

# **SINGLE PIECE WING SKIN UTILIZATION VIA ADVANCED PEEN FORMING TECHNOLOGIES**

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## Abstract:

DFMA-Design for Manufacturing and Assembly was employed by IAI and NMF Canada Ltd. to reduce total costs for the Galaxy aircraft program. Reduction of part count, elimination of costly joints, reduced assembly time and improved performance are all advantages of large monolithic structures replacing smaller multi-piece assemblies in the aerospace industry. Wing designers are no exception, seeking to design lightweight and stiff structures composed of fewer parts to manufacture, track and assemble. While materials strength, aluminum alloy plate size and machining technology have advanced steadily over the years, the ability to form increasingly complex curvature wing skins has traditionally limited many designs to multi-piece assemblies. By combining advanced shot peen forming with mechanical pre-stressing and warm forming techniques, NMF has developed a system to meet the technological requirements for modern aircraft wing design.

Key Words: Wing design, high wing sweeps, monolithic structures, supercritical wing, stringers, dihedral break, wing skin, low design costs, outer mold line (OML), inner mold line (IML), forming technology, forming techniques, warm forming, peen forming, tensile stresses, airframes, saturation shot peening, compressive stress, pre-stress spanwise, curvature, dihedral bend, aerodynamic smoothness.

## Wing Design:

Israel Aircraft Industries designed the Galaxy midsize business jet to fulfill a particular market segment, requiring a wide body with a continental range for eight passengers and intercontinental for a Paris to New York non stop access for four. First in it's class, the Galaxy builds upon the design success and outboard wing commonality with the smaller Astra business jet. Certified in late 1998, speed to market was a key advantage for IAI in winning it's market share.



Fig. 1: I.A.I. Galaxy business jet

Wing design is a complex task composed of finding an optimum combination of span, area, sweep and twist to minimize structural weight and drag, later optimized by analysis to obtain desirable lift distribution and effect on taper and thickness parameters. Supercritical wings used in modern designs employ high wing sweeps for its desirable effect on transonic wave drag. Even though an aircraft may be flying at subsonic speeds, portions of the wing may reach supersonic speeds and increased drag.

The swept supercritical wing is designed to delay the point at which it reaches supersonic speeds thus delaying increased drag. More aerodynamically efficient, modern wings place increased stresses on materials and the requirement for stiffer monolithic designs. Joints add flexibility and weight to a structure, and are a potential source of crack initiation and failure. Reduction of joints through use of larger monolithic structures is a primary strategic goal for cost and performance improvements.

