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Integrated Approach for Prediction of Stability Limits for Machining with Large Volumes of Material Removal

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Abstract

High-speed machining of thin-walled structures is widely used in the aeronautical industry.

Higher spindle speed and machining feed rate, combined with a greater depth of cut, increases the removal rate and with it, productivity. The combination of higher spindle speed and depth of cut makes instabilities (chatter) a far more significant concern. Chatter causes reduced surface quality and accelerated tool wear. Since chatter is so prevalent, traditional cutting parameters and processes are frequently rendered ineffective and inaccurate.

For the machine tool to reach its full utility, the chatter vibrations must be identified and avoided. In order to avoid chatter and implement optimum cutting parameters, the machine tool including all components and the workpiece must be dynamically mapped to identify vibration characteristics.

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3 The aim of the presented work is to develop a model for the prediction of stability limits as
4 a function of process parameters. The model consists of experimentally measured vibration
5 properties of the spindle-tool, and finite element calculations of the workpiece in (three)
6 different stages of the process. Commercial software packages used for integration into the
7 model prove to accomplish demands for functionality and performance. A reference
8 geometry that is typical for an aircraft detail is used for evaluation of the prediction
9 methodology.
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22 In order to validate the model, the stability limits predicted by the use of numerical
23 simulation are compared with the results based on the experimental work.
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30 *Keywords: High-speed machining; Regenerative chatter; Stability lobes; Finite element*
31 *analysis; Laser Doppler Vibrometry*
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38 **1 Introduction**

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41 An increasing trend in modern manufacturing industry points towards larger ranges of
42 variation in production systems. This is a direct consequence of the effort to satisfy
43 customer demands for fast deliveries of new products. The present situation in the
44 manufacturing industry is that they have to adjust much of their cutting processes as a
45 consequence of the uncertainty that exists in the influencing machining conditions. In order
46 to do this, techniques must be used to handle variations in the manufacturing conditions as
47 the frequent reconfigurations and setups generate.
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3 In manufacturing of components for aerospace applications, aluminium is one of the most
4 frequently used materials. In machining aluminium, higher spindle speed and machining
5 feed rate combined with a greater depth of cut, increases the removal rate and with it,
6 productivity. The combination of higher spindle speed and depth of cut makes instabilities
7 (chatter) a far more significant concern. In machining, chatter is perceived as an unwanted
8 excessive vibration between the tool and the workpiece, resulting in a poor surface finish
9 with possible initiation of micro-cracks. Chatter vibrations accelerate also tool wear which
10 has a deteriorating effect on the tool life, and the reliability of the machining operations.

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12 Especially for the cases where long slender end mills or highly flexible thin-wall parts are
13 involved, chatter is almost unavoidable unless special suppression techniques are used or
14 the removal rate of material is substantially reduced.

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16 Currently working with the preparation machining process, the natural frequencies of the
17 workpiece are measured and analysed when there is a problem with the quality of the
18 surface or cutting process. The manufacturing process is stopped just before the cutting
19 starts in the problem area and sensors are put in the same area. The extensive experimental
20 work is a limiting factor in application of this approach to manufacturing of aluminium
21 aerospace components. The removal of material in aerospace applications is vast and
22 figures up to 90% of the original volume which results in non-linear behaviour due to time
23 variant geometry and stiffness. Due to time and costs consuming experimental work, the
24 long-term goal is to develop a tool for the prediction of chatter vibrations that is based on a
25 digital prototype.

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27 The first attempt to describe chatter was made by (Arnold 1946). (Tobias and Fishwick
28 1958) presented a comprehensive mathematical model and analysis results of chatter

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3 vibrations. The importance of predicting stability in milling has increased due to advances
4 in high-speed milling technology. At high speeds, the stabilizing effect of process damping
5 diminishes, making the process more prone to chatter. On the other hand, stability limits
6 usually referred to as stability lobes exist at certain high spindle speeds which can be used
7 to substantial increase the chatter free material removal rate, provided that they are
8 predicted accurately, see e.g. (Smith and Tlustý 1993). (Wiercigroch and Budak 2001)
9 presented a critical review of the modelling and experimental investigations. In this work,
10 sources of nonlinearities, chatter generation and suppression in metal cutting are studied. In
11 the papers by (Moon and Kalmar-Nagy 2001, Balachandran 2001), the prediction of
12 complex, unsteady and chaotic dynamics associated with cutting processes through
13 nonlinear dynamical models is reviewed. A mathematical model of mechanics and
14 dynamics of general milling cutters is presented by (Engin and Altintas 2004).

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32 In general, several physical mechanisms causing chatter can be distinguished. Frictional
33 chatter due to friction between the tool and workpiece, mode-coupling chatter and thermo-
34 mechanical chatter caused by the thermodynamics of the cutting process are often called
35 primary chatter.

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Secondary chatter is caused by the regeneration of waviness on the surface of the
workpiece. This phenomenon is called regenerative chatter and is considered to be one of
the most important causes of instability in the cutting process.

During machining as the cutter tooth enters into the cut, the cutting system (tool-holder,
tool) deforms in bending due to applied cutting forces. Forces released by the tooth exiting
the cut cause the cutting system to vibrate with its natural frequency. The vibration leaves
small waviness on a surface of the workpiece, as illustrated in figure 1. If the following

