Shot peen forming on aluminum alloy saddle shape integral panels with stiffeners

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Keywords: integral panel with stiffener, shot peen forming, saddle shape, aluminium.

Abstract. Pre-stress shot peen forming is an effective plastic forming method for integral panels with stiffeners used in aeronautical industry. 1-stiffener 7B50 aluminum alloy panels and 3-stiffeners panels were pre-stress peen formed. The saddle shape deformation law of those workpieces was investigated. The results reveal that the contribution of peening parameters on 1-stiffener panel deformation is in following order: moving velocity of workpiece, air pressure and pre-load stress. The regression formula about the quantitative relationship between radius of curvature and peening parameters has been established. Moreover, with the proper elastic pre-stress loading and processing parameters, the integral panels with stiffeners can be formed to saddle shape by peening towards two directions. Furthermore, the spanwise bending deformation degree of panel after pre-stress shot peen forming is basic consistent with the regression formula which could afford some reference to peen forming future complex shape panels with stiffeners.

Introduction

Shot peen forming (SPF) is a metal plastic forming process which is widely applied in aeronautical industry. It has lots of advantages: firstly, panels can be deformed without forming moulds; secondly, it has good adaptability to the panel length; thirdly, it is provided with the potentiality of prolonging the fatigue life [1-2]. Advanced aircrafts will be designed to be more and more lightweight with the increasing need about fuel saving and mobility improvement. The large wing integral panels with stiffeners are likely to replace the multiple panels which are traditional splice joined with extruded sections in order to reduce the aircraft weight. However, the stiffeners make the panels be more rigid. Besides, the chordwise and spanwise curvature distributions of the panels are both complex. As a result, panels with biconvex or saddle shape will be hard formed.

To solve this problem, pre-stress shot peen forming (PSPF) comes out with the improvement of SPF technology [3]. The process of PSPF is that the panel is pre-bent by special tools which make the surface of the panel exist additional elastic stress before SPF. After a number of shots impacting the surface at high speed, the sub-surface of panel will be stretched. And then there will be residual stress in the middle of the material. The difference of the residual stress in the surface and middle of panel makes panel be bent. Many researches indicate that the formed curvature of aluminum alloy plate by PSPF is two or three times of that by conventional SPF using the same processing parameters. Consequently, PSPF has become one of the most useful methods for forming integral panels, especially, which with machining-made stiffeners [4].

A considerable amount of research on the SPF has been done during the last decade. Some researchers such as Gariepy et al. [5] investigated the influence of the rolling direction orientation with respect to the sample for aluminum alloy 2024-T3 specimens. C.Russig et al. [6] researched the SPF of fiber metal laminates on the example of GLARE which is used in the fuselage components for the Airbus A380. H.Y.Miao [7] et al. discussed the quantitative relationships between the prebending moment and the resulting arc heights of narrow strips and square strips. However, those papers do not provide much attention to the complex shape panels with stiffeners formed by PSPF. Therefore, the PSPF experiments were conducted based on 7B50 aluminum alloy panel with stiffeners in this paper. The relationships between the bending curvature and PSPF parameters have been established. The results could afford some basic reference to PSPF double curvature panels with stiffeners of future aircrafts.

Methodology

Material

Material studied in this work was 7B50 aluminum alloy whose mechanical characteristics are listed in table 1. The workpieces were 1-stiffener and 3-stiffeners panels shown in Fig.1. The length of each type of workpiece was 1200 millimeter (mm).

TABLE 1. Mechanical characteristics of 7B50 aluminum alloys

Elastic Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)
68	0.33	524	565

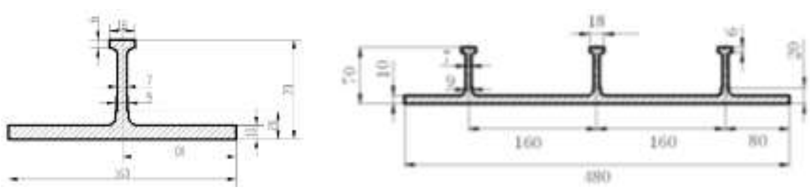


FIGURE 1. Sections of the 1-stiffener and 3-stiffeners workpieces

Experimental method for 1-stiffener panel

In order to set up the quantitative relationship between the deformed stiffeners (spanwise direction) curvature of workpiece and PSPF parameters, an orthogonal experiment was designed in which there were three factors. The factors were three main parameters of PSPF: peening air pressure which represents impacting energy by shots, moving velocity of workpiece which reflects the peening coverage and pre-load stress which expresses the early elastic strain existing at the surface of the part. Each factor had three levels thus there would be nine workpieces. In this orthogonal experiment, contribution of factors to the formed spanwise curvature could be analyzed by regression equation.

On behalf of making the panel skin be saddle shape, the stiffeners should be convex bent in spanwise direction. The peening area would be in the range from top surface of stiffener to geometry neutral plane of the panel in terms of the principle of SPF and the plate bending theory. After loading the pre-stress, there were two steps of peen forming. The peening area of step 1 was the top surface of stiffener, while that of step 2 were the two side-faces of stiffener (between top surface of stiffener and neutral plane), as shown in Fig.2.

