Experimental Investigation on Shot peen forming of 2198 Al-Li Alloy Plate

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Abstract

Fundamental shot peen forming experiments on Al-Li alloy 2198 plate were carried out to investigate the forming technique of thin skin integral reinforced panels. The effects of air-blast pressure, exposure time and pre-stress level on shaped curvature were investigated by experiment data analysis. The experimental results show that the shaped curvature decreases with exposure time, increases with air-blast pressure and pre-stress level. Exposure time is shown to be the main factor of process parameters affecting shaped curvature. A mathematical equation model for shaped curvature is proposed and was resolved through regression analysis method. A typical structure of fuselage panel was shot peen formed, which verified the effectiveness and accuracy of the mathematical equation model.

Keywords: Al-Li alloy; shot peen forming; experiments; equation model; fuselage panel

Introduction

Aluminum-Lithium alloys (AL-Li) has comprehensive advantages including relatively low density, high elastic modulus, high specific strength and stiffness, excellent fatigue strength, superior corrosion resistance and good weld ability [1-3]. More and more Al-Li alloys components are applied in modern aerial and space vehicles to meet their requirement of reducing weight while keeping strength. For example, AA2219-T8 is replaced by Al-Li 2198-T8 as the material of the fuel and oxidizer tank components in the Falcon 9 launch vehicle by SpaceX Company. The popularity of research on forming method for Al-Li alloy has been increased significantly worldwide [3-7]. Shot peening is a typical forming method in which the component surface is subjected to the collision of steel shots at a high speed that create plastic deformation. It has lower manufacturing costs and high flexibility because there is no need for dies. It also induces compressive residual stress field on up and down surfaces that improves fatigue resistance. The shot peening is largely used on integral reinforced panels of military and civil aircrafts as well as carrier rockets [8-10]. In this paper, fundamental shot peen forming experiments are employed to pile up experience and data on the third generation Al-Li alloy material: 2198-T8. Productive experiment on typical reinforced panel is carried out to validate the shot peening process model, which will establish the technical basis for the manufacturing of large Al-Li structure components especially of welded fuselage panels.

Fundamental experiment process

The experimental material is Al-Li alloy 2198-T8 with t=1.8mm in thickness. Its mechanical properties at room temperature are listed in Table 1.

Table 1. Mechanical Properties of Al-Li 2198-T8

Elastic modulus,GPa	Poisson ratio	Yield strength, MPa	Tensile strength ,MPa	Elongation rate %
71	0.31	461	511	9.9

Key parameters, including target material thickness, shot size, air-blast pressure, exposure time and pre-stress level, have significant impact on deformation for shot peening process. The exposure time is determined and controlled by translation velocity of the specimens. Orthogonal method is used to design experiments due to the quantity of influence factors. In this paper, as the target material thickness and shot size are fixed, air-blast pressure, translation velocity and pre-stress level are selected as the 3 designing variables with 4 response levels of each. The variables and values are shown in Table 2. Experiments are carried out by the orthogonal test method with its array of $L_{16}(4^5)$.

Table 2. Orthogonal array of experiments

Trials	Air-blast pressure (MPa)	Translation velocity (mm/min)	Pre-stress (MPa)
	A	B	C
1	0.10	2000	0
2	0.15	4000	92.2
3	0.20	6000	184.4
4	0.25	8000	276.6

The dimensions of the test specimen are 200*300 mm^2. As shown in Figure 1, the longitudinal exposure area is about 60 mm in width. Pre-stress is imposed on longitudinal direction which is shown in Figure 2.

