SIMILARITY RULES FOR THE SHOT PEENING PROCESS BASED ON FINITE ELEMENT SIMULATIONS

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ABSTRACT
Multiple shot impacts are analyzed using a three-dimensional Finite Element model with a user defined temperature- and strain-rate-dependent material formulation. Based on this analysis, a method was developed for the prediction of changes in the material state in areas close to the surface by applying similarity mechanics. This approach provides a tool for the quick estimation of interesting work piece properties after peening especially when a vast field of process parameter variations has to be analyzed. The predictions of the applied similarity mechanics were compared with an explicit Finite Element analysis.

SUBJECT INDEX
Finite Element analysis, similarity mechanics, residual stresses

INTRODUCTION
Finite Element (FE)-simulation of shot peening processes may be used to predict surface states after shot peening without costly experiments and provide clear physical results already in the design process. Especially when variations of process parameters are of high interest the claim for fast results can be met by applying similarity mechanics on this process simulation. Based on the 3D shot peening FE-simulation of (Schwarzer, 2003) and the similarity rules applied on a 2D single shot simulation in (Kotschenreuther, 2003) a promising tool for the quick estimation of interesting work piece properties after peening for a vast field of process parameters will be presented.

METHODS
Model Geometry and Material Definition
The FE-simulations were performed using ABAQUS/explicit by applying the procedure described in (Schwarzer, 2003). The work piece is defined as a cuboid with a quadratic base. The dimensions of this plate can be set to any designated value. The plate is meshed with hexahedral elements with reduced integration and an decreasing element size from the edges of the cuboid to the impact centre. Shock waves occurring after an impact shall not be reflected. Therefore the plate is framed by so-called “infinite elements”.
The shot is formulated as a rigid body half sphere with the mass and moment of inertia of a full spherical shot based on measurements of the cast steel shot. Size,

kinematics, impact location and order are parameterized and allow a vast field of a single or combined variation of the typical shot peening parameters.
The behaviour of the work piece material, quenched and tempered steel AISI 4140 (German grade: 42CrMo4), was properly described using a constitutive law considering the influence of temperature and strain-rate on the flow stress on the basis of thermally activated dislocation slip (Schulze, 2000). It was implemented into the finite element code using a user subroutine VUMAT (Kotschenreuther, 2003), (Schwarzer, 2003) together with the work hardening behaviour using a "generalized Voce" constitutive equation according to (Tome, 1984). The material behaviour was calculated adiabatically since 3D–elements with thermo-mechanical coupling were not available in the FE code. The lack of heat conduction can be tolerated for the realistic impact duration of few microseconds. The complete formulation consists of 9 material parameters that were determined by a numerical fit of data obtained from tensile tests at different temperatures and strain-rates to the material law similarly to (Schulze 2000). By comparing the shape of simulated and experimentally produced shot impacts, the material law could be validated.
To describe the contact between shot and work piece, isotropic Coulomb friction with a coefficient of friction $\mu = 0.4$ is used. The cast steel shot is modelled as a rigid body with a density of 7.85 g/cm^3.

To achieve a realistic modelling of a shot peening process an arrangement of the spheres was chosen that provides a closest packed dimple pattern on the surface with a certain impact order of the shots (Fig. 1). The grey marked inner area which can be approximated with a circle was used for the calculation of residual stress profiles.
As shown in (Schwarzer, 2003) the fact that the shots impact one after the other instead of impacting simultaneously has great influence on the developing residual stresses due to inhomogeneous plastic deformations and therefore changes in the local stress states.

