Available online at www.sciencedirect.com

ScienceDirect

Procedia Technology 15 (2014) 424 – 430

Procedia Technology

2nd International Conference on System-Integrated Intelligence: Challenges for Product and Production Engineering

Experimental analysis of cutting forces in actuated face milling of micro patterns

Berend Denkena, Jens Köhler, Alexander Seibel*

Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

---

Abstract

This article presents an experimental analysis on cutting forces in fast tool servo-based face milling of micro structures. These structures can be used as a binary information carrier [1]. For a proper process design on a wide range of materials, knowledge of the cutting forces is necessary. The analysis was conducted on the materials Al7075, AISI4042 and TiAl6V4. The investigated parameters are cutting speed, feed, depth of cut, variable depth of cut change and frequency of change. The experiments were conducted according to a full-factorial design using two levels for all parameters and with the tool in full engagement. The used tool system is based on a piezoelectric actuator, enabling tool tip deflections up to 4.5 kHz with an amplitude of 30 µm. A precise linkage to the angular spindle position allows adjusting the deflection over the width of the rotatory tool tip movement. In analogy to the information carrying micro patterns, sinusoidal structures are generated in the engagement range from 45 to 135 degrees angular tool tip position. In order to minimize possible superimposed vibrations of the dynamometer and amplitude gains of high frequency force signals, a filter is used. The filter is based on an inverse function of the force measurement transfer behavior system with mounted specimen. The effects are evaluated on the mean values of the extracted force signals between 45 and 135 degrees engagement range and compared to the effects of machining without variable depth of cut.

Peer-review under responsibility of the Organizing Committee of SysInt 2014.

Keywords: Fast tool servo; micro patterns; highly dynamic force measurement

---

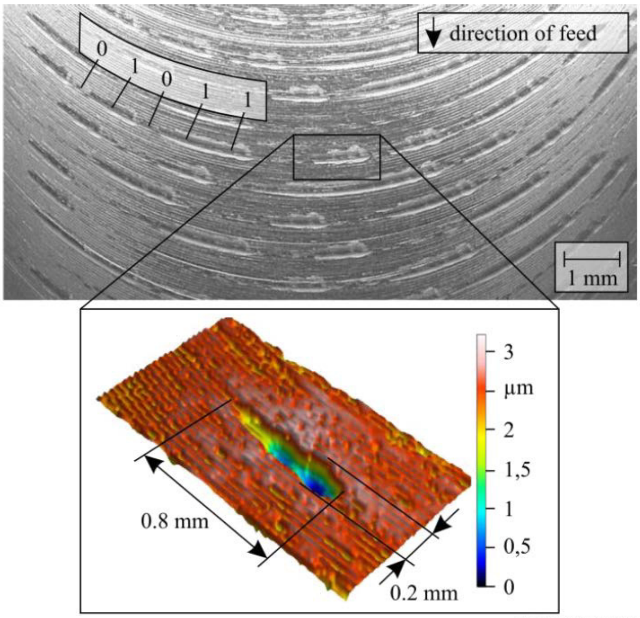
* Corresponding author. Tel.: +49-511-762-18234; fax: +49-511-762-5115
E-mail address: seibel@ifw.uni-hannover.de

Peer-review under responsibility of the Organizing Committee of SysInt 2014.
doi:10.1016/j.protcy.2014.09.001

