USING STRESS PEEN-FORMING PROCESS FOR INTEGRALLY STIFFENED WING PANELS

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ABSTRACT

The features of stress peen-forming are discussed by analysing the forming principles and through experimental research. If the wing panel is elasticly prebended in the chordwise direction during peen-forming, the chordwise contour curvature will be further increased, and at the same time the spanwise contour curvature will be decreased, thus the trend in conventional peen-forming for panel taking on the spherical shape can be conquered by using the stress peen-forming to a great extent. The result of experiment shows that the curvature radius in the prebending direction is inversely proportional to the peening pressure, the shot size and the prebending value under the saturated peen-forming condition, but it is independent of the nozzle stand-off distance (within 100 to 300 mm). In the paper, one practical example about forming integrally stiffened wing panels by stress peen-forming in the industrial applications is described.

KEYWORDS

Stress peen-forming; conventional peen-forming; curvature radius of limit; prebending value; wing panel.

INTRODUCTION

The conventional peen-forming possesses the features which cause the sheet metal to take on a spherical shape. When the integrally stiffened panel with little difference of stiffness in the chordwise direction and in the spanwise direction is peen-formed, the compound curvature of the deformation of the panel will happen surely. It is necessary to use the stress peen-forming process, if a simple curvature contour wing skin panel is required.

The stress peen-forming technique was applied to the forming of wing panel in the age of 1960's, but there were few papers in the respect of theory of stress peen-forming, most of the papers were about the applications in production. In this paper, the features of stress peen-forming are generally discussed by analysing the forming principles and through the experimental research and one practical example of integrally stiffened wing panels formed by stress peening.

INVESTIGATION OF THE FEATURES OF STRESS PEEN-FORMING

Analysis of the Features of Conventional Peen-forming

The layer of the shot peened surface of the part possesses the residual compressive stress. If the compressive stress layer of the peened surface is carefully removed, the part will return to its original flat condition (SP-84, 1954). This fundamental phenomenon shows that the sheet-metal curve is tightly concerned with the depth of the compressive stress layer and the magnitude of the residual compressive stress in the compressive stress layer. Therefore when analysis is needed, the plastic bending of the sheet occured during peen-forming can be considered as elastic bending, i.e. the residual compressive stress in the compressive stress layer is considered as the external force, the bending moment applied by it is considered as the external moment, by which the sheet is elasticly bent, as shown in Fig. 1, b.

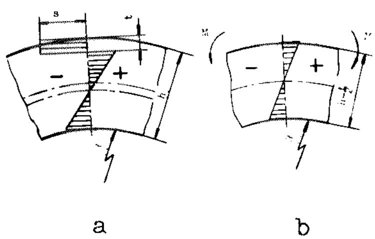

Fig. 1. Sketches of the residual compressive stress in the compressive stress layer turned into external bending moment
a. The residual stress and the bending deformation after peen-forming.
b. The elastic curve caused by moment M.

In order to simplify the analysis, it is assumed that: (1) the sheet metal is shot-peened uniformly; (2) it possesses the equal thickness and the uniform rigidity; and (3) it is in a free condition during peen-forming.

Thus, the bending moment M per unit periphery of the sheet is proximately expressed as follows:

$$M \approx S \cdot t \cdot h/2 \qquad (1)$$

where S is the average value of the residual stress in the compressive stress layer on the peened surface. t is the depth of the compressive stress layer on the shot peened surface and h is the thickness of the sheet.

The bending moment is uniformly distributed in all directions of the sheet so that the sheet deforms to take on a spherical shape when it is shot peened on one side only. For the bending moment, the ability of peen-forming the sheet is limited, and the minimum radius of curvature formed will be probably larger, therefore, the peen-forming curvature radius of the sheet can be calculated by means of the equation of the simple bending in the principle of elastic bending:

$$R = \frac{E\,(h-t)^3}{12\,(1-\mu)} \cdot \frac{1}{M} \qquad (2)$$

where R is the peen-forming curvature radius, E is the modulus of elasticity and μ is Paisson's ratio.

