Simulation of the Ultrasonic Shot Peening Process

P. Thuemmler 1, H. Polanetzki 1, V. Schulze 2

1 MTU Aero Engines, Munich, Germany
2 Institute for Materials Science and Engineering I, University of Karlsruhe, Germany

ABSTRACT
Ultrasonic shot peening (USP) is a novel process suitable for the shot peening of highly complex component geometries. In USP, unlike conventional shot peening where the shot is propelled by compressed air, the shot is energized by a sonotrode vibrating at ultrasonic frequency. There already exists a large body of literature describing the application of the USP technique. Yet it remains difficult to develop the process for a specific purpose, with problems ranging from chamber design to individual process parameters. Often, comprehensive experimental investigations are needed to find the optimum peening parameters. Also, peening results on complex component geometries reveal that the motion of the shot and hence the way the process works is still poorly understood. We propose to close that gap by developing an USP simulation software for the peening of random component contours. It will appreciably reduce the experimental effort required for the optimization of parameters. For use in engine construction, optimization of the process variables will afford distinct advantages, considering for instance that peening intensity, a characteristic used for process control, can be determined in advance across the entire component contour. The simulation will also permit to estimate component peening time.

KEY WORDS
Ultrasonic shot peening (USP), numerical simulation, shot velocity, peening intensity, peening time

INTRODUCTION

Conventional shot peening is a very popular mechanical work-hardening process and finds wide use in industrial applications. But since component geometries are growing ever more thin-walled and complex, they make work-hardening by conventional peening difficult. This is where, provided all component areas are accessible in the first place, the high, local energy density input of the shot stream may cause distinct component distortion. The growing number of such difficult-to-peen components, which in service are subject to high thermomechanical stresses, explains the need for peening techniques to supplement conventional shot peening. In this situation, ultrasonic shot peening holds great promise of novel avenues in engine construction.

An attempt is therefore made to improve the understanding of how USP works. At this time, neither the exact phenomena appearing during the process nor the effects of all peening parameters are sufficiently known. The scientific analysis of whether this technique is suitable for large or very complex component geometries such as blisks (integrally bladed discs) was also entirely neglected, yet. As it stands, it takes elaborate experimenting to learn whether the desired peening results can be obtained on component surfaces of complex shapes.

In a first step, through an experimental analysis of the effect of all potential influencing factors on the peening result, a basic understanding of the USP process is to be generated. By means of peening intensity, which is a common measure for monitoring peening processes, the action of the work-hardening process can be described in a simplified manner.

Representation of shot motion in a numeric simulation makes it possible to predict the applicability of the process on random components. This obviates the need for comprehensive preliminary studies to be conducted especially on complex component geometries. The overall effort expended in the development of peening processes can appreciably be reduced by acquiring an in-depth understanding of the phenomena occurring during the USP process. Additionally, for the industrial application of the process, it is important that the time needed to treat a component can be estimated. In this fashion, it can swiftly be assessed whether the process can be developed cost-effectively under the given circumstances.

METHODS

For the experimental investigations, a chamber configuration was selected that permitted variation of all particular peening parameters. Apart from the vibration amplitude of the sonotrode, the type of shot, the amount of shot in the chamber and, for instance, also the dimensions of the chamber could be varied. In this manner, it was investigated how variations in the chambers cross section and the distance between component and sonotrode surface affect the measured peening intensity.

The results obtained reveal that peening intensity varies very distinctly with the properties of the shot and the amplitude of sonotrode vibration. Considering saturation times, which are determined along with peening intensity, the component distance, the amount of shot and again the vibration amplitude play major roles. Accordingly, for developing the process, a problem description results that has several variables.

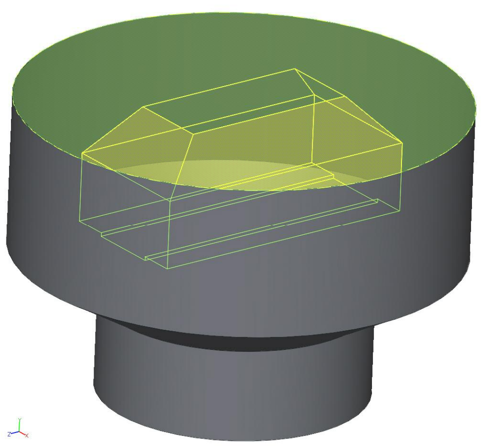

Figure 1: Peening chamber of the experimental setup from CAD-file must be transformed into a scatter-plot.