1. Introduction

The Collaborative Research Centre (CRC) 653, sponsored by the German Research Foundation (DFG), researches innovative component properties and concepts for their manufacturing and implementation in production engineering processes. One of the CRC's visions is the inherent storage of significant component information, such as production date, process parameters, process forces or even production drawings on the component itself [1]. In addition, these advanced properties provide an excellent basis to protect the component against plagiarism. The machining of defined micro patterns into the component surface during a finishing operation offers a promising possibility to store binary information (Figure 1). In [2] this approach was successfully performed with a specially designed piezo-electric milling tool capable of axial tool tip deflections up to 4.5 kHz with an amplitude up to 30 µm. Aiming to refine this method for industrial use, knowledge of cutting forces during machining of the micro patterns is essential. With this information the design of new tools and processes for different materials is possible. The force measurements are carried out in order to analyze the influence of excitation frequency and amplitude on cutting force components under different process conditions. So far detailed force measurements with fast tool servos hadn't been carried out [3,4,5] due to problems with dynamic effects of the dynamometer while using high excitation frequencies. This Paper uses an inverse filter technique [6] primarily used in force measurements for micro milling, to extend the measurable frequency range of a dynamometer.

The aim is to derive universal correlations for the interpretation of structuring processes which can be used to improve the mechanical design of tools. The materials Ti6Al4V, Al7075 and AISI4042 are machined with variation of the parameters excitation frequency, amplitude, cutting speed, feed and depth of cut.



Mk/62374 © IFW

Fig. 1. Machined micro patterns for information storage on the component surface [2].

2. Test Setup

The tests are carried out on a HELLER MCi16 milling centre. The structures are generated by using a piezo-actuator driven milling tool as also used in [1]. The tool is controlled by a real-time computer system. The control system receives the current angular position of the spindle and creates a sinusoidal deflection signal in a specified engagement area of the cutting edge. The process forces are measured in three directions with the Kistler MiniDyn C2 dynamometer. The transmission behavior, which is necessary for filtering of the force measurement data, of the measuring platform with mounted workpiece was defined by the impulse hammer method. The test setup is shown in Figure 2.

The tool head consists of a 20 mm face milling head with one insert. The flank face of the cutting edge is prepared in the form of a bar so that a constant chip thickness during machining of the structures in dependency of the structure depth can be maintained (Figure 3). The cutting edge was prepared by grinding.

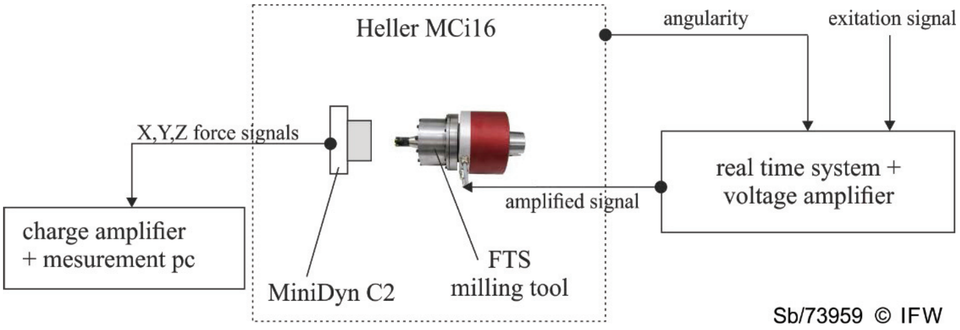


Fig. 2. Test setup.

3. Test Execution

In accordance with the structuring processes, the sinusoidal structures are generated in face milling with one insert and an engagement angle of the milling head of 45° to 135°. The sinusoidal excitation signal has the advantage that it cannot be influenced qualitatively by the transmission behavior (LTI system) of the tool. Only amplitude and phase can be influenced. This can be predicted by an existing transmission model and is taken into account during test interpretation. In order to prevent overlapping of structures, they are generated only every 10th revolution. The tests are run according to a full factorial two-stage test approach. The examined variables are varied with the values indicated in Table 1 for all three materials used.

Table 1. Chosen stages for parameters.

Stage	f_{struc} [Hz]	a_{struc} [µm]	f [mm]	v_c [m/min]	a_p[mm]
-	500	8	0.02	41	0.1
+	1500	17	0.07	82	0.2

The conditions of the machining process during structuring, the form of the structure and the prepared cutting edge are shown in Figure 3.