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3 tooth impact does not match the natural frequency of the cutting system, the chip thickness
4 will increase as well as the applied cutting forces that result in a larger deformation of the
5 system. The worst condition is when the vibration from cutting edges moves and the mirror
6 image of the surface waviness is 180° out of phase, see figure 1. In order to avoid chatter in
7 machining means that the tooth impact frequency has to match the natural frequency of the
8 cutting system. The ideal condition is when the surface waviness and cutting vibration are
9 in phase.
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27 Various models to predict the stability boundaries related to chatter have been suggested by
28 e.g. (Altintas 2000, Tlustý 2000, Li *et al.* 2000, Peigne *et al.* 2004, Solis *et al.* 2004 and
29 Toh 2004). These analytical-experimental models describe the cutting process dynamics
30 using cutting parameters that are constant for the spindle speed range under consideration.
31 This means that the dependencies of the dynamic behaviour of the milling machine or the
32 cutting process on the spindle speed are not modelled.
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41 In order to investigate such dependencies, dedicated experiments have been performed and
42 reported by (Faassen *et al.* 2003). In this paper, the method for prediction of the chatter
43 boundaries is proposed and applied to predict the chatter stability as a function of process
44 parameters. A method for calculation of stability limits considering the flexibility of
45 workpiece is presented by (Bravo *et al.* 2005).
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53 The approach that follows the methodology developed by (Altintas 2000) is illustrated in
54 figure 2. Here, the prediction of a stable cutting process is based on experimental modal
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3 analysis. For the evaluation of experiments and calculation of stability lobes, the
4 commercial software CutPro was used. CutPro is an analytic simulation software package,
5 developed for off-line milling process optimisation.
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10 In models discussed previously, the vibration properties of the workpiece are predicted
11 from the constant material parameters and the geometry. Alternatively, the vibrations
12 properties of the workpiece are calculated from experimental modal analysis.
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16 In manufacturing thin-walled structures, the material removal is vast which results in
17 significant changes of vibration properties. Due to it is unfeasible the use of constant
18 cutting parameters predicted for the complete machining process.
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23 In order to obtain reliable prediction for machining thin-walled components, an extensive
24 trial and error experimental work was needed. The main advantage of the proposed model
25 (approach) is using a digital prototype for the preparation of manufacturing process. This
26 means that all trial-error experiments are run numerically instead of using physical
27 prototypes which is absolutely necessary in the case of machining structures with vibration
28 properties that change during machining. Saving time and money is the most desirable
29 result of the application.
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2 Method

2.1 Digital model for prediction of chatter vibrations

The majority of critical frequencies are the natural frequencies of each component in the machining system. The machine tool itself and the workpiece are influencing the stability and have to be handled.

In order to avoid time consuming and expensive experiments, a supportive integrated tool based on existing commercial software was introduced, see figure 3. Application of a digital model facilitates the analysis of vibration and the prediction of a chatter-free cutting process. The proposed model integrates the analytical calculations of the tool (Altintas 2000) and the dynamic finite element analysis of the workpiece in several stages of the process.

The vibration properties of the spindle are investigated experimentally using Laser Doppler Vibrometry (LDV). The software CutPro was used for the evaluation of a stable cutting process just as any knowledge database.

In the presented digital model, the continuous machining process is discretized in time to obtain models of current stages in the machining process. Stages of the process when the cutting tool is changed are chosen for the analysis.

‘[Insert figure 3 about here]’

2.2 Definition of tool path and geometry for the analysis

A reference geometry that is typical for an aircraft detail, see figure 4, is used for evaluation of the prediction methodology. Material removal in manufacturing this detail is large. For the illustration, the volume of the initial stock was $1.896 \times 10^6 \text{ mm}^3$ and the volume after final milling operation was $0.218 \times 10^6 \text{ mm}^3$. The thickness of the initial monolith was 40 mm, the final thickness of the bottom was 1.0 mm and the flange thickness was 1.5 mm.

The structure has shown significant sensibility to vibrations during the machining. Before manufacturing, it must be first decided which operations are required to go from a stock geometry to the finished final component. A part programme for machining of the geometry is generated in a Computer Aided Manufacturing (CAM) system. The solid model of the structure that is created with nominal finished dimensions in a Computer Aided Design (CAD) system is transferred to the CAM module by selecting from the system database. In the presented work, the I-DEAS CAD/CAM system was used.

Modern CAM software offers high levels of support for creating tool paths which is necessary for the definition of the component geometry from a piece of stock material. The CAM software automatically creates suitable paths for the tool to follow by the use of built-in algorithms. It is generally possible to specify how critical parts of the tool path such as entry and exit from the part or significant changes in the direction of the tool path such as machining in a corner are to be handled.

In order to perform high speed roughing in volume milling, the scan type constant load is to be used. The milling is based on principles of constant cutting conditions, constant chip load, continuous tool engagement and also minimizing of sudden changes of tool direction.

For the optimization of the mentioned strategies, a smooth tool path is used starting from

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3 rough milling down to the finishing. In order to achieve as stable as possible tool path, the
4 machining is started from the middle of the working part with the direction outwards.
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8 The analysis of natural frequencies and response analysis are carried out for the sequence of
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10 as cut geometries (in-process stock geometries) that are identified to be significant for the
11 manufacturing process. The in-process stock geometry is generated from the current state
12 of the process at the end of each operation or even at discrete time intervals.
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16 I-DEAS/CAM software allows one to calculate and to export a solid model geometry for
17 each step (in-process stock) in the machining of the part. In-process stock is a
18 representation of the stock after the tool has cut away excess material for each operation.
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20 After a tool path is created, the software updates the shape of the in-process stock
21 geometry. For the first operation in the first setup, the tool path removes material from the
22 initial stock in the assembly.
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39 The updated in-process stock is saved and used for the next cutting operation. The
40 geometry for two significant stages of the process is shown in figure 4. The generation of
41 in-process stock sequences supports the definition of the time variant geometry for every
42 step in the machining process and preparation of simulation models for the stability
43 analysis.
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2.3 Modelling of stable milling processes

As mentioned previously, instabilities that can lead to chatter during milling operations are of interest. Roughing operations such as volume clear are often sensitive to chatter. Vibrations significant for finishing operations with a small radial depth of cut are a combination of regenerative chatter vibrations and forced vibrations.

A schematic workpiece-tool model of the milling process is represented by an equivalent two-degrees-of-freedom spring-mass-damper system and shown in figure 5. Details of modelling can be found in e.g. (Altintas 2000).

‘[Insert figure 5 about here]’

In figure 5, the feed direction and spindle rotation are shown for an up milling operation. The initial surface of the workpiece is smooth without waves during the first revolution, but the tool starts leaving a wavy surface behind because of the structural modes of the machine tool-workpiece system in the feed direction. When the second revolution starts, the surface has waves both inside the cut where the tool is cutting (inner modulation (t)) and on the outside surface of the cut owing to vibrations during the previous revolution of cut (outer modulation ($t - T$)). Depending on the phase shift between the two successive waves, see also figure 1, the maximum chip thickness may exponentially grow while oscillating at a chatter frequency that is close but not equal to a dominant structural mode in the system. Hence, the resulting dynamic chip thickness is no longer constant but varies as a function of vibration frequency and the speed of the spindle. Generally, the dynamic thickness can be expressed as follows:

$$h(t) = h_0 \sin \Omega(t) + [x(t) - x(t - T)] \sin \Omega(t) + [y(t) - y(t - T)] \cos \Omega(t), \quad (1)$$

where h_0 is the intended chip thickness, which is equal to the feed rate of the machine, and x , y are components of the dynamic chip thickness produced owing to vibrations at the present time t and one spindle revolution period (T) before. Assuming that the workpiece is approximated by a two-degree-of-freedom system in two uncoupled and orthogonal directions, the following equation of motion is obtained:

$$\begin{bmatrix} m_x & 0 \\ 0 & m_y \end{bmatrix} \begin{bmatrix} \ddot{x}(t) \\ \ddot{y}(t) \end{bmatrix} + \begin{bmatrix} c_x & 0 \\ 0 & c_y \end{bmatrix} \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \end{bmatrix} + \begin{bmatrix} k_x & 0 \\ 0 & k_y \end{bmatrix} \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} F_x(t) \\ F_y(t) \end{bmatrix}. \quad (2)$$

