Finite element simulation of peen forming process for integral panel with dihedral shape

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Abstract: Large integral stiffened panels are the main frame parts, which are widely used in modern aircraft and aerospace industry. Shot peen forming is a kind of process to form large integral wing skin panels of modern aircraft, which utilizes a stream of small hard shots with high velocity hitting the surface of the panel to form a specific shape. In this paper, the equivalent thermal loading method has been used to simulate peen forming process, in which produce equivalent deformation with bending moment and stretching on the cross section. Based on Almen C strip experiment, the relationships between the equivalent thermal loads and the process parameters are quantitatively constructed. Finally, an integral panel has been simulated. A desired dihedral shape is obtained by optimizing the peening area and peening intensity with FEM. The finial simulated shape of the integral panel is in agreement with that of the target shape. These results show that shot peen forming process can be simulated by using thermal loads according to the rule of equivalent deformation, which provide significant guidance to the process parameters optimization and predication in practical production.
Keywords: Shot peen forming, equivalent thermal loads, integral panel, dihedral shape

Introduction

Nowadays, there are more and more increasing demands for integral and aerodynamic structures to obtain higher performance for aircraft. The aerodynamic dihedral shape is a kind of double curvature shape, which concave in the spanwise direction and convex in the chordwise direction (see Fig.1), is often used in wing skin panels of modern aircraft to improve efficiency and consequently save fuel [1-4].

Compared with the conventional built-up panels, integral stiffened panels can meet the demands for high performance structures with higher strength and stiffness, lower weight, reduced fabrication costs and increased resistance to fatigue and corrosion. Large integral stiffened panels are the main frame parts, which are widely used in modern aircraft and aerospace industry. However, it is difficult to be formed for this kind of large integrally stiffened panels. Shot peen forming is a good method available to create such double curvatures consistently to the required accuracy in this type of complex integral panel.

Shot peen forming is a kind of process to form large integral wing skin panels of modern aircraft, which utilizes a stream of small hard shots with high velocity hitting the surface of the panel to form a specific shape as shown in Fig.2. The application of shot peening to form or correct the shape of components has been in process for over 60 years, especially in the aeronautic and aerospace industries, peen forming is above all carried out for the production of complex fuselage and wing skin components [3-7].

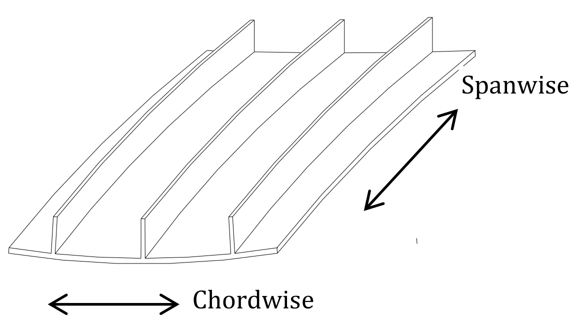


Fig.1 Sketch of the dihedral shape

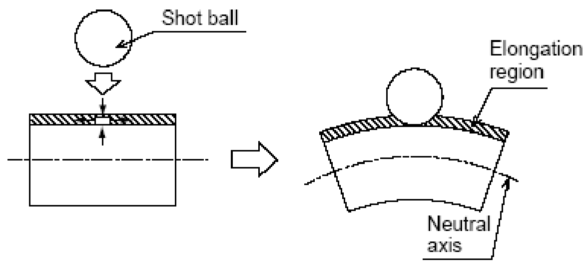


Fig.2 The principle of shot peen forming

However, the most disadvantage of the peen forming is that the forming process is very difficult to be controlled because of many process variables. Therefore, for a long time, the shot peen forming is a try-and-error process. It would need a huge number of tests, making it difficult to carry out effective setting of the forming conditions. Therefore, the deformation simulation was carried out using the finite element method as a pre-study before experiments.

From previous literatures [8-12], two kinds of FE simulation methods applied to the shot peen forming can be summarized: one is to build analysis models according to the real impact process and the other is to use the deformation equivalent principle, which is using other loads as the impact loads in the real process. In this paper, the latter one which is an equivalent thermal loading method is devised to simulate the forming process of the dihedral shape from a flat integral panel.

