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A New Strategy in Face Milling - Inverse Cutting Technology

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Abstract. The article describes a new technology in milling of the flat surfaces - Inverse Cutting Technology. The theoretical basics of the inverse cutting are formulated. The boundary conditions of the process depending on the cutting parameters are presented. The chip formation and chip flow by inverse milling are simulated. The comparison of cutting forces by conventional and inverse face milling is shown. Finally, cutting experiments were conducted to confirm the results of the 3D-FEM-simulation.

1 Introduction

Conventional face milling is one of the most explored processes in metal cutting. There has been meaningful research progress in stability of milling during recent years [1,2]. Nevertheless, there are stability problems in conventional face milling which cannot be solved because of the total of particular working conditions and the nature of the process. In fact, under unstable and semi-stable cutting conditions, when the protruding length of the tool is extended because of the unusual machining conditions, e.g. deep pocketing, a tool-axis deflection appears which negatively influences the finished workpiece form and surface quality [3,4]. According to this situation, there is a real need to reconsider the basics of the face milling. A few studies [3,5] have detected, that the undeformed chip thickness h leads to a stabilizing and the width of undeformed chip b to a destabilizing effect. Tönshoff and Denkena also examined, that the ratio of chip compression changes with the undeformed chip thickness [6]. It has been proven, that a reduction of chip relation, SV = b/h, leads to a considerable improvement of the dynamic behaviour which is important for milling under unstable and semi-stable cutting conditions [3,4,7,8]. If the cutting strategy is realised up to SV < 1, the cutting process enters a completely new and unexplored field of milling, where a lot of cutting parameters and mechanisms invert. It can be referred to "inverse" cutting technology.

2 Inverse Cutting Technology – Basics

The cutting process can be described using SV-factor [6,9]. It is a relation between the undefomded chip brightness b and the undeformed chip thickness h. The SV-factor is a variable of cutting depth a_p, feed per tooth f_z and main cutting edge angle κ_r of the process. The conventional face milling process has SV-factor greater than one. For example, in the milling process with parameter a_p = 3 mm, f_z = 0,3 mm/tooth and κ_r = 90˚, the SV is 10. The main idea of the inverse cutting technology is to reduce the cutting ratio b/h to an area below one. Therefore, the induced stress in the workpiece material decreases and its direction changes as well, so brittle material behaviour can be realized [10]. It is possible by reducing of depth of cut and by increasing of feed per tooth.

