Investigation on pre-stress shot peen forming process of aluminum alloy 2024-T351

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Abstract

Pre-stress shot peen forming is a method to form large integral wing skin panels. In this paper, a set of pre-stress experimental device of shot peen forming is developed and the influence of process parameters on the curvature of aluminum 2024-T351 are investigated. The rules of the comprehensive effect of air pressure of nozzle, movement velocity, thickness of part and pre-stress on finial curvatures are obtained. Based on multiple regression analysis method, finial curvatures prediction model of process parameters is established. The result shows that the maximum curvature deviation between the experimental results and the prediction ones is within 8.9%. It is found that the developed equation can be used to optimize the process parameters and to predict the finial curvatures after pre-stress peen formed.

Keywords Shot peen forming, pre-stress, regression analysis, wing skin panels.

Introduction

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. Nowadays, there are more and more increasing demands for integral and aerodynamic structures to obtain higher performance for aircraft. Pre-stress shot peen forming is becoming one of the key methods to form large integral wing skin panels.

In pre-stress shot peen forming process (Fig.1.), a work piece is elastically deformed in direction of required curvature by applying extra load through stressing fixture before shot peen forming, then whereby small round hard shots impact the surface of the work piece, elongation is produced due to local plastic deformation beneath the impacted surface. The convex curvature on the peened side is developed after unclamping due to local material flow induced by shot peening causing the residual stresses [1-4].

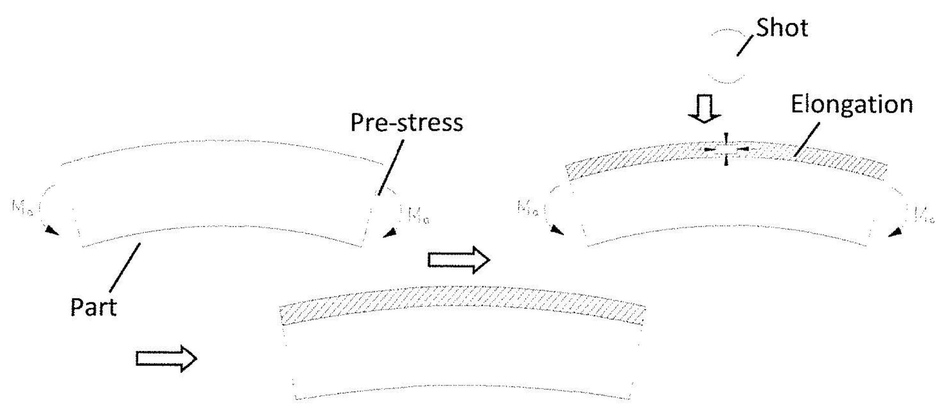

Fig.1 Schematic representation of the pre-stress shot peen forming process.

This process presents many advantages in terms of cost, production time and induced residual stresses. However, pre-stress shot peen forming is a complex process, in which many process variables can affect the curvature, such as the shot diameter, the shot velocity, the coverage ratio, the shooting angle and the material of shots and sheet etc. How to set the accurate process parameters to form a given pattern requires a certain experience and many trials and errors. The interrelationship between peening parameters and the specific final shape also need to be analyzed [5-8].

In this paper, pre-stress shot peen forming process of aluminum 2024T351 which is widely used in aircraft wing skin panels was investigated. The effects of process parameters on diameter of dimples and shape of curvature were analyzed. Based on multiple regression analysis method, a new equation was formulated to model the relationship between process parameters and finial curvatures, which can be used to optimize the process parameters and to predict the finial curvatures after pre-stress peen formed.

Experimental Methods

Test materials: The material used in this study is high strength aluminum alloy 2024(Al-Zn-Cu alloys) which is supplied in the form of commercially hot-rolled plate. The temper of this material is T351, which is processed by solution treatment followed by a cold water quench and stretching to 1% ~2.5%, then naturally aged. The mechanical properties of 2024-T351 aluminum alloy are shown in Table 1.

Table 1. Mechanical properties of 2024-T351 aluminum alloy.

