Development of a material model for visco-elastic abrasive medium in Abrasive Flow Machining

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Abstract

Abrasive Flow Machining (AFM) uses the visco-elastic properties of a polymeric carrier, combined with abrasive grains, as a tool for machining of difficult to reach geometries, such as holes or cavities. Due to the design of the workpiece holding device and variable flow rates, the complex shear modulus of the polymer can locally be influenced and thus a targeted removal on the workpiece can be produced. As a result there is a reproducible material removal, causing requested polishing, deburring or edge rounding. Due to shear thinning and visco-elastic behavior of the tool, the process simulation for AFM is very complex and has not been implemented yet including an exact physical material model. Initial machining parameters so far are based on experience and extensive experimental research. This publication gives an insight into the investigation of modeling the abrasive media in AFM by adapting the standard Maxwell model of elastomers and extending it to the Generalized Maxwell model. Assuming the material removal of the process being caused by the shear stressed dependent bonding of the abrasive grains, a fundamental material model, easy to be integrated in conventional simulation programs, is developed and presented in this paper.

Keywords: Abrasive Flow Machining; Visco-Elasticity; Material Model; Simulation

1. Introduction

AFM is a finishing process with high potential for substitution of manual manufacturing and can be applied to a wide range of wear-resistant hard materials. As a tool the process uses a polymeric carrier and abrasive grains (e.g. silicon carbide, boron carbide, diamond). This suspension is being pressed alternately between two pistons like a fluid column along the workpiece surfaces to be machined. Since machining of complex geometries is possible, this method is very suitable for the post-processing of areas of workpieces that cannot be reached conventionally. Process design is iterative and requires several testing series with variable process parameters, such as machining time, flow velocity and the design of the workpiece fixture. Thus a simulation with exact material properties aims to reduce the costs of integrating the process into the production chain. Due to its high disperse mass fraction, the process cannot be simulated as a two-phase flow and the abrasive media is modelled as a homogeneous isotropic material. Current material models, such as by UHLMAN [1] or MIHOTOVIC [2] already include the shear ratio dependent viscosity, but not the complex shear modulus which determines the reaction on shear stress. For a process simulation allowing conclusions regarding material removal, an AFM tool model including shear modulus needs to be developed.

In the first step, the target of a simulation, which will be implemented by use of the current material model, is not to predict surface roughness or the amount of removed material. Furthermore, the physical behaviour of abrasive media should be modelled as exact as possible in order to predict the location of material removal and optimize flow rates leading to homogeneous machining results. The simulation will be applied on workpieces, manufactured by Selective Laser Melting (SLM) at first. These parts are often characterized by free form design and a high surface roughness, what makes the finishing of SLM-parts with...
conventional processes rather challenging. Therefore AFM is very suitable for finishing of additive manufactured parts. The simulation will be validated with experimental machining of simple workpieces (surface and edge finishing), before it can be applied to complex geometries.

2. Principles of AFM processing

An AFM machine (Fig. 1) consists of upper and lower cylinder, each housing a piston, which moves up and down simultaneously, controlled by a hydraulic unit. Between both cylinders the workpiece is positioned and surrounded by the fixture. The fixture keeps the workpiece and the abrasive suspension in place during machining. Its design directly influences the flow channel and thus material removal.

Before filling the lower cylinder and workpiece holder, the abrasive medium needs to be kneaded and brought up to machining temperature. The reason therefore can be found in the polymeric structure of the carrier material. The molecular chains need to be stretched several times to initiate their ability to bind the abrasive grains. Another theory for the importance of heating up is the high percentage of air in the media.

After gapless filling, workpiece and fixture are clamped between both cylinders by application of up to 200 bar clamping pressure. These high pressures are necessary to keep the abrasive suspension inside the holding device. During the process, media pressures of more than 150 bar can be measured. With the movement of both pistons from bottom to top, the medium is being pressed along the surfaces to be machined until reaching dead top center. By moving the pistons back to bottom dead center, one machining cycle has passed. The number of cycles, required for the desired work result, can be entered into the touch control panel of the machine as well as the other parameters controlling the process. These are the hydraulic pressure on the pistons or the piston velocity for newer machines. New machines also can apply a counter pressure to ensure continuously machining in cavities of different diameters. Another important parameter is the media temperature, which has a high influence on the rheology of polymers. The common machining temperature is between 30 °C and 40 °C depending on the aimed result and controlled by heating and cooling regulator.

The other component of the process layout is the composition of the media. The texture of the carrier is decisive for polishing, deburring or edge rounding effects, depending on the geometry to be machined. Further grain material and size as well as abrasive mass fraction of the entire suspension need to be adapted to the machining strategy.

3. Measurements

The measurements are carried out with an often used multifunctional AFM media from MICRO TECHNICA TECHNOLOGIES, Kornwestheim. From previous works, such as Szulczynski [3], is known that the visco-elastic behavior of the polymeric carrier varies with the amount of added abrasive grains. To determine the influence of the abrasive mass fraction, measurements with 0 % (Fig. 2), 33 %, 50 %, 60 % and 67 % silicon carbide grains of size F80, \( d_G = 185 \, \mu m \) in average, are performed.

