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Discrete Element Modelling of Drag Finishing

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Abstract

Drag finishing is a machining process that is used to improve the surface topology of workpieces. Workpieces are moved through a bulk of differently shaped abrasives, the so called media. Material removal is caused by the relative motion between workpiece and media. The material removal rate is mainly depending on the contact intensity between workpiece and media. Up to now there is no viable way to determine the intensity of single contacts empirically. However, a sound understanding of single contacts with respect to impact forces and velocities could greatly improve process comprehension and reduce trial and error process design efforts. For that reason the movement of media and workpiece is modelled using the Discrete Element Method (DEM). In this paper a comprehensive approach is presented covering formulation, calibration, validation and utilization of the DEM. Media is considered as an aggregation of elastic particles that are subject to contact, damping and gravitational forces causing particle movement. Geometric boundary conditions, i.e. workpiece and drag finishing bowl, are implemented as elastic facets. Contact forces are calculated according to a non-linear, simplified Hertz-Mindlin contact force model. Energy is dissipated by viscous damping and friction at contacts. Necessary parameters of the model are determined experimentally. The validation of the model's behaviour shows good agreement with experimental data. Finally the model is used to determine local contact intensities on the workpiece surface and between particles. By analysing simulated contact forces, the formation of dominant contact chains between particles is observed and investigated.

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1. Introduction

Drag finishing is a versatile machining process that is used to improve the surface topology of workpieces. These are moved in a bulk of abrasives, the so called media. Caused by the relative motion of workpiece and media, material of the workpiece is removed. In contrast to other mass finishing processes, like vibratory or centrifugal disc finishing, workpieces are fixed by a clamping device and media is not agitated in drag finishing. Industrial drag finishing processes are usually carried out with a fixed track setup that guides the workpieces through the media on a set or only slightly adaptable trajectory. A major benefit of the fixed workpiece setup is that workpieces cannot collide. Typical applications of drag finishing include medical implants, gear components, turbine blades or rounding of cutting tool edges [1,2,3]. A newly developed and patented setup is robot guided drag finishing [4], where an industrial 6-axes robot is used to guide workpieces through media, resulting in versatile trajectories and precise setting of workpiece velocities [5]. By increasing workpiece velocities higher pressure than in vibratory finishing processes can be achieved resulting in increasing material removal rates and quicker processing. In addition the defined trajectories of the workpieces allow for enhanced machining of certain features at complex workpieces.

A lot of researchers have presented models for mass finishing processes so far. Most of them are descriptive models for vibratory finishing that correlate process parameters with surface quality for certain workpieces. MATSUNAGA [6] investigated contact mechanisms and velocity fields in vibratory finishing, but did not establish a correlation between processing results and measured or observed process characteristics. Additionally HASHIMOTOS findings [7] are of high relevance to the field of mass

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finishing. Based on empirical studies he established basic rules for mass finishing processes that were confirmed in large parts by a recent investigation of UHLMANN ET AL. [8]. SPELT'S group [9,10,11,12,13] established a correlation between process forces, contact mechanisms and reachable surface quality in vibratory finishing. An important finding of SPELT'S group is the identification of three major contact modes that occur when spherical media is used in vibratory finishing: single impact, free rolling of single spheres and rolling of spheres in packages [13].

Nomenclature

α	empirical constant
c_n	damping coefficient in normal direction
c_t	damping coefficient in tangential direction
d_s	submersion depth
e_n	coefficient of restitution in normal direction
e_t	coefficient of restitution in tangential direction
E	Young's modulus
F_n	normal force
F_t	tangential force
G	shear modulus
h_f	height of filling
k_n	contact stiffness in normal direction
k_t	contact stiffness in tangential direction
μ_{ij}	friction coefficient of material combination i, j
m	mass
n_b	number of balls
R_b	radius of balls
R_i	radius of particle i
ρ_i	density of material i
δ_n	displacement in tangential direction
δ_t	displacement in normal direction
$\Delta\tau$	time step
t_p	process time
ν_i	Poisson's ratio of material i
v_t	contact tangential velocity
v_w	workpiece velocity

The significance of contact forces and mechanisms in mass finishing processes has been emphasized by many researchers [9,14,15,16]. It has been shown that contact forces and impact velocities have great influence on process outcome in terms of material removal, roughness and hardness of the workpiece. As a consequence there have been many investigations on how to measure forces and impact velocities on the workpiece. Most of them make use of in situ measurement of contact forces. Costly measurement devices with high sampling rates have to be used to record maximum impact forces [9]. Furthermore a major handicap of this approach is the dependence of force magnitudes on sensor surface compliance [9,17]. CIAMPINI ET AL. [14] proposed to extract normal impact velocity from measured forces instead. Based on the determined impact velocities, energy imparted to arbitrary workpieces can be inferred, disregarding compliances. Nevertheless forces have to be measured for all considered machine settings and workpiece geometries. Directly obtaining impact velocities in mass finishing processes is also challenging, as measuring devices have to be placed appropriately in the bulk media. HASHEMNIA ET AL. [18] have developed a laser displacement probe that is able to measure impact and bulk flow velocities in vibrationally fluidized beds. Other reported approaches concentrate on measuring workpiece or bulk flow velocity, e. g. using spatial and time-based analyses of photographs [19]. Instead of force or velocity based approaches CIAMPINI ET AL. [11] used an almen strip system, common in shot peening applications, to characterise the effect of different process parameters on the aggressiveness of a vibratory finishing process. Having simulated the occurring impacts with an electromagnetic apparatus they found that normal impacts are dominating in vibratory finishing. Because in situ force and impact velocity measurement is a complex task susceptible to disturbances in the measuring chain, a different approach is presented, that allows for modelling of contact intensities for arbitrary workpiece geometries and materials using the Discrete Element Method (DEM).

Up to now results from two different approaches towards a deterministic numerical process model for mass finishing have been reported:

- Modelling of the motion of spherical media with the DEM [20,21,22,23,24]
- Modelling of the media's velocity fields using Computational Fluid Dynamics (CFD) for centrifugal disk finishing [19] and vibratory finishing of immobilized cylinders [25]

Notably, only CARIAPA [19] and UHLMANN ET AL. [20] look at the three-dimensional movement of abrasive media in their models. All other approaches consider mass finishing processes with spherical steel or glass media or are restricted to two dimensions. CARIAPA'S approach allows for a qualitative prediction of material removal. The work of UHLMANN ET AL. on a comprehensive process model [20] combines an empirical geometry based model for surface roughness prediction [8] with contact intensity simulation using DEM. Using this comprehensive process model a quantitative prediction of material removal and roughness should be possible.

2. Discrete Element Method (DEM)

In the following a model to numerically simulate contacts between abrasive media and workpieces using DEM will be presented. The goal is to simulate the number, type and intensity of contacts between workpieces and abrasive media for finite areas of any workpiece. The DEM-model is used to simulate a small-scale drag finishing process. Findings from the model are utilized to broaden process comprehension.

The approach presented in this paper is based on the work of UHLMANN ET AL. [8], in which bulk motion is modelled using the open source framework Yade [26]. Media is considered as a bulk of discrete, elastic, spherical particles that overlap depending on contact forces, the so called soft-particle approach. In contrast to the hard-particle approach, that is based on instantaneous exchange of momentum when contact occurs, the soft-particle approach allows for multiple