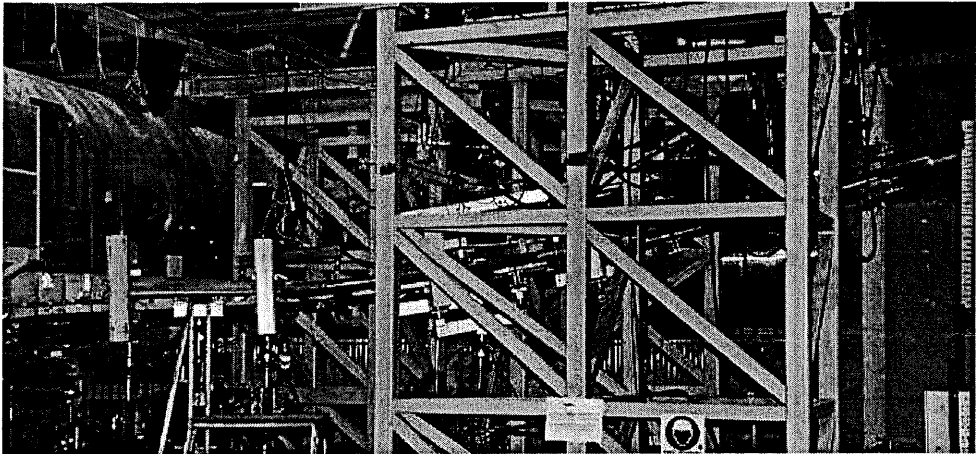


Fig. 2: Static testing of the Galaxy wing



Fig.3: Load at 100 % and 120 % of ultimate

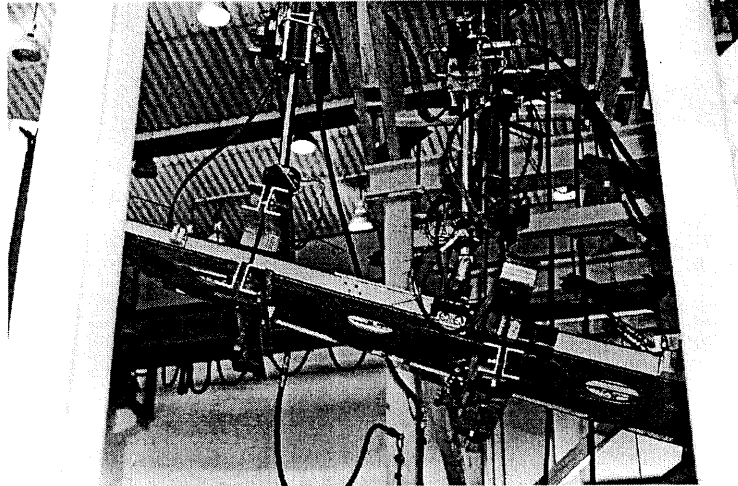


Fig. 4: Static testing certification of the Galaxy wing design

The smaller Astra aircraft was designed with thin, swept, supercritical wings to optimize performance. The upper wing skin flying with high compressive forces was originally designed from aluminum Al 7075 integrally stiffened skins. The wing was assembled from three peen formed wing skins for manufacturing ease. Stiffening stringers running the length of the panels were blended out at the dihedral break existing at rib 6, in order to facilitate wing skin forming constraints. The lower wing was designed using aluminum Al 7475 for its excellent fatigue resistance in tension and fracture toughness properties.

When IAI approached the new Galaxy project, the concept called for a larger and wider body aircraft with the existing wing being utilized as much as possible. The loads on the wing increased considerably. In order to keep design costs to a minimum, the upper wing skin was upgraded to aluminum Al 7150-T7751, which gave a 25% increase in strength. An additional increase in strength was achieved by forming the dihedral break located at rib 6 with continuous stringers along the entire span. Most of the outer mold line (OML) of the wing from rib 2 outboard was kept the same as the Astra wing. From rib 2 inboard, the wing and CTS (carry through structure) were redesigned and enlarged.

