PERFORMANCE AND LIMITS OF HIGH-DYNAMIC MILLING PROCESSES BASED ON TROCHOIDAL TOOL PATHS

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ABSTRACT: The application of trochoidal or wave milling strategies, with important variables such as machining strategy, cutting tool, workpiece material und machine tool were investigated and the process behavior assessed. Machine tool capability of realizing these highly dynamic processes was of particular interest. For this purpose, experiments with the methods of static and dynamic wave milling were carried out on machine tools using different drive concepts. The experiments used steel- and aluminium-based workpiece materials, as well as different tool diameters, and were monitored by a wide range of measurement instrumentation. It was shown that the critical factor is the dynamic behavior of the machine tool, with the permissible jerk of the axes being the most relevant parameter. The use of dynamic wave milling strategies led to significant deviations from the process time calculated by the CAD/CAM system. Nevertheless, the application of dynamic wave milling delivered advantages regarding the amount and uniformity of the tool load, chip formation and the quality of the workpiece surface. Static wave milling revealed advantages regarding the real machining time. Based on these results, approaches for further research are recommended and potential practical applications discussed.

KEY WORDS: milling, tool, parameter, trochoidal, chips

1 INTRODUCTION

The high degrees of freedom for tool paths and cutting tool design permit a wide range of different machining milling strategies. One such modern milling strategy is the so-called trochoidal, or wave milling using solid carbide end mills. The use of sophisticated CAD/CAM-systems to generate complex tool paths results in commonly reported benefits such as high material removal rates, significant reduced tool wear and improved workpiece surfaces (Djurica et al., 2015, Wu et al., 2016).

2 DYNAMIC MILLING STRATEGIES

In conventional milling processes, tool diameter is chosen to match slot width, which in turn means large slots require equivalently large, and invariably expensive, cutting tools. The high contact width and a contact arc of 180° means cutting speeds and feed rates usually need to be low. Nevertheless, this strategy is often associated with high cutting and machine tool loads, lengthy machining and reduced workpiece surface quality caused by chatter marks (Kalveram, 2006). Trochoidal or wave milling strategies take a different approach and can be divided into 'static' and 'dynamic' machining processes.

Contrary to conventional milling strategies both use tool width significantly smaller than the planned slot width, and an overlapping circular feed path as opposed to the linear feed path used in conventional milling (Figure 1).

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In static trochoidal milling, the form of tool path is cycloid. The diameter of the circular tool path is determined by the diameter of the tool and the desired slot width. The distance between successive paths corresponds to the maximum contact width. The basic advantage of this machining strategy is a significant reduction in the the thermal and mechanical load at cutting edge of the tool,allowing higher depths of cut and cutting speeds. In addition, static trochoidal milling allows increased feed velocities and metal removal rates.

In dynamic trochoidal milling strategies the tool path is spiral or lenticular, where the period between successive passes is equivalent to the maximum tool feed rate. In addition to tool path shape, dynamic milling strategies use a feed rate continuously adapted to the actual contact width, thereby keeping the mechanical load at the cutting edge as stable as possible and mean chip thickness near constant. Material-specific maximal permissible contact width and engagement angles are important factors for thermal load at the cutting edge. In practice, powerful CAD/CAM software programming is used to calculate dynamic trochoidal tool paths, factoring in cutting tool and material properties and machine tool characteristics. Due to the relatively low tool load associated with dynamic trochoidal milling, this method is recommended lower power rated machines with good dynamic and a rapid reaction control unit. Dynamic milling processes are typically used for the efficient machining of pockets and other contours where the tool path pattern approaches the final workpiece geometry with every cut and feed

