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The investigation of the chip behaviour during the end milling cutting process

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Abstract. Generally the study, evaluation and general understanding of end milling cutters are complicated by the complexity of the cutting process and of the cutting tool. The main performance factor of the end milling cutters is given by the durability of the tool. In practice the sound analysis of the tool engaged in the cutting process is used as a simple predictability mean to forecast the future durability of the tool. An alternative or complementary tool to predict future durability is the investigation of the chip behaviour. Chip behaviour investigations can also give clues concerning the possible improvement of the cutting tools. The current article presents a detailed chip behaviour investigation for 5-fluted end milling cutters with different performances and various geometries when approaching different types of metal cutting operations in 42CrMo4 alloy steel. Current study can be applied in future researches regarding the evaluation and the development of end milling cutters. Furthermore the current approach can be used on other types of cutting tools.

1 Introduction

The metal cutting technology continues to be the main and most precise manufacturing technique in the world today. Current trends and research in ultra-precision metal cutting anticipate an even greater role for this technology in the future.

The first scientific approaches to analyse the dynamics of the cutting process and behaviour of the metal chip was made by Merchant [1], which introduced the shear angle model for orthogonal metal cutting, and by Lee and Shaffer [2], which introduced the slip line field theory in the chip formation process, as an attempt to apply the plasticity theory to the problem of orthogonal metal cutting. From these early models, more precise and more detailed models have been developed by taking into consideration the influences of friction, temperature, work-hardening and strain-rate [3-5]. Although this early chip formation models are the base for the metal cutting theory, they are not in full correspondence with the applied experiments.

In the field of milling cutting process, first attempts to create a model for a milling process, were made by Young [6], whose research was based on Oxley's predictive

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machining theory [7]. Young used Oxley's predictive theory for forces, temperatures and stresses in relation with the material flow, which he applied on the chip segments of a divided milling chip with varying thickness. In his study he considered the chip segments as constant geometrical elements. Young's model has been validated trough similar results of amplitude and geometry of the force profile in applied experiments.

Oxley’s generalized predictive machine theory has been widely used to define specific cutting situations and specific materials. Ekanayake et al. [8] applied the theory to predict cutting forces in high speed milling of AISI 1045 and AISI 4140, while Li et al. [9] predicted forces in helical end milling. Masmali et al. applied Oxley’s theory to predict the forces of a non-uniform helix angle milling cutter [10] and conducted a geometric chip analysis for helical end milling tools [11]. Masmali’s model results show significant similarities with the models of the experimental results. However there are still inconsistencies that can be improved, like the force variation between the analytical model and the experimental results on the tool-axis direction.

Other studies in the field of milling cutting process have focused on the effort to investigate chip formation, chip morphology and tool wear in the case of high speed milling of hardened steels [12-14]. Meanwhile Ning et al. [15] and Wu et al. [16] have classified the chip obtained through milling in different groups. By interpolation of the previous two chip classifications, four major chip types are obtained: stable (complete), unstable, critical and severe chips. More recent Patwari et al. [17] developed a mathematical model to predict the instability process of the chip formation by using the concept of chip serration frequencies.

Although much research has been done in the direction of studying, understanding and theorizing the end milling cutting process, the scientific effort is far from a universal solution for the complex process. Firstly the complexity of the process, which distinguishes itself from simple metal cutting procedures like turning and drilling, is given the interconnected cut along two cutting edges: primary or major cutting edge, located on the tools diameter, and secondary or minor cutting edge, located perpendicular to the tools axis. This aspect complicates the effort to apply orthogonal cutting theory in milling cutting. Furthermore, in previous studies there have been found no considerations regarding the dynamic non-linear chip behaviour in the cutting process, the influence of the tools geometry on overall stability and the influence of the secondary surfaces (as seen in Figure 1), surfaces that are not in direct cutting contact with the chip, on the chips removal success and tool stability. Therefore, the current article will present a different approach to the study, evaluation and understanding of the end milling cutting process, which is based on simple practical observations, resulting from the investigation of the chip behaviour of 5-fluted milling cutters with different geometries and performances when approaching different types of milling cutting operations in 42CrMo4 (EN 10269:2008) alloy steel.

