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Process force and technology model for designing and controlling finishing operations with rotating grinding tools

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ABSTRACT

Today the technological design of fine machining processes like finishing of plane surfaces is still a procedure based on experience. In addition, finishing technology is the result of an empirical approach. Innovative methods for designing and controlling finish operations make use of models and the implementation of procedures that allow the derivation of optimal technological parameters and process control strategies as well as the prediction of cutting behaviour of abrasive tools. These process and technology models are based on measuring and evaluating process variables like process forces or cutting torque and parameters of the electric drive like motor current or torque. With these models a finishing process is achieved on the basis of mathematical and technological principles wherein the grinding tool works in a self-sharpening condition providing optimal results.

1. Introduction

The control and influence of cutting behaviour of a grinding wheel is one of the essential challenges in precision machining with geometrically undefined cutting edges. Therefore, knowledge of the technological correlation between actuating variable and process variable as well as the working result is a central requirement. This paper introduces a model and a procedure to describe the cutting behaviour of a used grinding wheel within a specific system. The model represents a special constellation consisting of cutting material, raw material and shape element at the workpiece within a system consisting of machine tool, clamping system, grinding tool, workpiece and coolant. For this process system the cutting behaviour of the used grinding wheel can be predicted.

This process and technology model as well as the specific procedure is developed for finishing with rotating grinding wheels. This is a precision machining process with geometrically undefined cutting edges and rotating cup grinding wheels. According to DIN 8589 T11 this process is classified as longitudinal face grinding with circular feed motion. This operation developed from short-stroke-honing of plane surfaces. The oscillating honing stone was replaced by a rotating cup grinding wheel, which stays in areal contact with the rotating workpiece. This machining process is also known as rotary honing or microfinish and combines features of honing and grinding. In Fig. 1 important specifications of the finishing process are summarized. As finishing operations are force controlled processes, the normal and tangential forces are actuating variables and not resulting process parameters. This finishing process is used

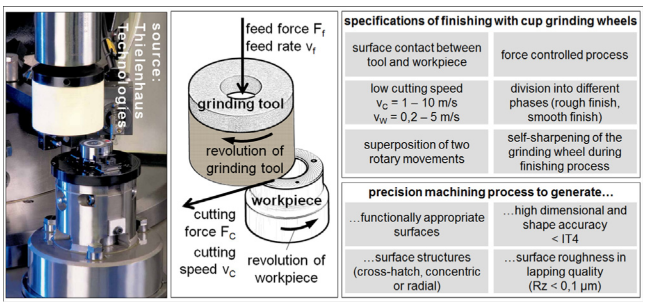

Fig. 1. Finishing – overview of process and technology.

to machine plane or spherical shape elements on small workpieces which require high quality in flatness and roughness. Applications can be found in the automotive industry and its components suppliers, medical engineering and valve industry.

2. Technology and process development

Finishing operations are known as sensitive and force controlled processes. The parameters of process technology and process control are designed on empirical and experimental approach or on the basis of experience [1–4]. Such approaches in designing process technology are complex and time-consuming procedures. Fig. 2 shows an overview of different process strategies applied for finishing operations in series production processes. The correlation between feed rate and feed force to calculate the actuating value of force control is determined empirically [1]. Such a theoretical correlation is shown in Fig. 2a. The finishing process with rotating grinding wheels constitutes a cycle which is divided into various process phases with different purposes. Whereas in

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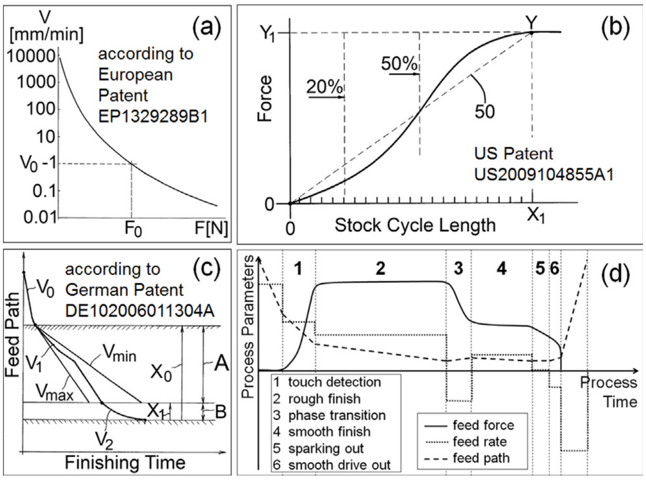

Fig. 2. Strategies for design and control of finishing processes.

the first process phases a high material removal rate (MRR) is set to rapidly achieve a desired size, the MRR decreases steadily in the following process phases to achieve a high shape and roughness quality. This kind of process control is shown in Fig. 2c. In the first process phase (A) the rough finishing the feed force is controlled within a maximum v_{max} and a minimum v_{min} limit of feed rate. These feed rates represent a high MRR. In the following smooth finish process phase (B) the feed rate decreases steadily once the required size, shape and roughness quality has been achieved. The history of feed force and feed rate to achieve the required quality is determined by an empirical approach [2]. One further process strategy is shown in Fig. 2b. The force follows a previously determined optimal history depending on size, shape and roughness requirements [4]. In most cases the feed force is the command variable of the process control. Present developments demonstrate the use of parameters of electric drive like motor current or torque [3]. Today, finishing cycles practiced in production processes are divided into the phases of roughing, smoothing and fine-smoothing. Fig. 2d shows a finishing cycle which is divided into two process phases roughing (2) and smoothing (4). The difficulty in designing a finishing process with several phases is defining the technological parameters that create the optimal cutting behaviour, the optimal pre-condition for the next phase, achieving the required quality for each field. Reducing the number of phases reduces the effort of designing finishing processes.