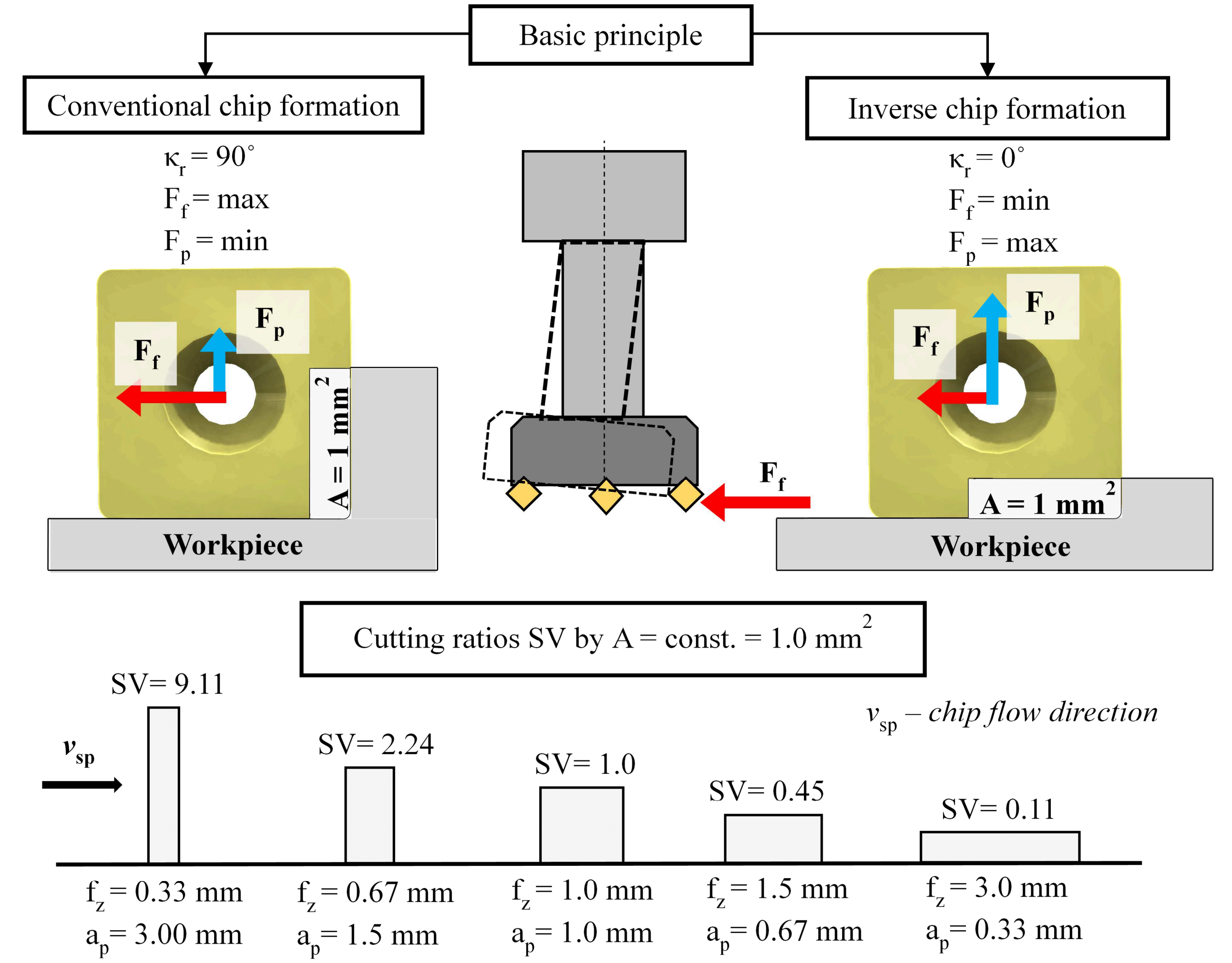

Fig. 1: Basic principle of inverse chip formation

The basic principle of inverse chip formation for a constant chip cross section A is schematically presented in Figure 1. The threshold from inverse to the conventional chip formation is SV = 1. Another difference to conventional milling is $\kappa_r = 0°$ (instead of $\kappa_r = 90°$) on the main cutting edge which reverses the chip flow. Derived from the presented basic principle, a completely new constellation of cutting parameter with the following features and modifications arises (Tab.1).

Table 1: Parameter comparison between conventional and inverse chip formation

Conventional chip formation	→	Inverse chip formation
$\kappa_r \leq 90°$	→	$\kappa_r = 0°$
$SV \geq 1$	→	$SV < 1$
a_p	→	f_z or f_u
f_z	→	a_p
F_f max	→	F_f min
F_p min	→	F_p max

With modifications given, the following effects in the field of inverse chip formation are expected:

- Increase of the dynamic stability in the milling process by:
  - Maximizing of passive force F_p and its impact into the machine spindle,
  - Minimizing of feed force F_f and decrease of radial tool deflexion;
- Gain in efficiency, because feed f_u can be increased with the length of the cutting edge;
- Optimization of chip formation and chip flow by a strongly negative positioning of the cutting edge (side rake angle γ_f = negative). A so called “pulling” cut appears with a favourable skiving effect. This can lead to less chip compression and lower chip temperatures [3,9];

- The partial cutting edge stress decreases with the length of the cutting edge used. A large feed f_u leads not only to an increase of efficiency, but also decreases the cutting edge wear;
- The general wear behaviour is also influenced by the impact condition of the cutting edge. The first impact does not take place at a single cutting edge point. Moreover a much greater penetration time exists (time from the moment of first contact till complete penetration), which reduces the impact impulse significantly. The long cutting edge under κ'_r = 0° leads to an improvement of the surface quality;
- As the tool cutting edges in the „inverse“ milling head are axially staggered, not all cutting inserts machine critical cutting depths. Hence, cutting material is saved. Compared to that, the cutting edges in conventional milling wear out the same, no matter what cutting depth is realised.