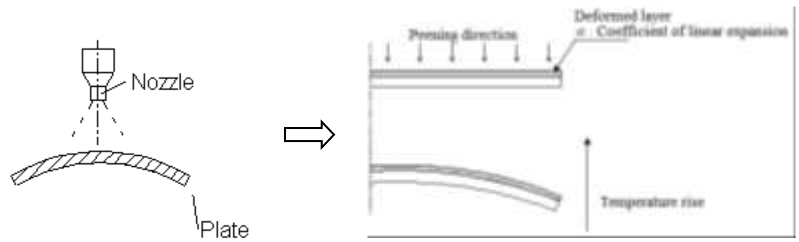
Equivalent FEM model construction

In order to simulate the peen forming process accurately, the modeling must be account for the overall effects that shot peening induced in the material. Growth and curvature must be met with by the model. In order to simulate the forming process, an equivalent deformation method using the thermal loads to produce the equivalent deformation is presented [8~10]. In the temperature gradient field, the internal stress generated in the free rectangular plate is [9]:

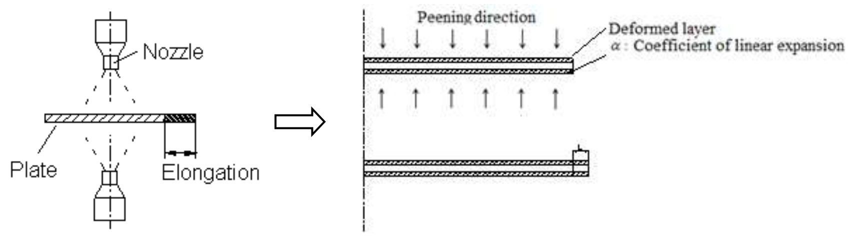
$$\sigma = -\frac{\alpha ET(z)}{1-\gamma} + \frac{1}{2c(1-\gamma)}\int_{-c}^{c} \alpha ET(z)dz + \frac{3Z}{2c^3(1-\gamma)}\int_{-c}^{c} \alpha ET(z)zdz$$
$$= \sigma_t + \sigma_F + \sigma_M \qquad (1)$$

In which σ_t is the stress generated by temperature, σ_F and σ_M is stretching stress and bending stress generated by temperature gradient individually. From a macroscopic view, shot peen process is similar to the deformation of the rectangular plate in single dimension temperature field, which producing a bending moment and a stretching on the cross section.

According to the deformation equivalent principle, an equivalent thermal loading method is devised to simulate the peen forming process. Under uniform peening, a model with a coefficient of linear expansion only at the plastically deformed layer under the peened surface is employed, as illustrated in Fig.3. When the part is heated, the equivalent thermal loads are applied to the panel, which, in combination with the coefficient of thermal expansion, the extension tendency of the deformed layer has the effect of producing a bending moment and a stretching force on the cross section, and the deformation caused is similar as that of the shot peen forming.



