

# Development of Shot Peening for Wing Integral Skin for Continental Business Jets

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*Experiments and finite element analysis of shot peen forming of wing skin panels integrated with stringers showed that the radius of panels deformed by peening could be expressed as a function of thickness and shot peening intensity. We verified that panels could be deformed into a saddle shape or twist by shot peening both sides of the panel at the same intensity, elongating it. Simulation of deformation by shot peening was based on thermal stress analysis using the finite element method. Unexpected waving of the panel edge could be well simulated and prevented based on simulation.*

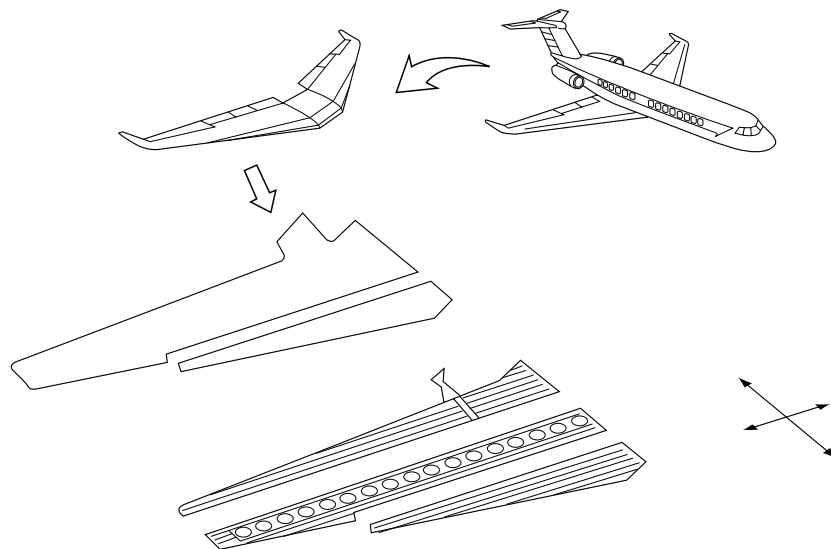
## 1. Introduction

An 8-person “Continental Business Jet” with a flight range of 5 700 km (capable of Trans-American flight) and a maximum cruising speed of Mach 0.8, developed under a joint venture of Mitsubishi Heavy Industries, Ltd. (MHI) and Bombardier Inc. (Canada), successfully flew its first flight in August 2001. In this joint venture, MHI was engaged in development, detailed design and manufacture of the wings and product support.

The main structural feature of the Continental’s wings lies in the adoption of an integral skin. This refers to a skin formed from thick plate with integral longerons (stringers). Unlike the usual built-up skin where the skin and stringers are coupled with rivets, the integral skin does not need rivet couplings and seals to ensure oil tightness of the fuel tank. Further, as there is no deterioration in strength caused by rivet holes and little likelihood of compressive loads causing buckling (because of the integral skin with

stringer), the weight can be drastically reduced. On the other hand, since most of the materials undergo cutting, this involves wastage loss, causing the material costs to rise. In addition, because of the high structural rigidity of the integral skin itself, it is difficult to shape the skin.

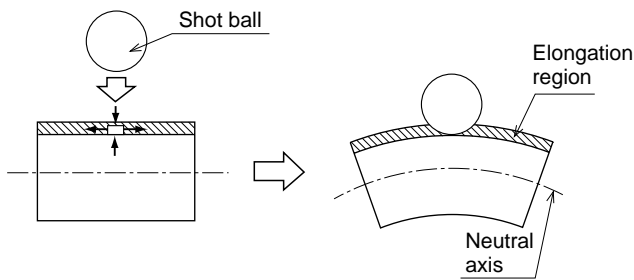
As shown in **Fig. 1**, one skin of the continental business jets wing is composed of 2 top faces and 3 bottom faces, with one piece being approximately 10 m (length) by 1 m (width). Since the shaping of such a large skin integrated with the stringers would be too difficult using conventional stretch forming, shot peening which does not need a forming jig, was adopted to shape the component parts. A shot peening is a method of bending metallic plates by compressive stress generated on the surface of the metallic plate through deformation caused by crushing the plate surface by colliding steel balls several millimeters in diameter against its surface with high velocity (**Fig. 2**). We experimented with forming the wing skins of the jets with complicated curved shapes



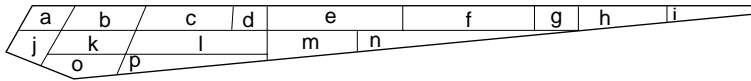
**Fig. 1 Schematic illustration of wing integral skin for continental business jets**  
 The wing structure and the skin structure are shown.