An extensive literature and patent research has shown a lack of publications scoping inverse cutting. However, there are a few other cutting processes using the effects of a changing chip relation. For example high feed milling [11,12] and so called large angle cutting (with κ_r of about 15° to 30°). It is mentioned for the first time in the dissertation by Batt [4], where the field of inverse chip formation depending on the chip relation SV for SV < 1 is represented. Because this special field of cutting is completely unexplored, it is of high interest for research and industrial applications.

It is obvious, that the suchlike direction-change of the resulting force F_z vector can highly influence the stability of machine-tool-workpiece system. The requirements to the cutting tool design, cutting micro and macro geometry, workpiece clamping system etc. should be reconsidered in detail. At the Institute of Manufacturing Technology and Quality Management (IFQ) of Otto-von-Guericke-University of Magdeburg and at Institute of Manufacturing Science of University of Miskolc basics investigations to verify the theory of the invers milling process were performed. First, a series of FEM-simulation were calculated. After that, the practical test were made. The set-ups and results of the simulation and practical investigations are described in the following parts of the article.

3 Simulation

In the last years the Finite element method has become a usual instrument for the prediction of chip flow, cutting forces, temperature, plastic/elastic deformations, impact conditions of a milling process [13–15]. The FEM-software "AdvantEdge" by Third Wave Systems was used for the simulative study. This program is uniquely intended for modelling of cutting processes. Table 2 shows the cutting parameters which were constant for all the experiments. The workpiece material was AlSi7Mg0.3 (HV_{10} 80) with ultimate tensile strength R_m=300 N/mm^2 and yield strength R_p=220 N/mm^2. The cutting insert with no coating was made of cemented tungsten carbide and defined as an undeformable, rigid body. The materials constants of the cemented tungsten carbide were defined and based on the AdvantEdge`s standard-materials list. In the processes no cooling liquid was utilized. The friction coefficient of the process was determined to 0.2. The tool was positioned in the middle of workpiece, its working surface was 60x250 mm.

Table 2: Constant cutting parameters

a_e	κ_r	r_ε	r_n	D	v_c	γ_p	γ_f	α
[mm]	[°]	[mm]	[mm]	[mm]	[m/min]	[°]	[°]	[°]
60	90	0.2	0.015	110	97	0	0	7

Within five steps a conventional face milling process (SV = 10) was changed to an inverse cutting process (SV = 0.1). The chip cross-section area A was kept constant at 0.8 mm^2, which is typical for industrial applications. Table 3 shows the parameter set-ups for the five experiments.

Table 3: Cutting parameters for variation of cutting ratio

	EX 1	EX 2	EX 3	EX 4	EX 5
	chip cross-section area $A = a_p \cdot f_z = b \cdot h = 0.8$ [mm^2] = *constant*				
Depth of cut a_p, [mm]	2.8	1.4	0.893	0.56	0.28
Feed per tooth f_z, [mm/tooth]	0.286	0.571	0.893	1.429	2.857
Cutting ratio SV = b/h, [-]	10	2.5	1	0.4	0.1

In 3D-FEM, the tool was meshed with elements between 0.025 and 0.3 mm in size. The major and minor cutting edges were defined with a very fine mesh in order fit r_n =15 µm. The workpiece was meshed with elements between 0.025 and 2 mm. The remeshing parameters of AdvantEdge were following: the minimum edge length of elements surrounding the refined region (chip bulk) was 0.0567; the minimum edge length of elements near the cutting edge, which is within the refined region (cutter edge) was 0.0433 and the radius of refined region was 0.429. The set-up parameters of FEM-elements for all the simulative investigations were the same.