![Fig. 1: Experimental setup for AFM processing](image-url)
Visco-elastic materials are classified by the complex shear modulus $G^*$. Its real part $G'$, the storage modulus, represents elastic abilities and the imaginary part $G^*$, the loss modulus, represents dissipative abilities.

$$G^* = G' + iG^*$$

By use of rotational viscometer „RT 20 Rotovisco“ by HAAKE, $G'$, $G^*$ and viscosity $\eta$ can be determined: The suspension is torqued between two parallel plates which oscillate with a shear stress of 50 N/mm² upon the probe; higher values would lead into non-linear region of response and therefore inexact results. Oscillation frequency is varied from $5 \times 10^{-5}$ Hz to $4 \times 10^7$ Hz; upper bound given by the viscometer, lower frequencies would cause too long measurements.

By measuring amplitude and phase shift of the resulting deformation, $G'$ and $G^*$ can be derived directly as a function of oscillation frequency. Each measurement is repeated 10 times with a different sample to average possible anomalies. The result of the measurements for the polymeric carrier is shown in Fig. 2.

### 4. Rheological Model

Polymers, such as the carrier of the AFM media, are known to react to deformation in the following way: For fast stress, the material can-not follow the deformation. Due to its structure of long chains of molecules, the chains cannot untangle that fast and the polymer has a high elasticity, dissipation of energy is low. On slow deformations (quasi-static), the molecules can adapt to the stress easily – the elasticity is therefore low. Dissipation is low, again, since there is no problem for the polymer to follow the stress. In case of moderate shear ratios, the molecules can follow the stress continuously, but not as easy as on slow stress. Dissipation has its peak there, and elasticity raises.

The described behavior can be better under-stood by looking at the structure of polymers more detailed. Polymers consist of long chains of molecules. Those chains are bound very weakly together and are conglomerated in steady-state condition. In contrast to regular solid materials, whose state is defined by the lowest energy, the conglomerated condition of a polymer is mostly an entropic effect. Due to this, polymers easily align to the direction of a force. After taking off the force, the chains re-turn into the conglomerated state. The higher the temperature, the faster they return and bring the polymer into steady-state condition [6, 7].

A simple model for polymers is the Maxwell element, which for example is commonly used for the modeling of rubber [8]. By connecting a purely elastic spring with stiffness $K$ and a purely viscous damper in series, one obtains the storage and loss modulus as a function frequency of deformation. Assuming a complex, frequency dependent stiffness for the damper

$$\eta_1(\omega) = i\eta_0(\omega)$$

the complex modulus of spring and damper connected in series can be expressed as

$$G^*(\omega)_{Maxwell} = \frac{G_i i \eta_0 \omega}{G_i + i \eta_0 \omega}$$

and simplified to

$$G^*(\omega)_{Maxwell} = \frac{G_i (i \eta_0 \omega G_i + (\eta_0 \omega)^2)}{G_i^2 + (\eta_0 \omega)^2}$$
In equation (4) real and imaginary part can be separated what leads to storage and loss modulus

$$G'(\omega)_{\text{Maxwell}} = G_1 \frac{(\omega \tau_1)^2}{1 + (\omega \tau_1)^2}$$  \hspace{1cm} (5)$$

$$G''(\omega)_{\text{Maxwell}} = G_1 \frac{\omega \tau_1}{1 + (\omega \tau_1)^2}$$  \hspace{1cm} (6)$$

with relaxation time

$$\tau_k = \frac{\eta_k}{G_k}$$  \hspace{1cm} (7)$$

Relaxation time is a value for the time of stress relaxation in the material. The behavior of elastomers is usually being modeled by an additional softer spring $G_0$, connected in parallel to the Maxwell element (Fig. 3).

$$G'_1 = G_0 + G_1 \frac{(\omega \tau_1)^2}{1 + (\omega \tau_1)^2}$$  \hspace{1cm} (8)$$

$$G''_1 = G_1 \frac{\omega \tau_1}{1 + (\omega \tau_1)^2}$$  \hspace{1cm} (9)$$

The curve progression with typical values of $\eta_1$ and $G_1$ for visco-elastic materials shows a high correspondence between model and measurement. $G_0$ can be neglected, because it only shifts the value of $G'$. The higher $\omega$, the higher is $G'$. $G''$ is low for low and high frequencies but has a peak at $\omega = \frac{1}{\tau_1}$. This corresponds exactly to how polymers react to stress and is therefore an appropriate model for them.

By applying the Standard model to the results of the viscometer measurements for the polymeric carrier of the AFM media, accordance between measurement and model is established with some deviation for $G''$ at higher frequencies (Fig. 5). These simple equations work well for an approximation of the visco-elastic properties. Adding grain to the polymeric carrier changes its viscoelastic behavior additionally [3], so that the approximation is less accurate (Fig. 6).