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**Fig. 2 Principle of shot peen forming**  
The deformation principle of shot peening is shown.



**Fig. 3 Example of area division for the same peening condition**  
An example of the division in the region, where shot peening is carried out under the same condition, is shown.

ranging from a bend radius 1 300 mm to almost flat by adjusting the quantity and speed of the steel balls.

This paper describes the results of the forming tests of the actual parts and the deformation simulation using the finite element method (FEM).

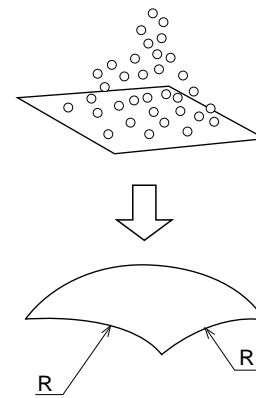
## 2. Shot peening test of wing integral skin

### 2.1 Technical problems for actual skin forming

The wing of the continental business jet is not only conical in shape, but has an irregular shape with a twist, like a saddle shape with a curve in the longer direction. In order to bend a flat plate into such an irregular shape, it is necessary to deform each material so as to elongate (stretch) the length. Further, since the material itself varies largely in structural rigidity, i.e. the thickness is reduced from the wing root to the wing tip, and the thickness in the stringers and the part coupling with the ribs is increased, it is necessary to select shot peening conditions suitable for the changes in plate thickness. These technical problems can be broadly divided into three parts: (1) setting the shot peening conditions for the curved shapes in the flight direction, (2) prevention of spherical deformations and (3) setting of shot peening conditions specific to the wing skins of continental business jets. Hence, in our test we used both partial specimens and the full-size specimens.

### 2.2 Setting the shot peening conditions for curved shapes in flight direction

The curved shapes of wings in the flight direction (chord shapes) of all aircraft, including the continental business jets, have curvatures with complicated changes in order to obtain the specified aerodynamic performance. In actual practice, however, doing shot peening by precisely changing the peening conditions according to the curvature radius and plate thickness of the wing skin over a large area take an extremely long time and is therefore unfeasible. Consequently,



**Fig. 4 Spherical deformation by shot peen forming**  
When a flat plate with uniform thickness is subjected to shot peening, a spherical deformation occurs.

we divided the wing skin into 16 regions as shown in **Fig. 3**. Next, supposing the curvature radius in these regions to be constant, we obtained the average plate thickness in each region before setting the peening conditions according to the average plate thickness and the average curvature radius. This forming method was developed by MHI when developing of the "Global Express" high-speed business jet, jointly with Bombardier Inc. (Canada). During the process of development, we studied and determined the effect of plate thickness and intensity (shot peening strength) on the curvature radius on the basis of the data obtained through using specimens with different plate thicknesses. The wings of Global Express used a built-up skin and had no stringers. Eventually, however, it was found that the presence or absence of stringers had little effect on forming the chord shape, and the newly developed forming method proved effective for forming the wing skin of continental business jets, ensuring that the specified chord shape was achieved.

### 2.3 Prevention of spherical deformation

Since the compressive stress caused by shot peening the material surface is isotropic, when the steel balls are projected on one side of the flat plate, the plate takes a spherical shape (equivalent to a spherical part), with the curvature distributed in all directions (**Fig. 4**). This phenomenon is based on the principle of deformation, and is generally difficult to get rid of. In the case of the wing skin for continental business jets, the adoption of integral stringers makes the bending deformation in the longer direction of the wing less likely to occur because of the non-isotropic properties of the structural rigidity of the material. However, as the forming of the chord shape ended, the center portion was found to show a deformation (bulge) of approximately several millimeters even in the longer direction of the wing. In order to correct this, we elongated the stringers by shot peening the

stringers alone, thus proving that the spherical shape could be corrected. This correction is possible because of the integral skin. In the case of a built-up skin, which does not have structural non-isotropic rigidity, this method cannot be used to correct the spherical deformation. The wing skin for continental business jets also has some regions with notched (cutout) stringers where the skin is connected to the rib. In such regions, the above method cannot be used to correct the spherical deformation. We therefore used a press to carry out forming in such regions prior to shot peening in order to prevent the spherical deformation by shot peening.