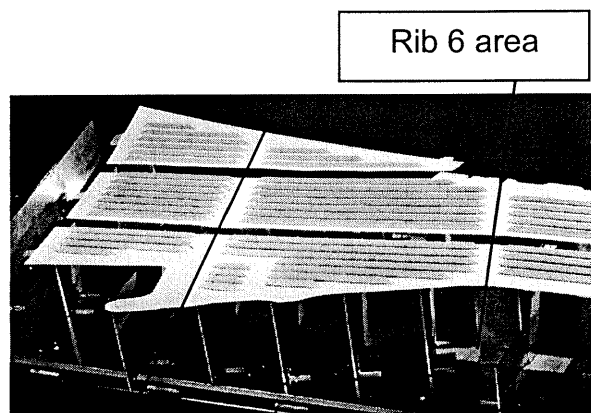


Fig. 5: Three piece wing skin

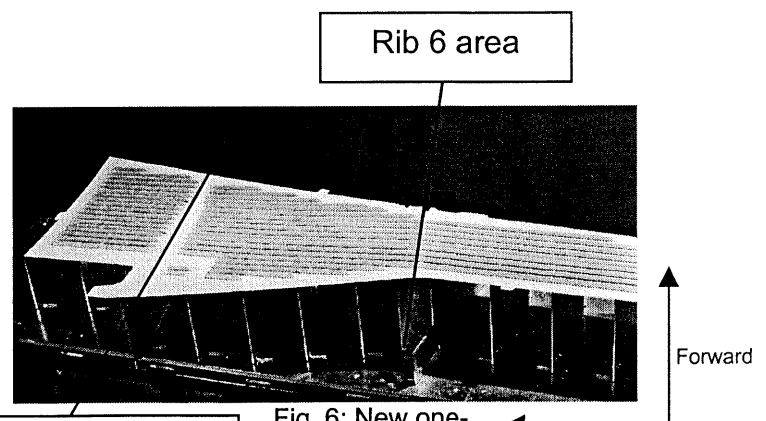
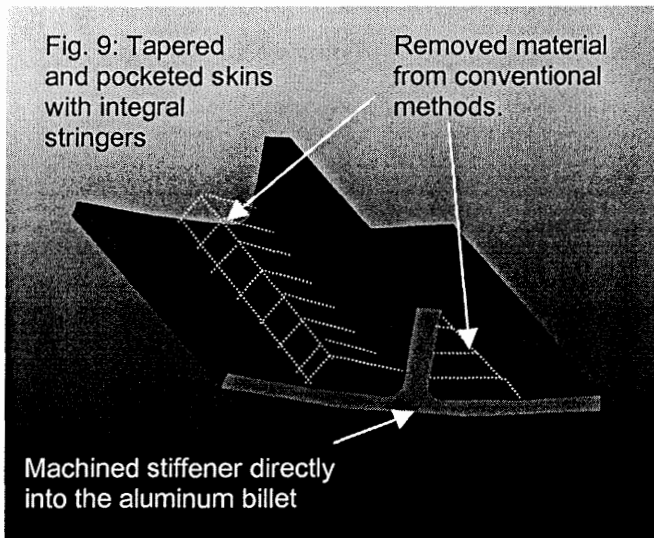
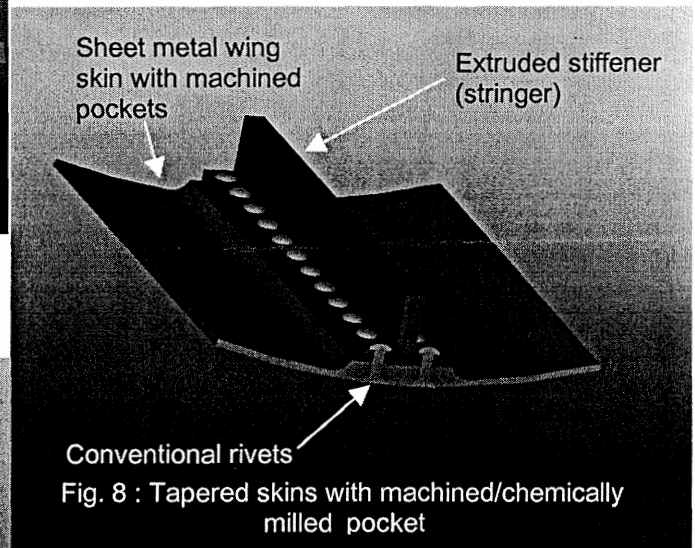
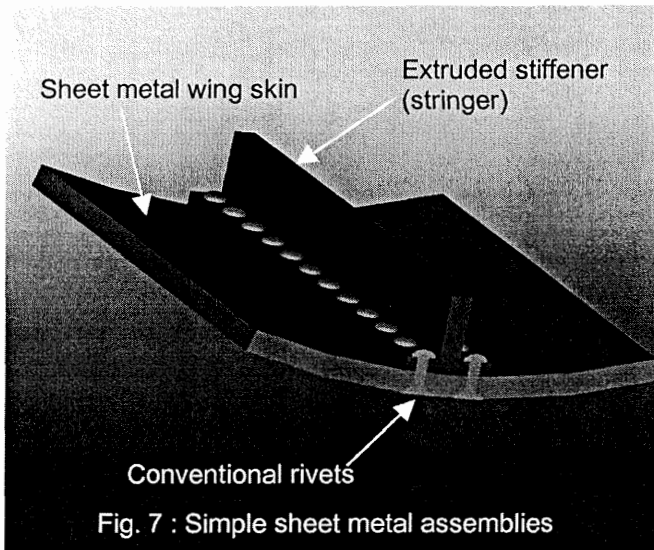


Fig. 6: New one-piece skin

Forming Technology:

Wing skins have evolved from simple sheet metal assemblies (Figure 7) to tapered skins with machined/chemically milled pockets (Figure 8), to tapered and pocketed skins with integral stringers (Figure 9), to finally larger skin/stringer designs replacing multi piece assemblies (Figure 6). A balance between forming costs and need to reduce weight and costs has resulted in the evolution of numerous forming techniques.