(a) one-sided peen forming



(b) double sided peen forming

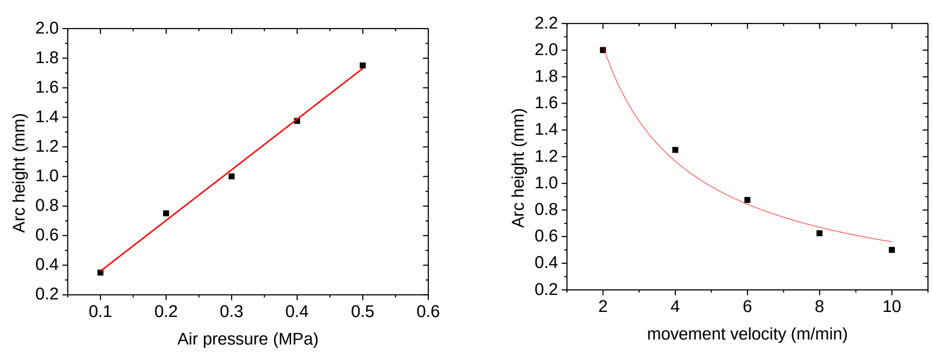
Fig.3 Analysis model for simulation

In order to relate the equivalent thermal loads, which simulate the peen forming process, to process parameters air pressure of nozzle and movement velocity, Almen C strip were selected to be shot peened under several peening air pressure and movement velocity. Figure 4 is the relationship between arc height of C strip with air pressure and velocity. From it can be seen that the arc height is directly proportional to the air pressure and inversely to movement velocity. The relationship is given as follows:

$$i = 2.8\frac{p^{0.8}}{v^{1.1}} \qquad (2)$$

Where i is arc height of Almen C strip [mm], v is movement velocity [m/min], p is air pressure[MPa].

Meanwhile the equivalent thermal loads FE model was built according to the material of the Almen C strip, its size, and the experimental condition. Figure 5 shows the simulated deformation when shot peen formed the Almen C strip. Under the same condition, the equivalent thermal loads (temperature T) in FEM which result in the same arc height with experiment are obtained.



（a） Air pressure （b） Movement velocity

Fig.4 The relationship between arc height of Almen C strip with air pressure and velocity

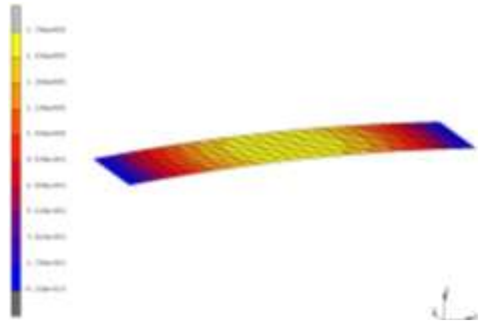


Fig.5 Simulated and the deformation of Almen C strip

From figure 6 the relationship between equivalent thermal T loads and the arc height i is given as follows:

$$T = ki \tag{3}$$

Where T is the equivalent thermal loads [°C], i is arc height of Almen C strip [mm], k is the scale coefficient [°C/mm]. Based on the experiment and FEM result, k is decided as 480.7[°C/mm]. Combining Eq.(2) and Eq.(3), gives Eq. (4), which relate the equivalent thermal loads and the process parameters air pressure of nozzle and movement velocity.

$$T = 1345.96 \frac{p^{0.8}}{v^{1.1}} \tag{4}$$

FEM simulation of integral panel

Before FEM simulation there are some supposed that the thermal loading process is a steady process, and then the shot peen forming process can be simulated with static implicit FEM. A simple integral panel with 7 ribs was selected as analytic target. The dimension of panel is about 5055mm×1120mm×10mm, with which the height of rib is about 60mm (shown as Fig.7). The material of the panel is aluminium 2024T351. The mechanical properties of the material are shown in Table1.

It was meshed using 4-node multi-layer shell elements which describe the grades of temperature from the peened surface to the other surface. During FEM simulation, multi-layer shell element with specified coefficients of thermal expansion is applied to peened area. When the equivalent thermal loads applied, this results in thermal strains being distributed through the thickness of the shell and allowing the plate to reach equilibrium induces a stress distribution across the thickness similar to that shown in shot peen forming process.