3. Model considerations in finishing with grinding wheels

3.1. Technological considerations in designing finishing processes

Today the influence of actuating variables on process parameters and working result at finishing processes are investigated in only few published studies compared to grinding [5,6]. Influencing factors are the grinding wheel, the workpiece, the technological parameters, the coolant, the machine tool and the machine environment. Process-determined parameters in finishing are the feed rate, the cutting speed and the velocity of the workpiece. By taking into account all influences and correlations, the task in designing of finishing processes contains the determination of optimal technological parameters for any specific system consisting of cutting material, raw material and shape element at the workpiece. These parameters have to correspond to the point or field wherein the grinding wheel works in a self-sharpening condition. This "Technology Field" represents the point wherein the used grinding wheel produces the optimal performance and the required qualities are reached in an economical grinding time. The theoretical consideration of the optimal technology window is carried out for a single abrasive grit. Fig. 3 illustrates the optimal technology field. The course of a single abrasive grit from point P1 to

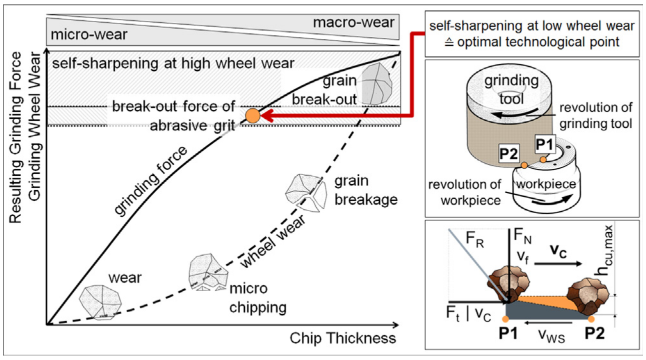

Fig. 3. Description of the "Optimal Technology Field".

P2 at a constant cutting speed and feed rate is considered. The cutting grain enters the surface of the workpiece with a certain chip thickness and depending on feed rate and cutting speed the abrasive grit leaves the surface at a maximum chip thickness. It is known from theory that an increasing material removal rate causes increasing chip thickness, grinding force, grinding wheel wear, form and roughness deviations as well as a possible negative influence of the subsurface properties [7–11]. Depending on the amount of the force various kinds of mechanical wear may occur.

At low grinding forces micro-wear in terms of abrasion and micro chipping is occurring. Higher grinding forces cause increasing macro-wear in the form of grain breakage and upon exceeding the bonding force, grain break-out. Finishing is characterized by a self-sharpening mechanism. In the transition between micro-wear and macro-wear the active cutting forces exceed the mechanical bonding strength of the grinding wheel, upon which the cutting grain breaks out. The self-sharpening mechanism is a combination of progressive abrasive wear and time-delayed exceeding of bonding strength. Beyond the break-out force, self-sharpening is always present, but the high chip thickness and the high cutting force cause an increased grinding wheel wear. The optimal technology field is the point of self-sharpening at a low grinding wheel wear. In what follows, a model and procedure for finding the optimal technology field are introduced.

3.2. Process force and technology model for finishing operations

The aim of the model is the prediction of the cutting behaviour of a used grinding wheel within a considered system. The models are based on a practical procedure to determine cutting and process behaviour. For a considered system, characteristic curves of the actuating parameters are determined. These curves describe the influence of the actuating variables on process variables. Process variables are parameters describing the cutting behaviour of the grinding wheel and the process condition in a best way. These process parameters can be the feed force F_f and the cutting force F_C. The characteristic curve can be determined by a programmed cycle within the control of the machine tool. The process parameter feed force can be determined by a piezo-electric force sensor. The process and technology model consists of the characteristic curve of feed rate CCVF and the characteristic curve of cutting speed CCVC. The CCVF describes the history of feed force or cutting force versus feed rate and grinding time.

The CCVC describes the history of feed force or cutting force versus cutting speed and grinding time. On the basis of these measured histories the cutting behaviour is describable.

Fig. 4 shows an example of the CCVF. In this example the feed force represents the process-describing variable. On the basis of the feed force history different process conditions and cutting behaviours can be derived. Within the feed rate range of 0.001–0.005 mm/s the force increases continuously. In this range, the low chip thickness resulting from the low feed rate causes micro-wear. The cutting grains become blunt and the kinematic cutting edge