A higher accuracy is obtained with the Generalized Maxwell Model, where several Maxwell elements are assembled in parallel (Fig. 4). With this extension of the Standard Model, more than one relaxation time is taken into account and real polymers can be characterized [8]. Furthermore, this model can be adapted to the measured results of all abrasive medias. The equations for the Generalized Model are

$$G'(\omega,n) = G_0 + \sum_{k=1}^{n} G_k \frac{(\omega \tau_k)^2}{1 + (\omega \tau_k)^2}$$  \hspace{1cm} (10)$$

$$G''(\omega,n) = \sum_{k=1}^{n} G_k \frac{\omega \tau_k}{1 + (\omega \tau_k)^2}$$  \hspace{1cm} (11)$$

A program is implemented to determine the required number of elements $n$ and to calculate the parameters $G_0, G_k$ and $\tau_k$. Starting with $n = 1$ (Standard Model of visco-elasticity), initial conditions are calculated and a nonlinear curve fit is done to approximate the measurement. If deviation $d(n)$ is not within specified
range, \( n \) is incremented and the process is started again. This is done until either the deviation is within the range or increasing \( n \) does not yield a sufficient decrease of deviation. The relative deviation \( D(n) \) describes the increase of the deviation compared to the Standard Maxwell Model \( n = 1 \).

The program detects a reliable model of the medias under examination in this paper for \( n = 5 \). Compared to the Standard model, a high compliance with the measured results can be mentioned. The deviation for small frequencies is very small and negligible as there is no material removal expected for shear ratios of the range smaller than 1 Hz. Five Maxwell elements mean 11 variables \((G_0 \ldots G_5 \text{ and } \tau_1 \ldots \tau_5)\), which need to be integrated into upcoming simulations.

\[
d(n) = \sum_\omega |G^*(\omega)_{\text{Measure}} - G^*(\omega,n)_{\text{Model}}| \quad (12)
\]

\[
D(n) = \frac{d(n)}{d(1)} \quad (13).
\]

**Fig. 5:** Standard Maxwell Model applied on polymeric carrier

**Fig. 6:** Measurement compared with Standard-Maxwell Model and Generalized Maxwell Model

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Adaption of model to measurement:

Standard Maxwell Model

- Storage Modulus \( G' \) (measurement)
- Loss Modulus \( G'' \) (measurement)
- Storage Modulus \( G' \) (model)
- Loss Modulus \( G'' \) (model)

Media: Polymeric Carrier

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Generalized Maxwell Model

- Storage Modulus \( G' \) (measurement)
- Loss Modulus \( G'' \) (measurement)
- Storage Modulus \( G' \) (model)
- Loss Modulus \( G'' \) (model)

Media: Polymeric Carrier with 50 % SiC
By increasing the number of Maxwell elements to \( n = 5 \), deviation is reduced to \( 2.5 \times 10^{-3} \) of the deviation of the Standard model (\( n = 1 \)). Further increasing of \( n \) does not yield any major decrease of deviation in the current version of the program. A comparison between the generalized Maxwell model for \( n = 5 \) and the Standard model is shown in Fig. 6. The generalized model comes up with a high correlation to the measured curve for 40 °C. Using equations (8) and (9), the AFM media can be characterized very exactly within the frequency range of the process. Furthermore, it is possible to adjust these equations to every AFM media measured by rotational viscometer.

5. Conclusion and Outlook

A material model for the abrasive media in Abrasive Flow machining is developed in the present work. By extending the Standard Model for visco-elastic materials to the Generalized Maxwell Model, equations are found to characterize the shear modulus of the AFM media as a homogenous, isotropic material with a minimum of deviation. With relaxation time \( \tau \) a new value is found for the characterization of any AFM media. As the next step, the material model will be implemented into a conventional simulation tool. Furthermore experiments and simulations will be performed and validated. The developed material model allows a separated consideration of the impact of storage and loss modulus on material removal. In future, the simulation can help to design workpiece fixtures to achieve a targeted homogenous material removal on workpieces with complex geometries. The simulation will reduce effort and costs of the entire process layout as well as the threshold of inhibitions of manufacturers to integrate AFM into the production chain.

For validation of upcoming simulations suitable experimental setups are to be found and carried out. It is planned to validate the simulation with surface and edge rounding tests. By machining of extremely rough generative manufactured surfaces, the impact of different influenced shear ratios on resulting material removal can be determined. The impact on material removal can be measured on the surface of the workpieces after machining. Parallel to these experiments, the same tests are going to be simulated using the physical model developed in the present work with varying abrasive mass fraction. The results of simulation and experiments will be validated and allow conclusions on material removal depending on shear ratio and complex shear modulus. The validation of simple geometries allows the application of the simulation to complex geometries, as it is common for generative manufactured parts. These simulations can be used to determine, whether the AFM process with its visco-elastic tool is suitable for achieving the required result or if other, conventional finishing processes need to be taken into account.

Furthermore, the model can be applied to every AFM media with different viscosity, grain size and abrasive mass fraction, what can help to choose the media when setting up the process. By use of the implemented program, the equations which characterize the material are found automatically. This includes adjusting the model to worn abrasive medias and to include fatigue into process simulation. This can help to predict lifetime of the AFM media: The simulation will lead to a continuously efficiently production.

REFERENCES