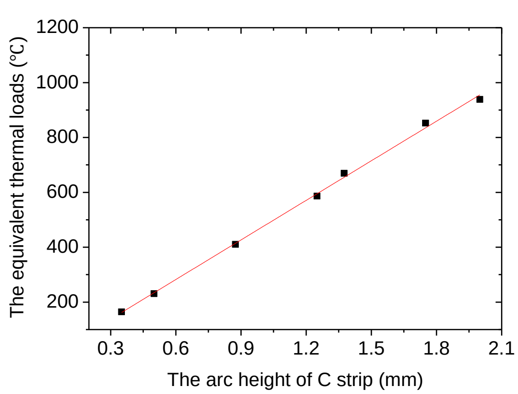


Fig.6 The relationship between arc height and equivalent thermal loads

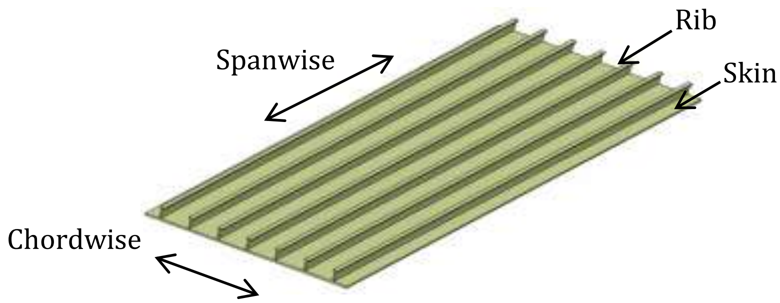


Fig. 7 Sketch of the integral panel with ribs

Table 1 Mechanical properties of the material

Young's modulus [MPa]	Poisson's ration	Yield stress [MPa]	Strength stress [MPa]	Coefficient of linear expansion[10^{-6} • $℃^{-1}$]
72000	0.31	290	434	23.8

Usually two steps are needed to form a flat integral panel into a dihedral shape, firstly chordwise curvature is achieved with peening on one surface only, and then the spanwise shape is formed by stretching the ribs on both sides [10, 13, 14].

(1) The first step : chordwise curvature deformation. Chordwise curvature is achieved by peening the external surface of the panel. One-sided peen forming model shown in Fig.2(a) is adopted to simulate the skin of the panel. The peening path is shown in Fig.8, where the shade bands express the peening area. The equivalent thermal loads applied to the external surface are the same intensity as 200°C. To form the dihedral shape, single curvature in the chordwise direction is formed first, as shown in figure9.

(2) The second setp : spanwise curvature deformation. Subsequent to chordwise curvature deformation, spanwise shape is formed by shot peening both sides of the ribs at the same intensity, elongating it. The double sided peen forming model shown in Fig.2(b) is adopted to simulate the rib of the panel. As a result of a applicition along the longitudinal extension of the rib it is possile to produce convex curvatures. The curvature can be influenced by the height of the rib where are peend. A kind of single rib structural part is selected here to analyse the relationship between the curvature deformation along the spanwise and the peening area of the rib (shown in Fig.10). From Fig.11 the maximum deformation can be obtained when peening area above the neutral axis of the rib. Therefore, Peening surface above the neutral axis of the rib is adopted to simulate the spanwise deformation. The peening paths are optimized according to the target shape of the panel. Figure12 is the peening path of spanwise curvature deformation, where the shade part express unpeened area.