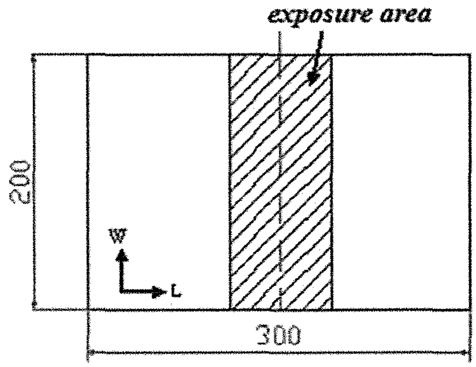


Fig. 1 Specimen with exposure area indicated

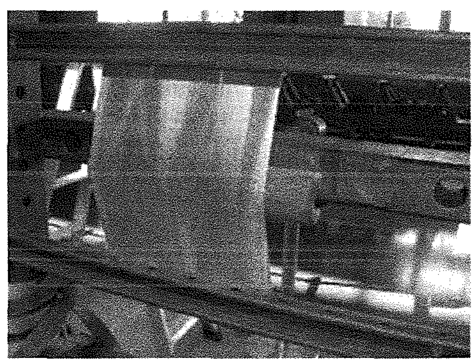


Fig. 2 Specimen in pre-stress

Experimental data and analysis

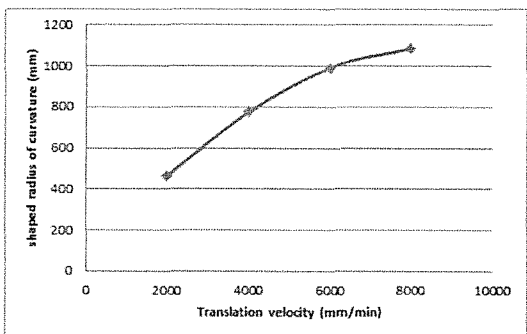
The contour precision of part component is one of the most important objectives for sheet metal forming, and sheet peen forming is no exception. The general contour error is 0.5mm or less for sheet panel components. Experiments are carried out to obtain the relationship between the process parameters and shaped curvature, which can establish the fundamental technical base for precise shot peen forming. The effects of key parameters on shot peen forming in the dominant deforming direction are investigated using average and range method.

The experimental average and range analysis results are shown in Table 3. The shot peening ability is defined to increases as the shaped curvature decreases. Comparing the effect of each parameter on forming ability, the most influential factor is the translation velocity, the next is air-blast pressure, and the last is pre-stress level. So the influential order of key parameters from maximum to minimum is translation velocity, air-blast pressure and pre-stress level.

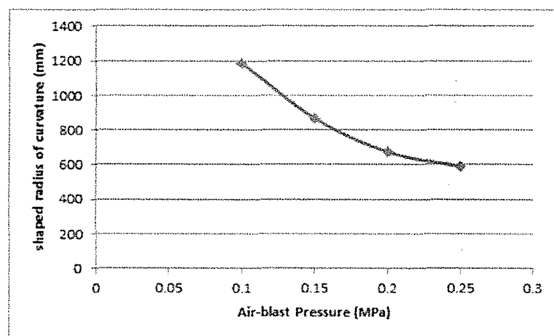
The influential ability of each parameter on shot peen forming can be obtained by the experimental data analysis. As shown is Figure 3, the horizontal component is parameter level and the vertical component is shaped curvature. The analysis results show that the shaped curvature increases with the translation velocity, decreases with the air-blast pressure and decreases with the pre-stress level.

Table 3. Experimental data and range analysis results of shot peening of Al-Li 2198-T8

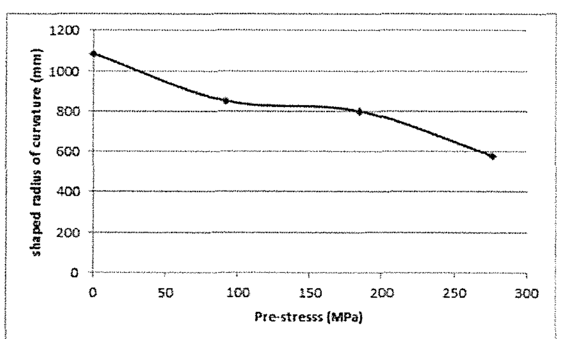
Range analysis results		Air-blast Pressure (MPa)	Translation velocity (mm/min)	Pre-stresss (MPa)
		A	B	C
Sum	K_{1j}	4746.20	1860.69	4340.72
	K_{2j}	3464.75	3101.133	3404.42
	K_{3j}	2700.09	3964.84	3203.53
	K_{4j}	2355.71	4340.10	2318.08
Average	$K_{1j}/4$	1186.55	465.17	1085.18
	$K_{2j}/4$	866.18	775.28	851.10
	$K_{3j}/4$	675.02	991.21	800.88
	$K_{4j}/4$	588.93	1085.02	579.52
Range	R_j	597.62	619.85	505.66
Optimal level		A4	B1	C4