Temper	Elastic module [MPa]	Yield strength [MPa]	Tensile Strength [MPa]	Elongation [%]
T351	72000	367	472	18.1

Experimental method: Orthogonal design is an experimental design used to test the comparative effectiveness of multiple intervention components[9,10]. In this paper, the main factors were studied based on orthogonal experiment design method. The principle variables which affect the peen forming process include air pressure of nozzle (p), movement velocity of the part (v), thickness of the part (t) and applied pre-stress(σ_0). Each of factors has three levels, assuming that the interactions are negligible. Pre-stress is about 50%~90% of yield stress of this material. Applied stress direction and peening area are shown in Figure 2.

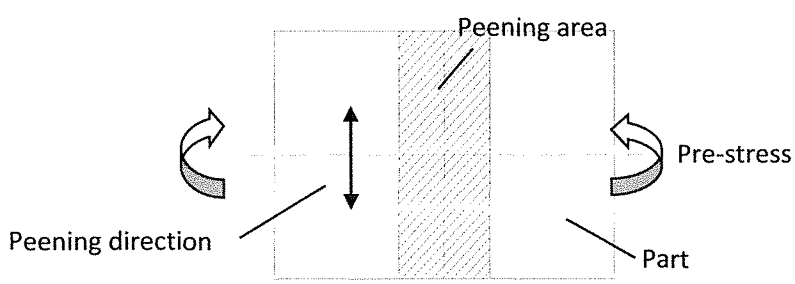

Fig.2 Schematic representation of applied stress direction and peening area.

Flexible pre-stress fixture design: For convenience of applying stress, flexible pre-stress fixture was designed by which the part is subjected to a constant bending moment between the fixed clamps as shown in Figure 3. Elastic pre-stress was achieved by adjusting the height of support at the fixture center. According to pure elastic bending theory, the strain at outside surface of the part is the function of the relative bending radius (R/t), as shown in Eq. 1. The radius of curvature (R) can be calculated by Eq. 2. Combining Eq. 1 and Eq. 2 gives Eq. 3, the pre-stress applied on the part can be characterized by measuring the height of the arc under pre-stressing conditions.

$$\varepsilon = \frac{1}{2\frac{R}{t} - 1} \tag{1}$$

$$R = \frac{L^2 + 4f^2}{8f} \tag{2}$$

$$\sigma_0 = \frac{Et}{2\left(\frac{L^2 + 4f^2}{8f}\right) - t} \tag{3}$$

Where σ_0 is pre-stress [MPa], ε is the strain at inside (outside) surface of the part, t is the thickness of the sheet [mm], R is the radius of curvature [mm], L is the distance between the two fixed clamp [mm], f is the height of the arc [mm].

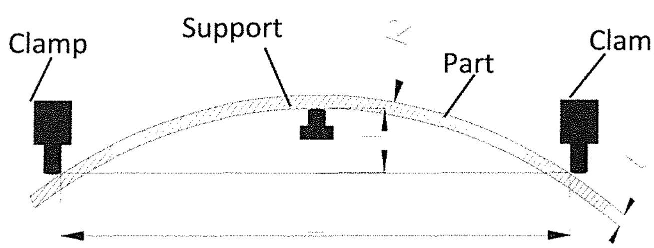

Fig.3 Pre-stressing fixture.

Results and Discussion

Experimental result: According to planed experimental scheme, the results of the curvature radius are obtained as listed in Table 2.

Table 2. Pre-stress shot peen forming experiment factors and results.

NO.	Air Pressure p [MPa]	Velocity v [mm/min]	Thickness t [mm]	Pre-stress σ0 [Mpa]	Radius [mm]
1	0.2	2000	5	348.7	645.2
2	0.2	4000	10	275.3	2758.6
3	0.2	6000	15	201.9	13333.3
4	0.4	2000	15	275.3	2857.1
5	0.4	4000	5	201.9	851.1
6	0.4	6000	10	348.7	1454.5
7	0.6	2000	10	201.9	1632.7
8	0.6	4000	15	348.7	2352.9
9	0.6	6000	5	275.3	583.9

Effect of process parameters on the radius of curvature: To qualitatively analyze the effect of several variables on the final radius of curvature, the maximum difference analysis was introduced to measure the degree of influence of four variables in present experiment[10]. The analysis results are listed in Table 3. It is very obvious that all the observed variables have significant effect on the radius of curvature in this experiment. It also can be concluded that thickness has the maximum influence on the radius of curvature, followed by air pressure, then applied stress and velocity. The symbols in Table 3, T is level sum, m is level mean, R is range.