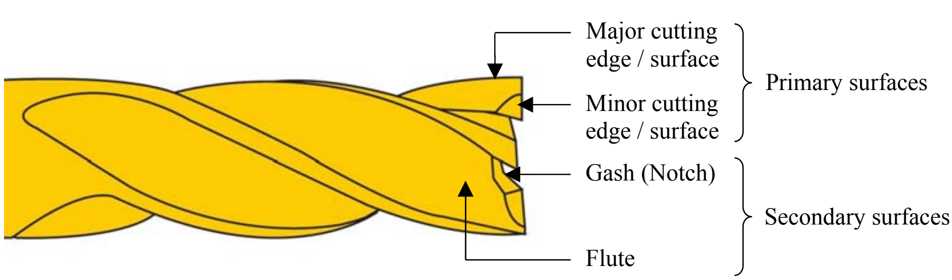

Fig. 1. End milling cutters surfaces and cutting edges.

2 Experimental setup

The experimental setup, as shown schematically in Figure 2.a., consists of the following major components: the machine tool, the tool clamping device (tool holder), the end milling cutter, the workpiece, the workpiece clamping unit and the high-speed camera.

The machine tool for the experiments is the universal milling machine for 5-sided / 5-axis machining DMU 85 monoBLOCK® (Figure 2.b.) manufactured by DMG MORI.

The tools tested are 5-fluted end milling cutters with Ø12mm cutting diameter (*abbr.* D) and with different geometrical characteristics and performances. The geometrical differences consist in the following parameters: spiral angle (38° / 45°), minor cutting edge position (under and above center), rake angle of major cutting edge (7° / 9°), rake angle of minor cutting edge (5° / 10°), core diameter (between 6 mm - 7,8 mm), corner geometry (chamfer / radius) and geometry of center cutting (with and without center-cut). Another geometrical aspect that should be taken into consideration is the use of different gash and flute profiles. The tools used were clamped with the help of a Gühring HPC precision clamping chuck.

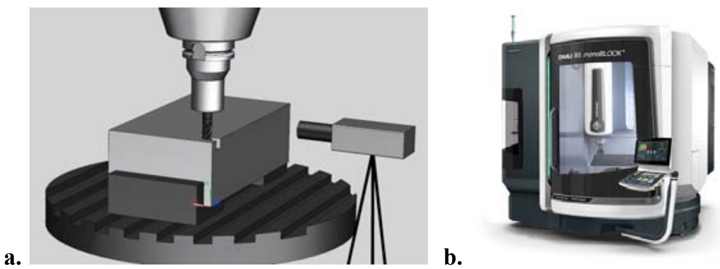

Fig. 2. Experimental setup: a. schematic representation and b. universal milling mach. DMU 85 monoBLOCK® [Courtesy of DMG MORI]

The workpiece used for the testing is a 42CrMo4 (EN 10269:2008) alloy steel block.

The cutting operations and parameters are shown in table 1. Additionally, it should be mentions that the experiments were made using the down milling method and were conducted in a dry environment, the cooling been done only with air.

The major component which makes the investigation of the chip behaviour possible is the high-speed camera. Although the experiments were conducted using an additional normal video camera, no conclusive observations have been made, using this method.

Table 1. The machining parameters for the experiments (*abbr.* exp.): cutting speed (*abbr.* v_c), spindle speed (*abbr.* n), feed per tooth (*abbr.* f_z), axial depth of cut (*abbr.* a_p), radial depth of cut (*abbr.* a_e)

Experiment 1: HPC Roughing	
Exp. 1.1	v_c = 200 m/min (n = 5305 RPM); f_z = 0,12 mm/rev; a_p = 1xD; a_e = 0,1(6)xD
Exp. 1.2	v_c = 200 m/min (n = 5305 RPM); f_z = 0,12 mm/rev; a_p = 1xD; a_e = 0,25xD
Experiment 2: Slotting	
Exp. 2.1	v_c = 135 m/min (n = 3581 RPM); f_z = 0,08 mm/rev; a_p = 0,25xD; a_e = 1xD
Exp. 2.2	v_c = 135 m/min (n = 3581 RPM); f_z = 0,08 mm/rev; a_p = 1xD; a_e = 1xD
Exp. 2.3	v_c = 160 m/min (n = 4244 RPM); f_z = 0,08 mm/rev; a_p = 1xD; a_e = 1xD
Experiment 3: 5°/10°/15° Ramping	
Exp. 3.1	5° ramping; v_c= 160 m/min (n= 4244 RPM); f_z= 0,08 mm/rev; a_p= 0-0,5xD; a_e=1xD
Exp. 3.2	10° ramping; v_c= 160 m/min (n= 4244 RPM); f_z= 0,08 mm/rev; a_p= 0-0,5xD; a_e=1xD
Exp. 3.3	15° ramping; v_c= 160 m/min (n= 4244 RPM); f_z= 0,08 mm/rev; a_p= 0-0,5xD; a_e=1xD