Here, the terms $m_{x,y}$, $c_{x,y}$ and $k_{x,y}$ are the modal mass, damping and stiffness, respectively, and F_x and F_y are the tangential and radial cutting forces components resolved in x , y directions. The tangential and radial components of cutting forces are proportional to the axial depth of cut a , the dynamic chip thickness $h(t)$ and can be expressed as follows:

$$\begin{aligned} F_t(t) &= K_f ah(t) \\ F_r(t) &= K_r F_t(t) \end{aligned} \quad (3)$$

The coefficients K_f and K_r are cutting constants in the feed and normal directions. Equation (2) can be rewritten in a more compact matrix form as follows:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(u(t) - u(t - T)). \quad (4)$$

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6 Equation (4) is a time-delay differential equation and is solved numerically. For the
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8 solution of the dynamic response problem, the mode superposition method can be used.
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10 The mode superposition method for time-history analysis is based on normal mode
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12 dynamics. Normal mode dynamics calculates the natural frequencies and natural modes of
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14 vibrations by means of the finite element method (FEM). Mode shapes and natural
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16 frequencies are used for identification of structural resonances that may produce an
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18 undesirably large structural response to the dynamic input. Further, the response of
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20 structures to dynamic inputs can often be assumed to be a combination of the mode shapes
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22 corresponding to each mode. This lets the mode shapes construct a numerically efficient
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24 representation of the structure (modal representation) for use in further analyses.
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29 The Lanczos method is applied to the present analysis as the most effective method for the
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31 solution of large-scale problems.
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34 35 36 37 ***2.4 Calibration of the simulation model*** 38

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40 For the machine tool to reach its full utility, the vibrations that contribute to chatter must be
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42 identified. It is usually the mismatch between the frequency response of the spindle and the
43
44 frequency behaviour at the cutting point (contact between cutter and workpiece) which
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46 contributes to uncertainties in the machine modelling. In order to obtain reliable results, a
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48 simulation model that is a model of the real behaviour has to be used. The more the process
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50 is accurately simulated; the closer to reality results will be obtained. This is a way to
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52 decrease the possibility of modelling errors.
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3 In order to make a more accurate prediction of the dynamic behaviour of the cutting
4 process, Laser Doppler Vibrometry (LDV) was used for calibrating the simulation model.
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6 LDV is a non-intrusive optical method that is fast becoming common for vibration
7 measurements. The non-contact nature of LDV means that the structure can be analysed
8 without introducing additional mass loading which is important in the cases of light
9 weighted, thin-walled parts. Basically, the device is a heterodyne interferometer based on
10 the Doppler effect of backscattered light, as schematically presented in figure 6. A laser
11 beam is divided by a beam splitter (BS) into a reference beam and an object beam. The
12 reference beam reflects on a mirror (M) and is redirected to a modulator where the beam is
13 then shifted by a known amount of frequency (f_B). This frequency shift is needed for
14 resolving the direction of the measured vibration velocity. Systems differ by the method
15 used for obtaining this frequency shift; our Polytec laser vibrometer uses an acousto-optic
16 modulator (Bragg cell) with a frequency shift of about 40 MHz. The object beam reflects
17 from the target and, hence, is Doppler shifted (f_D) due to the target velocity and mixes with
18 the shifted reference beam on the photo detector. Depending on the optical path difference
19 between these two beams, they will interfere constructively or destructively. When the
20 target is moving, the intensity measured by the photo detector will be time dependent.
21 Frequency demodulation of the photo detector signal by a Doppler signal processor
22 produces a time resolved velocity component of the moving target.
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‘[Insert figure 6 about here]’

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3 In the application of laser vibrometry to experimental modal analysis, the surface of the
4 vibrating object is scanned. A scan is a sequence of single point measurements. Two small
5 servo controlled mirrors in the scanning head make it possible to deflect the beam both in
6 the horizontal and the vertical direction. The measured data in each scan point is then
7 compared to a reference signal. In this case, the measured object is excited by an electro
8 dynamic shaker. A force transducer at the driving point acts as a reference. Mode shapes
9 and frequencies are then extracted from the measurements data by the LDV system
10 software.

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12 The LDV was used to calibrate the boundary conditions in the FEM model and also to
13 experimentally determine the vibration properties of the setup cutting tool–spindle. Details
14 about measurements on the spindle are presented in (Rantatalo *et al.* 2004).

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16 The performance of the finite elements is evaluated using the stock part that is fixed in the
17 measuring frame by means of flexible suspensions (rubber band). The flexible fixture
18 allows the part to reproduce all rigid body modes. A shaker is used to excite the stock by a
19 random pulse. The first non-singular mode and the corresponding natural frequency of
20 1947 Hz were chosen to illustrate the result of the experiment, see figure 7.

21
22 The finite element model with the same type of flexible constraint allowing all rigid body
23 modes is analysed using an eigen-problem solver. For the FEM discretization, 10-node
24 tetrahedron elements with quadratic interpolation were used. Material parameters for the
25 reference part were as following: Elasticity modulus 7.1×10^4 MPa, Poissons ratio 0.315,
26 Density 2.8×10^{-6} kgmm⁻³.

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28 The material type was: Zn-Mg-Cu-Zr-Al – aircraft grade.