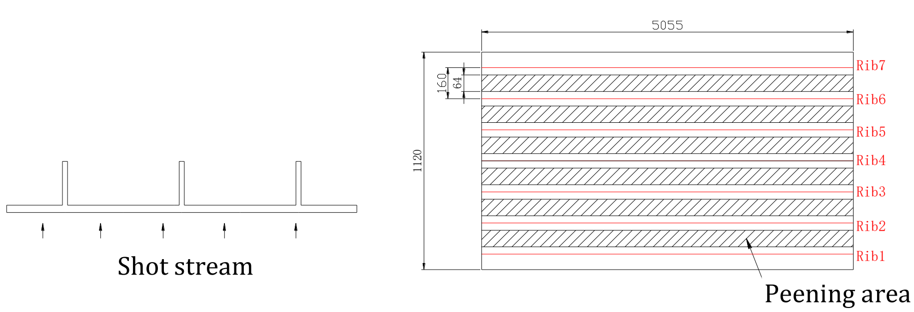


Fig. 8 The peening area of chordwise curvature deformation

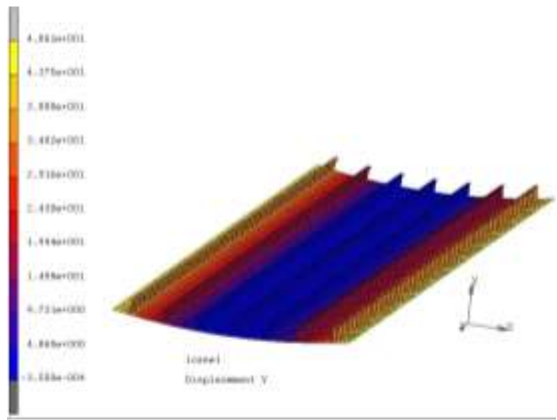


Fig.9 Single curvature in chordwise direction after first step peen formed

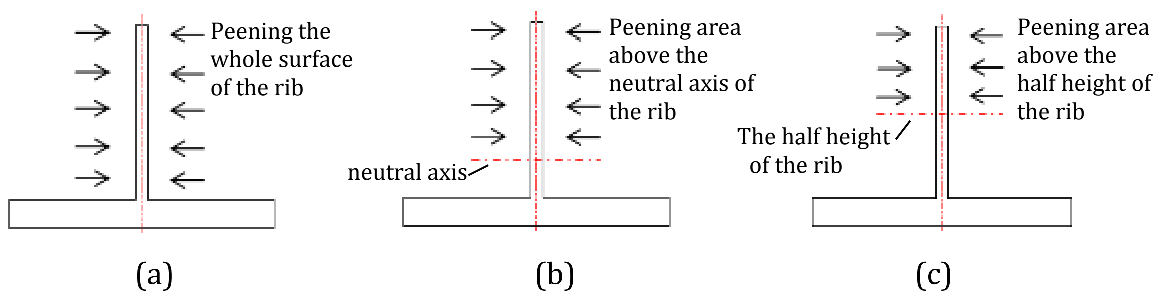


Fig. 10 Peening on the different surface of the rib

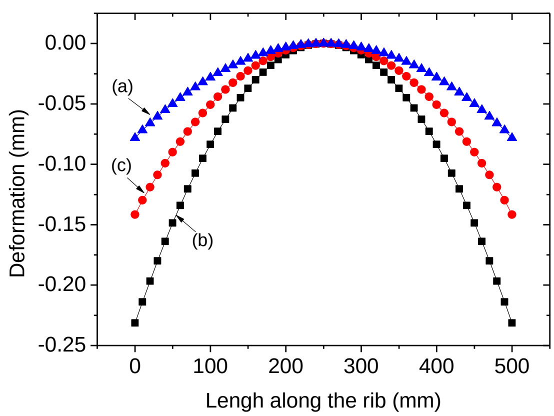


Fig.11 The relationship between curvature deformation along rib and peening area of the rib