#### 2.4 Setting the shot peening conditions specific to the wing skin of continental business jets

The wing skin for continental business jets has the special problem that the skin has, as mentioned above, a saddle shape and a twist. In order to form a flat plate into such shapes it is necessary to partially elongate (stretch) the material. Shot peening is primarily a method used for bending. However, we also applied this method for elongation. We shot peened both sides of the material with equivalent intensity, so that the material could not bend in either direction (and thus maintaining balance), eventually leading to the elongation of the material. In our experiment, we shot peened both sides of a strip specimen with a constant thickness at different intensities in order to obtain the relationship between elongation and intensity. However, when a larger intensity was applied to obtain a longer stretch, the section began to buckle, causing waving deformations to appear. Therefore, we set the peening conditions using the simulation technology to be described later, and verified a specimen with the same shape as the actual skin in order to experiment with a real restraint state. We discovered through our experiments and verified that for elongation it is important to avoid local shot peening and to carry out deformation little by little over a wide range instead of applying a specified amount of mechanical elongation to a specified place.

### 3. Deformation Simulation using Finite Element Method (FEM)

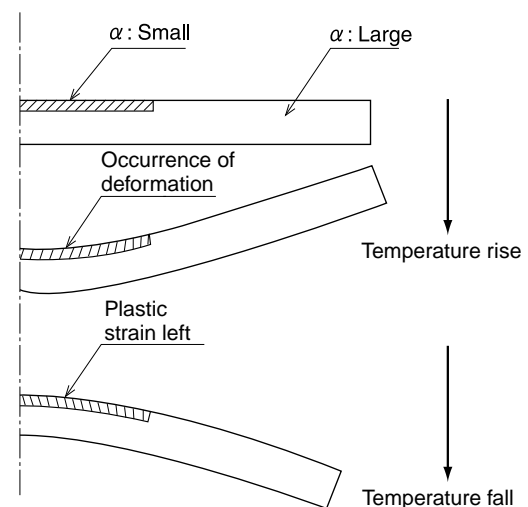
#### 3.1 Necessity of deformation simulation

The relationship between the curvature radius and the plate thickness and peening intensity provides the basic data for setting the forming conditions in shot peening. However, the actual skin does not have a uniform distribution of thickness, which shows a rich variation. Prediction against macroscopic deformation is possible by using this basic data. However, there are a lot of problems requiring study before setting the detailed forming conditions, since depending on

the distribution of the plate thickness and shape at each section of each part, changes in structural rigidity and the state of restraint, out-of-plane bulges (camber) and waving may occur. It would be possible to verify all these one by one through experiments, but this would need a huge number of tests, making it difficult to carry out effective setting of the forming conditions. Therefore, we carried out deformation simulation using the finite element method analysis (FEM analysis) as a pre-study before the experiments in order to gain a rational understanding of the heterogeneous deformations, etc. confirmed during the experiment.

#### 3.2 Establishment of analysis method

The problem we encountered during deformation simulation using FEM analysis was how to introduce the plastic strain only in the vicinity of the material surface (deformation caused by the steel ball peening). Simulative process as it may be, it is practically impossible to carry out analysis by allowing several hundred or several thousand steel balls to collide against the material surface. Therefore, we devised a new analysis method where the whole material is heated to a specified temperature before being cooled down using a model with a small coefficient of linear expansion (rate of elongation due to temperature rise) only at the surface of the material as illustrated in **Fig. 5**. When the material is heated, it is difficult for the surface alone to elongate, so that stretched by the other parts easy to elongate the plastic strain gets applied only to the surface. Later, as the material is cooled down to its original temperature, the surface alone gets elongated (deformed), causing the compressive stress to remain only on the surface, a state similar to shot peening. The deformation after the material is cooled down to its original temperature shows a similarity with the bend deformation caused