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3 The simulation result – first non-singular mode with a frequency of 1970 Hz is also
4 presented in figure 7. The simulation shows good agreement with the experiment.
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15 The next step in the calibration of the finite element model was an accurate definition of the
16 boundary conditions for the analysis. The workpiece was mounted on the machine table in
17 a Liechti Turbomill machining centre by the use of stiff clamps. The setup containing the
18 stock part and the shaker is shown in figure 8.
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24 The frequency response to a random signal was measured by means of a LDV. The first
25 mode with corresponding frequency is shown in figure 9. A sequence of numerical
26 experiments was run to iterate to the correct stiffness of the fixing clamps. The result of the
27 analysis is presented in figure 9. Again, the first mode and frequency of the fixed stock
28 were chosen to compare the numerical result with the experiment. The simulation shows
29 again good agreement with the experimental results.
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48 **3. Modelling results and experimental verification**

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53 ***3.1 Evaluation of a stable cutting process***

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3 The digital model, constructed and calibrated in previous sections was used to pursue an
4 analysis of stability boundaries. The sequence of as cut geometries shown in figure 4 was
5 used for generation of FEM models. During the machining, the initial stock mass of 5.31 kg
6 is reduced to 0.61 kg after finishing the operations. This factor and a lack of symmetry in
7 geometry which is very common in this type of manufacturing had large impact on the
8 vibration properties. In order to show the significant changes of the vibration properties, the
9 first natural frequency and the modes of the initial stock and final geometry were chosen
10 for the comparison. The simulated first frequency 2940 Hz for the stock decreases after the
11 final milling operation to 800 Hz. Simulated and LDV experimental results for the final
12 geometry are shown in figure 10.

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‘[Insert figure 10 about here]’

The FE model used for solving the eigenvalue problem was also used for transient response analysis by including appropriate initial and boundary conditions. Transient analysis compares the dynamic response of a structure to a set of simultaneous transient excitations. The response at each time instant was calculated by combining the modal response obtained using time integration. The workpiece was loaded by a short force pulse in two orthogonal directions in the plane $x - y$ which was parallel to the bottom plane of the workpiece.

The frequency response functions (FRF) in mm N^{-1} obtained from FE analysis for a sequence of cut geometries and also obtained from LDV measurements on the spindle were exported into the CutPro software were used for processing and stability lobes calculations. Features implemented in the CutPro software for the generation of data describing a

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3 machining process. In the preparatory stage, the cutter data and cutting coefficients for the
4 current workpiece material and a cutting force model were defined. After all the
5 preparatory steps were accomplished, the necessary input data to continue with the stability
6 lobes calculation were available.
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12 The stability lobe defines region of stable and unstable cutting zones as a function of
13 maximum depth of cut and spindle speed and is used to select appropriate machining
14 parameters. Stability lobes that are predicted for the initial stock geometry and for a $\phi 40$
15 mm CoroMill cutter are shown in figure 11. Finish milling of the final geometry is done
16 using a $\phi 16$ mm CoroMill R216 cutter. The predicted stability lobes for final operations are
17 presented in figure 12.
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43 ***3.2 Experimental verification***

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46 In order to study the accuracy of the prediction, the stability boundaries in terms of depth of
47 cut and spindle speed obtained by FE modelling had to be validated with the experimental
48 procedures.
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53 A comparison of stability lobes predicted by the experimental modal analysis using CutPro
54 with stability lobes calculated by the use of FEM analysis is presented in figure 13. The
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3 prediction based on FEM analysis yields lower values for the critical depth of cut than the
4 prediction based only on experimental procedures. The difference in critical depth of cut
5 above all for higher spindle speeds can be explained by the fact that the FEM-based
6 prediction involves analysis in 3D that is not the case in the experimental approach. The
7 prediction based on experimental modal analysis involves only excitations and response
8 measurements in the same direction (testing in 1D space).
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20 A series of milling tests in the Liechti machine were performed for the verification purpose
21 on the initial monolithic stock with a R390, \varnothing 40 mm tool. The spindle speed and feed rate
22 were kept constant at 9500 rpm and 3000 mm min⁻¹, respectively, while the axial depth of
23 cut was varied. Three different axial depths of cut, 1.5 mm, 2 mm and 3 mm were studied.
24 The cuts were placed sequentially along the y-direction. The radial depth of cut was equal
25 to the radius of the tool. The length of each cut was 58 mm and for the next cut, the tool
26 was moved to the right by a distance of 42 mm leaving 2 mm between the cut paths. The
27 range of depth of cut was sufficient to move the system across different regions of stability.
28 These cutting points are marked in figure 13. At a 1.5 mm depth of cut, the system was
29 clearly within the stable region of the curve predicted by the experimental work, and falls
30 just within the stable region of the stability curve predicted by the FEM analysis. At a 2
31 mm depth of cut, the system was inside the stable region of the experimental predicted
32 curve but outside the FEM based one. Finally, at a 3mm depth of cut, the system fell
33 outside the stable region of the two curves. A Brüel & Kjaer Type 4393 accelerometer was
34 mounted on the workpiece, about 10 cm from the tool path, in the feed direction. Also, a
35 Brüel & Kjaer Type 4189 microphone was used for sound recordings. The microphone was
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3 placed about 70 cm from tool path, directed towards the tool. The sensitivity of the
4 accelerometer and the microphone was $0.314 \text{ pC m}^{-1} \text{ s}^{-2}$ and 45.5 mV Pa^{-1} , respectively.
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8 The data were sampled at 32.8 kHz and a low-pass filter of 10 kHz was used. After
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10 machining, the generated surface quality was examined in order to determine about the
11 process stability. Figure 14 shows a photo of the milled surface.
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15 At a 1.5 mm depth of cut, the sound pressure level, SPL at the spindle rotation frequency
16 was 99 dB, and the surface finish was very good, see Figure 14(a). The system was in a
17 stable state. At a 2 mm depth of cut, the SPL was 103 dB and the surface finish was
18 acceptable but not perfect, see Figure 14(b). Removed chips were smeary and sticking on
19 the tool, and hence, a coolant was needed. The system was in a transition state between the
20 stable and unstable positions. At a 3 mm depth of cut, the SPL was 106 dB and the
21 accelerometer level was higher, especially at about the 10th, 22nd, and 51st spindle
22 harmonics. The surface finish was bad, (see Figure 14(c)) and the system was unstable.
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34 ‘[Insert figure 13 about here]’
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37 ‘[Insert figure 14 about here]’
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42 **4. Conclusions**

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45 Chatter is a dynamic phenomenon that can appear in machining at almost any spindle
46 speed. Stable machining cannot be achieved without investigating the influence of chatter
47 on the cutting process. A standard way to obtain reliable prediction of a stable machining
48 process is the application of the methodology based on the experimental modal analysis.
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50 This approach requires, in the case of thin-walled structures, extensive trial and error
51 experimental work.
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In this work, an integrated tool for prediction stability boundaries was presented. A digital model for the milling process based on integration of CAD, CAM, and FEM was developed. Commercial software packages used for integration into the model prove to accomplish demands for functionality and performance. Not only does the suggested approach give safer machining, it also carries promises of an overall higher productivity.