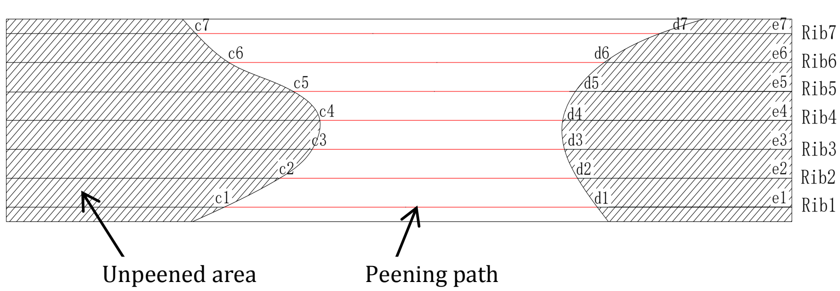


Fig. 12 The peening area of spanwise curvature deformation

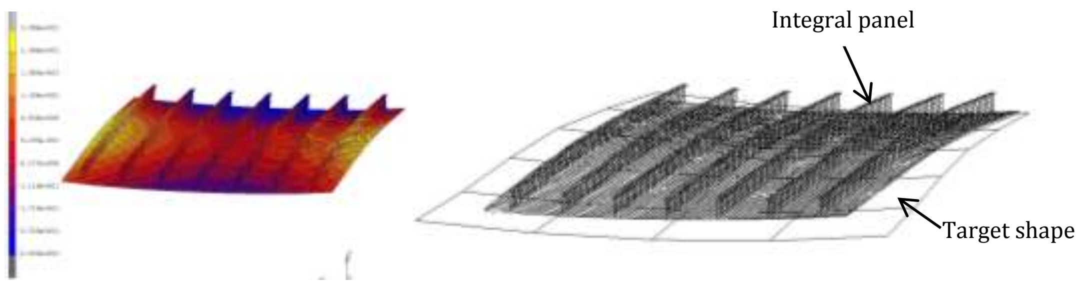


Fig.13 The final dihedral shape after peen formed

An integral panel has been simulated with this method, as shown in Fig.13. A desired dihedral shape is obtained by selecting a suitable peening area and peening intensity based on the above analysis. The simulated shape of the panel is in agreement with that of the target shape,which the maxium difference is 1.5 mm. These results show that shot peen forming process can be simulated by using thermal loads according to the rule of equivalent deformation.

Conclusion

1) The simulation of the shot peen forming process was confirmed as possible by making a model with a coefficient of linear expansion only at the peened surface, using the equivalent thermal loads to produce the equivalent deformation. Based on Almen C strip experiment, the relationships between the equivalent thermal loads and the process parameters are quantitaivly constructed.
2) A flat integral panel can be peen formed into dihedral shape, by whcih firstly chordwise curvature is achieved with peening on one surface only, and then the spanwise shape is formed by stretching the ribs on both sides.
3) This simulation method can be used to simulate the deformation tendency and predict the peening area, leading to finding a right peening intensity according to the required contour.

References

[1] Rongfu Chang, Manufacturing technology for aircraft panels, National defence industry press P.R.China, 1992.9
[2] X.Huang, Y.S.Zeng. Investigation on pre-stress shot peen forming process of aluminum alloy 2024-T351, Proceedings of the 12th international conference on shot, Vols.12(2014),433p.
[3] P.O'Hara, Developments in the shot peening process, Materials and Design, Vol.5,No.4 (1984), 161p.
[4] H.Y. Miao, D. Demers, S. Larose, C. Perron, Experimental study of shot peening and stress peen forming, Journal of Materials Processing Technology 210 (2010), 2089p.
[5] A.Friese, J.Lohmar, F.Wüstefeld. Current applications of advanced peen forming implementation. Proceedings of the 8th international conference on shot peening (ICSP-8), Garmisch-Partenkirchen, Germany, 2002, pp.53-62.
[6] S.E.Homer, R.D.Vanluchene. Aircraft wing skin contouring by shot peening. J. of Material Shaping Technolog,1991,9, pp89-101.
[7] Kishor M. Kulkarnl, John A. Schey and Douglas V. Badger, Investigation of Shot Peening as a forming process for Aircraft Wing Skins, Journal of Applied Metal Working, Vol.1, No.4, 34p.
[8] Andrew Levers, Alan Prior, Finite element analysis of shot peening, J. of Materials processing technology, 80-81(1998), 304p.
[9] Yuansong Zeng, Finite element simulation of shot peen forming, Proceedings of the 8th international conference on shot peening (ICSP-8), Garmisch-Partenkirchen,Germany, 2002, 554p.
[10] Wu Wei, Zeng Yuan-song, Huang Xia, Li Zhi-qiang. Finite element method simulation of shotpeening wing skin panel. Transactions of Nonferrous Metals Society of China, 2005,15(2),443p.
[11] Takeshi Yamada, Takayuki Takahashi and Makoto Ikeda et al. Development of shot peening for wing integral skin for continental business jet. Technical Review. 2002.6 Vol.39 No.2, 57p.

[12] Xiaoming Kang. Shot peen-forming simulation[D]. Northwestern Polytechnical University. 1999
[13] Xia Huang, Yuansong Zeng, Zhiqiang Li. Finite element simulation of peen forming process for the saddle shape. The International Technology and Innovation Conference,2006.
[14] Guoxiang Lee, Shot peen forming. National defence industry press P.R.China, 1982.9