The influence of each factor under different levels on the radius of curvature in pre-stress shot peen forming process has been analyzed in this experiment. The radius of curvature as a function of p, v , t and σ_0 is plotted as a, b, c, d in Fig. 4. From this figure, it can be seen that the radius of curvature decreases with increasing air pressure at the initial stage and gradually reaches stabilization with the increasing of the air pressure; a increasing trend of the curvature radius is observed when thickness increases; the overall trend of the curvature radius changes with velocity is that it increases with the increasing of velocity; as for pre-stress, the trend of the curvature radius decreases with the increasing of the pre-stress and gradually reaches stabilization with the increasing of the pre-stress.

Table 3. Maximum difference analysis of the result

Level	Air Pressure [MPa]	Velocity [mm/min]	Thickness [mm]	Pre-stress [Mpa]
1	I (0.2)	I (2000)	I (5)	I (348.7)
2	II (0.4)	II (4000)	II (10)	II (275.3)
3	III (0.6)	III (6000)	III (15)	III (201.9)
T_1	16737.1	5134.9	2080.2	4452.7
T_2	5162.8	5962.6	5845.8	6199.7
T_3	4569.5	15371.8	18543.4	15817.1
m_1	5579.1	1711.7	693.4	1484.2
m_2	1720.9	1987.5	1948.6	2066.6
m_3	1523.2	5123.9	6181.1	5272.4
R	4055.9	3412.3	5487.9	3788.1