Analysis of the Features of Stress Peen-forming

The stress peen-forming is defined as a process in which first the sheet is bent on the bending fixture in one direction only, then the surface to be tensile stress is shot peened so that the desired contour curvature can be obtained, but when bending on the fixture, the tensile stress at the most external fiber of the sheet should not be at and beyond its yield strength.

In order to simplify the analysis it is assumed that: (1) the sheet metal is shot-peened uniformly; (2) it possesses the equal thickness and uniform rigidity and (3) it is under the condition of the elastic prebending in the x direction during peen-forming (**Fig. 2**).

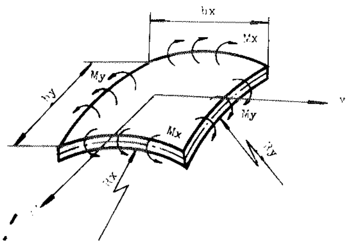

Fig. 2. Sketch of bending direction

During stress peen-forming, the peened surface is struck by numerous pellets of shot in a stretched condition. Under the action of same impacting energy, the comparison between stress peen-forming and conventional peen-forming proves that the stretched condition is of great advantages to the metal stretch on the peened surface and increases the depth of compressive stress layer and the average value of the residual stress in the compressive stress layer (Mattson, 1954). As the elastic prebend is only applied in the x direction, tensile prestress induced in the x direction will be $1/\mu$ times larger than that in the y direction, thus the residual compressive stress in the compressive stress layer in the x direction is more than that in the y direction. According to the analysis for the conventional peen-forming principles, in the peened surface, the bending moment My formed by the residual compressive stress in the x direction is much more than Mx in the y direction.

As the applied prebending moment causes sheet elastic deformation only, after the sheet is shot-peened and is taken away from prebending fixture, additional prebending disappears and the internal stress and the strain in the sheet caused by the prebending moment is also eliminated. Therefore, when analysing the curve deformation of stress peen-forming, [1] it can be considered that the conventional peen-forming is carried out with the sheet in clamping conditions (no prestress), so that the action of the residual compressive stress induced by shot peening can be only considered when the forming radius of the sheet is calculated. By means of the simple bending equation of the sheet in two directions as well as conventional peen-forming, the contour curvature radius Rx of the sheet in the prebending direction and its radius Ry in the direction perpendicular to prebending direction after stress peen-forming can be written as follows:

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[1] If the thickness of the sheet is much more than the depth of compressively stressed layer, the average value of residual compressive stress for conventional peen-forming is approximately equal to that for peen-forming in the clamping condition, the detail is described in the references. (**Саверин**, 1955).

$$Rx = \frac{E\,(h - t_w)^3}{12} \cdot \frac{1}{My - \mu Mx} \qquad Ry = \frac{E\,(h - t_w)^3}{12} \cdot \frac{1}{Mx - \mu My} \tag{3}$$

where My and Mx are respectively the bending moment per unit periphery of the sheet in the prebending direction or in the direction perpendicular to it in stress peen-forming, t_w is the depth of the compressive stress layer of stress peen-forming.

Rx is divided by Ry, we can obtain $\frac{Rx}{Ry} = \frac{Mx - \mu My}{My - \mu Mx} = \frac{Mx}{My} \cdot \frac{(1 - \mu \frac{My}{Mx})}{(1 - \mu \frac{Mx}{My})}$

As $Mx < My$, on the above equation $\frac{Mx}{My} < 1$, $(1 - \mu \frac{My}{Mx}) < (1 - \mu \frac{Mx}{My})$

thus, $\frac{Rx}{Ry} < 1$, $Rx < Ry$.

In addition, the experimental values shown in table (see the next section) may prove that the difference between the bending moment Mx in the direction perpendicular to prebending direction of the stress peen-forming and bending moment M of the conventional peen-forming is not obvious. It is considered that $M \approx Mx$.

