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Intelligent tools for predictive process control

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Abstract

In complex machining processes which require long processing times, e.g. incorporating hardened or difficult to cut materials, free form surface shapes of the workpieces, such as milling of dies and molds, the avoidance of critical tool and process conditions is essential with respect to the quality of the final part and the efficiency of manufacturing. The progress of tool wear leads to changing cutting conditions, process forces and vibrations which affect the workpiece surface quality. On the other hand, tool vibrations due to varying engagement scenarios and process parameters close to the stability limits provoke an accelerated tool wear behavior.

This paper first introduces comprehensive experimental studies regarding the relationship between tool wear progress and tool vibrations during milling. The investigations focus on long and slender ball nose milling cutters which are usually applied in die and mold manufacturing within semi-finishing and finishing process steps. An automated analysis setup was developed which allows recording the tool wear progress and milling behavior with a very high resolution. With respect to process simulations involving the tool wear state, a detailed database is provided by these experiments. Secondly, the paper presents a new approach for a sensor integrated long and slender ball nose milling tool which detects the process vibrations close to the cutting zone. By combination of the experimental data and the sensory tool, predictive process control strategies can be implemented in order to avoid critical wear and vibrations situations.

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Keywords: Tool wear progress; Tool vibrations; Intelligent Tools

1. Introduction

In milling operations of complex parts, tool vibrations and instable process conditions occur due to the typically low dynamic stiffness and damping of the long-cantilevered and slender tools which are necessary to reach deep holes and cavities without collision [1-3]. Such tool vibrations lead to chatter marks or waviness on the workpiece surfaces, increased tool loads and accelerated tool wear. Progressed tool wear also affects the machined surface and finally tool breakage can occur, which severely damages the workpieces. Vice versa, the tool wear has a significant effect on the dynamic behavior of the engaged milling tools [4]. These effects exemplarily occur in machining of dies and molds, of components for energy turbines and of additively manufactured parts. Surface defects or damages are inacceptable for the functional behavior and quality of products in these market sectors. Critical tool vibrations have to be avoided by an appropriate tool and process layout [5] or immediately identified by monitoring systems during the running process [6-11] to allow an interruption, tool change or adaptation of process parameters, like spindle speed and feed rate [12-15]. Thus, advanced process-layout and optimization methods, adapted tool properties as well as powerful process monitoring and adaptive control systems constitute essential means for the enhancement of the machining performance, reliability and efficiency [16-18].

Within the research project "DynaTool", research partners from Germany (ISF/TU Dortmund; GFE Schmalkalden; IFQ/OvGU Magdeburg), Austria (IFT/TU Vienna) and Belgium (KU Leuven) cooperate intensively, in order to achieve solutions which help to overcome the afore

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mentioned challenges. This paper presents first results obtained at the IFQ, dealing with semi-finishing and finishing milling processes as applied in die and mold manufacturing.

A first goal of the research work is to identify and, if possible, to quantify correlations between the progress of tool wear, process forces and tool vibrations. Such correlations can subsequently be used for simulation purposes, tool and process layout, and sophisticated process monitoring and adaptive control strategies. A second goal is the development of a sensor equipped intelligent tool, which allows measuring of tool vibrations with a maximum sensitivity regarding tool wear states and process conditions.

2. Experimental analysis of tool wear and tool vibrations

In a first step, an experimental test setup was realized which allows investigations on tool wear development, related tool vibrations and process forces during milling. Long an slender milling tools were analyzed by use of this test setup. These tools tend to vibrate due to excitations by the process forces and because of their relatively high dynamic compliance. In machining of free form surfaces, different engagement situations occur along the tool path, which lead to varying process force distributions and excitation directions. Here, defined and constant inclination angles between tool axis and workpiece surface were applied.

2.1. Setup of test processes

The applied process setup involves a copy milling cutter with an overall length of 120 mm and a shaft diameter of 12 mm. Different cutting inserts can be installed and clamped by a locking screw. A ball nose cutting insert (PVD TiAlN-coated carbide) with a diameter of 12 mm, a width of 2,5 mm and two cutting edges was used here. The milling tests were carried out at a five-axis machining center DMG HSC55 linear. The two-axis rotary table of this machine was used to apply defined engagement angles between the tool axis and the flat workpiece surface (Fig. 1).

Fig. 1. Setup of test process (here inclination angle α = 45°)

The workpiece material was steel 1.2379 (X153CrMoV12) with a tensile strength of 860 N/mm² and a hardness of 255 HB. Horizontal straight milling tool paths (x-direction) were applied and distributed about the workpiece so that the material is cut in layers maintaining the cutting conditions during a long term test run. The milling parameters were chosen to $n = 5{,}300\ min^{-1}$, $v_f = 2{,}380$ mm/min, $a_e = 0.2$ mm and $a_p = 0.5$ mm; they are subject to variation in future tests. For machining one complete workpiece surface layer, 330 tool paths had to be conducted.

2.2. Setup for automated process and tool analysis

In order to provide measuring data with a high resolution, e.g. for further use as a data base for process simulations and development of monitoring strategies, an automated measuring setup was developed. In terms of measuring the progress of the tool wear, 'high resolution' means recording tool wear data frequently after relatively short tool path sections; e.g. after each straight path across the workpiece surface leading to 330 tool wear measurements for each machining layer. This requires an automated measuring procedure and an approach which allows wear measuring of the clamped tool at the milling spindle within the workspace of the machine. For this, a measuring CMOS camera (type BASLER acA4600-10uc) with 4,608 x 3,288 pixels was installed at the machine table (Fig. 2). Taking high resolution digital photographs by the camera is triggered by use of a light barrier which detects the milling tool when it enters the measuring position above the camera.

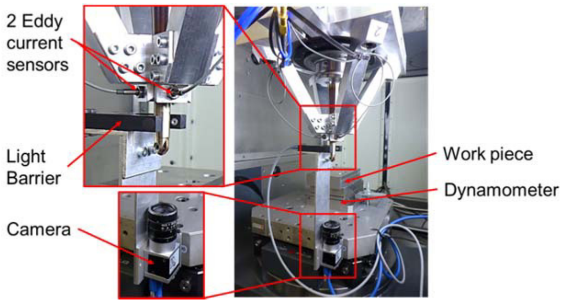

Fig. 2. Setup for measuring tool wear, tool vibrations and process forces

In addition to the tool wear progress, the process forces and the tool vibrations were measured by the realized test setup. For measuring process forces, a KISTLER dynamometer (type 9257a) was used. In order to allow measurements of tool vibrations during the milling process, two eddy current sensors (MicroEpsilon eddyNCDT 3100 EPS08) were installed at the spindle with a special mounting device (Fig. 2). Thus tool shaft vibrations can be recorded close to the tool tip.

For assessing the bandwidth and frequency response of the eddy current sensor (ECS) setup, a comparative analysis was carried out using a hammer excitation and applying a reference 3 axis acceleration sensor (Fig. 3). Since the cutting insert and the reference sensor have quite similar masses (4.29 g compared to 3.94 g), the influence of the mass of the additional acceleration sensor at the tool shaft can be reduced by dismounting the cutting insert.