3 Observations, results and discussions

The goal of the experiments was to observe and determine the chip behaviour during the end milling cutting process, when using 5-fluted end milling cutters, and to look for any significant correlation between the milling process stability and the chip behaviour.

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3.1 The investigation of the chip behaviour for HPC roughing

The experiment 1.1 shows several differences between the stable and the unstable milling process. The chip behaviour can be observed through the release pattern of the chip from the gash and flute and the movement of the chip after the contact with the tool has been interrupted.

In the stable situation (Figure 3.a) a orderly movement of the chip without showing restraint behaviour to the tools flute can be observed, whereas in a unstable situation (Figure 3.b) the movement is slightly erratic with restrained behaviour to the flute. The bottom part of the chip, the part which is cut by the minor cutting edge, twists after bottom cut and leaves a more pronounced scratch on the machined surface in the unstable operation. The release of the chip is done synchronized in stable and disorganized in unstable situations. In the last case, after the tool contact release, a greater twist of the chips can be noticed.

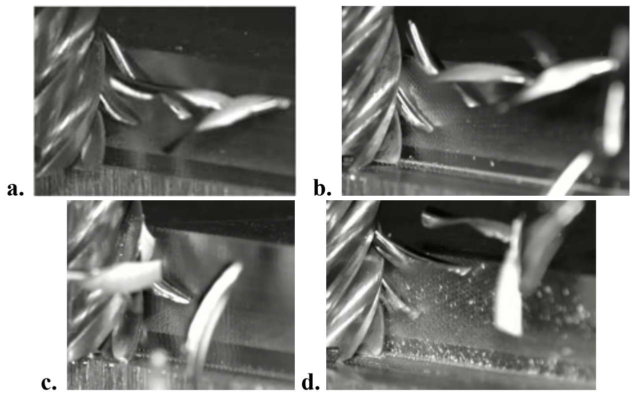

Fig. 3. Chip behaviour in HPC roughing operations: a. stable, b. unstable process (exp. 1.1), c. stable, d. unstable process (exp.1.2)

Furthermore, the chip from the stable situation is intact and no supplementary elemental chips (punctiform shape) are observed, while in unstable conditions there are serrated chips and a few elemental chips detected.

The experiment 1.2 is similar to the first experiment, but the chip behaviour differences are more pronounced. The stable situation (Figure 3.c) shows a further orderly movement of the chips with no restrains to the tools flute, while the unstable situation (Figure 3.d) shows a extreme erratic movement with a more visible restrained behaviour to the tools flute. The scratched surface of the workpiece becomes more visible in unstable conditions. The release of the chip is done more disorganized in unstable situations. The chips serrations are bigger in the unstable situations and more elemental chips are observed, which adhere to the machined surface.

Additional there has been observed scratches in tools flute, which are more visible for tools with big core diameter. The release trajectory of the chips is bigger for tools with bigger spiral angle and the scratches on the surface of the workpiece are less wider for tools with small spiral angle.

3.2 The investigation of the chip behaviour for slotting

The experiment 2.1 shows a bigger chip agglomeration in the machined slot between the stable (Figure 4.a) and the unstable (Figure 4.b) processes. In various unstable conditions, there have been observed chips that are stopped in the flute, being transported back in the cutting process and composing clusters of stacked chips.

In the experiment 2.2 and 2.3 similar observations have been made. The chip agglomeration has in this operation a more visible influence. In unstable conditions (Figure 4.d) this chip behaviour is more pronounced in comparison to stable situations (Figure 4.c). The extreme cases of this behaviour, as seen in Figure 4.e, can lead to tool failure. Although agglomerations occur, in stable conditions the chips are evacuated much faster.