In order to avoid the usual mismatch between the frequency response of the spindle and the frequency behaviour at the cutting point (contact between cutter and workpiece) which contributes to uncertainties in the machine modelling, dedicated experimental procedures which were based on LDV measurements were used.

The non-contact nature of the LDV makes accurate and fast measurements possible with an easy setup without any mass loads. This is of crucial importance when measuring on thin-wall structures with low mass and rigidity since the eigen mass of the accelerometers disturbs the measurements. Due to the complex geometry and fixture of the detail the dynamic FEM models needed to be validated and improved, especially regarding boundary conditions where even small changes in the fixture could result in considerable differences in the natural frequencies.

The LDV was also able to make measurements on the rotating spindle, spindle housing, tool, tool holder, workpiece, clamps and machine table in one setup and gave an overall picture of the machining.

The performed milling tests showed good agreement with the predicted stability lobes (at 9500 rpm). Machining just within the stable region predicted using the FEM analysis resulted in the best surface finish.

5. Acknowledgement

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10 11 **7. Figure Captions**

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15 Figure 1. Chip thickness variation (dashed area) between the tool and the workpiece. In phase thickness
16 generation is shown in upper half of the figure and out of phase generation in lower half.
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21 Figure 2. Prediction of the chatter-free cutting process based on experimental approach.
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25 Figure 3. The model for the prediction of the chatter-free cutting process that integrates numerical simulation
26 with experimental procedures based on LDV measurements.
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31 Figure 4. Sequence of in-process stock (as cut) geometries: Left - initial stock; right – final geometry.
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35 Figure 5. Regenerative effect due to chip-thickness variation.
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39 Figure 6. Schematics of the scanning Laser Doppler vibrometer. The laser beam is divided into a reference
40 beam and an object beam. These two interfere on the photo detector and the velocity of the target is obtained
41 after demodulation of the signal. Beam splitter (BS), mirror (M), laser frequency (f), Bragg cell frequency (f_B)
42 and Doppler frequency (f_D).
