Numerical simulation of stress peen forming with regular indentation

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Abstract

Stress peen forming is widely used to form the thin components with complex shapes in the aerospace industry. The prestress has an influence on the residual stress profiles, thereby influencing the peen forming forces: bending moment and stretching force for shaping the component. A static one-shot FE model was performed to investigate the residual stress profiles of single shot indenting under different prestresses and loads. A static four-shot FE model was performed to investigate the overlapping of the stress fields of adjacent shots indenting. The simulation results reveal that the tensile prestress enhances the indentation diameter and the plastic region size resulting in larger and deeper compressive residual stresses. The average peen forming forces of regular distributed four shots are four times the forming forces of one of shots when the separation distance of adjacent shots is larger than the plastic region size of one shot indenting. Experiments with different prebending arc heights and indenting gaps were carried out on aluminum alloy 2024-T351 strips with a developed Brinell hardness tester. The experimental results validated the simulation results.

1. Introduction

Shot peen forming is a widely used process in the aircraft industry for shaping a metallic component to a desired

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profile. To form the component such as a wing panel that has a larger curvatures in chordwise direction than in spanwise direction, stress peen forming can be applied. In the stress peen forming, a bending load is applied on the panel in chordwise direction to produce an elastic tensile stress distribution beneath the peening surface before and during peening. As a result, the component will obtain a larger curvature in the chordwise direction. The prestresses influence the residual stress profiles, thereby influencing the peen forming forces (bending moment and stretching force) and resulting shape of component.

Several experimental and numerical works have been carried out to research the residual stress distribution and the deformation of a component in stress peen forming. Li (1981) discussed the forming principles of the stress peen forming and presented experimental results under different forming parameters. Barrett and Todd (1984) showed that the magnitude of compressive stress is related to the elastic strain applied during stress peen forming. Xie et al. (2012) measured the residual stress profiles along different directions in titanium matrix composites treated by stress peening with various prestresses. Miao et al. (2010) revealed a linear relationship between the resulting arc height and the prebending moment. Miao et al. (2011) simulated the induced stress profiles of stress peening with 100% coverage under different bending moments.

When the shot velocity is much less than the sound speed, the dynamic effects can be neglected (Al-Obaid, 1995). In the present work, first, a static one-shot finite element (FE) model is utilized to determine the relationship between the forming parameters and the average forming forces corresponding to the induced stresses of peen forming. Second, a four-shot FE model is used to investigate the overlapping of the stress fields of adjacent shots indenting with various coverage values. Third, a set of experiments is carried out to validate the simulations.

2. Simulation model

As shown in Fig. 1, the projected area of one shot dimple with radius \( a \) is \( S_{\text{dim}} = \pi a^2 \). Each shot owns a square region of side length \( d \) and area \( A_c = d^2 \). The shot peening coverage can be calculated geometrically as \( C = S_{\text{dim}} / A_c \).

To study the effects of the average induce stresses on the deformation of a plate, the equivalent bending moments per unit width (\( M_x, M_y \)) and the balanced stretching force per unit width (\( F_x, F_y \)) of the induced stresses are calculated with the equilibrium equations (Al-Hassani, 1981)

\[
\int_0^h \sigma_{xx}^{\text{ind}} dz + F_y = 0, \quad \int_0^h \sigma_{yy}^{\text{ind}} dz + F_y = 0, \quad \int_0^h (h / 2 - z) \sigma_{xx}^{\text{ind}} dz + M_x = 0, \quad \int_0^h (h / 2 - z) \sigma_{yy}^{\text{ind}} dz + M_y = 0 \tag{1}
\]

![Fig. 1. The influenced region of (a) one shot impacting and (b) four shots impacting and (c) an equilibrium element with unit width and length.](image)

2.1. One-shot model

The FE model shown in Fig. 2(a) is used to investigate the static process that one shot indenting a target involving prestress. A shot with radius \( R = 1.25 \) mm is normally applied at the symmetrical position of the one-quarter model of the target. The dimensions of the one-quarter model are height \( h = 5 \) mm, length and width \( L = 6 \) mm. The shot is assumed to be rigid.

The target material under study is aluminum alloy Al2024-T351, true stress-true strain curves were fitted using the power-law hardening model from conventional tensile tests by Heerens et al. (2009). The material parameters are elastic modulus (\( E \)) 73 GPa, Poisson’s ratio (\( v \)) 0.33, yield stress (\( \sigma_y \)) 343 MPa, strength coefficient (\( K \)) 804 MPa and strain-hardening exponent (\( n \)) 0.159.
In the first step of the simulation, symmetry boundary conditions are imposed on the \( x=0 \), \( y=0 \) and \( y=L \) planes; the nodes on the \( x=0 \) and \( z=0 \) line are fixed in the \( z \) direction. Linearly distributed pressure with an amplitude of \( \lambda \sigma_y (h-2z)/h \) along the \( z \) direction is applied on the \( x=L \) surface of the target. \( \lambda \) denotes a ratio of the maximum prebending stress on the surface to the yield stress of material. Values of the prestress ratio \( \lambda \) from 0 to 1 determine the magnitude of the pressure.