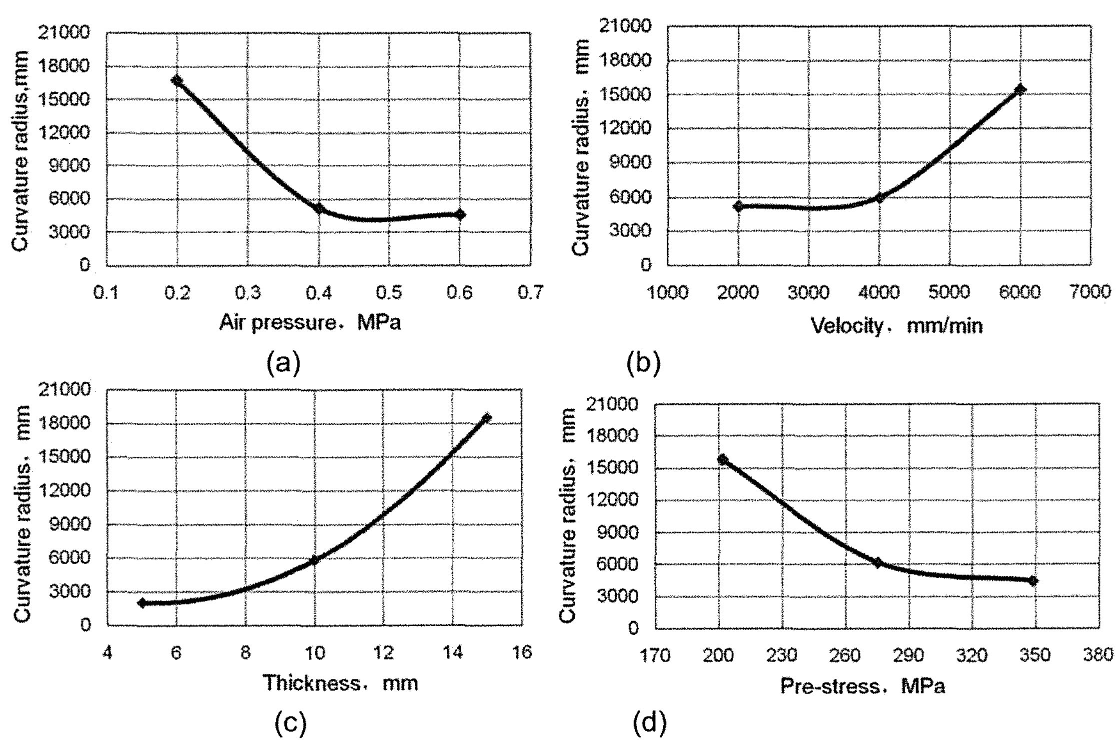

Fig. 4 The effect of process parameters on the radius of curvature.

Multiple factor regression analysis: In order to obtain the quantitative relationship of the combined effect of various factors and the finial radius of curvature, which can be used to further optimize the process, multiple regression analysis is used and the regression equation is formulated, as shown in Eq. 4.

$$R = 1278.3 \frac{V^{0.39} t^{1.68}}{P^{0.74} (\sigma_0 + 1)^{1.31}} \tag{4}$$

Where, p is air pressure of the nozzle [MPa], v is movement velocity of the part [mm/min], t is the thickness of the part [mm], σ_0 is pre-stress [MPa].

Input the related process parameters into the regression equation and calculate the radius of curvature in this situation, then compare it with experimental result (Table 2), and the comparison is shown in Fig.5, from which it can be seen that the calculated values according to mathematical model based on orthogonal regression are in consistent with the experimental values and the maximum error is less than 8.9%.

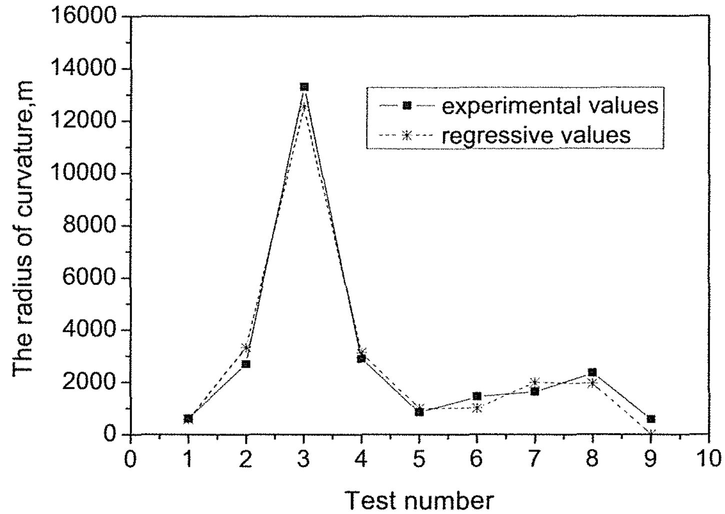

Fig.5 Comparison between the calculated curvatures and the experimental results.

Validation with other experimental data: Validating experiments were performed under different process parameters from above experiments(Table 2). Based on regression equation, the calculated results of the finial radius of curvature are compared with the experimental results, as shown in Table 4. It is found that regressive values are in good agreement with experimental values and the maximum error is 7.4%.

Table 4. Validating experiments and results

Process parameters				The finial radius of curvature [mm]		The relative error [%]
Air Pressure [MPa]	Velocity [mm/min]	Thickness [mm]	Pre-stress [Mpa]	Experimental values	Regressive values	
0.3	2000	5.5	348.7	476	507.5	6.6
0.4	3500	6	275.3	852.5	803	5.8
0.5	3000	7	201.9	1145.5	1061.2	7.4

Conclusion

The effect of four main variables on the final curvatures has been studied through the combination of orthogonal design and multi-factor regression analysis. The radius of curvature decreases with increasing air pressure and the pre-stress, however it increases with the increasing of velocity and thickness. Among the four factors, thickness has the most significant influence on the radius of curvature, followed by air pressure, then applied stress and velocity. The regressive equation can be used to model the relationship between process parameters and the finial radius of curvature. The predicted curvatures are in good agreement with experimental values and can be to predict the finial curvatures after pre-stress peen formed.

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