Abstract: Shrink-fit chucks are often used in high speed milling processes as they offer high torque transmission and low eccentricity due to their symmetric design. In some cases the milling cutter slips out of the shrink-fit chuck during high speed milling processes. This phenomenon, called tool extraction, is an unexplained problem with no repeatability so far. In this paper, experimental investigations such as SEM and residual stress measurements on the clamping surface of shrink-fit chucks affected by tool extraction are presented as well as a mathematical approach which aims on the prediction of failures due to process machine interaction. Within the mathematical approach a finite element model of tool and tool holder is coupled with a cutting force simulation in order to compute the resulting stresses in the interface of those components.

Keywords: shrink-fit chuck, tool extraction, finite-element-method, residual stress

1. INTRODUCTION AND MOTIVATION

Thermal shrink-fit chucks are particularly used in heavy and high speed machining processes due to their ability of transferring high torque and providing high concentricity. The phenomenon of tool extraction where the milling cutter slips out of the shrink-fit chuck during the milling process is a problem which is mainly reported from high speed cutting processes and also in heavy-duty machining [Fladerer, 2007]. The cause of this phenomenon is presently unknown but it is legitimately assumed that it is an effect from the interaction of the milling process and the tool / tool holder machine dynamics. Obviously, when the tool starts slipping out of the shrink chuck the process forces raise extremely – in high speed milling processes this happens within a few milliseconds. As a result, not only the milling cutter and the workpiece, which have values up to several tens of thousands of dollars, are damaged. There is even the risk of a spindle damage or an injury of the worker by splintering parts.

Within the DFG Priority Program “SPP 1180”, which focuses on interactions between structures and processes in technical systems, the Institute of Production Engineering and Machine Tools (IFW) and the Numerical Analysis Group at the Institute for
Applied Mathematics (IfAM) at Leibniz Universität Hannover are cooperating within the project "Numerical Computation Methods for Process-Oriented Structures in Metal Chipping". The mentioned research project focuses on the interactions between the chipping process and the machine structure. The main objective of this project is to clarify the cause of tool extraction with the help of a mathematical model supported by means of experimental investigations. It is ambitioned to develop a model in order to support the design of process-oriented components such as chucks and tools, and predict failures due to process interaction [Denkena, 2008]. This paper shows partial results of the experimental investigations regarding shrink-fit chucks subjected to tool extraction. Moreover, the concept of the mathematical model, which finally is going to be used to predict failures, due to process interactions, is explained as well as the already modeled components and interactions are described.

2. ANALYSIS OF FAILURE MODES

In order to analyze the cause of tool extraction several shrink-fit chucks (milling cutters were extracted during the process) were investigated. New shrink-fit chucks and those being used regularly serve as references. To reduce differences resulting from the production process all shrink-fit chucks are from the same manufacturer.

![Figure 1: Damaged workpiece, tool extraction with serrated end mill Ø 25 mm](image)

Figure 1 shows the results of a high speed cutting process failure (aluminum workpiece material) where tool extraction occurred. For the shown process a serrated carbide end mill (Ø 25 mm) was used. Due to the tool extraction effect the axial cutting depth increased by approximately 5 mm over a length of 28 mm. The marks on the workpiece right before the point of process interruption indicate severe vibrations of the tool when it slipped out of the shrink-fit chuck.

As tool extraction implies a relative movement between the tool shank and the tool holder, the contact surface of the tool holder is analyzed more in detail.
The Ø 25 mm shrink-fit chuck shown in Figure 2 was affected by tool extraction. The chuck has been split in several parts as shown on the right in order to gain access to the clamping surface. With these parts surface measurements at different magnitudes using scanning electron microscope (SEM) were performed (see Figure 3).

In Figure 3a a section of the clamping surface of a shrink-fit chuck being used for several clamping cycles without tool extraction is shown. On the surface the grinding grooves from the manufacturing process can clearly be identified in the circumferential direction. Moreover, the surface is flattened due to the previously applied clamping pressure.
The bright marks on the surface of the shrink-fit chuck in Figure 3b appear to be caused by the tool shank revolving in the chuck and piecewise slipping in the axial direction. Furthermore, the residual stresses in axial (x) and circumferential (y) direction were determined by X-ray diffraction measurements. For the presented measurements five damaged shrink-fit chucks with different tool diameters were analyzed. The results are compared to new shrink-fit chucks and to those which have been subjected to several clamping cycles.

![Figure 4: Normalized residual stresses (contact surface) of new, normally used and shrink-fit chucks affected by tool extraction](image)

The results shown in Figure 4 are the mean values for the overall clamping surface of 10 measurement points for the new, 18 for the chucks with several clamping cycles and 82 points for the five damaged shrink chucks. The mean values are each related to the residual stresses of the new shrink chuck.