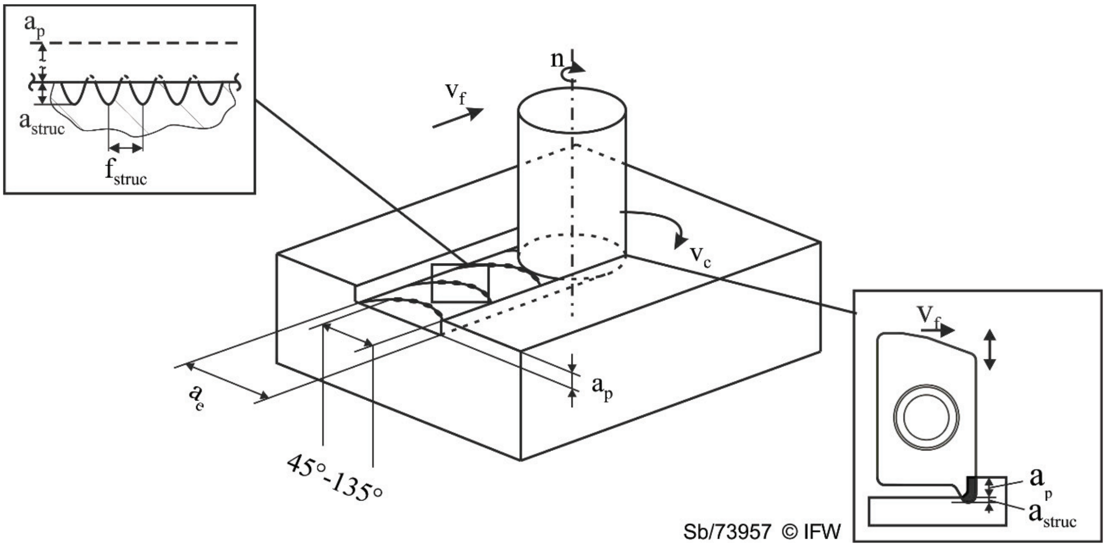


Fig. 3. Conditions of machining processes.

4. Processing of Measurement Data

Before evaluating the results of the measurements, the recorded forces are cleansed up from the falsifying self-oscillation of the dynamometer by means of an inverse filtering method [6]. In order to determine how the structuring is influencing the cutting forces, the average differences of force progression at one revolution with and without structuring in the engagement area of structuring are used. In the following those forces are called structuring forces F_{struc}. This is carried out for the force components F_c, F_{cN} and F_z. A statistical statement can be made by averaging the structuring forces over 10 machining operations. A schematic diagram of processing the data is shown in Figure 4.

