Velocity characteristics of shot ball corresponding to impeller blade shape based on discrete element analysis

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Introduction

Shot peening is a technique that improves resistance characteristics from external fatigue loading by producing beneficial compressive residual stress on the metal surface [1]. Impeller-type shot peening equipment is widely used. Usually, plate blades have been used in impeller-type shot peening equipment due to their low cost. However, plate blades wear out frequently and need to be replaced at the same rate. In addition, frequent replacement and repair of damaged blades may cause increased maintenance costs. For this reason, a researcher theoretically calculated the shot velocity by designing the blade with a curved shape, and confirmed its effect [2]. However, in the equation, the shot velocity was calculated using only the velocity component corresponding to the impeller rotation. That is, physical properties such as the material, sizes of the shot ball and blade, and friction were not considered. For this reason, in this study, an improved blade shape was proposed to increase the shot velocity at the same impeller rotation, based on the discrete element (DE) analysis. The plate, curved, and plate-curved blades were adopted in the DE analyses. Additionally, the compressive residual stresses were investigated with respect to the physical characteristics in the single-shot impact finite element (FE) analysis model.

Objectives

In this study, shape optimization of the blade was performed to improve the shot velocity. First, the DE analysis model of the plate blade was established, and the shot velocity was obtained and compared with the calculated velocity. From this result, the validity of the DE model was verified and extended to the curved and plate-curved blade models. The computed shot velocities were obtained by DE analyses at the moment of their respective departure from the blade tip, and were subsequently compared with each other. These shot velocities were employed in the single-impact FE model to obtain the compressive residual stresses and enable their comparison. Ultimately, the improved blade shape resulting in the most effective peening residual stress was selected.

Methodology

Discrete element analyses

In this study, the optimal shape of the blade was designed based on the planar impeller with outer diameter D_I = 490 mm. Equation (1) was used to calculate the shot velocity for the case of the plated blade [3].

$$v = 2\sqrt{2}L\pi N \quad (1)$$

Here, v is the shot velocity, L is the length of blade, and N is the revolution per minute of the impeller. The relationship between the blade length L and the impeller radius R_I is $L = 0.897R_I$. Curved and plate-curved blades, as shown in figure 1, were modeled using the CAD software and analyzed using the commercial DE analysis software EDEM2017 [4]. In figure 1, θ is the angle resulting in the optimum shot velocity. The value of θ is 31° for a curved blade [2] and 45° for a plate-curved blade. Carbon steel was used as the material for both the shot ball and the blade in the DE model. The rigid shot ball had a diameter (D_S) of 0.8 mm and the value of friction coefficient (μ) in the DE model was set as 0.3. The initial shot velocity (v) supplied from the center of impeller was set to 0.5 m/s.