These pressure leads to prestresses \( \sigma_{xx}^{\text{pre}}(z) = \lambda \sigma_y (2z-h)/h \), \( \sigma_{yy}^{\text{pre}}(z) = \nu \sigma_{xx}^{\text{pre}}(z) \) and equivalent moments per unit width \( M_{xx}^{\text{pre}} = -\lambda \sigma_y h^2/6 \), \( M_{yy}^{\text{pre}} = \nu M_{xx}^{\text{pre}} \).

The values of \( \lambda \) under study are 0, 0.2, 0.4, 0.6, 0.8 and 1. In the second step, the boundaries of the target are fixed at the current position. The target is subjected to a shot indenting with a load \( F \) at normal incidence. The values of \( F \) under study are 1839, 1226 and 612.9 N. One quarter of the force is loaded on the rigid FE shot considering the shot loaded at the symmetric center. In the third step, the pressure applied on the right surface is removed. The boundaries of the target are restricted to its initial position to obtain the induced stresses.

The average induced stresses per element layer in the region \( A_s \) are calculated from the stress components and the corresponding current volume of the elements. The balanced bending moments and the balanced stretching forces are calculated from the average induced stresses with Eq. (1). The indentation diameters under different \( F \) and \( \lambda \) are obtained by detecting the maximum indenting depth when \( F \) reaches the maximum in the second step of the simulation.

### 2.2. Four-shot model

The study is further extended to investigate the influence of adjacent shots indenting on the internal stress field. Fig. 2(b) shows the FE model used to simulate the processes that a prestressed target is indented successively by four shots each of radius \( R=1.25 \) mm. The target dimensions are \( 8(L) \times 8(L) \times 5(h) \) mm. Four shots locate at the four vertexes of a square with side length \( d \). The values of \( d \) under study are 1, 2, 3 and 4 mm. The shot is treated to be rigid.

![Fig. 2. One-quarter of discretized geometries of target used in (a) one-shot model and (b) four-shot model.](image)

The simulation procedure is also carried out by the same three steps as the one-shot model. The prestress ratios under study are 0, 0.425, and 0.85. The target is successively pressed by the four shots with order of 1-2-3-4. The load \( F \) under study is 1839 N. Considering the loading locations of the four shot, shot marked 1 is loaded 1839/4 N, shot marked 2 and 4 loaded 1839/2 N and shot marked 3 loaded 1839 N (Fig. 2(b)). Finally, the average induced stresses, and corresponding equivalent bending moments and stretching forces are calculated in the region \( A_s \).

### 3. Experimental procedure

A set of static indenting tests were performed on Al2024-T351 strips with a developed Brinell hardness tester. In order to obtain regular distributions of the shot indentations, a manual cross slide is fixed on the work table of the Brinell hardness tester to precisely locate the indenting positions. The prebending deformation of the specimen is obtained by clamping the specimen on a strip holder. The dimensions of the strips are \( 100 \times 30 \times 5 \) mm.
In order to validate the simulation results, the indentation diameters under different prebending arc heights and indenting loads were measured. Three strips were respectively bended with arc heights of 0, 1 and 2 mm. An indenter with a 2.5 mm diameter carbide ball is used. Each strip was indented with loads of 612.9, 1226 and 1839 N at different positions. The indentation size is determined by measuring two diagonals of the indentation on an optical microscope.

With load of 1839 N and indenter diameter of 2.5 mm, regularly distributed indentations with separation distances of 2, 3 and 4 mm in association with prebending arc heights of 0, 1 and 2 mm are produced on other nine test strips, respectively. The prestress ratio \( \lambda \) corresponding to the prebending arc height 0, 1 and 2 mm are 0, 0.425 and 0.85, respectively. The resulting radii of curvature in the width and length directions of the test strips are obtained by measuring the arc heights with an arc height gauge.

4. Results

4.1. Indentation and plastic region size

The simulated indentation diameters are compared with the experimental results in Fig. 3(a). It can be seen that the simulated values are consistent with the experimental values, which confirms the simulation model. The indentation diameter increases with increasing the prestress ratio corresponding to increasing the tensile prestress beneath the indenter.

The plastic region size is determined with the maximum principal logarithmic strain at the boundary no greater than 0.002. \( r_x \) and \( r_y \) denote the radii of the plastic region along the \( x \) and \( y \) directions, respectively. Fig. 3(b) shows the values of the plastic region sizes under different loads and prestress ratios. It can be seen that larger load produces larger plastic region. With increasing the prestress ratio, the \( r_x \) increases slightly while \( r_y \) increases obviously. The material on the \( y=0 \) plane is yielded later than the material on the \( x=0 \) plane since the prebending load applied in the \( x \) direction producing a tensile stress field in the \( x \) direction in the target near the indenting side.