If the same sheet metal is uniformly shot-peened with the same shot-peening parameters, the comparison between the curvature radius obtained by stress peen-forming process and that obtained by conventional peen-forming process is carried out [the equation (3) is divided by the equation (2)] , it can be discovered in the x direction:

$$\frac{Rx}{R} = (1 - \mu) \left(\frac{h - t_w}{h - t}\right)^3 \frac{M}{My - \mu Mx} = \frac{1 - \mu}{1 - \mu \frac{Mx}{My}} \cdot \frac{M}{My} \cdot \left(\frac{h - t_w}{h - t}\right)^3$$

, due to given $Mx < My$, $Mx \approx M$ and $t < t_w$, thus $\frac{M}{My} < 1$, $\frac{1 - \mu}{1 - \mu \frac{Mx}{My}} < 1$ and

$\left(\frac{h - t_w}{h - t}\right)^3 < 1$ therefore $\frac{Rx}{R} < 1$, $Rx < R$. Similarly, in the y direction

$$\frac{Ry}{R} = \frac{1 - \mu}{1 - \mu \frac{My}{Mx}} \cdot \frac{M}{Mx} \cdot \left(\frac{h - t_w}{h - t}\right)^3$$

, when the thickness of sheet is much more than the depth of compressively stressed layer, $\left(\frac{h - t_w}{h - t}\right)^3 \approx 1$. As $M \approx Mx$ and $Mx < My$, thus $\frac{M}{Mx} \approx 1$, $\frac{1 - \mu}{1 - \mu \frac{My}{Mx}} > 1$, therefore $\frac{Ry}{R} > 1$, $Ry > R$.

It will be seen from above analysis that the comparison between the stress peen-forming and the conventional peen-forming under the same conditions is carried out, the stress peen-forming possesses such features that the forming radius decreases in the applied prebending direction and increases in the direction perpendicular to prebending direction, the changes of forming radius increase with increased prestress value, therefore the trend in conventional peen-forming for panel taking on the spherical shape can be conquered by use of stress peen-forming to a great extent.

Experimental Research of Stress Peen-forming

The experimental research of stress peen-forming has two tasks: one task is to verify the conclusion obtained by the above analyses and the other task is to find the relations among[2] the forming curvature of the limit in the prebending direction,[3] prebending values and shot-peening parameters.

There are two kinds of flat sheet specimen with 2 mm thickness made from the queching aluminium alloy LY12CZ, the only difference between them is the overall dimensions. The specimen with the overall dimensions 76 x 76 mm is used for the first kind of experiment. The arc height of the specimen after test is measured by means of the curvature gauge with 50 mm span. The specimen with the overall dimensions 19 x 76 mm is used for the second kind of experiment. The arc height of the specimen after test is measured by means of Almen gauge. All specimens are shot-peened the type Pw-1 peen-forming machine. During the shot-peening, the different prebending value is applied to the specimen by the bending die with a specific curve radius, then the specimen is clamped by the clamping plates along the opposite sides of the specimen in the curve direction (Fig. 3).

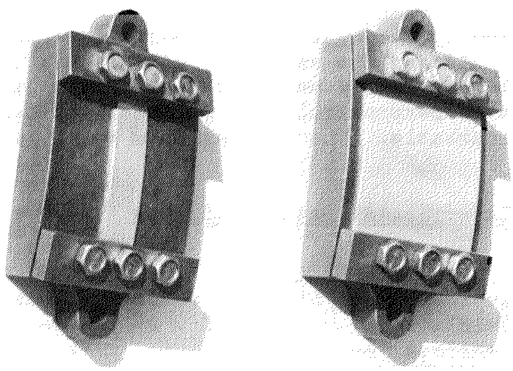

Fig. 3. Prebending and fixture of the specimen

The relations between curvature radius of limit and prebending values in the prebending direction or in the direction prependicular to prebending. Figure 4 illustrates the effect of prebending values on the curvature radius of limit in two directions. The curves of Figure 4 show that the curvature radius in the prebending direction decreases with the increase of prebending values, on the contrary, the curvature radius in the direction perpendicular to the prebending direction increases with the increase of the prebending values, and these test results accord with the analytical conclusions of above section. If the prebending value is 0.4 % during peen-forming, the curvature radius of limitation in the prebending direction is reduced by two-thirds and that in the direction perpendicular to prebending direction is increased 2.5 times. Assuming it is one specimen, the difference of the curvature radius of limit in two directions increases from 1.1 times at a prebending value of 0 to 8.5 times at a prebending value of 0.4 %.