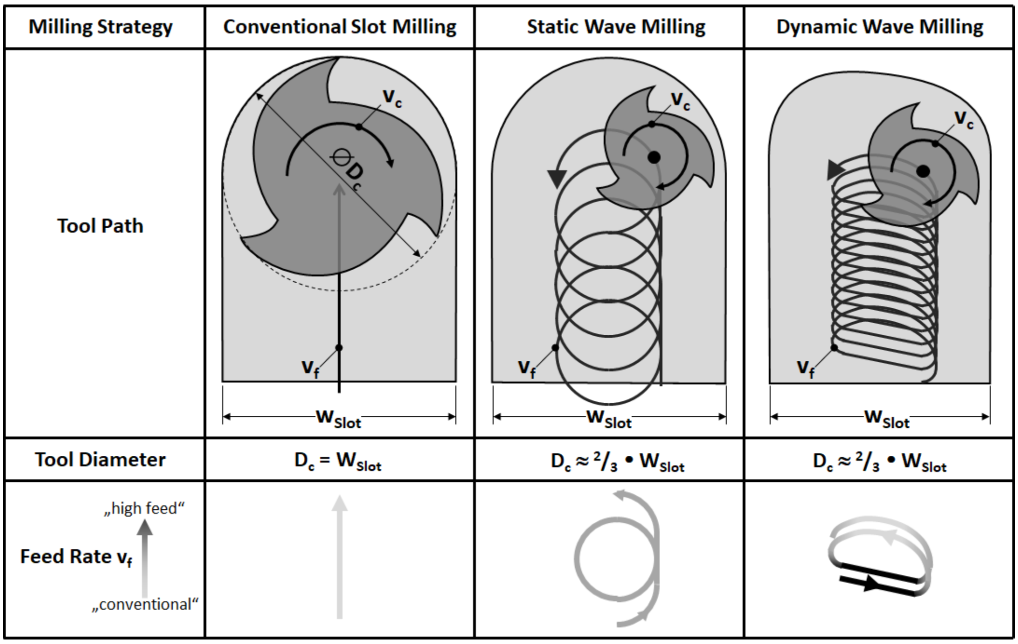

Figure 1. Tool path for slot milling, static trochoidal milling and dynamic trochoidal milling

rate is applied to continuously changing engagement conditions.

The advantages of dynamic trochoidal milling are comparatively high metal removal rates, reduced thermal and mechanical loads, and a significantly more uniform distribution of mechanical load during engagement. The high depth of cut results in low roughness values comparable to finished surfaces. The method is commonly applied for steels, stainless steels and aluminium as well as for nickel- or titanium-based heat resistant alloys.

3 EXPERIMENTAL BOUNDARY CONDITIONS

In experiments carried out in the Laboratory for Production Engineering at the Dortmund University of Applied Sciences and Arts, angled slots were cut along the machineX- and Y axes in a cubic workpiece using static and dynamic milling strategies. The feed rate profiles along X and Y axes depended on the strategy used. Using conventional slot milling in direction of the X-axis, the feed rate in Y-direction is zero; the feed rate in the X-direction matches the designated feed rate. With static trochoidal milling, the feed rate in X- and Y-direction changes throughout the cycloid. When feeding to the subsequent cycloid, the feed rates correspond to that of a conventional slot milling path. Tool paths for the dynamic trochoidal milling were generated using the iMachining module of SolidCAM.

The experiments were carried out with solid carbide end mills of diameter8, 10and 12 mm (heat-treated steel SAE4140H, 42CrMo4) and the aluminium wrought-alloy (EN-AW 6082, AlMgSi1). The width of the machined slot was set to 16 mm and the depth of cut was double that of the tool diameter.

In addition to variation of milling strategy, tool diameter and workpiece material, the influence of the machine tool and especially the drive concept was of particular interest, with special focus on the ability to achieve the desired feed rates. Two different 5-axis machining centres were used for the experiments. Machine 1 is equipped with conventional ball screw drives and machine 2 with linear actuators in all translational axes.

Throughout the experiments, the axial feed forces and torque were measured and recorded with a wireless sensory tool holder. The feed rates were logged from the machine control unit directly to the analysis software. After completion of the experiments, the resulting chips and the machined surfaces were analyzed for surface structure and characteristics with a high resolution digital microscope.