**Fig. 5 Principle of analysis model for simulation**  
A model of simulating deformation due to shot peening is shown.

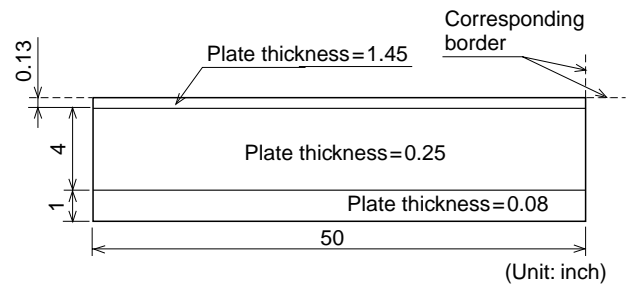
**Table 1 Comparison experiments and analyses on deformation by shot peening**

Intensity (inch)		Curvature radius (mm)		
		Material thickness = 0.125 inch	Material thickness = 0.18 inch	Material thickness = 0.25 inch
0.0007	Experimental result	6 625	12 500	23 500
	Analytical result	6 517	12 480	22 932
0.01	Experimental result	953	2 150	4 083
	Analytical result	1 367	2 832	5 656

by shot peening. The curvature radius obtained through the deformation simulation of the plate using this analysis method and the results obtained through tests are compared in **Table 1**. At a high intensity (0.01 inch), the simulated curvature radius tends to be larger than the test results, but shows excellent conformance to the test results when the intensity is low (0.0007 inch). A quantitative upper limit seems to exist, but qualitatively, the deformation tendency is well reproduced, so that it enables a rational understanding of the deformation phenomenon during shot peening.

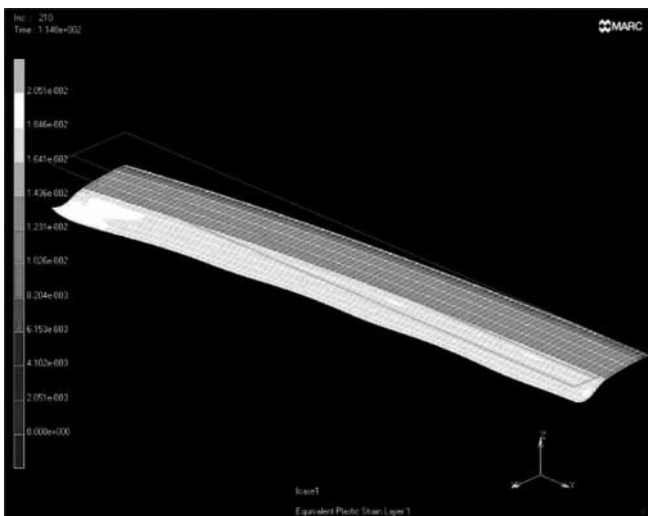
### 3.3 Deformation analysis of the step section for installing leading edge parts

The leading edge section of the wing skin for continental business jets (the side in the traveling direction of the aircraft: see Fig. 1) has a part with a slightly opened U-shape in order to form a protruding shape on the wing. These leading edge parts are installed on both the upper and lower skins. Since the installation section overlaps and is coupled using rivets, the plate is reduced to half the plate thickness (step section), so that this is a region with a sharp change in plate thickness. In this step section, the step was confirmed, through a forming test using a

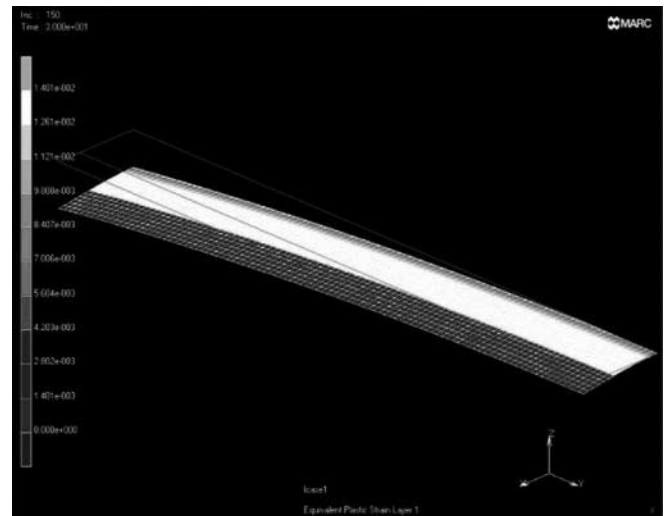
**Fig. 6 Analysis model for the waving deformation**