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48 Figure 7. Left – FEM analysis of the stock with flexible suspension. The colour scale represents the
49 normalized first mode corresponding to the first natural frequency of 1970 Hz. Right – LDV measurements.
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51 The colour scale represents quantitative displacements corresponding to the first frequency of 1947 Hz.
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56 Figure 8. Photo of the setup with the stock and the shaker mounted in the Liechti machine.
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5 Figure 9. First mode and natural frequency are shown for the comparison of LDV measurements with FEM
6 analysis. Left – FEM modelling. The colour scale represents the first normalized mode corresponding to the
7 first natural frequency of 2940 Hz. Right – Experimental result. The colour scale represents quantitative
8 displacements corresponding to the first frequency of 2835 Hz.
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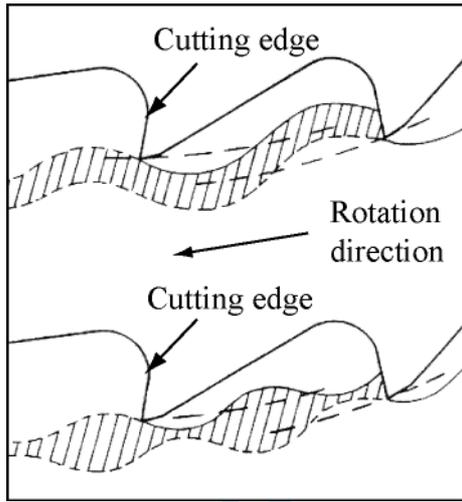
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15 Figure 10. The first natural frequency and mode for final geometry. Left – FEM modelling. The colour scale
16 represents the first normalized mode corresponding to the first natural frequency of 800 Hz. Right –
17 Experimental result. The colour scale represents quantitative displacements corresponding to the first
18 frequency of 685 Hz.
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25 Figure 11. Stability lobes for the initial stock and a $\phi 40$ mm Sandvik Coromant CoroMill 390 cutter predicted
26 using FE analysis.
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31 Figure 12. Stability lobes for the finishing of the final geometry and a $\phi 16$ mm Sandvik Coromant R216 cutter
32 predicted using FEM analysis.
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37 Figure 13. Comparison of stability lobes predicted for the initial stock. Dashed curve: predicted by FEM
38 analysis, solid curve: predicted using Experimental Modal analysis and circle: performed milling tests.
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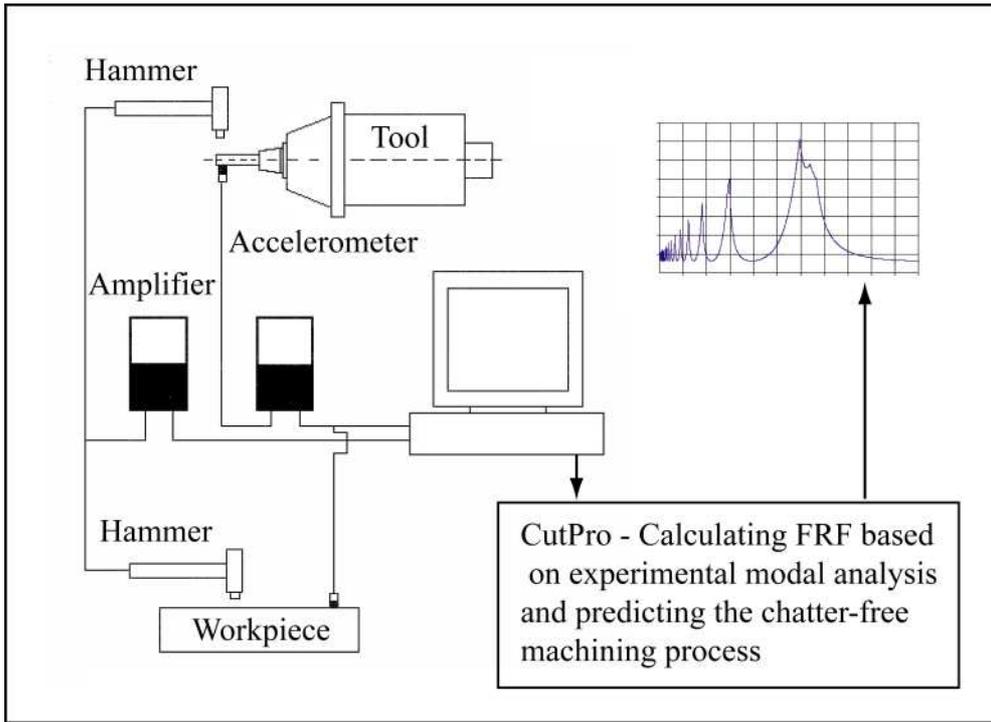
42 Figure 14. Photo of the machined surface. (a) 1.5 mm axial depth of cut, (b) 2 mm axial depth of cut and (c) 3
43 mm axial depth of cut.
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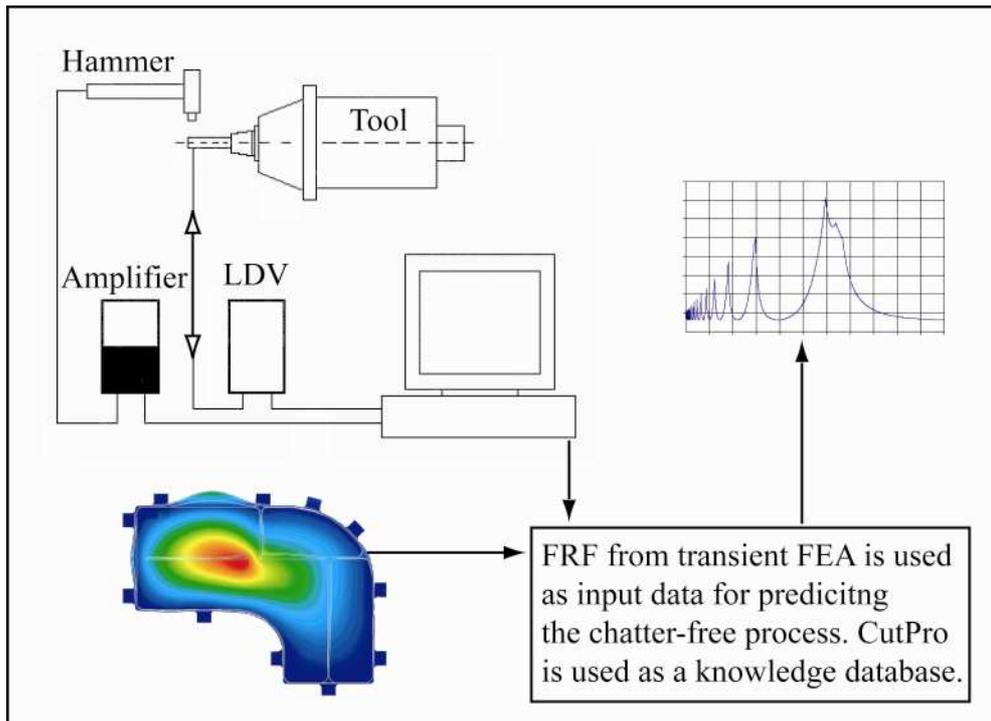
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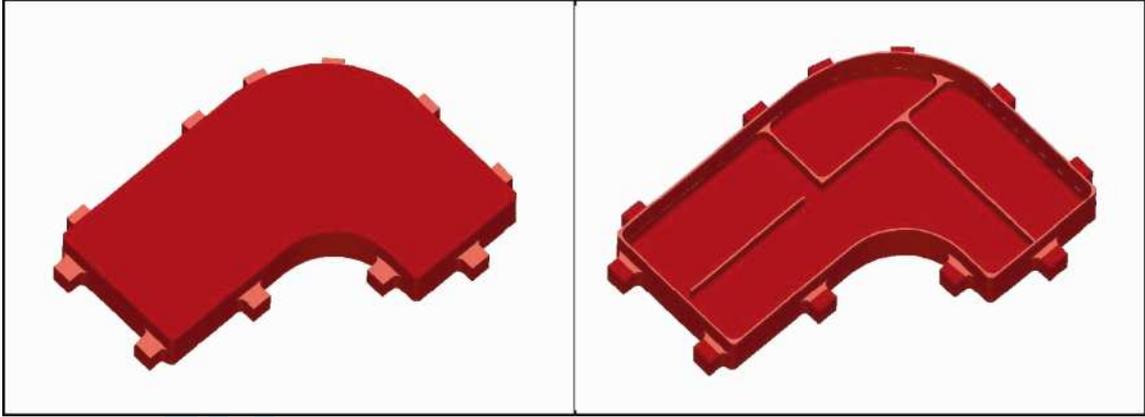
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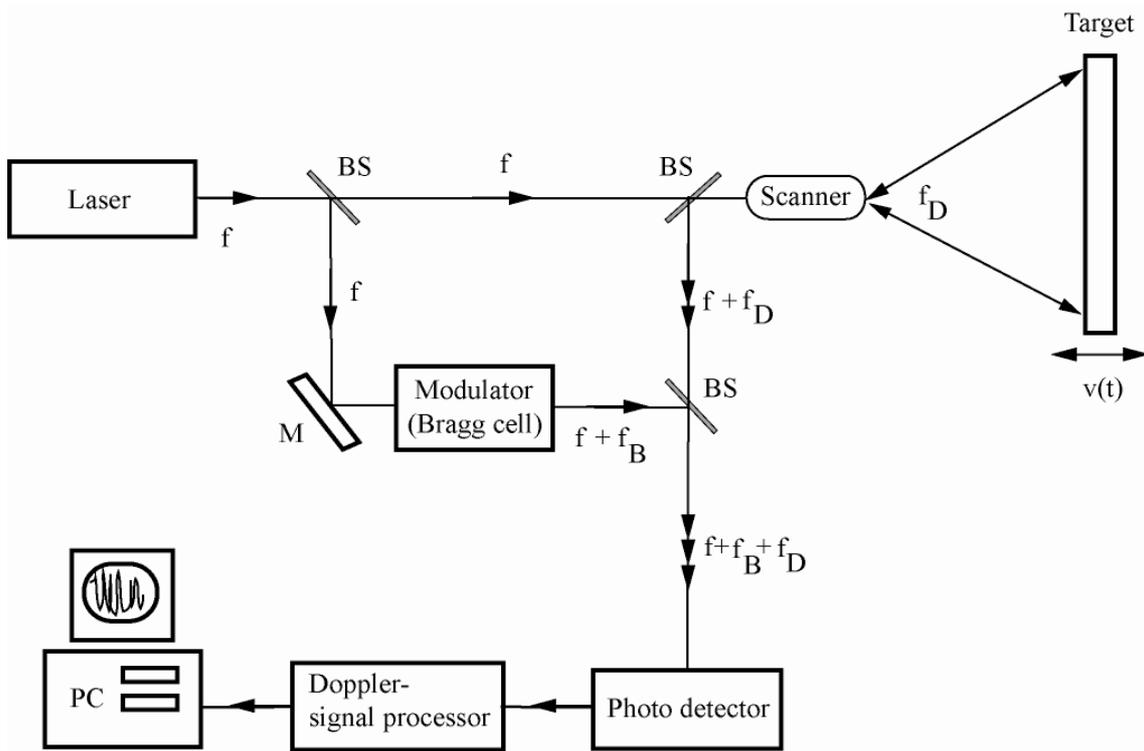