The plotted stress amplitudes prove that – compared to the reference shrink-fit chucks – the residual stresses in shrink-fit chucks affected by tool extraction are significantly higher than in chucks which are new or were normally used. Especially in the circumferential direction the residual stresses have increased at a higher percentage than in axial direction.

Thus, neglecting thermal effects so far, it appears that not only axial slipping between tool shank and shrink-fit chuck but rather circumferential slipping is a main phenomenon when tool extraction occurs. Hence, it is assumed that due to dynamic...
interaction between the tool and the workpiece tool extraction is a combination of axially and circumferentially slipping. Once, static friction is lost, axial force induced by the right handed helix angle of the milling cutter leads to an axial relative movement. The marks in the front of the clamping area at the damaged shrink-fit chuck indicate a stick slip behavior. This may be caused by the dynamic process forces in transverse direction. A similar effect is described in [Urriolagoitia, 2000].

3. MATHEMATICAL MODELLING (OF TOOL AND TOOLHOLDER)

In order to numerically simulate the tool extraction (resulting from process forces) a three-dimensional transient FE-model is coupled with a geometrical chipping force model. These two models and the method of coupling are described within the following.

3.1 Finite element model of tool and tool holder

The chipping forces in a high speed milling process affect the tool in axial, transverse and tangential direction. Thus, a three-dimensional FE-model of the tool and the tool holder appears to be appropriate to characterize the effects resulting from the process loads (Figure 5).

![Finite Element mesh of the tool tip](image)

**Figure 5: Cross section of the FE-model consisting of the tool and tool holder**

Furthermore, a transient treatment is necessary in order to describe the dynamic system. Therefore, the discontinuous Galerkin method (DGM) is applied to obtain a discrete system in time domain. The tool and the tool holder are denoted by $\Omega_1$ and $\Omega_2$, respectively equipped with the corresponding material parameters. Due to the complex structure and the large contact interface between tool and tool holder a transient model involving contact elements is not feasible. Therefore the structure is considered as an inhomogeneous compound given by $\Omega = \Omega_1 \cup \Omega_2$ (Figure 5).

The governing partial differential equation describing the dynamic process is the elastic wave equation for the displacement vector $u$. 

\[ \rho_0 \ddot{u} - \nabla \sigma (u) = f \text{ in } \Omega \]  
\[ (1) \]
where \( \rho \) is the density function, \( \sigma \) the stress tensor and \( f \) denotes given volume forces. In order to circumvent large displacements due to the rotation of the body the system is expressed in rotational coordinates. The forces of the chipping process are applied on the cutting edges, such that the cutting edges at the tip of the tool define vertices of the FE-mesh.

The contact pressure resulting from the shrinking process is approximated within the model by using heat strain. More precisely, a negative temperature change is applied to the tool holder. Using a linear heat strain law the contact pressure on the interface between tool and tool holder gives an approximation of the shrinking process. Then during the cutting process a change in the stresses at the interface between tool and tool holder indicates whether slippage of the tool occurs.

### 3.2 Calculation of process forces

The calculation of cutting forces is based on the assumption that the forces arise proportionally to the infinitesimally small cross-sectional surface \( A' \) and the arc length \( b' \) of the uncut chip [Denkena, 2006], [Altintas, 2000]. Thereby, the proportionality of the surface is adjusted by the shear force coefficient \( K_{tra,c} \) and that of the arc length by the cutting coefficient \( K_{tra,e} \). Based on the tangential, radial and axial force components \( F_{tra} \) in tool coordinate system

\[
\{ F_{tra} \}_j = \{ K_{tra,c} \}_j A'_j + \{ K_{tra,e} \}_j b'_j
\]

the force components \( F_{xyz} \) in machine tool coordinate system arise by transformation to Cartesian coordinates

\[
\{ F_{xyz} \}_j = [T] \{ F_{tra} \}_j
\]

Integrated across the length of the cutting edges being engaged, they result in the process force \( F_{xyz} \) against the tool rotation angle \( \varphi \):

\[
\{ F_{xyz} (\varphi) \} = \sum_{j=1}^{z} \sum_{i=1}^{m} \{ F_{xyz} \}_j
\]

To get the process force progression, only the time reference has to be established. For this purpose, \( \varphi \) will be represented as a function of the time \( t \).

However, the force data extracted in such a way are temporary quantities which would arise at a cutting process without any deviation of the end mill. To consider self-excited vibrations of the tool, the process model was integrated into the structure simulation of the machine tool. Therefore, deviations of the structure, caused by the process forces, have to be implemented into the material removal model. The simulation uses the cutting-edge trajectory, resulting from the movement of the tool for the calculation of undeformed chip-thickness \( h' (\varphi) \). The chip-thickness is calculated by the intersection of the tool trajectory (see Figure 6), in reality the tool trajectory as well as resulting chip thickness is mainly influenced by the relative movement between the cutting edge and workpiece [Denkena, 2007].
Therefore, the effects of tool deflection have to be included in the calculation, which is done in several iteration steps. Starting with a non-deformed chip geometry, the force calculation is carried out and transformed into deflection, using the deflection model of the tool. The deformation of tool trajectory leads to a modification of undeformed chip thickness, which is calculated in a subsequent iteration step. The procedure converges if no significant geometry deformation as well as force change appears any more.