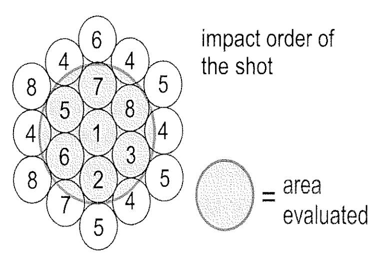

Fig. 1: Arrangement and order of impacts as well as area evaluated to calculate the residual stress profile and roughness

Similarity Mechanics

According to the Buckingham theorem (Buckingham, 1914), a dimensionless output value *a* of a physical problem depends only on $p = n - q$ dimensionless numbers D_1, ..., D_n, where n is the number of influence parameters and q is the rank of the dimension matrix (Kotschenreuther, 2003).
In this study the influence parameters are: shot diameter d, shot velocity v, impact angle α, distance between dimple centres l determining coverage, initiate temperature T_i, friction coefficient μ, Young's modulus E, Poisson's ratio ν, density of plate and shot ρ_p and ρ_s and the above mentioned 9 remaining material parameters, hence altogether 19 influence parameters. Further parameters characterizing the impact arrangement and sequence are not considered here and were always kept constant.
In this case the rank of the dimension matrix equals the number of the relevant fundamental units: length, mass, time and temperature. That means that to fully

describe the scaling problem of the impacts it is necessary to consider $p = 19 - 4 = 15$ dimensionless numbers. The knowledge of the functional dependencies of a dimensionless output a on the 15 numbers $a = a\,(D_1, \ldots, D_{15})$ would then completely describe the scaling problem.
As previously described in (Kotschenreuther, 2003) the choice of the dimensionless numbers is done in a way that whenever possible, each varying influence parameter only affects a single number. As can be seen below the shot velocity for example only affects the so called Cauchy number, giving the ratio of the impact velocity to the internal sound velocity of the plate.
Three process parameters and hence their according similarity numbers were varied:

$$Si = \frac{\dot{\varepsilon}_0 d}{\sqrt{E/\rho_p}}, \qquad Ca = \frac{v}{\sqrt{E/\rho_p}}, \qquad \alpha \tag{1}$$

where Si is the size number representing the shot diameter. Ca is the Cauchy number describing the shot velocity. α is the angle between the normal to the work piece surface and the impact velocity vector. The remaining 12 dimensionless numbers were kept constant and describe the coverage, the initial process temperature, the friction and the material properties.

Dimensionless Output Values

The results of the simulation were evaluated using the characteristics of the residual stress profile in a dimensionless manner. In order to get normalized values the residual stress components perpendicular and parallel to the projection of the velocity onto the surface at the surface and in the maximum $\sigma^{RS}_{0\perp}$, $\sigma^{RS}_{0//}$ and σ^{RS}_{max} were related to the Young's Modulus E. The depths of maximum and zero residual stresses z_{max} and z_0 as well as the roughness R_t of the dimples were related to the shot diameter d.

Estimation of Output Values

The determination of the full functional dependence of an output variable a on the 15 similarity numbers would exceed a maintainable computational effort. Therefore only the 3 process parameters were taken into account and as further simplification, a product ansatz, stating

$$a\,(Si, Ca, \alpha) = \frac{1}{a_0^2} \cdot a_{Si}(Si) \cdot a_{Ca}(Ca) \cdot a_\alpha(\alpha) \tag{2}$$

was made, where a_0 represents the output value for standard material and process parameters and $a_i\,(i)$ are functional descriptions of the influence of the dimensionless input parameter i on the output parameter when all other input parameters were kept constant at standard values $Si_0 = 1.10 \cdot 10^9$ (acc. to $d = 0.564\ mm$), $Ca_0 = 6.77 \cdot 10^{-3}$ (acc. to $v = 35\ m/s$) and $\alpha_0 = 0°$.
With tolerable computational costs of hardly more than a dozen of calculation variations for the deduction of the one dimensional functional relationships it is possible to determine interesting output values for arbitrary input values within minutes by using the product ansatz whereas a single FE-analysis and its evaluation take about 24 hours in this example. The impressive time advantage of the product

ansatz is then given when the number of different parameter variations that are of possible interest exceeds the number of necessary FE-analyses for the determination of the functional dependence of the output values from one input value.