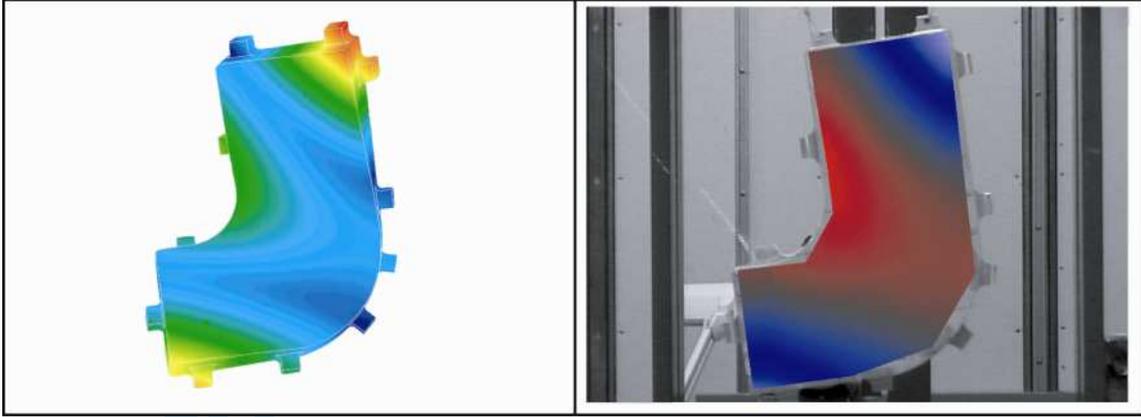
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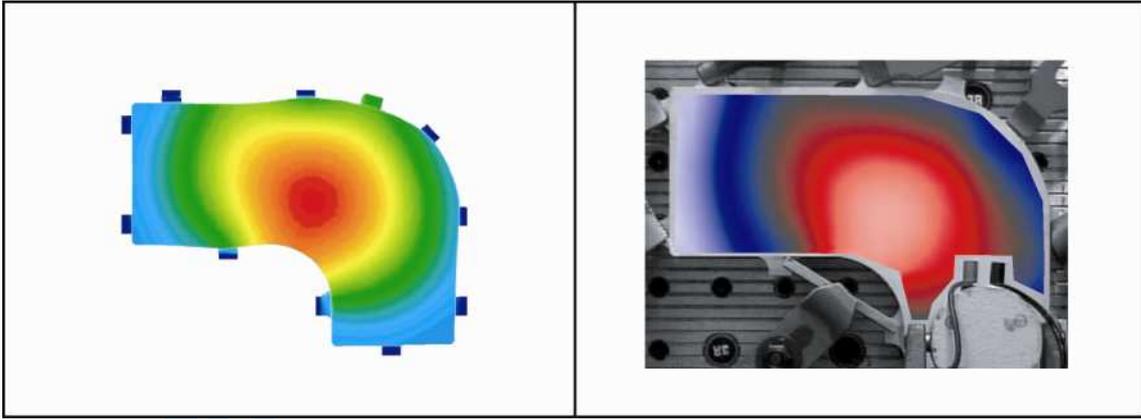
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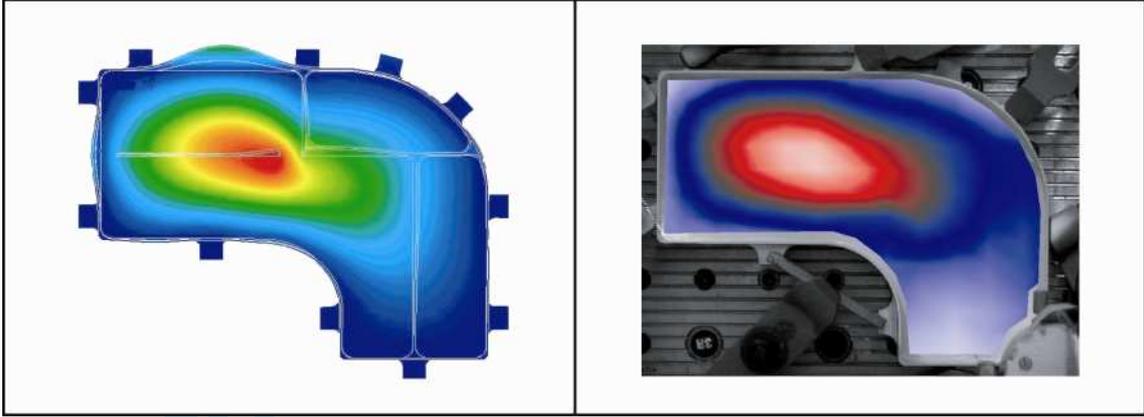
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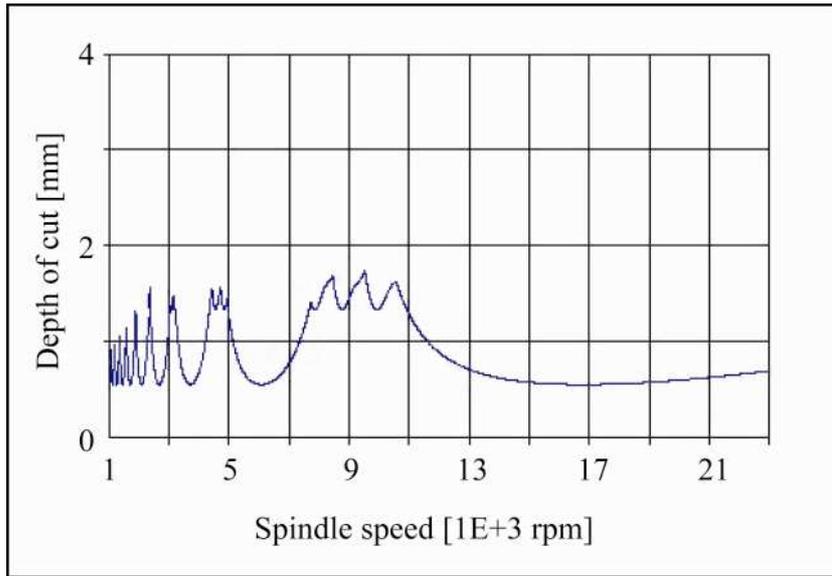
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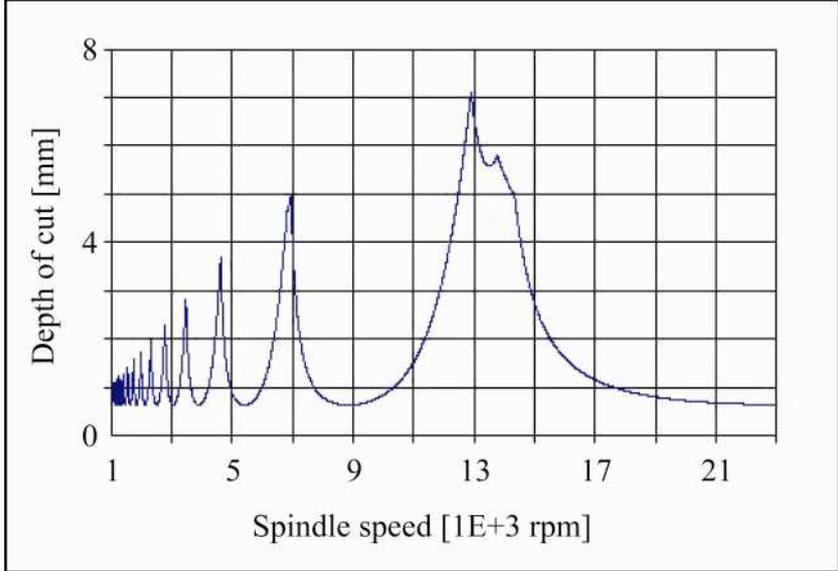