(A) Translation velocity vs. shaped curvature



(B) Air-blast pressure vs. shaped curvature



(C) Pre-stress vs. shaped curvature

Fig. 3 Relations between parameters and shaped curvature

The regressive analysis method is used to analyze the exact relation between each parameters and shaped curvature for optimization. With reference to the results of range analysis, the reasonable mathematical equation is assumed to take the form:

$$R = K \frac{V^i}{(\sigma_0 + 1)^m P^n} \tag{1}$$

Where P is air-blast pressure, MPa. V is Translation velocity, mm/min. σ_0 is Pre-stress on surface of specimen, MPa

Making a log transformation on both sides of Eq. (1), it is derived to the form,

$$\ln R = \ln K + i \ln V - m \ln(\sigma_0 + 1) - n \ln P \tag{2}$$

Assuming $Y = \ln R$ $b_0 = \ln K$, $X_1 = \ln V$, $X_2 = \ln(\sigma_0 + 1)$, $X_3 = \ln P$

$$\text{Thus: } Y = b_0 + iX_1 - mX_2 - nX_3 \tag{3}$$

So Eq. (1) is transformed into a linear form which can be resolved by multiple linear regression method. Least-square method is used to calculate the parameters in Eq. (3),

$$Y = -1.1439 + 0.7551X_1 - 0.1201X_2 - 1.0172X_3 \tag{4}$$

So the equation with values for the relation between shaped curvature and process parameters is,

$$R = 0.3186 \frac{V^{0.7551}}{(\sigma_0 + 1)^{0.1201} P^{1.0172}} \tag{5}$$

Substituting the process values of experiments into the mathematical equation model, the regressive curvatures are calculated and compared with the experimental curvatures. As shown in Figure 4, the regressive curvatures from the mathematical equation model and the measured experimental curvatures are very close. So this mathematical equation model derived from experimental data is accurate and can be referenced in engineering manufacturing.

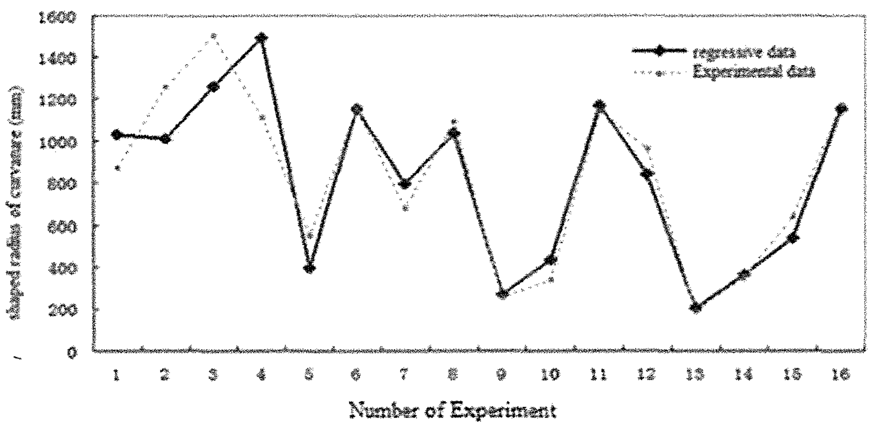


Fig. 4 Comparison of the regressive and experimental curvatures

Shot peen forming experiment of typical structural component

As shown in Figure 5, a part of welded component of aircraft fuselage is in single curvature with radius of R=1776mm. The dimension size is 360*800mm^2 and it has three "┐" section welded ribs with interval distance of 120mm. The thickness of skin part is 1.8 mm.