3.3 Coupling of the models
The interaction between the cutting process and spindle tool components in a milling process cannot be calculated directly, because of the dependencies between cutting forces and tool deflection. Therefore a coupled simulation method was developed which calculates the spindle tool deflection from the FE-Model and returns the results to the cutting force simulation (Figure 7). This iteration process is repeated until the difference of two subsequent calculated forces and deflections respectively fall below a lower bound. In this case the iteration for the current time step would converge and the following time step is being computed.

Figure 6: Geometrical calculation of undeformed chip-thickness.

Figure 7: Coupling of cutting force model and FE-simulation of tool and tool holder.
The coupled simulation model considering tool-workpiece interaction delivers cutting forces, which can be used for the calculation of contact stresses in the tool-shrinkage intersection zone. Especially for the simulation of axial tool extraction, the influence of relative movement on resulting cutting forces is important. In Figure 8 the cutting forces in radial ($F_r$), axial ($F_a$) and tangential direction ($F_t$) acting on the first cutting edge of the tool during a rotation for the process force model without structural deflection (open loop) and the coupled models (closed loop) are compared.

For the shown simulation the cutting edge was discretized into ten axial segments. On this account the cutting force decreases stepwise towards zero as the cutting edge exits the material. Within an “open loop” simulation the cutting forces are calculated from the cutting edge trajectory and the calculated chip thickness with an ideally stiff tool. In contrast the “closed loop”-simulation considers the real dynamic stiffness of the tool which can also take regenerative effects due to dynamic tool deflection into account. From Figure 8 it is obvious that considering the tool deflection within the cutting force calculation has significant influence on the amplitude of the simulated cutting forces.

### 3.4 Influence of the cutting forces on the contact pressure

With the calculated process forces and considering the dynamic tool deflection the resulting stresses in the contact zone of tool shaft and tool holder can be computed. Hence, the time step for this transient simulation has to be very small due to the dynamic effects (about 50 microseconds) the simulation is very time consuming. Therefore, first calculations were performed with a coarse finite element model.
For closer investigation on the stress distribution in the contact zone the process forces were input to a further FEM simulation with a fine meshed model. Figure 9 shows the simulated change from unloaded shrink-fit in contact pressure and frictional stress on the clamping surface due to the process forces for a single time step related to revolution angle $\phi = 3$ (see Figure 8).

On the one hand, due to the radial component of the cutting force a bending of the tool occurs. This results in an increasing contact normal pressure $\sigma_N$ at the front of the contact surface and a decrease on the opposite side. On the other hand the axial and tangential cutting force components cause frictional stresses $\sigma_F$ in the contact zone with a maximum at the front of the contact surface. Both, frictional stress and the decrease of contact pressure may result in local slipping between the tool shank and the clamping surface. Considering $\sigma_F \leq \mu \cdot \sigma_N$, where $\mu$ denotes the friction coefficient between the tool shank and the clamping surface, and the allocation of the stresses as shown in Figure 9 it can be assumed that slipping will start at the front of the clamping surface. In the further development of the mathematical model the calculated stresses in the contact zone of tool shaft and shrink-fit chuck will provide the ability of predicting failures due to process interactions.

4. SUMMARY AND OUTLOOK

In the context of the priority program SPP1180 the interaction between the metal removal process and the machine structure is focused. In this paper, experimental investigations on the unsolved phenomenon of tool extraction out of shrink-fit chucks during high speed cutting processes are presented. In detail, SEM as well as residual stress measurements of the clamping surface of shrink-fit chucks affected by tool extraction are presented. Analyzing the tool contact surface of shrink-fit chucks that were previously affected by tool extraction showed that residual stresses in the axial and circumferential direction are significantly higher than in new or normally used chucks. Hence, it is assumed that the tool extraction phenomenon is a combination of axially and
circumferentially slipping. Moreover, the mathematical approach using a finite element model of the tool and the tool holder coupled with a cutting force model within a fully transient simulation is presented. The coupling of the two simulation models is realized by exchanging process forces and tool displacements in every time step until convergence is achieved.

The problem of tool extraction occurs at the interface of the chuck and the tool shank. Hence, the main focus is to calculate pressures and frictional stresses in the contact zone in order to predict parameters of the cutting process causing a relative movement between the two components. Further research work will be spent on extending the mathematical model in order to consider the dynamic behavior of the motor spindle and the tooling machine as well as on detailed experimental investigations of the distribution of the residual stresses in the clamping zone and local changes in the material structure.

The aim of the described project is to clarify the cause of tool extraction and to develop a mathematical model in order to support the design of process-oriented structures such as collet chucks and tools.

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REFERENCES