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2 The forming curvature of limit is referred to as forming curvature during saturation shot peening.

3 Prebending value is referred to as the elongation of sheet-metal at the most external fiber where the sheet-metal is curved on the prebending fixture, the unite of the elongation is %.

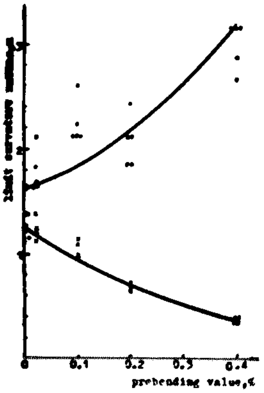

Fig. 4. The effect of prebending value on the curvature radius of limit in two directions

x -- prebending direction

● -- the direction perpendicular to prebending direction

Peening parameters:

peening pressure	4 kg/cm^2
iron shot diameter	2 2.5 mm
coverage	100 %

In addition, the experimental data also show that the dispersion of the conventional peen-forming (i.e. the prebending value = 0) is maximum. This means that the repeatability of parts in the prestress peen-forming is pretty good.

If the moments Mx and My that cause the specimen to take on shape (see below table) are calculated by the equation (3) and the experimental data of Fig.4, it can be seen that the differences between the moment for conventional peen-forming and the moments in the direction perpendicular to prebending direction for prestress peen-forming are not remarkable. That is why $Mx \approx M$ can be presumed in analysis of above section.

TABLE Analysis of the Experimental Datum of Stress Peen-forming

Prebending value		Radius of prebending die, mm		Prebending moment, kg - mm		Average arc height of specimen, mm		Limit curvature radius of specimen, mm		Forming moment, kg - mm	
ε %	σ kg/mm^2	Rxo	Ryo	Mxo	Myo	fx	fy	Rx	Ry	Mx	My
0	0	∞	∞	0	0	0.28	0.25	1112	1249	5.92	6.24
0.02	1.4	5000	∞	0.35	1.07	0.26	0.17	1200	1830	4.40	5.44
0.1	7.2	1000	∞	1.77	5.36	0.30	0.15	1040	2080	4.26	5.99
0.2	14.4	500	∞	3.54	10.72	0.45	0.15	694	2080	5.11	8.56
0.4	28.8	250	∞	7.10	21.44	0.85	0.10	367	3120	6.52	15.20

Notes:

(1) σ and ε are respectively the stress and the strain at the outside fibre of the sheet-metal during prebending, and it is the condition of conventional peen-forming when their values are equal to nought;

(2) The footnote x represents the prebending direction and footnote y represents the direction perpendicular to prebending direction (Fig. 2);

(3) The breadth of the specimen taken is 1 mm when the bending moment is calculated;

(4) The span of a curvature gauge is 50 mm.

Effect of the main technological parameters on the curvature radius of limitation in the prebending direction. The effect of the main technological parameters (peening pressure, shot sizes, nozzle stand-off distance and prebending value etc.) on the curvature radius of flat strips of aluminium alloy is researched (the peening time parameter is not considered because the curvature radius of limit is obtained under the condition of saturation shot-peening). During the test, the orthogonal tabe $L_9(3^4)$ is used to arrange the experiment of those factors (the level of the factors 3 is taken for all), then the experimental data are disposed by using a quadratic orthogonal multinomial and the method in which interaction is omited part, and the following relations can be obtained ultimately (during the test, the nozzle stand-off distance is also arranged as an experiment factor whose levels: 100, 200 and 300 mm are taken, but the experiment results show that the arc height is independent of that during the saturation shot-peening):