RESULTS

The two charts in Fig. 2 show the dependence of the dimensionless output values on the *Si*-number with a variation range of 0.5 – 3.5 Si_0 while all other 14 input values remained constant. Results of the computations with standard values are highlighted with larger symbols. With increasing *Si*-number the normalized maximum and surface residual stresses decrease slightly although the impact energy, proportional to the shot mass, increases with the third power of the diameter. This development of the residual stresses can be explained considering Hertzian stress theory with higher and sharper stress distribution caused by decreasing radii of the contact partners. Despite an impact angle of α_0 = 0° the residual stress components in two perpendicular directions spanning the surface of the work piece differ systematically of about 20 %. This may be an artefact caused by the asymmetric impact order in the simulation. A total constancy of the dimensionless ratio z / d over *Si* was determined for the depth of the maximum stresses, the zero-crossing depth of the stresses and the output value for the roughness depth R_t / d meaning that the bare depth and roughness values increase linearly with ascending shot diameter.

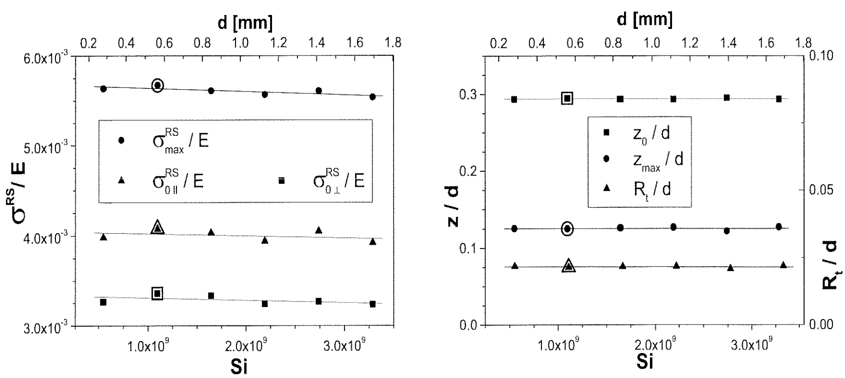

Fig. 2: Dimensionless output values vs. *Si* for constant $Ca = Ca_0$ and $\alpha = \alpha_0$

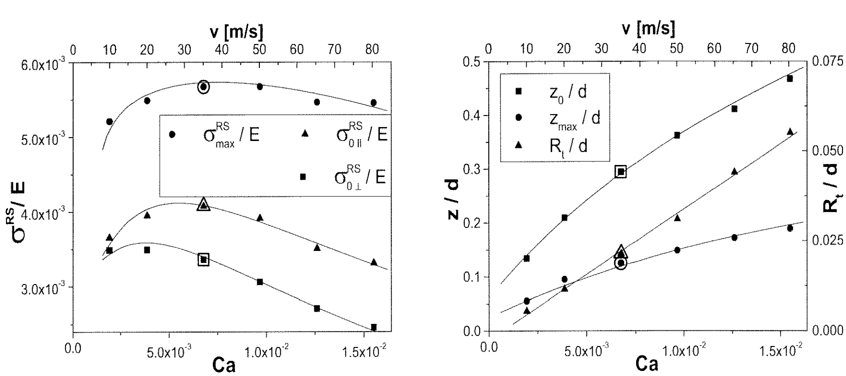

Fig. 3: Dimensionless output values vs. *Ca* for constant $Si = Si_0$ and $\alpha = \alpha_0$

In Fig. 3 the investigated output values for a *Ca*-variation of a shot velocity range from 10 to 80 m/s are shown. The average residual stresses initially increase, reach a maximum value for medium *Ca*-numbers or velocities and decrease for increasing *Ca*. This can be attributed to the softening influence due to the high temperature caused by heat generation in the plate by plastic deformation, which exceeds the hardening influence of increasing strain rate at high *Ca*-values . In contrast, the diminishing total impact energy and smaller strain rates cause the small σ^{RS} / E values for small *Ca*-numbers. The normalized depth values z_0 / d and z_{max} / d show a degressive growth and an increasing difference between the two output values with increasing *Ca*. The roughness ratio R_t / d linearly increases with increasing *Ca*.