The analysis model used for simulating waving deformation at the step section is shown.

partial model specimen, to have a waving deformation. Here, we adopted a deformation simulation using FEM analysis to find a way of preventing the waving deformation. The waving deformation is attributed to using the same intensity on the material, which has different plate thicknesses, when peening the chord shape. This causes excessive deformation (excessive elongation) of the thin section compared with the thick section because of the low rigidity of the thin plate. Hence, we tried a combination of different intensities using the model with a simple shape shown in **Fig. 6**. As a result, it was confirmed that the waving deformation could not be altogether prevented even if the step section were to be formed by using a relatively low intensity. It was further revealed that the waving deformation would not occur if the step section was not subjected to forming (**Fig. 7**). In the case of an actual skin which was shot peened with the step section excluded, no waving deformations were observed on the step section, proving the effectiveness of the results of deformation simulation. In this way, in addition to the study of the precise forming conditions, we investigated setting effective forming conditions by combining the forming test using specimens and the deformation simulation using FEM



(a) Occurrence of waving deformation



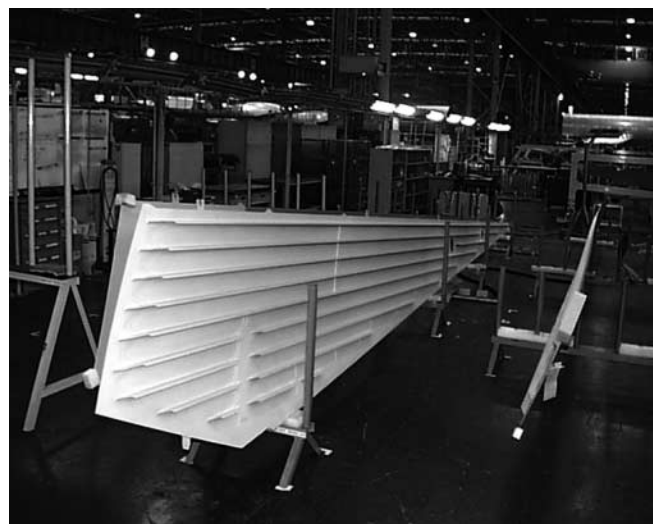
(b) No occurrence of waving deformation

**Fig. 7 Results of finite element analysis on the waving deformation**

A step section not subjected to shot peening can prevent the occurrence of waving deformation.



(a) State of assembly



(b) Appearance of wing skin

**Fig. 8 Appearance of the wing structure for continental business jets**

The appearance of the wings for continental business jets during assembly and the appearance of integral skin is shown.

analysis, and introduced new shot peen forming equipment in December 1999. Consequently, it took us no more than four months to successfully manufacture the first wing skin for continental business jets in April 2000 (**Fig. 8**).

#### 4. Conclusion

In the process of developing shot peening for wing integral skins for continental business jets, we conducted forming tests using specimens and carried out deformation simulations using FEM analysis to obtain the conclusions given below.

- (1) The bending deformation (curvature radius) of plate (sheet) material caused by shot peen forming can be arranged in terms of plate thickness and intensity, and this relationship can also be applied to forming the chord shape of the integral skin.
- (2) It is possible to use shot peening to form saddle shapes and shapes needing twists or elongation of the material by applying an equivalent peening

intensity to both sides of the material.

- (3) The spherical deformations occurring when shot peening the integral skin can be corrected later by elongating the stringers only through shot peening.
- (4) The simulation of shot peen forming deformation was confirmed as possible by making a model of a material having a small coefficient of linear expansion of only the surface by using finite element method (FEM) analysis before calculating for heating and cooling the model.
- (5) This simulation method can be used to reproduce the waving deformation which occurs during shot peen forming, leading to finding a preventive measure against the waving deformation.

#### Reference

- (1) Ohta, T. et al., Development of Advanced Production Technology for Wing Integral Tank for GLOBAL EXPRESS, Mitsubishi Juko Giho Vol.33 No.3 (1996) p.162