4.2. Overlapping of adjacent indenting stress

When two indentations are near, the stress fields will be overlapped between them. The average induced stress and equivalent bending moment and stretching force in area \( A_c \) under different separation distances \( d \) are obtained from the one-shot model and the four-shot model.

With increasing the averaged region, the equivalent moments of one indenting decrease sharply in the beginning then slowly approach to zero, as shown in Fig. 4. The prestress ratio has larger influence on the equivalent moment in the \( x \) direction where applied the prebending load while less influence on the equivalent moment in the \( y \) direction. The equivalent stretching forces have the same tendency as the bending moments.

Fig. 4(a) plots the equivalent bending moment \( M_x \) vs. region size \( d (= l) \) of the one-shot model, four times the equivalent bending moment \( M_x \) vs. region size \( d (= l) \) of the one-shot model and the equivalent bending moment
$M_x$ vs. separation distance $d$ of the four-shot model with load of 1839 N and without prestress. Fig. 4(b) shows the curves corresponding to the stretching force $F_x$. It can be seen that the curve corresponding to four times one-shot indenting intersects the curve corresponding to the four-shot model at a separation distance $d_c$. When the separation distance $d$ is larger than the critical distance $d_c$, the forming forces induced by four shots are four times the forming forces induced by one shot in the same acting region. When $d < d_c$, the forming forces induced by four shots are lower than the forming forces induced by one shot in the same acting region. The same tendencies are also found in the simulations with the prestress ratios of 0.425 and 0.85.

The values of the critical distance $d_{cx}$ in the $x$ direction and $d_{cy}$ in the $y$ direction are detected according to the tendencies of the simulated results. Compared to the plastic region sizes ($r_x$, $r_y$), the critical distances $d_{cx}$ and $d_{cy}$ are approximately twice $r_x$ and $r_y$, respectively.

![Fig. 4](image1)

Fig. 4. Comparison of (a) equivalent bending moment vs. $d$ and (b) equivalent stretching force vs. $d$ of one-shot model and four-shot model with load $F=1839$ N and prestress ratio $\lambda = 0$.

![Fig. 5](image2)

Fig. 5. (a) Simulated Mises stress distribution and (b) max. principal plastic strain distribution of four-shot model with indenting gap of 4 mm and (c) test strips with indenting gaps of 2, 3 and 4 mm.

![Fig. 6](image3)

Fig. 6. (a) Bending moments $M_x$ vs. coverage and (b) $M_y$ vs. coverage under load $F=1839$ N with prestress ratio $\lambda$ of 0, 0.425 and 0.85.
4.3. Comparison with experimental results

Fig. 5(a) and (b) shows the simulated Mises stress and the max. principal plastic strain of the four-shot model with indenting gap of 4 mm. Fig. 5(c) shows three of experimental strips with indenting gaps of 2, 3 and 4 mm.

The equivalent bending moments per unit width of the test strips are calculated with $M_x = D \left( \frac{1}{R_x} + \frac{\nu}{R_y} \right)$ and $M_y = D \left( \frac{1}{R_y} + \frac{\nu}{R_x} \right)$, $D = \frac{Eh^3}{12(1-\nu^2)}$.

The curves of bending moment vs. separation distance shown in Fig. 4 can be transformed to the curves of bending moment vs. coverage. Fig. 6(a) compares the simulated and experimental values of the bending moment in the $x$ direction with different coverage and prestress under load $F = 1839$ N. Fig. 6(b) compares the values in the $y$ direction. It can be seen that the transformed results from the one-shot model and the simulated results of the four-shot model are in good agreement with the experimental results. Under the same coverage, the bending moment in the prebending direction increases obviously with the increase of the prestress ratio while the bending moment in the perpendicular direction increase slightly.

5. Conclusion

A static one-shot FE model and a static four-shot FE model were performed to investigate the residual stress field and average peen forming forces under different forming parameters. The effect of the prestress upon the indentation diameter and the plastic region size is examined and discussed. The average forming forces induced by four shots indenting are compared with the values induced by one shot indenting. The results reveal that the tensile prestress enhances not only the residual stress but also the indentation diameter and plastic region size. The average forming forces induced by four-shot indenting are four times the average forming forces induced by one-shot indenting within the same region when the separation distance of adjacent shots is larger than a critical distance. The critical distance is approximately equal to the plastic region size of one-shot indenting. When the shot separation distance is larger than the critical distance, the forming forces can be obtained with the one-shot model, otherwise the four-shot model considering the simulation resources cost. Furthermore, experiments are carried out on a developed hardness tester. The bending moments of the formed test strips are calculated from the measured radii of curvature of the test strips and compared with the simulation results. The simulation results are in good agreement with the experimental results.

The current work indicates that the one-shot FE model and the four-shot model are capable of predicting the average forming forces for various forming parameters, further predicting the resulting shape of a component after peen forming process. The regularly indenting test can be used to investigate the peen forming process with uniform indentation distributions and precise coverage values.

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