4 EXPERIMENTAL RESULTS

4.1 Dynamics and Tool Load for Static Trochoidal Milling

The results clearly show that for static trochoidal milling,the interpolated feedrate deviated from the programme value (see Figure 2). During the cycloid, the actual interpolation feedrate corresponds to the designated feedrate of the CNC-code. But for the linear tool path, when the tool moved to the subsequent cycloid, the interpolated feedrate decreased. Feed in Y-direction was zero during the linear motion. The limited dynamics of the machine tool was not able compensate with response in the X-axis feed rate. With increasing tool diameter and feed per tooth, the disparity between designated and observed feed rate increased.

Based on the sickle-shaped engagement of the tool and the application of a constant feed rate, tool load showed a cyclical behavior. The maximum load was reached in the middle of the slot width, based on the highest tool engagement. During the contact-free tool, the torque, Mc, was approximately zero. At the same time, the axial force F preached a positive maximum, due to end face friction of the cutting tool. Minimum forces occurred parallel to maximum torque and were attributed to the spiral angle of the cutting edges resulting in tensile forces on the tool.

4.2 Dynamics and Tool Load for Dynamic Trochoidal Milling

In contrast to static trochoidal milling, in dynamic trochoidal milling the designated feedrate is adapted to contact width. This results in several sections with different feeds during a tool path cycle. Figure 3 illustrates that to some extent the achieved interpolation feedrate lies significantly below the designated feedrate of the CNC program code. The relatively large difference between actual and designated feedrate was attributed to the limited dynamics of the machine tool, in particular, the permissible jerk. The very short tool path in combination with limited jerk of the drives does not allow for the necessary velocity and acceleration during the contact free tool path. As a result, the maximum acceleration of the machine drives can be reached with neither strategy.

The benefits of the feed rate adaption become obvious when considering tool load. Compared to the static milling process, the maximum torque as well and axial force is halved and the plot reveals an almost linear progression. Again, the negative values of the axial forces are based on the cutting edge helix. However, in contrast to the static milling cycle, the loads reach the zero during the contact free tool path. This can be attributed to the iMachining cycle which retracts the cutting tool by one hundredth of millimeters during the idle path.

4.3 Influence of Machine Tool

All experiments were conducted on two different machine tools using different drive concepts. The measured and recorded signals for the feed rate were distinguished by a factor of two with respect to acceleration and jerk in the linear axes. The results are summarized in Figure 4 for an