The three levels of each factor were defined in table 2. Other processing parameters of PSPF were as follows: diameter of shot D=3.18mm, mass flow Q=12Kg/min, nozzle distance of step 1 L_1=300mm, nozzle distance of step 2 L_2=140mm.

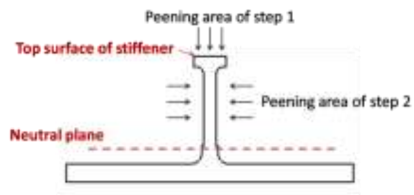


FIGURE 2. Peening areas of two steps

TABLE 2. The PSPF parameters for 1-stiffener panel

Workpieces number	Air pressure (MPa)	Moving velocity of workpieces (mm/min)	Pre-stress (MPa)
1S-1	0.2	1000	288.2
1S-2	0.2	5000	393
1S-3	0.2	9000	497.8
1S-4	0.35	1000	497.8
1S-5	0.35	5000	288.2
1S-6	0.35	9000	393
1S-7	0.5	1000	393
1S-8	0.5	5000	497.8
1S-9	0.5	9000	288.2

Experimental method for 3-stiffeners panel

Two 3-stiffeners panels were PSPF with different parameters to further research on deformation rules. The process of 3-stiffeners panels being elastic pre-bent was finite element (FE) simulated using ABAQUS software, as shown in Fig.3. The bending curvatures of two panels after different pre-loading (260MPa and 520MPa respectively) were measured according to the output results of FE. Fig.4 shows the 3-stiffeners panel which has been pre-stress bent.Chordwise deformation of 3-stiffeners panel was conducted before spanwise deformation. The SPF area for chordwise deformation was the whole exterior surface of the panel in order to make panel be convex in chordwise direction. There were five 1200mm-long peening paths in the exterior surface. The gap between each peening path was 80 mm. After that, three stiffeners were peen formed to make panel be bent towards spanwise direction. The peening area of stiffener was same with that of the 1-stiffener panel. The PSPF parameters for chordwise and spanwise deformation were listed in table 3.

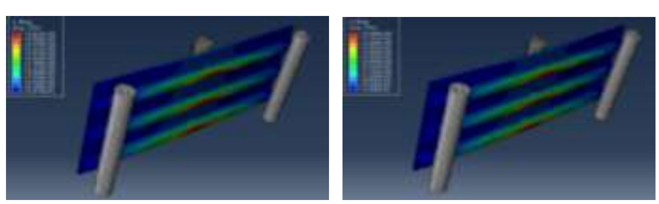


FIGURE 3. FE of pre-stress processing

FIGURE 4. 3-stiffeners panel after pre-stress process

TABLE 3. The PSPF parameters for chordwise and spanwise deformation

Workpieces number	Deformation direction	Air pressure (MPa)	Moving velocity of workpieces (mm/min)	Pre-stress (MPa)
3S-1	chordwise	0.3	8000	/
	spanwise	0.45	8000	260
3S-2	chordwise	0.45	6000	/
	spanwise	0.45	4000	520

Results and analysis

Results of 1-stiffener panel

The stiffener-top-surfaces of the nine panels were all convex bent in the spanwise direction after PSPF. The deformation degree could be reflected by radii of curvature which were illustrated in Fig.5. It can be seen that the radii of curvature were from 23.3 to 136.1 meter (m). In order to research the effects of different PSPF parameters on the radii of curvature of workpiece, range analysis of orthogonal experiment was conducted in this study. The range of each factor represents the degree of contribution on the radii of curvature. Fig.6 illustrates the three ranges contrast bars after the different PSPF. It demonstrates that the maximum and minimum extent of influence on bending curvature is respectively moving velocity of workpiece and pre-stress.

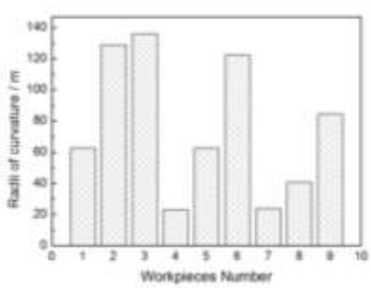


FIGURE 5. The deformation of nine 1-stiffener panels after PSPF

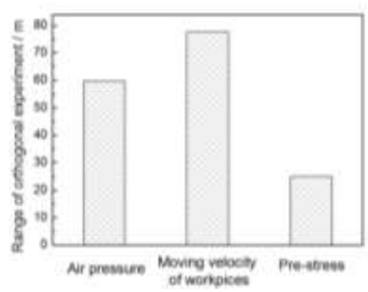


FIGURE 6. The range values of three factors

The regression analysis of the radius of curvature R was performed in order to obtain quantitative relation between R and each factor. According to the experience equation, R could be expressed as Eq.1,