when the shot diameter is 0.3~0.5 mm, $f=0.7P+19W+0.2$, the error is ± 3.6; (4)

when the shot diameter is 1~1.2 mm, $f=2.5P+39.5W-4.4$, the error is ± 3.3, (5)

when the shot diameter is 2~2.5 mm, $f=7.5P+65W-10.9$, the error is ± 4.0; (6)

where f is the arc height measured by an Almen gauge No. 2 (0.01 mm), P is the peening pressure (kg/cm^2) and W is the prebending value (%).

The arc height of the above equation can be converted into the curvature radius [$R=15751/f^{(mm)}$, the unite of f is 0.01 mm], the curves expressed by the curvature radius of limit are shown in Fig. 5.

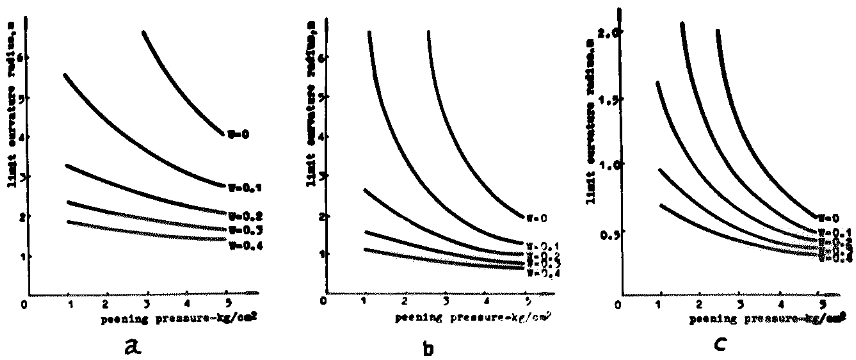

Fig. 5. Curves of the relations among curvature radius of limit, peening pressure and prebending value on the flat strips of LY12CZ aluminium alloy (without relation to nozzle stand-off distance, strip thickness 2 mm)
a) cast iron shot diameter 0.3~0.5 mm,
b) cast iron shot diameter 1~1.2 mm,
c) cast iron shot diameter 2~2.5 mm.

It can be obtained from the above that the curvature radius of limit in the prebending direction is inversely proportional to the peening pressure and the shot diameter and prebending value for the stress peen-forming, and it is independent of the nozzle stand-off distance (within 100 to 300 mm), however in the above factors the prebending value has maximum effect on the curvature radius, peening pressure smaller and the shot diameter minimum.

PRACTICAL EXAMPLE OF STRESS PEEN-FORMING INTEGRALLY STIFFENED WING PANELS

This section introduces one practical example of stress peen-forming integrally stiffened wing panels. It is formed by type PW-2 peen-forming machine. (Fig. 6).

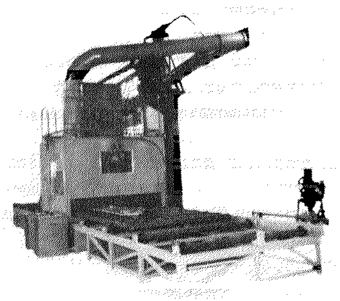

Fig. 6. Type PW-2 peen-forming machine

The integrally stiffened wing panel with 2.8 m log and 1.1 m wide made from aluminium alloy LY12CZ is shown as Fig. 7. The longitudinal stiffeners with ⊥ section are aprallel distribution and the height of stiffeners is 12 mm; there are many lateral hills at the connections of panel and wing ribs, its depth is 3.5 mm, and skin-thickness is 1.5 mm.