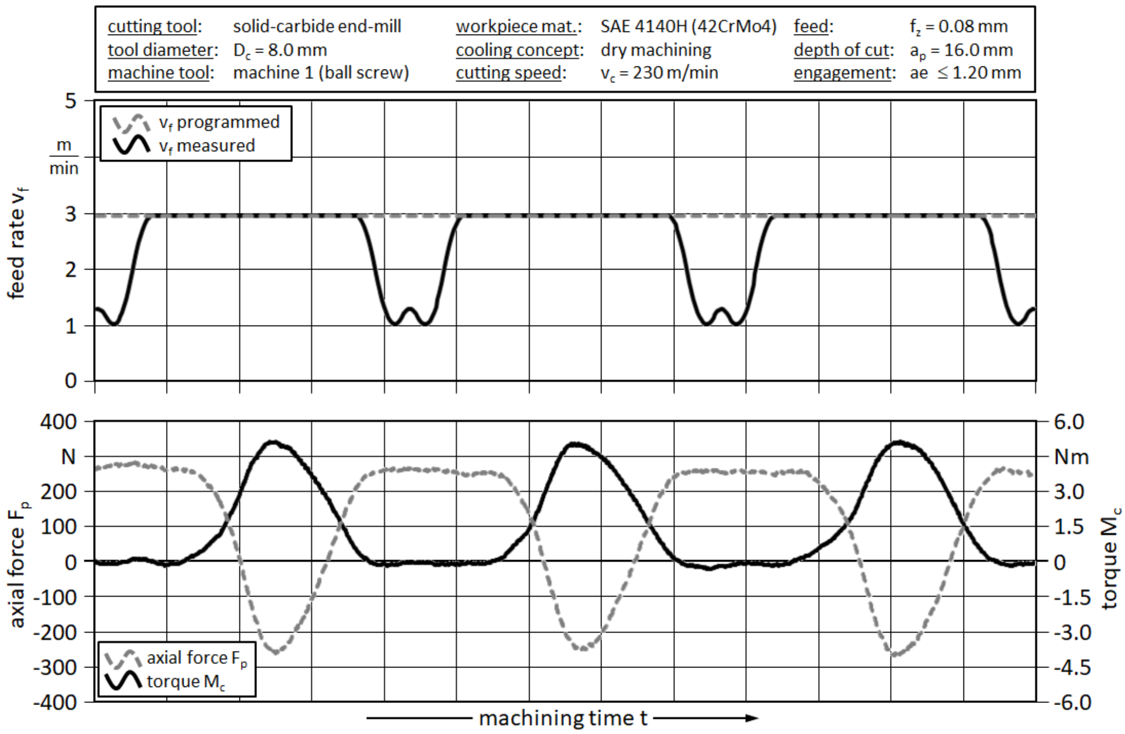

Figure 2. Experimental results for static milling of SAE 4140H with ball screw drives

example of the static milling strategy.

The figure shows the permissible jerk of machine 1 to be 20 m/s³, and for machine 2 to be 15m/s³. The measured values correlate with the settings of the corresponding control units and were initially defined by the machine tool manufacturer. However, these settings were not expected since the linear motion drive of machine 2 allows for significantly higher velocities and accelerations.

The higher jerk setting of machine 1 means that this machine tool can change velocity and acceleration 25% faster than machine 2. In static trochoidal milling, the higher acceleration lead to a greater reduction in total feed rate, which as evidence at the minimum at approximately 1100m/s of the lower curve. With respect to this reduction the greater difference to the desired feed rate of 2350 m/s results in longer machining times for the machine with higher dynamic parameters.

In contrast to this phenomenon, the dynamic trochiodal milling strategy is basically determined by the dynamic parameters of the machine tool. A comparison of the real machining time compared with the theoretical machining time calculated by the CAD/CAM-software revealed a difference of 9% to 27% for machine 1 and about 200% for machine 2. Since the same slot width was set, the time difference increased with tool diameter due to a decrease in the acceleration paths.