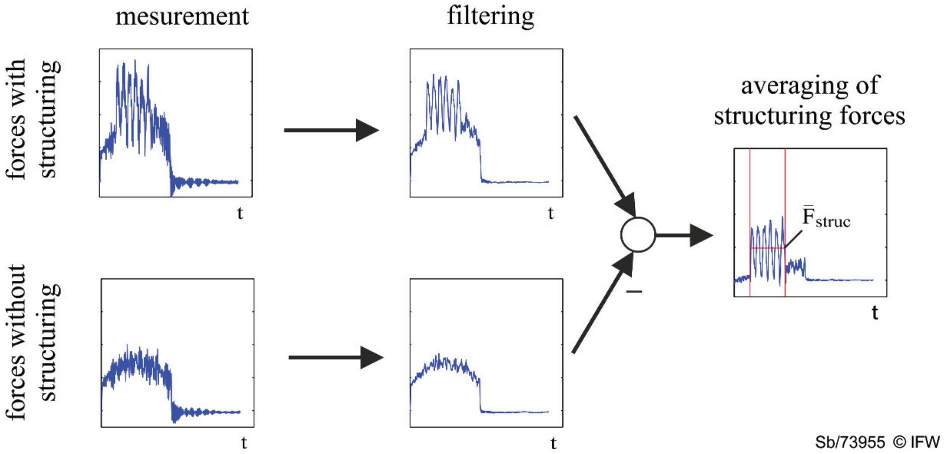
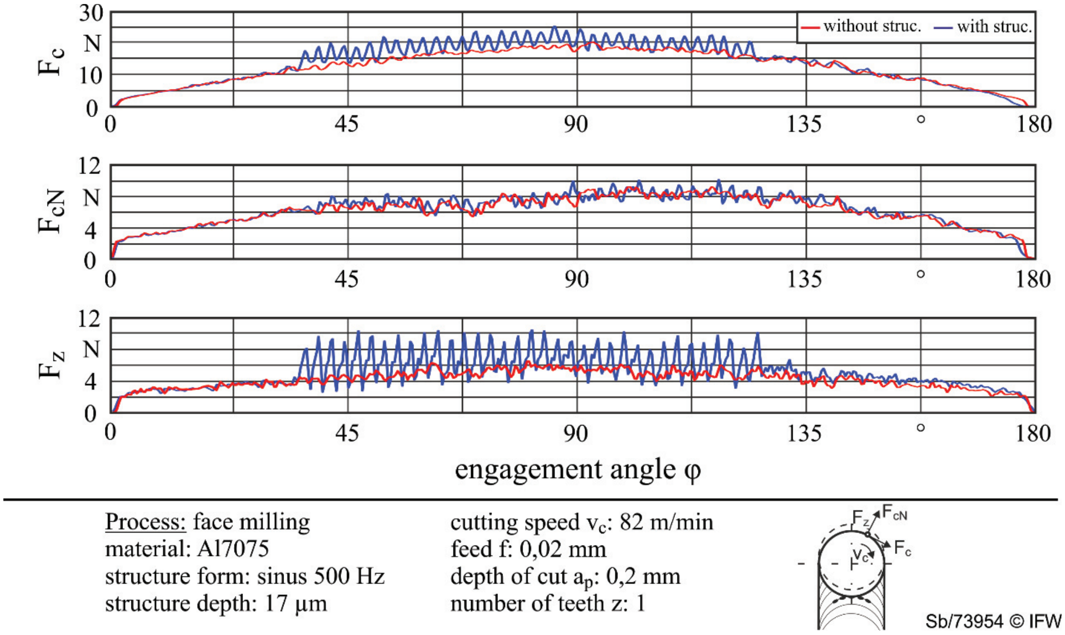


Fig. 4. Schematic diagram of the method to determine the average structuring forces.

5. Results of the Cutting Force Measurement

Figure 5 displays exemplary the process forces while machining Al7075. It can be seen that the sinusoidal structuring force is clearly visible in the cutting and passive forces. The structuring force progressions are symmetric concerning their gradient and descent. As a conclusion, no measurable influence of the changing shear zone can be given.