However, the question, how exactly the shot moves inside the chamber, remains disregarded in these considerations. This defines the aim of the numerical simulation software, which has been developed. The simulation program needs information about the chamber and component geometries to be provided by drawings from CAD (Figure 1). Also the properties of the shot, the vibration characteristics of the sonotrode and the coefficients of restitution of the shot interacting with the chamber and component are to be defined.

Since in this simulation the focus is solely on describing the shot motion, the effect of the shot impacts on the properties of the component material is not a primary concern.

It is only the coefficient of restitution describing the transfer of energy from the shot to the component that needs to be considered.
The following influencing factors have been taken into account:

- energy that is transformed by plastic deformation of component and peening shot and
- dissipation of energy by the viscoelastic properties of component and peening shot.

The coefficients of restitution for chamber walls and caps made from plastics, glass and hardened steel were determined via high-speed exposures from a glass chamber. Despite different impact velocities and angles only minor variations in the coefficients of restitution were noted in all investigations. The following coefficients of restitution were determined for the various materials used:

- Chamber walls of round chambers (polyethylene): $\varepsilon_{PE} = 0.7$
- Glass chamber wall for high-speed exposures: $\varepsilon_{glas} = 0.7$
- Cap of round chamber and glass chamber (hardened steel): $\varepsilon_{cap} = 0.9$

The biggest challenge is how to realistically describe the energy transfer from the Sonotrode (titanium, vibration frequency 20 kHz) to the peening shot. The relative velocities of the two members, which depend on the vibration phase of the sonotrode, must be taken into account when defining the acceleration force acting on the peening shot and when describing the coefficient of restitution. These interactions have been described in FEM simulations using ABAQUS. The functional relationships determined are now available as input data for the simulation program.
The change in the coefficient of restitution between shot and sonotrode surface can be described as a function of the shot velocity:

$$\varepsilon_{Ti}(v) = -0.1103 \cdot \ln(v_{Shot}) + 0.9234 .$$

To keep the complexity of the program as low as possible, the force of the air friction which counteracts the velocity vector of a shot particle remains disregarded. However, the effect of gravitation on the shot velocity, which is likewise rather small, must be considered in the simulation since the force influences the shot trajectory.

RESULTS

To verify the simulation model, certain velocity distributions from high-speed exposures were compared with simulation results and match very closely (Figure 2).

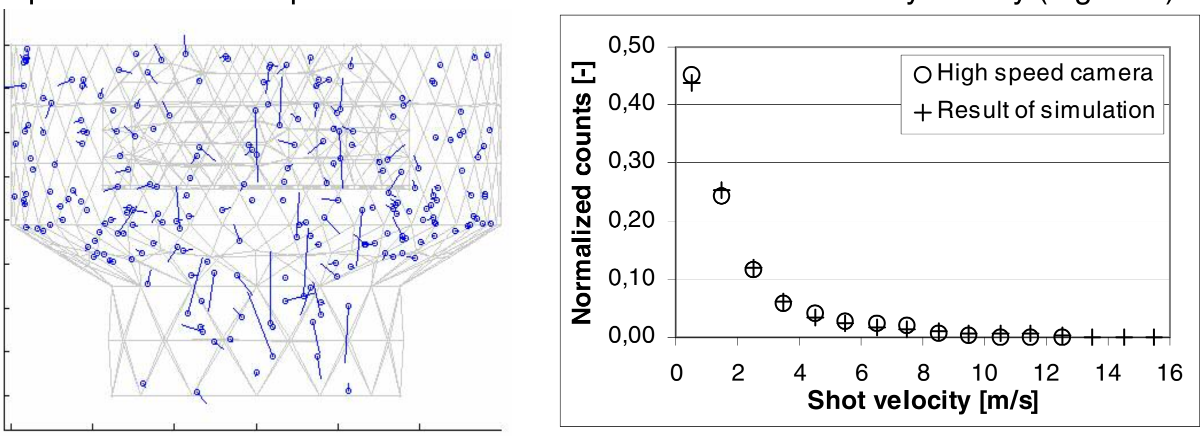

Figure 2: After computation, the motion of the shot in the chamber can be mapped in all planes (left). A comparison of the velocity distributions determined by means of high-speed exposures and those determined in simulations shows good conformity (right).