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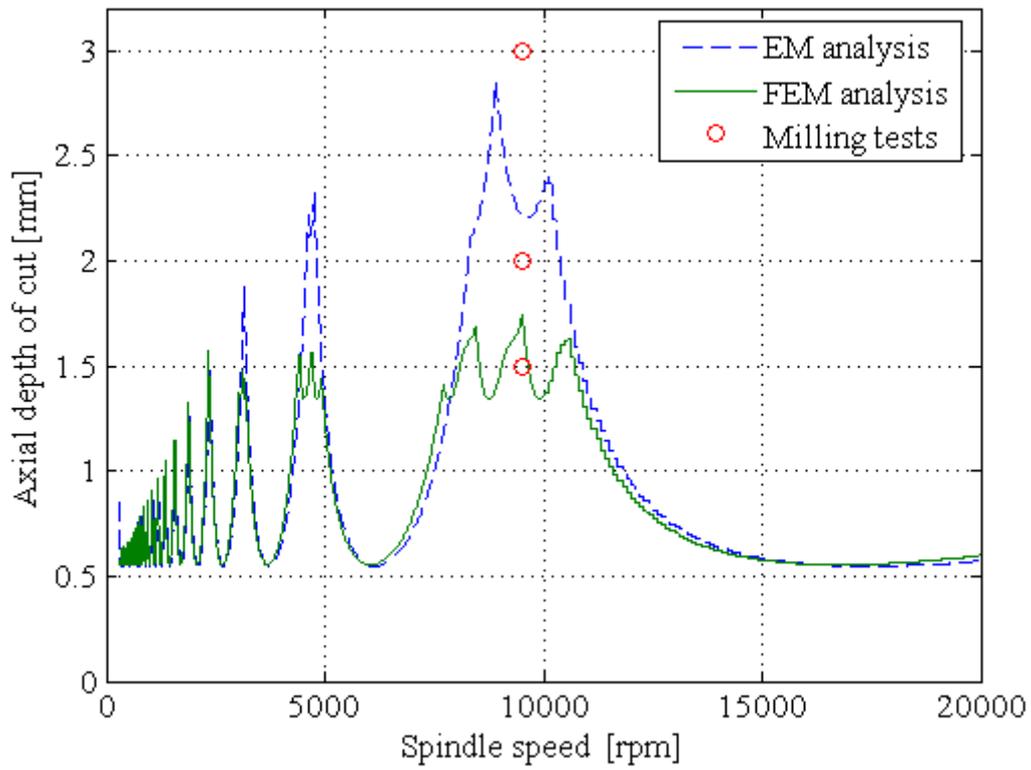


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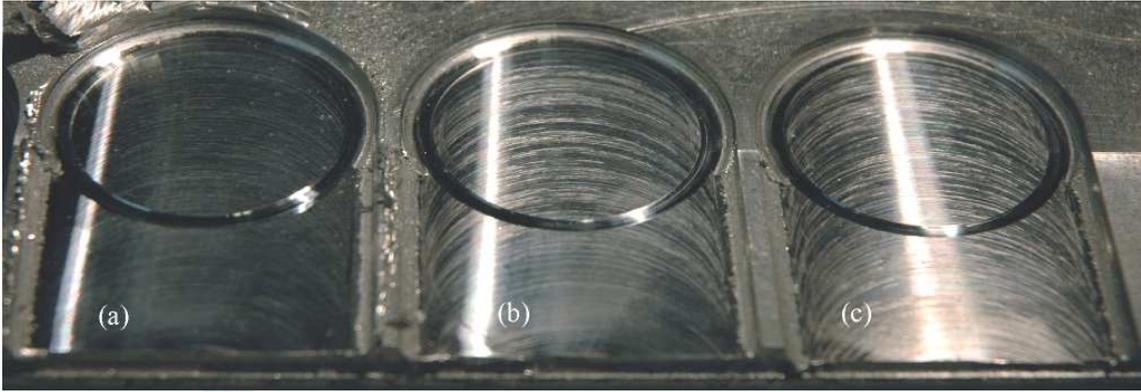


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