$$R = K\frac{V^m}{P^n(\sigma+1)^\alpha} \tag{1}$$

where P is air pressure, V is moving velocity of workpiece, σ is pre-stress.
Two sides of Eq.1 were logarithmic transformed, as shown in Eq. 2,

$$\ln R = ln\ k + m \ln V - n \ln P - \alpha \ln(\sigma + 1) \tag{2}$$

Defining $Y = \ln R$, $b_0 = \ln k$, $X_1 = \ln V$, $X_2 = \ln P$, $X_3 = \ln(\sigma + 1)$, Eq.2 was transformed to Eq. 3,

$$Y = b_0 + \mathrm{m}X_1 - \mathrm{n}X_2 - \alpha X_3 \tag{3}$$

As a result, Eq.1 was inverted to a multivariate linear regression formula. The coefficients were calculated by Orgin software.
Eq.4 shows the equation about the radius of curvature R, which reflects the deformation of workpiece in spanwise direction.

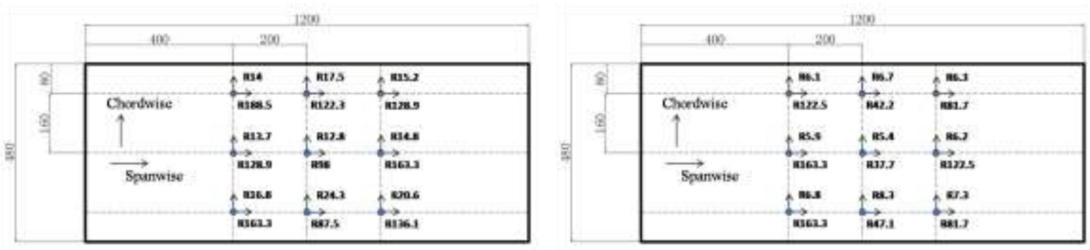
$$R = 6543.9 \frac{V^{0.541}}{P^{0.957}(\sigma+1)^{0.542}} \tag{4}$$

Results of 3-stiffeners panel

The 3-stiffeners panel was bent in both chordwise and spanwise direction after PSPF. The panel exterior skin was convex bent in chordwise direction while it was concave bent in spanwise direction. As thus, 3-stiffeners panel was appearing saddle shape which was typical characteristic in aircraft wing panel. The radii of curvature of nine points in the outside surface of panel were measured in two directions, as shown in Fig.7. It reveals that the radii of curvature of 3S-2 in both two directions are obviously lower than that of 3S-1. This is because the prebending load and SPF intensity of 3S-2 are greater than that of 3S-1. The results are in accord with the effect rules of SPF parameters on deformation degree. In the peening area, the materials near indentations induced by high speed shots would generate plastic strain which could make them be stretching towards all around. Thus, the material in the peening area will be growing. Under the condition of pre-bending, the more the growth of impacted material is, the more deformation of the panel will be.
In response to the data of chordwise curvature, the variation trend of radii of curvature is approximate parabolic. The largest convex curvature is in the middle of chordwise line. The minimum radius of curvature of 3S-2 is 5.4 m which is 57.8% lower than that of 3S-1. In light of the radii of spanwise curvature, the closer to the middle of panel, the larger the concave curvature is. The minimum radii of curvature of 3S-1 and 3S-2 are respectively 98 m and 37.7 m.
Putting the value of PSPF parameters (listed in TABLE 3.) for spanwise deformation into the regression equation achieved from 1-stiffener panel (Eq.4) experiment, the minimum radii of spanwise curvature of two panels were calculated. The computed values were respectively 89 m and 42.1 m which were 9.2% and 11.7% deviation from the actual measurement values. This result reveals that the regression equation derived from orthogonal investigation could be basically conform to the law of stiffener deformation. Furthermore, it could offer some basic reference to PSPF saddle shape panels with stiffeners.

Conclusions

In this paper, the deformation rules of 1-stiffener 7B50 aluminum alloy panel after PSPF have been investigated in orthogonal experiment. Besides, two 3-stiffeners panels have been formed to saddle shape with different processing parameters. The following conclusions could be drawn:



(a) (b)

FIGURE 7. The radii of curvature of two 3-stiffeners panels: (a) 3S-1; (b) 3S-2

(1) The regression equation about the quantifiable relation between radius of curvature and PSPF parameters has been established. The effectiveness of factor on deformation degree of 1-stiffener panel is in following order: moving velocity of workpiece, air pressure and pre-load stress, if other parameters are not changing.
(2) Under the condition of proper elastic pre-stress loading, the integral panels with stiffeners can be formed to saddle shape by peening exterior surface toward chordwise direction and peening stiffeners toward spanwise direction. The more pre-stress loading and peening intensity result in the more saddle deformation amount of the panel.
(3) Predicting the deformation degree in spanwise direction of integral panels with stiffeners after SPF could refer to regression equation whose theoretical value is nearly 10% deviating from practicable value.

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