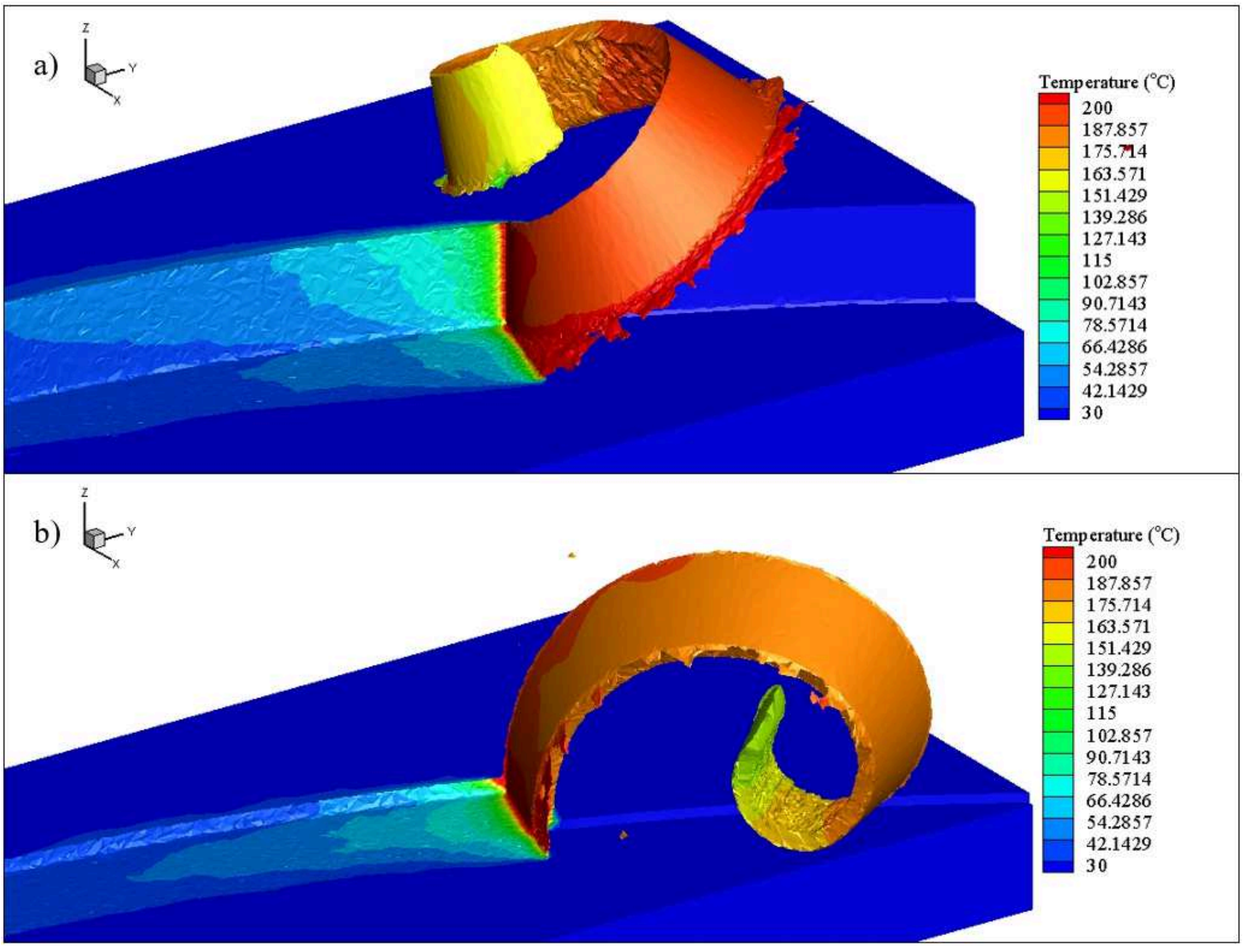

Fig. 4: Simulation of Chip flow under relation of a) a_p/f_z =10 and b) a_p/f_z =0.1

The chip formation and the chip flow with constant cutting geometry of the tool insert are completely different in comparison to conventional cutting. In Fig.4 the chip flow is illustrated at a tool rotation angle of φ_A= 132°. According to the chip form classification given in [6,16], in the inverse face milling of AlSi7Mg0.3, spiral chips occur, controversy to the conventional cutting where the helical chip segments are build. It is a consequence of a less chip compression. As a result a low deformed chip thickness during inverse cutting occur (Fig.5). Furthermore, the chip temperature during inverse cutting is lower, which affects the tool life.