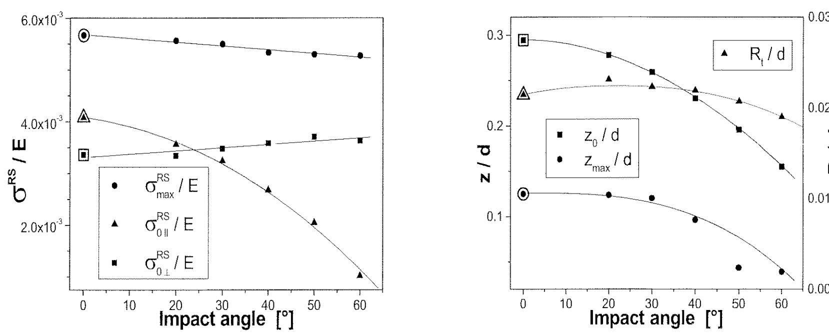

Fig. 4: Dimensionless output values vs. α for constant $Si = Si_0$ and $Ca = Ca_0$

As can be seen in Fig. 4 for varying impact angles there is a difference between the surface residual stresses perpendicular and parallel to the velocity projection. The smaller constraint in the parallel direction and the higher shear components result in smaller σ^{RS} / E values for increasing impact angles while the values in the perpendicular direction increase slightly. Both z_0 / d and z_{max} / d show a negative parabolic course with increasing α but the influence of the impact angle is less distinct for z_{max} / d than for z_0 / d. The influence of α on R_t / d is marginal from 0 to 40° and leads only for higher impact angles to reduced R_t / d values.

In order to test the product ansatz for evaluating the influence of changes in multiple input parameters the output values were compared with the results of an explicit FE-calculation. Therefore all three process parameters were set to a value significantly different from the standard. The chosen parameters are as follows: $Si_1 = 2.74 \cdot 10^9$ ($d_1 = 1.41mm$), $Ca_1 = 1.26 \cdot 10^{-2}$ ($v_1 = 65$ m/s), $\alpha_1 = 30°$. The dimensionless output values were determined according to equation (2).
The results of the interesting output values are given in Tab. 1 and show remarkable accordance for the normalized maximum residual stress component and the zero- and maximum-stress depth values with a relative error of less than 3 %. The relative differences of 6 to 10 % for the output values of the residual surface stresses and the roughness may still be improved for accurate predictions in the late dimensioning process. Anyhow, it is obvious that the product ansatz is a powerful method for surface characteristics after shot peening processes.

	product ansatz	simulation	rel. error [%]
σ^{RS}_{max}/E	$5.392 \cdot 10^{-3}$	$5.282 \cdot 10^{-3}$	2.1
$\sigma^{RS}_{0\perp}/E$	$2.762 \cdot 10^{-3}$	$2.988 \cdot 10^{-3}$	8.2
$\sigma^{RS}_{0//}/E$	$2.738 \cdot 10^{-3}$	$2.584 \cdot 10^{-3}$	6.0
z_{max}/d	0.16153	0.16152	0.01
z_0/d	0.3701	0.3599	2.8
R_t/d	0.0448	0.0408	9.6

Tab. 1: Comparison of the output values determined by similarity rules and a separate Finite Element analysis for the input parameters Si_1, Ca_1 and α_1

CONCLUSION

A three-dimensional Finite Element-model with multiple shot impacts was used to simulate the shot peening process. The work piece material was assigned a temperature- and strain rate-dependent behaviour. In order to provide a means for a fast determination of interesting output values for arbitrarily chosen input parameters similarity mechanics were applied to this shot peening simulation. A complete dimensional analysis was carried out and the functional dependencies of several output values from dimensionless process parameters were determined. The method of combining similarity mechanics with Finite Element-simulations was shown to be powerful for the quick estimation and prediction of the surface material state of this process. Further endeavours are running to refine the accuracy of the results.

ACKNOWLEDGMENTS

The financial support of the Deutsche Forschungsgemeinschaft (DFG) is gratefully acknowledged.

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