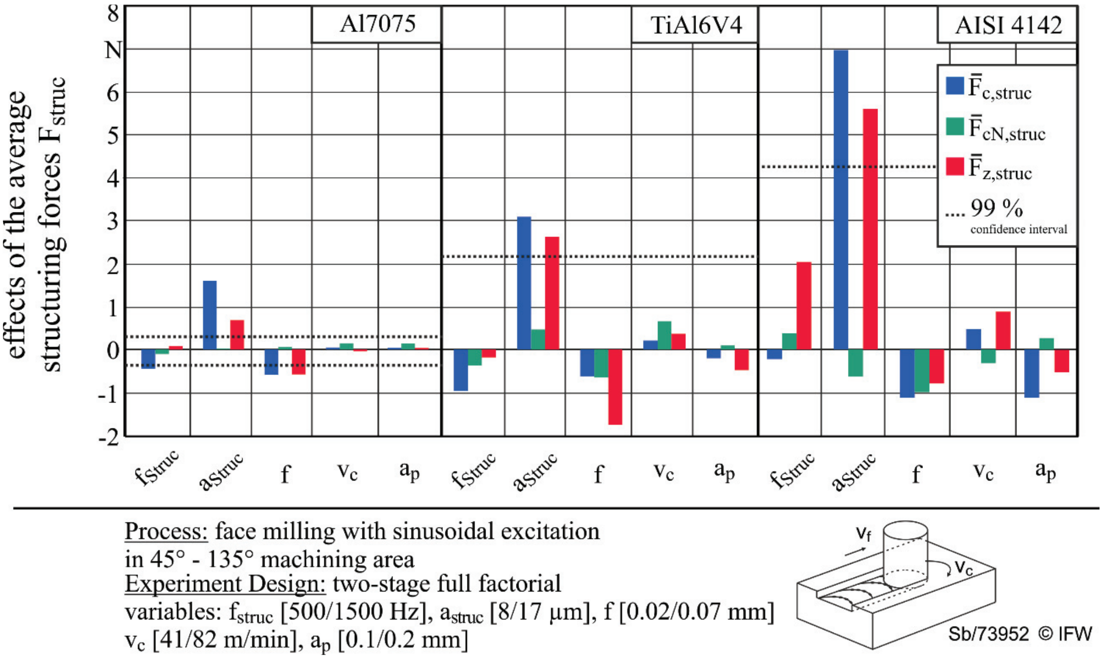
Process: face milling
material: Al7075
structure form: sinus 500 Hz
structure depth: 17 µm
cutting speed v_c: 82 m/min
feed f: 0,02 mm
depth of cut a_p: 0,2 mm
number of teeth z: 1

Fig. 5. Exemplary force progressions during structuring.

The effects of the average structuring forces were determined according to a statistical evaluation and provide information about an average change in force depending on the examined parameters (Figure 6).

The evaluation shows that significant effects on cutting and passive forces exist at a 99% confidence interval depending on structuring amplitude and partially on feed. Especially the effect of the structuring amplitude shows a double to triple average increase in force compared to the superior effects.

Since the reciprocal effects of the investigated parameters are below a 95% threshold, they are not displayed in Figure 6. Neither the structuring frequency nor the resulting different effective speed at the cutting edge have an influence on the structuring forces.



Process: face milling with sinusoidal excitation in 45° - 135° machining area
Experiment Design: two-stage full factorial
variables: f_{struc} [500/1500 Hz], a_{struc} [8/17 µm], f [0.02/0.07 mm]
v_c [41/82 m/min], a_p [0.1/0.2 mm]

Fig. 6. Main effects of the average structuring force of different materials.

The relatively high increase of the structuring force regarding the total depth of cut is primarily related to the rapid increase of the chip thickness to the full width of the bar at the cutting edge. As well as the change in chip width dependent on the excitation signal.

In Figure 7 the average cutting forces of all measurements dependent on depth of profile are plotted and confirm that there are no dependencies of the structuring forces on feed and cutting depth. The evaluation by using averaged values is allowed in this case due to a low scatter of the measurement values of 1 – 2 N. It has to be noted that the structuring forces in face milling operations are independent from regular machining conditions. The total forces while structuring result from the named conclusions as it follows:

$$F_{i,total} = F_{i,regular} + k_{i,struc} * a_{struc}(S(\varphi)) \qquad \text{with } i = c,z \tag{1}$$

Thereby Fi,regular represents the cutting forces without structuring. The constant ki,struc is the gradient coefficient, which is calculated as a product of the specific cutting force constant and an equivalent chip thickness. The structuring depth depends on the deflection signal S(φ) which is dependent on the engagement angle φ.

The linearity of the increase of structuring force results from the independency of the specific cutting force constant from chip width [7] and the rapid increase of the chip thickness to a static value of the whole structuring. This is verified by the constant amplitude of the structuring forces throughout the whole engagement area (Figure 5).

