoid measuring the residual stresses from the micro-milling process. A total of three measurements per specimen were conducted to secure the results.

The results show compressive stress states for all specimens. The magnitude of these stresses is quite similar for all samples regardless of overlap and stroke. A comparison with regular MHP processes (e.g. results published in [13]) shows, that surface modification with cutting inserts produces viable compressive residual stresses.

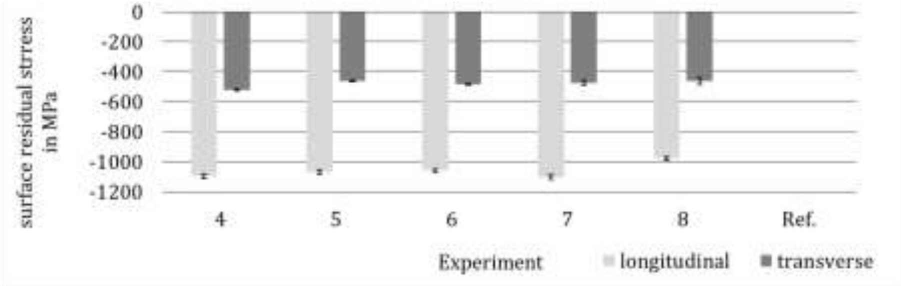

Figure 4: Change in surface residual stresses after experiments 4 to 8 compared to the reference.

Work hardening of the material was measured by X-ray diffraction (FWHM) as shown in Fig. 5. The applied surface modification resulted in a uniform increase of FWHM from 2.76° (Reference) to between 4.40° and 4.88° both transverse and longitudinal. This reflects a significant work hardening of the specimen's surface.

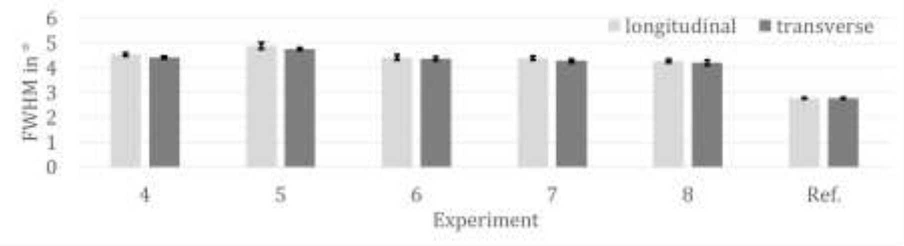

Figure 5: Change in FWHM after experiments 4 to 8 compared to the reference.

Conclusions

In this work, mechanical surface modification of AISI4140QT was conducted using cutting inserts. While the resulting topography is not quite on par with that of conventional MHP processes, work hardening and residual stress states of the surface are comparable to conventional MHP processes. The process parameters of the experiments conducted lead to uniform values thus potentially allowing a decrease of stroke while still creating relevant results. It can be concluded, that mechanical surface modification through hammering with cutting inserts is a viable way to enhance surface layer states of steels.

Further work may now focus on more detailed analyses of sensitivity of process parameters and finding an ideal cutting insert and cutting edge geometry for surface modification. Furthermore, an experimental setup able to realize necessary kinematics for integration of the surface modification process into machining operations needs to be developed. Afterwards, an examination of the potential productivity and profitability of industrial usage is paramount.

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