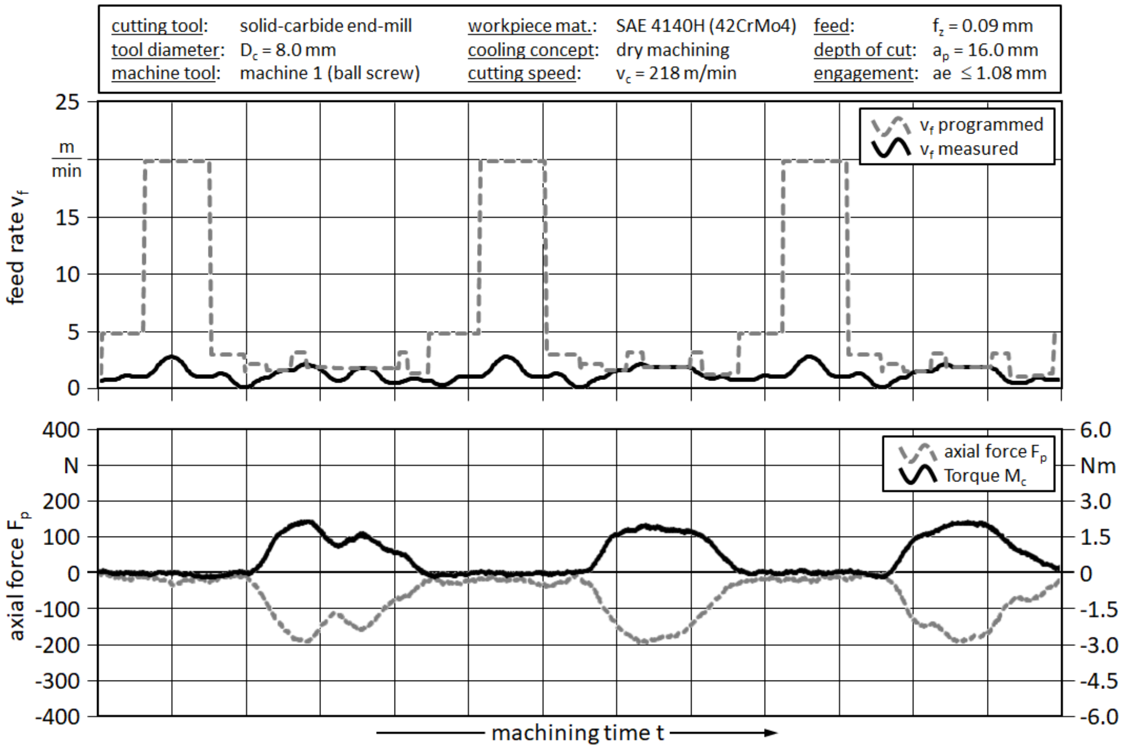

Figure 3. Experimental results for dynamic milling of SAE 4140H with ball screw drives

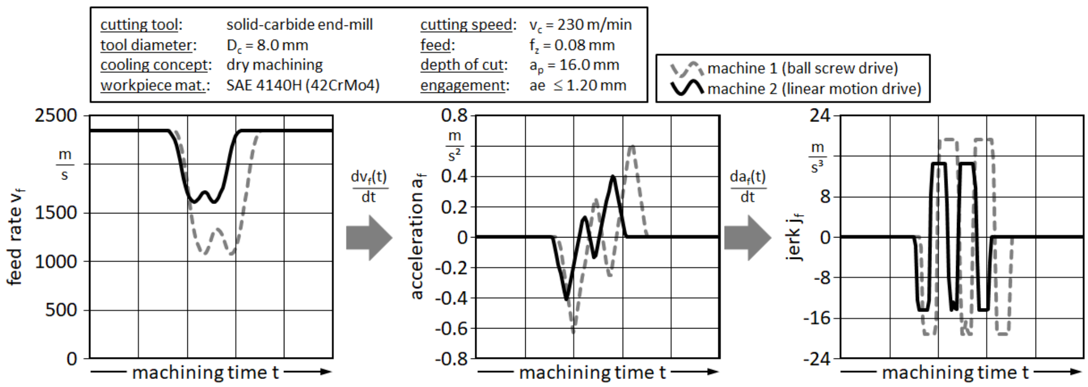

Figure 4. Feed rate, acceleration and jerk for static milling on different machine tools

4.4 Process Comparison

In addition to the time phenomenon, a distinct, strategy-related influence on chip formation was observed. The chips obtained from dynamic trochoidal milling are constant in shape and size. This is a result of the uniform average chip thickness resulting from continuously adjusted feedrates. In contrast to this, the average chip thickness using static trochoidal milling changed during tool engagement which led to significant differences regarding chip size and shape. In addition to uniformity, the chips obtained with the dynamic strategy are considerably thinner.

Based on the tool lift-off during the idle path in the dynamic strategy, the workpiece surfaces revealed improved values for roughness values compared to those for the static strategy. During the feed motion in static milling the tool is constantly in contact with the workpiece surface which leads to squeezing and friction between the tip of the tool and the bottom of the slot.

5 CONCLUSIONS

The benefits of modern trochoidal milling strategies are basically determined by the boundary conditions of the whole machining system. It was shown that the dynamic adaptation of the feed rates leads to a constant load to the cutting tool at significantly reduced values. The dynamic of the machine tool, mainly determined by the jerk, is crucial for a productive milling process. However, in case of a static trochoidal milling strategy the machining time could benefit from low dynamic value settings.

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