In unstable conditions the chips have a tendency to be stopped in the flute, which together with the chips from the near and dense agglomeration are being cut several times. The chips from this event are chips with multiple longitudinal cuts or long and thin chips. Additional there have been observed short, needle and elemental chips.

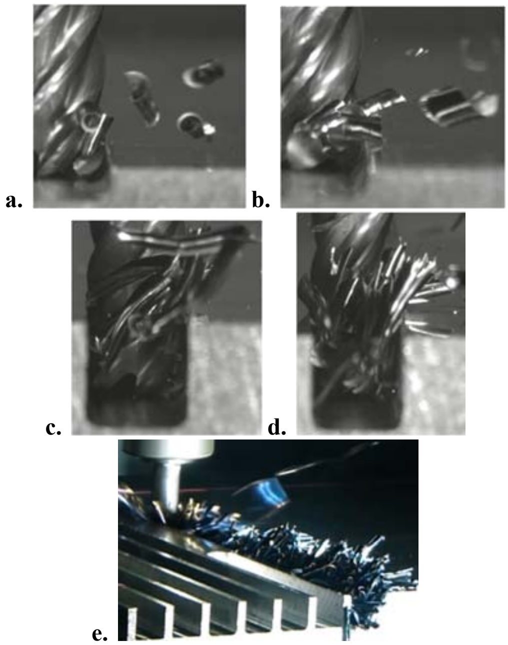

Fig. 4. Chip behaviour in slotting operations: a. stable, b. unstable process (exp.2.1), c. stable, d. and e. unstable process (exp.2.3)

3.3 The investigation of the chip behaviour for 5°/10°/15° ramping

The performance of the milling cutters and chip behaviour in ramping is very similar to the slotting operation.

The experiment 3.1 shows significant differences between the chip behaviour in stable (Figure 5.a) and unstable (Figure 5.b) situations. Right at the beginning of the cut ($a_p \approx 0$mm) the chips have the tendency not to detach themselves from the machined material, becoming so very long spiral chips. Under stable situation as the tool progresses in depth, these long chips are removed and the process behaves similar to slotting. The initial formation of these long chips gives clues for understanding the processes failure. In some cases this long chip consists of a cluster of attached chips, which slide on the flute as more chips are added, and in other cases the chips are welded on the flutes surface, building a long chip formed by the pressing of the welded chips. This second type, if not removed during the cut, can destabilize the process. As observed, the simultaneous filling of more clearance surfaces (gas and flute) can have a catastrophic result by leading to tools failure.

The experiments 3.2 (Figure 5.c - stable; Figure 5.d - unstable situation) and 3.3 show similar observations as previous. The chance of multiple simultaneous filling of the clearance surfaces increases and so the failure rate becomes greater.

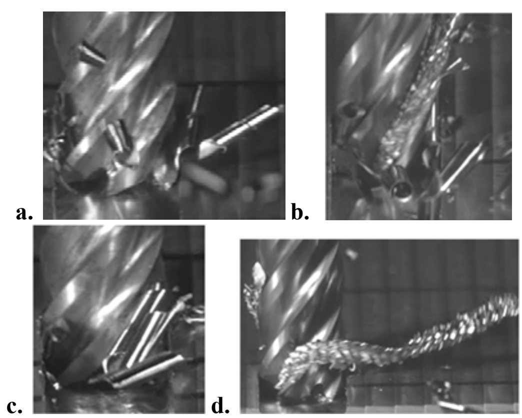

Fig. 5. Chip behaviour in 5°/10° ramping operations: a. stable, b. unstable process (exp. 3.1), c. stable, d. unstable process (exp. 3.2)

4 Conclusions

In the current article was accomplished the investigation of the chip behaviour during the cutting process with 5-fluted end milling cutters. It has been shown that the stability of the cutting process is in direct correlation with the chip behaviour. The chip behaviour and thus the performance of the process are conditioned by the geometry of the tool.

Furthermore, it has been noticed that the secondary surfaces have a great role in the chip behaviour and tool performance. Influences of these surfaces are subject for further studies.

The investigation of the chip behaviour is a quick and more direct method, which can be used to inspect the formation and the removal succes of the chip. In comparison to traditional techniques is provides more information about the cutting process and about the performance of a tool's geometry. This method can be used for further academic researches and can help the private sectors need of improving cutting tool faster.

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