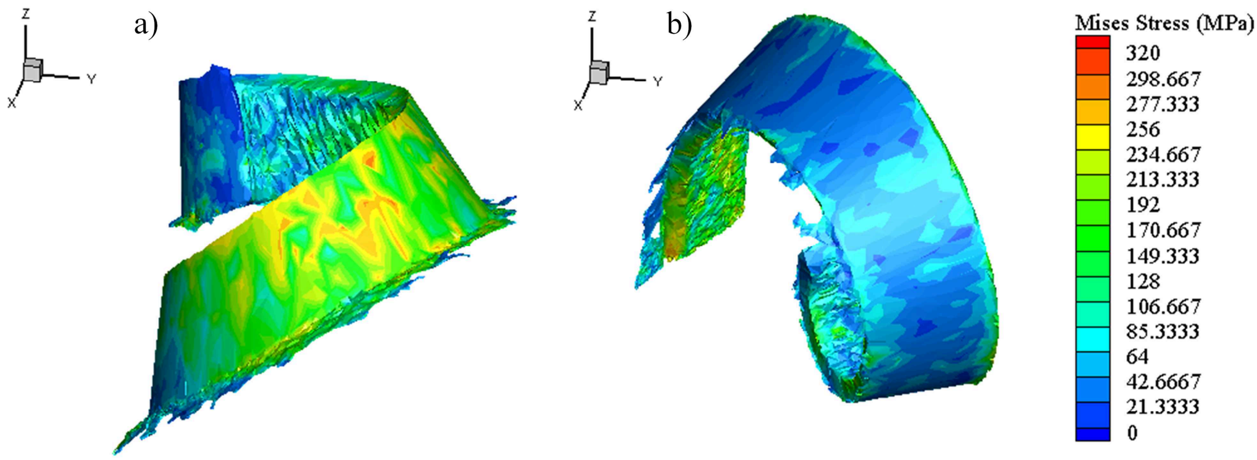

Fig. 5: Mises stress of conventional (a) and inverse (b) chips

The simulated absolute temperature can be significant different (± 20 %) from the real process temperature, which wasn't verified during the experiments, because this time it wasn't a subject of investigation. According to the fact, that no tool body or insert holder were modelled, the simulated and experimental chip form cannot be compared, because the contact between tool body and chip influences the end form of the chip. Besides, the chip end form, as well as forces are affected by friction coefficient between rake face and chip [17,18], what is also a subject of future studies.

The force-measurement results of 3D simulation were compared within the next chapter. In order to confirm the result of 3D FEM-simulation the practical tests were conducted.

4 Experiments

The experiments were performed with the same cutting conditions as the simulations were. The tests were carried out on the 3-axis tool machine DMU 60 E by Deckel Maho. For the tests was used a milling tool designed by Institute of Manufacturing Technology and Quality Management (IFQ). The design of this milling cutter with shanks style of tool inserts' holder enables the using of different cutting insert with only one tool body [19]. The tool design has enough stiffness depending on chatter characteristics and is also appropriate for the operations with inverse cutting ration [4]. A 85° parallelogram-form cutting inserts were extra prepared for the tests. The minor rake face of the insert was grinded to achieve the bigger length of the minor cutting edge, well known as wiper geometry. Theoretically, exactly the minor cutting edge should do the main cutting work, on the contrary to the conventional process. The clearance angle $\alpha = 7^{\circ}$ was manufactured according to simulation set-up. The measured cutting edge radius r_n of the prepared insert was 15 ±1 µm. The authors understand that the cutting insert prepared this way cannot be used for the wear investigation, because of elevated adhesion tendency on the cutting edge, but it was feasible to investigate the basic regularity of inverse cutting.

The 3-component-dynamometr type 9255B by Kistler was used for the force measurement. The measured standard force deviation by all the test was less than 5 %.

