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Generation of functional surfaces by using a simulation tool for surface prediction and micro structuring of cold-working steel with ultrasonic vibration assisted face milling

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ABSTRACT

The industrial production of technical systems is characterized by increasing demands on performance sustainability, resource efficiency and manufacturing costs. As a result, surfaces with special properties become more important. Therefore, their functionalisation is subject of many fields of research. Typical application ranges are improving haptics, the generation of optical effects or the reduction of friction in mechanical as well as fluidic systems. Furthermore, functional surfaces can contribute to an increase of the adhesive strength of coatings and coating systems, respectively. This can extend the implementation possibilities for the substrate material. Due to its defined cutting edge geometry and kinematics, the ultrasonic vibration assisted milling (UVAM) represents a suitable method for a reproducible generation of a defined micro structure. Accordingly, an ultrasonic vibration system was implemented in a high precision machining centre and initial experimental investigations were carried out. Moreover, a surface simulation tool was developed and used for the structure design and modelling, which predicts a virtual micro structure using the relevant parameters. In the first tests, a high degree of conformity with the machined surfaces could already be achieved. Thus, a possibility for economic micro structuring of components made of steel was developed.

1. Introduction

The combination of machining processes and (ultrasonic) vibrations is still subject of different researches. In case of ultrasonic vibration assistance typically resonant systems with a frequency of about 20 kHz are applied. Using this type of system higher working outputs are achieved with a reduced energy input. Resonance occurs when the chosen excitation frequency is matched with an eigenfrequency of the system. Most of the existing ultrasonic systems use piezoelectric actuators to excite the system. The actuator's eigenfrequency is influenced by the system's mass, the stiffness and the damping behaviour. In the case of resonance, the amplitude is depending on the damping behaviour.

There are some industrial applications for vibration assisted machining. Usually, the goal is to reduce the cutting force or increase the tool life, respectively. In addition, a decrease of the surface roughness value is often intended as Brehl and Dow already summarize in the analysis of different vibration superimposed machining processes (Brehl and Dow, 2008). Very few researcher address a micro structuring of the workpiece surfaces by a superimposed oscillating motion. Guo and Ehmann used elliptical ultrasonic vibration assisted turning for the generation of micro structures in aluminium and copper through a variation of the feed and the cutting direction (Guo and Ehmann, 2013). Using a superimposed oscillation motion in the sub-ultrasonic range (with a frequency of approx. 3 kHz), Zhu et al. (2016) connected a slow-tool-servo (STS) with a fly-cutting tool and generated micro as well as nano structures in brass with diamond tools.

However, with regard to the ratio of the machining parameters as well as the vibration parameters and the tool geometry, respectively, there are some possibilities for a reproducible surface micro structuring processes. For example, such surfaces may contribute to ensuring a sufficient adhesion strength of CVD diamond layers on steel. A specific aim within this is the reduction of residual stresses within the diamond layer, as well as the reinforcement of mechanical interlocking and the chemical bonding activities.

At Chemnitz University of Technology, ultrasonic vibration assisted

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Nomenclature

Symbol

a_e	Width of cut (mm)
a_p	Depth of cut (µm)
A_P	Mathematical amplitude: “only peak “(µm)
A_{US}	Ultrasonic amplitude: peak-to-peak (AUS = 2·AP) (µm)
D_{tool}	Tool diameter (mm)
f_{sim}	Sampling rate (s^{-1})
f_{US}	Ultrasonic frequency (kHz)
f_z	Feed per tooth (µm)
g	Dexel in the tool coordinate system (-)
h	Dexel in the workpiece coordinate system (-)
i	Multiple of the minimum temporal resolution (-)
n_{tool}	Spindle speed (min^{-1})
N	Number of intersections per period (-)
P	Material ratio (%)
P	Path vector (-)
Sa	Arithmetic mean height (µm)
Sdr	Developed interfacial area ratio (%)
Sk	Core roughness depth (µm)
Spk	Reduced peak height (µm)
Str	Texture aspect ratio (%)
Svk	Reduced valley depth (µm)
Sz	Maximum height (µm)
t_{sim}	Minimal temporal resolution (s)
v_c	Cutting speed (m/min)
v_f	Feed (mm/min)
v_{US}	Maximum speed of the oscillation (m/min)
Vm	Material volume ($µm^3/µm^2$)
z	Number of teeth (-)
α	Clearance angle (1°)
λ	Wavelength of the oscillation (µm)
ϕ_p	Rotatory angular displacement (rad)

turning has been investigated for different applications to generate various surface micro structures. While Nestler and Schubert investigated the effect of different directions of the ultrasonic vibration motion on the surface parameters at external turning experiments (Nestler and Schubert, 2014), Zhang et al. (2014) used the same ultrasonic vibration assistance system for the micro structuring of the specimen's flat surface with face turning by the variation of the process parameters.