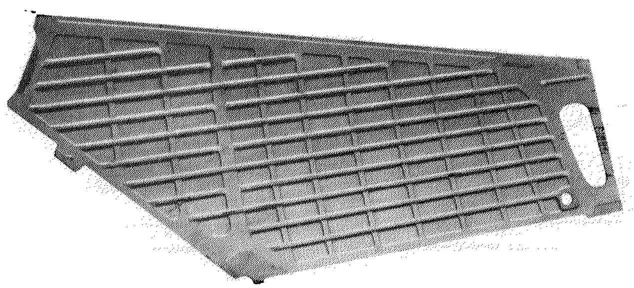

Fig. 7. An integrally stiffened wing panel of fighter

It is diffcult to form such integrally stiffened panel, especially more difficult to form the contour curvature at the front edge of the panel, because the longitudinal stiffeners intersect with a wing generatrix (the intersecting angle adjacent to the leading edge approximate to 10°) and the curvature radius at the front edge is smaller ($R \lessapprox 600$ mm) and the thickness of the panel at the front edge is 5 mm. In addition, the difference of the panel stiffness in the chordwise direction and in the spanwise direction is small, therefore, if conventional peen-forming is adopted, not only the contour curvature at the front edge of the panel can not be formed, but also the undesirable and greater bending in the spanwise direction of the panel will be caused after forming. The problem can been solved successfully by stress peen-forming.

The fixture used for stress peen-forming is shown in Fig. 8. It consists of the rib plates (contour plates), the base and the climpes. The contour surface of the rib plates constitutes the contour of the fixture that is produced according to contour of the panel, the curvature radius of which is uniformly diminished, in order that the generatrix of panel prebended can be ensured to conside with that of panel part and the panel will be elastically prebend only in the chordwise, will not be prebend in the spanwise. The reasonable diminished value has relation with prebending value, they are determined by experience and actually it is unnecessary to calculate it exactly.

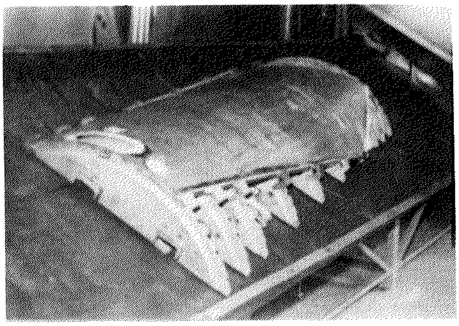

Fig. 8. Prebending of the prestress fixture in the chordwise

The interval of the rib plates in the fixture can not be too large, otherwise the longitudinal corrugate contour will appear. When the opposite sides of the panel are clamped by clampes, a spacer strip should be built in, or else the longitudinal corrugating can also appear at the both edges clamped.

Besides, the wider the panel, the greater the arch-up will be and the middle portion of prebended panel in the breadth separates from the contour plates, which results in overbend after clamping. Therefore, this effect should be considered while selecting the peen-forming parameters and the peening intensity should be reduced at the middle area of the panel in the breath.

During the peen-forming, the shot diameter is chosen 2~2.5 mm, the distance of nozzle from work-piece is 100~250mm, the peening pressure and the coverage (is controlled by changing the feed rate of the table and peening times) are varied according to the contour curvature of the part and the panel thickness until the acceptable contour of panel is obtained.

CONCLUSION

1. The sheet-metal deforms to take on a spherical shape during the conventional peen-forming. During stress peen-forming, the curvature radius decreases in the applied prebending direction and increases in the direction perpendicular to the prebending direction, their changes of forming radius increase with increased prebending value. Therefore, the trend in the conventional peen-forming for panel taking on the spherical shape can be conquered by use of the stress peen-forming to a great extent, and this is useful for forming the wing panels with simple curvature contour.

2. During stress peen-forming, the curvature radius of limitation in the prebending direction is inversely proportional to the peening pressure, the shot diameter and prebending value, but it is independent of the nozzle stand-off distance(within 100 to 300 mm). However in the above factors the prebending value has maximum effect on the curvature radius, peening pressure smaller and the shot diameter minimum.

3. one kind of integrally stiffened wing panels has been peen-formed by stress peening.

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