Apart from shot velocities, as a result of simulation computation, the accumulated energy input into the component can be indicated for each component area (Figure 3), as can the number of hits. When individual peening parameters are varied, the variations in the peening result are noted to be exactly the same as in the experimental investigations. When the values of energy input into the component surface are juxtaposed with the peening intensity, a correlation function between the two quantities becomes clearly apparent.

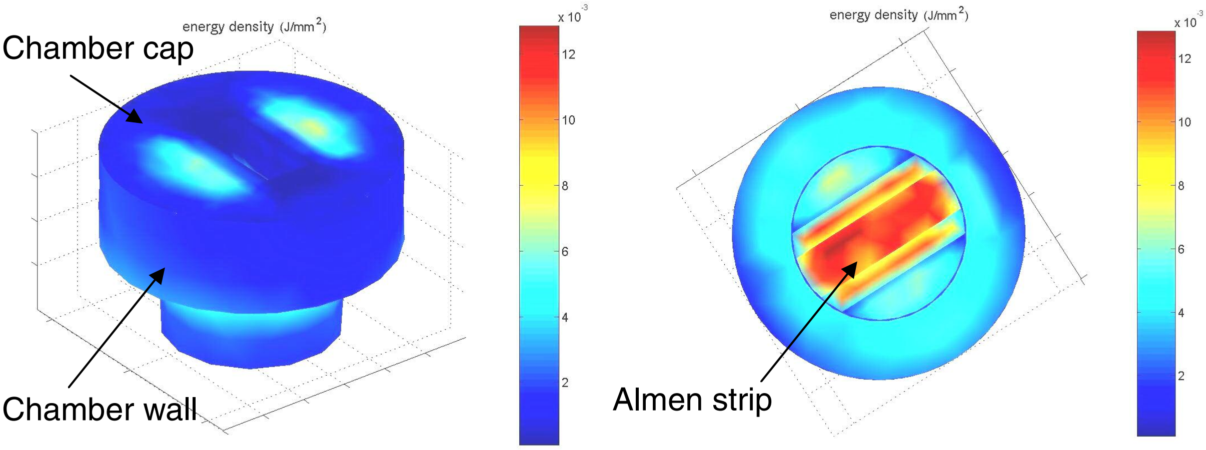

Figure 3: Results of the simulation of a chamber setup from the experimental investigations. Shown here is the energy density that is input into the component and that can be correlated with the peening intensity.

The proper function of the simulation thus confirmed, transfer to complex component geometries to be peened can now be made. The special advantage provided by this simulation is that it not only permits the peening intensity to be verified on selected positions of the component but that, moreover, it enables the energy input to be mapped across the entire component contour. The energy input can in turn be correlated with intensity. Going by the number of hits per unit of area and the resultant overlap of shot impacts, the time needed for peening a component can be estimated. It is especially the energy density and coverage in critical component areas that can provide a clue as to the general suitability of the process for work-hardening diverse component groups. The peening parameters are set optimally when peening intensities are distributed homogenously and peening times are short.

DISCUSSION

The newly developed simulation software makes it possible to reconstruct and describe the motion of peening shot in the chamber. Distinct dependencies of peening results on individual peening parameters were noted that now no longer need to be determined exclusively by experiment. The simulation program can predict the peening result for random component contours and therefore appreciably facilitate the effort required to find the optimum peening parameters. The simulation can also indicate how a component chamber can optimally be designed.

A critical factor for the proper function of the simulation, however, is the exact definition of the boundary conditions. To determine the coefficients of restitution, resort needs to be made to FEM simulations, which assumes the existence of a comprehensive data base on the materials used (chamber and component).

CONCLUSION AND IMPLICATIONS

The simulation program here developed for the first time enables the mapping of every conceivable industrial application of ultrasonic shot peening. It provides detailed results that previously could be attained only through laborious experimental investigations. Accordingly, the development effort needed to design a peening chamber and define suitable USP parameters can appreciably be reduced.