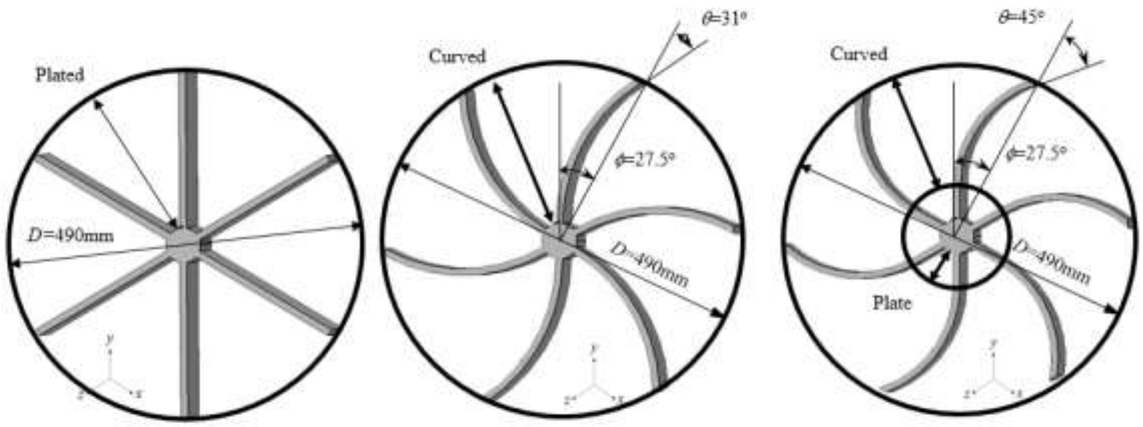

Figure 1. Plated, curved, and plate-curved blades for DE analysis

Finite element analyses

Figure 2 shows a 2-D axisymmetric FE model for single-shot impact using the axisymmetric four-node bilinear, reduced integral element (CAX4R; ABAQUS [5]) [3]. The FE material model for the material AISI4340 with a radius of 3 mm and a height of 3 mm was employed. The bottom of the material model was fully fixed and the roller boundary conditions were imposed along the axisymmetric axis. The penalty algorithm was applied to the contact point of the material and the shot ball. The shot ball velocities employed in the FE model were 85 m/s, 102 m/s, and 113 m/s. The FE model consisted of approximately 3100 nodes and 3000 elements. The AISI4340 material was quenched at 815 °C and tempered at 230 °C for 2 h. The material has the following characteristics: yield strength σ_0 = 1510 MPa, tensile strength σ_t = 1860 MPa, elastic modulus E = 205 GPa, Poisson ratio ν = 0.25, density ρ = 7850 kg/m^3. The rigid shot ball was also considered.

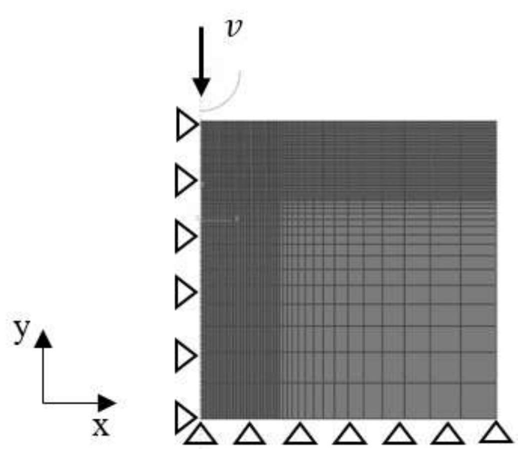

Figure 2. 2D symmetric FE model for single-shot impact

Results and analysis

Shot velocities based on discrete element analysis

For the impeller speed of 2600 rpm, the shot ball velocity was obtained by the DE analysis and subsequently compared with the calculated velocity value. Table 1 presents the analyzed and calculated shot ball velocities. After the DE analysis, the shot velocity v was 85.9 m/s and the value of velocity v calculated from equation (1) was 84.9 m/s. The validity of the DE model was confirmed with the error of 1.2%.

Table. 1 Comparison of computed v with calculated v in the plated blade

D_I (mm)	Speed (rpm)	Calculated v (m/s)	Computed v (m/s)	Error (%)
490	2600	84.9	85.9	1.2

Figure 3 shows the computed shot ball velocities along the blade length for the three types of blades. The x-axis corresponds to the impeller radius ($D_I/2$) and the y-axis indicates the shot ball velocity at the position when the shot ball runs along the blade plane. For the impeller speed of 3200 rpm, the shot ball velocities for the curved and plate-curved blades were obtained as 101.5 m/s and 112.7 m/s, respectively. As a result, it was confirmed that the plate-curved blade produced the most effective shot ball velocity. Figure 4 shows the shot balls projecting from the blade tip of the curved and plate-curved blades.

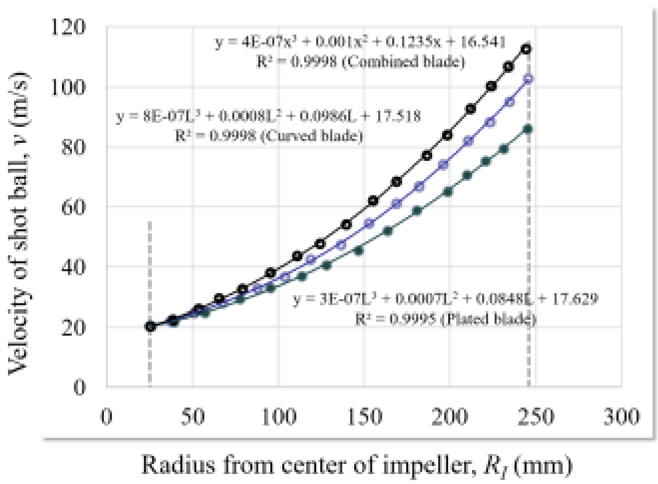

Figure 3. Shot ball velocities with three types of blades.