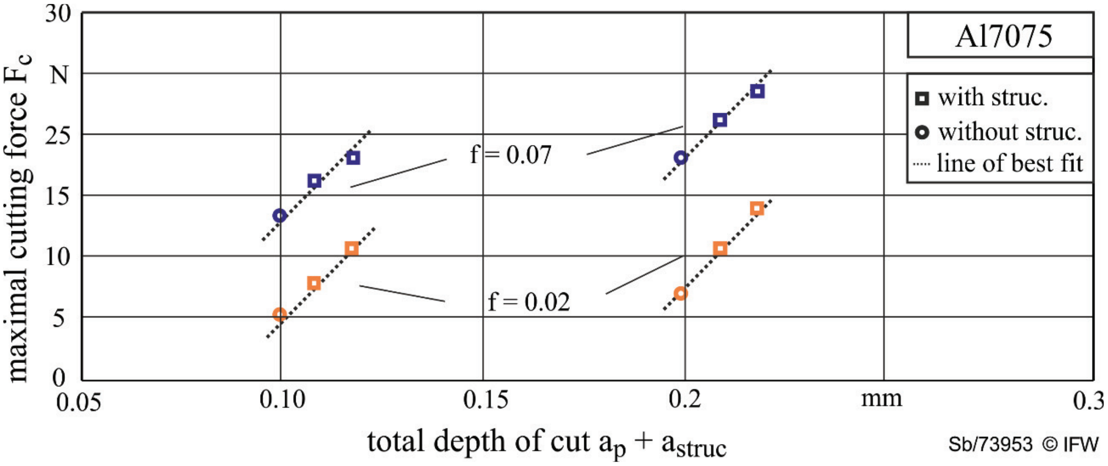


Fig. 7. Dependency of cutting force on depth of profile during structuring on the example of Al7075.

6. Summary

In conclusion it can be stated that the structuring forces necessary for machining of information carrying structures are largely dependent on the structuring amplitude and the macro geometry of the cutting edge. The results indicate that the structuring frequency and cutting speed do not affect the process forces. The structuring forces can be expressed by a linear behavior with a defined increase factor for the whole engagement area.

Since structuring increases the process forces significantly, precision errors may occur in the structuring depth to be attained if tools are not designed with sufficient stiffness. Therefore, structuring tools have to be sufficiently stiff in design and application, especially when machining steels like AISI4042.

Acknowledgements

The presented investigations were undertaken with support of the German Research Foundation (DFG) within the Collaborative Research Centre (CRC) 653 “Gentelligent Components in their Lifecycle“. The authors would like to thank the DFG for its financial and organizational support of this project.

References

[1] Denkena B, Henning H, Lorenzen LE. Genetics and intelligence: new approaches in production engineering, Prod. Eng. Res. Devl. 2011;4/1:65-73.
[2] Denkena B, Köhler J, Mörke T, Gümmer O. High-Performance Cutting of Micro Patterns. Procedia CIRP 2011;1:144-149.
[3] Lu X, Trumper DL. Ultra fast tool servos for diamond turning. CIRP Annals – Manufacturing Technology 2005;54/1:383-388.
[4] Woronko A, Huang J, Altintas Y. Piezoelectric tool actuator for precision machining on convertional CNC turning centers. Precision Engineering 2002;27/4:335-345.
[5] Trumper DL, Lu X. Fast Tool Servos: Advances in Precision, Acceleration, and Bandwidth, Towards Synthesis of Micro-/Nano-systems. London: Springer Verlag Limited; 2007. p. 11-19
[6] Magnevall M, Lundblad M, Ahlin K, Broman G. High Frequency Measurements of Cutting Forces in Milling by Inverse Filtering. Machining Science and Technology 2012;16(4):487-500.
[7] Denkena B, Tönshoff HK. Spanen Grundlagen. Berlin, Heidelberg: Springer Verlag; 2011. p. 55-56