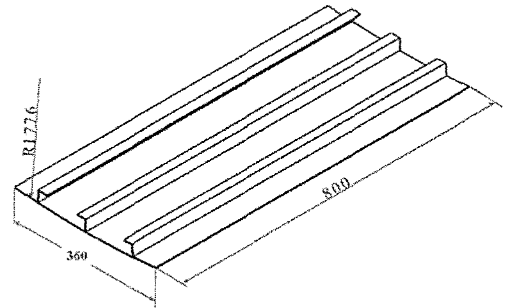


Fig. 5 Typical structural part component

The typical part component has curvature perpendicular to the ribs and has no curvature along length of ribs. The skin part will be only deformed while ribs have no bending during shot peen forming. Therefore, the corresponding part of ribs on skin surface is masked. The shot peening path is shown in Figure 6. Pre-stress is imposed on the skin surface between that of ribs in order to increase the deformation ability. Clamping force is imposed on the margin of skin part to avoid distortion in longitudinal direction. The pre-stress locations are shown in Figure 7. Process parameters are calculated by the mathematical equation model before and are shown in Table 4.

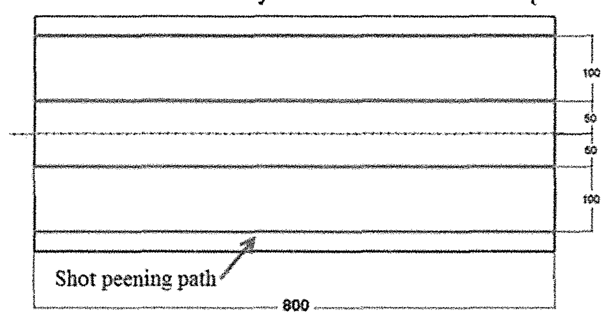


Fig. 6 Shot peening path

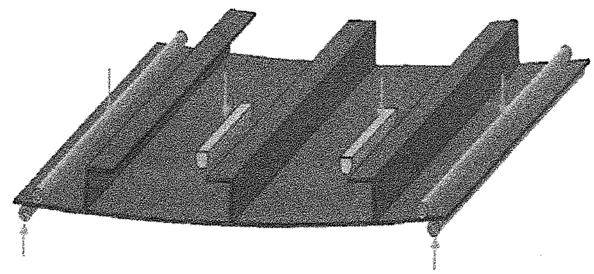


Fig. 7 The pre-stress locations

Table 4. Shot peening parameters

Parameter	Value
Air-blast pressure, MPa	0.15
Translation velocity, mm/min	13100
Pre-stress, MPa	41.1

Figure 8 shows the deformed part component of experiment. As shown in Figure 9, the profile accuracy is checked by a handset profile gauge. The gap between gauge and part surface is less than 0.5mm of the acceptable error range, which confirmed the effectiveness of equation model derived from fundamental experimental data.

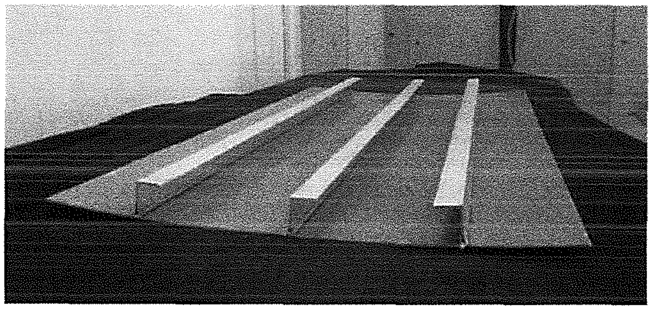


Fig. 8 Deformed part component

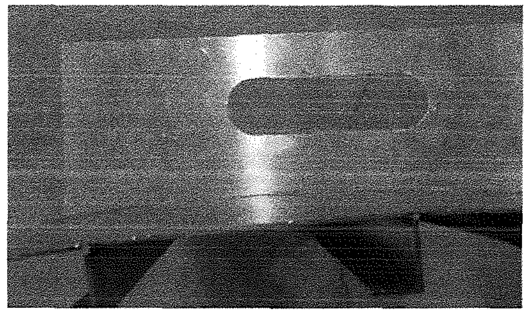


Fig. 9 Check with handset profile gauge

Conclusion

The main conclusions of this work are as follows:

1. For shot peen forming on Al-Li alloy, the most influential factor is the translation velocity, the next is air-blast pressure, and the last is pre-stress level. The shaped curvature increases with the translation velocity, decreases with the air-blast pressure and the pre-stress level.
2. The mathematical equation model derived from experimental data by regressive analysis method is accurate and can describe the relation between the shaped curvature and process parameters, which is validated by shot peen forming experiment of a typical welded panel component.

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