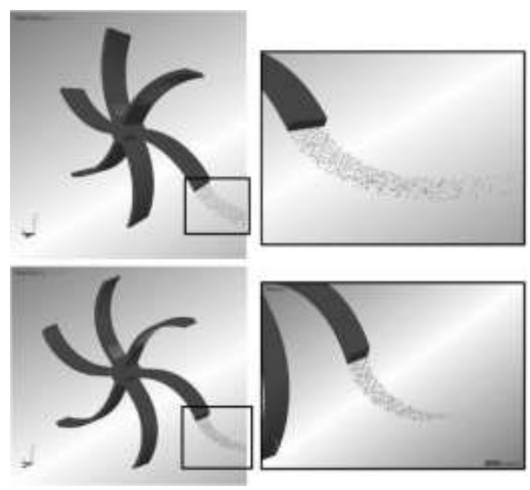

Figure 4. Projection of shot balls for curved (up) and plate-curved (bottom) blades.

FE analysis of residual stress by single-shot impact

Figures 5 and 6 show the shot peening residual stresses when the shot velocities (plate type: 85 m/s, curved type: 102 m/s, plate-curved type: 113 m/s) were employed in the FE model for the single-shot impact. The residual stresses were obtained at the impacted position from the surface to the depth direction. The results showed that both the curved and plate-curved blades generated more effective peening residual stresses than that of the plate blade. The peening residual stresses for the curved and plate-curved blades were almost similar but confirmed that the plate-curved blade was more effective.

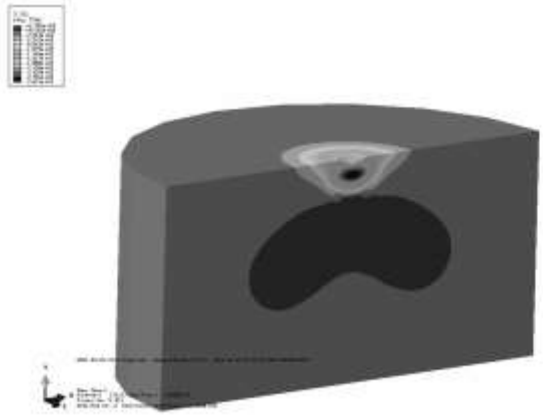

Figure 5. Distribution of residual stress in single-shot impact FE model.

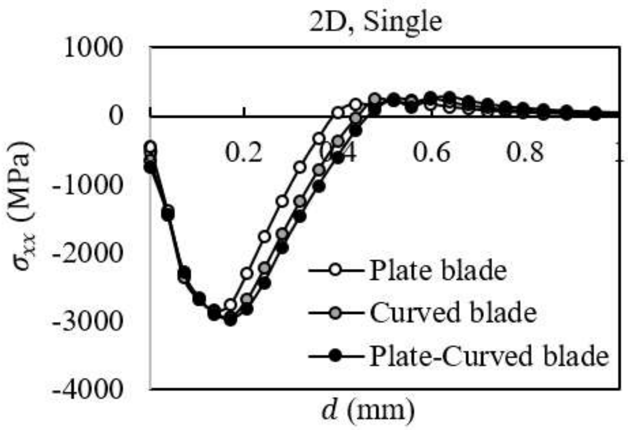

Figure 6. Residual stresses for three types of blades

Conclusions

In this study, the shape optimization of the blade was carried out to improve the shot velocity. An improved blade shape was proposed based on the DE analysis, to increase the shot velocity when the impeller rotation was the same. The plate, curved, and plate-curved blades were employed in the DE analyses. Additionally, the compressive residual stresses were investigated in the single-shot impact FE analysis model with physical characteristics. The results of the DE analyses confirmed that the plate-curved blade gave the most effective shot ball velocity. The FE analyses results showed that the peening residual stresses for curved and plate-curved blade were almost similar but confirmed that the plate-curved blade was more effective.

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