Denkena investigated the use of vibration-assisted machining for the production of micro structures for in-process information storage. On the one hand, turning experiments with a highly dynamic piezo-driven tool holder with a natural frequency of 6 kHz were carried out. In connection to the sinusoidal tool motion perpendicular to the workpiece the depth of cut changed periodically in cutting speed direction and therefore left different micro grooves with a data density of 4 kBit/cm^2 on the machined surface (Denkena et al., 2010). On the other hand, a conventional milling tool equipped with a piezo-driven fast tool servo system to superimpose the face milling operation with a high dynamic movement along the rotatory axis. This enabled the in-process generation of Data-Matrix-Codes (DMC) without any additional machining steps (Denkena et al., 2016). Commercially available systems that enable ultrasonic vibration assisted machining are offered by SAUER GmbH of the DMG-MORI Group as well as by SCHOTT-Diamantwerkzeuge. The main application is grinding of brittle-hard materials such as glass or ceramics, which is often described as ultrasonic assisted milling. Gong et al. (2010) found that the tool wear is much lower when using rotary ultrasonic milling (RUM) of hard and brittle materials (aluminium ceramics and optical glass) compared to a conventional strategy. In contrast, Kuo and Tsao. (2012) found an increase in tool wear as well as surface roughness in a similar experimental design. Also El-Taybany et al. (2017). did not determine positive effects of the RUM during its application, but even an increase of the processing force in the axial directio. However, the value of the maximum torque was reduced compared to an application without RUM. Although the process is named milling, they all used cylindrical hollow grinding tools with diamond grits.

There are only a few research results with respect to milling, especially face milling, with ultrasonic vibration assistance according to (Lauwers et al., (2014)). The complexity of the superimposed motion as a function of the required workpiece surface is one of the main reasons. However, various research approaches exist in this field, mainly considering a superimposition of the oscillation in the feed direction and / or the cutting direction. A one-directional vibration excitation can be used depending on the process parameters both for decreasing (Ko et al., 2011) and increasing of the surface roughness values (Shen et al., 2011). The generation of predefined micro structures (“squamous surface”) was carried out from Tao et al. (2016). They used the ultrasonic vibration excitation of the workpiece in the direction of the feed during face milling and concluded, that the most significant influences on ultrasonic vibration assisted milling surface textures are the feed, the parameters of the ultrasonic vibration and the ratio of the vibration frequency and the spindle speed. Shen and Tao used a peripheral milling process to generate micro scaled as well as micro furrowed textures on the specimen's surface by an one-directional vibration excitation perpendicular to the feed direction and also the workpiece axis of the workpiece (Shen and Tao, 2015). This was realised by a variation of the spindle speed as well as the feed.

A two-directional excitation with a vibration superimposition of the milling process in the feed and the cutting direction serves mainly for a reduction of cutting forces, to increase tool life and thus also to reduce surface roughness values. As shown from Ding et al., (2010b), the vibration superimposition of the workpiece in a micro milling process of hardened tool steel leads to a lower surface roughness and less tool wear. The best results were achieved with the highest amplitudes (3 µm) and frequencies (3 kHz) compared to a conventional micro milling process. Moreover, in the micro milling of glass Jin and Xie (2015) obtained an improvement of the surface quality (decreased surface roughness) with the vibration superimposition in the feed and the cutting direction. They found that the oscillation in normal direction as well as high frequencies (up to 11 kHz) are mostly responsible for decreasing the surface roughness.

The superposition of vibrations in the direction of the tool axis during milling has an influence on surface structure formation and is described for example from Maurotto and Wickramarachchi (Maurotto and Wickramarachchi, 2016). The results of the investigations show that a change in the surface roughness can be achieved by the variation of the machining parameters as well as the vibration parameters. Furthermore, they concluded that due to the symptomatic tool wear it is necessary to develop tools as well as coatings for the application of (ultrasonic) vibration assisted milling processes. Kuruc et al. (2014) demonstrated the dependance of the surface roughness on the ratio between a constant ultrasonic frequency and the spindle speed in a micro milling process of an aluminium alloy. Different superposition effects (interferences) can occur which have a high influence on the surface characteristics and cannot be fully explained yet. In addition, experimental investigations using a multi-edged milling tool were carried out. They further intensified such effects by using cutting geometries which differ from each other.

It is shown that vibration assisted machining processes enable the generation of predefined surface micro structures. However, due to its