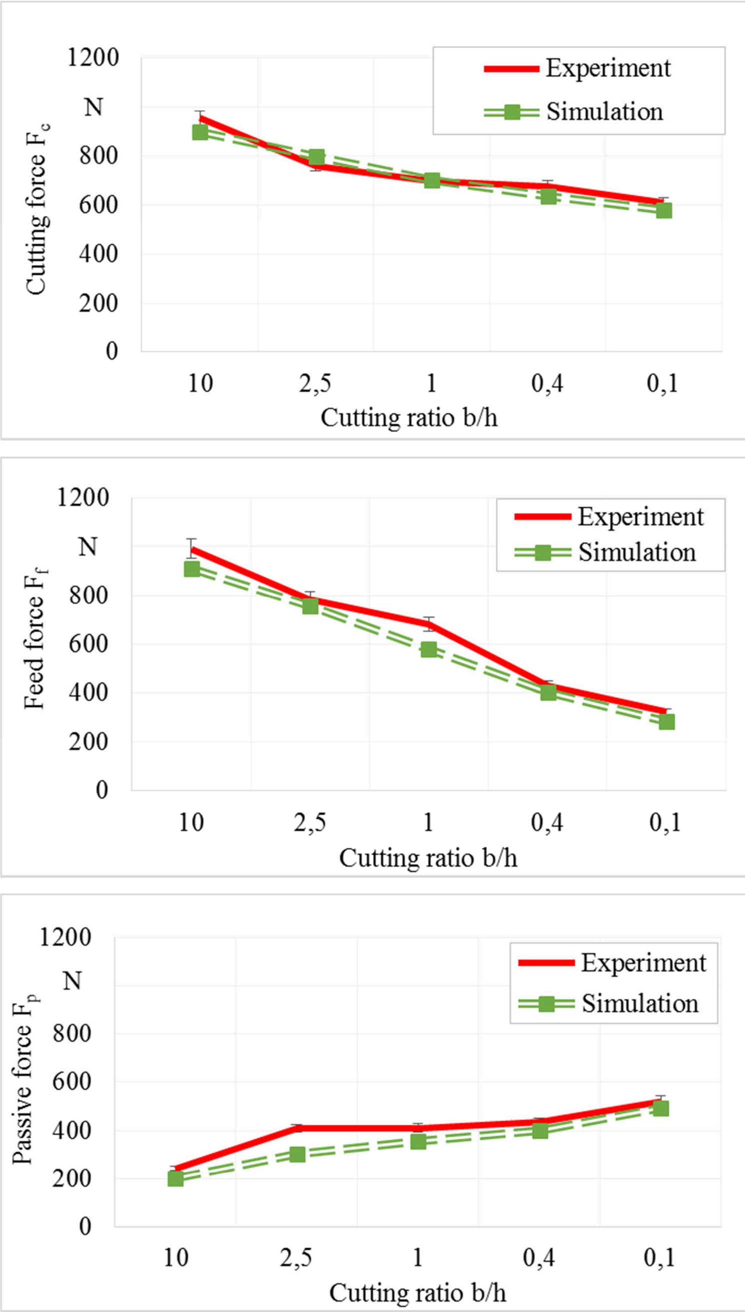

Fig. 6: Force measurements results of simulation and practical experiments

As it can be seen in Fig. 6, the results of the real force measurement confirm the legitimacy of simulated results. Indeed, the maximizing of passive force F_p, as well the minimizing of feed force F_f were achieved. The experiments prove that the changing of cutting ratio SV from 10 to 0.1 decreases the cutting force F_c by 36 %. Similarly, the feed force F_f was reduce by 66%. At the same time, the inversion of cutting ratio results the increasing of passive force to 215 %. It means that the direction of the resulting force F_z vector is positively changed. The value of resulting force F_z was led down to 60 %. Consequently, the machine spindle receives the cut-in impact and the radial tool deflexion should be decreased. Within the main effect of the inverse cutting technology is achieved. Hence, the theory is verified.

5 Summary

The theory of Inverse Cutting Technology, as well as possible advantages were formulated. To approve the theoretical hypotheses the basic investigations in face milling process were performed. 3D-FEM simulations and practical experiments have proven that the inversion of cutting ratio SV from 10 to 0.1 by constant undeformed cross-section in face milling leads to:

- Decreasing of cutting force F_c to 64 %;
- Reducing of feed force F_f by 66 %;
- Increasing of passive force F_p by 2.1 times, what is of a big advantage.
- Decreasing of resulting force F_z to 60 %;
- Change of chip formation and chip flow mechanisms (lower deformation of the chip).

Thus, direction and the value of the resulting force F_z vector are changed in this way that machine spindle receives the cut-in impact and the radial tool deflexion should be decreased. Under such circumstances, the face milling process is more stable. Briefly, it can be said that the inverse cutting technology can be utilized for particular industrial applications with a significant benefit. Future investigations will deal with optimal cutting parameters, wear phenomena and different insert geometries.

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