Hot forming or “bump forming” of wing panels required that the alloy panel be heated to 350+/-25°F before and during deformation with pressure rams and contour tooling. A small area is heated, deformed and moved in a calculated pattern. It would take hundreds of bumps to complete a given panel. While higher temperatures would facilitate the forming operation, over aging of the finished temper would result in a deterioration of the mechanical properties. The process was also highly dependent on skilled craftsmanship and therefore operator dependent.

Age forming or creep forming, in a heated pressurized autoclave, was developed to form large heavy panels with abruptly changing thicknesses. The process requires the soft solution heat-treated aluminum panel (W condition) to be sealed against special over formed contour tooling. While in the autoclave, a combination of heat and pressure deforms the panel onto the tooling, while ageing the alloy to final heat-treat temper. Residual stress of the finished panel is minimal although significant springback at the end of the cycle requires several tool iterations or extensive process experience to achieve the desired form. The thinner the panel the greater the springback. Other disadvantages include high tooling costs, volumetric growth of some alloys during precipitation hardening, and lack of re-processing for adjustment or rework of the contour.

Stretch forming was developed and is used frequently to form complex geometries in uniform thin sheets. Alloy sheets are heat treated to a soft temper, stretched over a mandrel, heat treated or aged to final heat treat temper and edge trimmed of excess material. In areas where lightening of pockets is required, chemical milling and masking of heavier sections may follow to remove excess weight. While common for fuselage skins and thin leading edges of wings, stretch forming is not suited for wing skin forming, due to difficulty in handling integral stringers and controlling panel edges.

Cold forming or break forming is used to form simple bends in plates. When repeated in multiple operations, a series of operations can be used to form bends or single curvatures. Complex curvatures found in the saddleback area of a wing break or dihedral is not possible to form with simple cold forming alone. Restrictions of break angle, forming radius and material thickness guidelines are recorded in aerospace process and materials specifications so as not to overly yield the alloy plate, causing dangerous tensile stresses and tears in the stretched surface.

Peen forming, a derivative of shot peening, is a cold work process of stretching material to impart variable compressive stresses in the panel surface, resulting in the ability to form desired complex curvatures without form tooling. As opposed to all other forms of metal forming, the compressive stresses used in this process virtually eliminate tensile cracks during forming and the need for non-destructive testing for induced flaws. Lack of thermal processing during complex forming operations allows NMF the ability to use sophisticated stretcher plate alloy tempers without adversely altering mechanical properties of the component.

Warm forming, a variation of cold forming, is used at NMF to increase the bending capability of alloy panels, without working the material above its ageing temperature. Maintaining the workpiece at 270+/-10°F (below alloy aging temperature) enables a specified time of exposure without deteriorating mechanical properties. Take for example the dramatic forming of an Astra Carry Through Structure (CTS) upper skin (Figure 10(a)). Originating as a flat integrally stiffened machined plate, the final structure exhibits two 28-degree bends with 1.25" radii. Cold forming would exceed the allowable deformation for 3/16" thick material, whereas operating at the above elevated temperatures increases 7075 material elongation up 40%, reduces modulus by 10%, and most importantly lowers yield strength by 25%.

Warm forming operations create basic form, on a standard break press with final adjustments of the required tolerances controlled with peen forming technology. The flexibility of peen forming in this example is essential to form these parts with the multiple curve axis ability added to the sharp angle deflection of the mechanical forming.

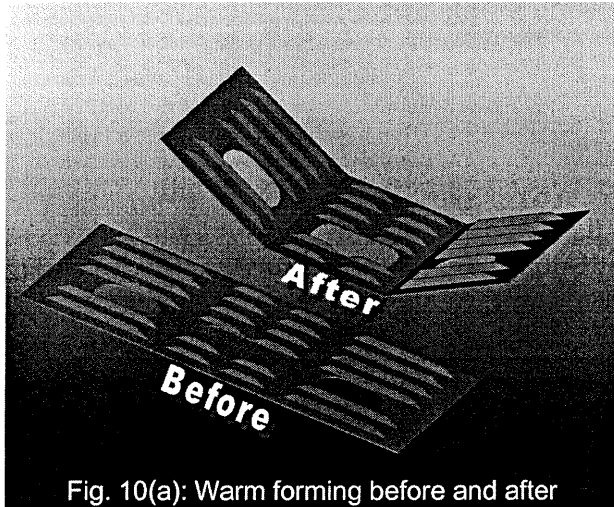


Fig. 10(a): Warm forming before and after

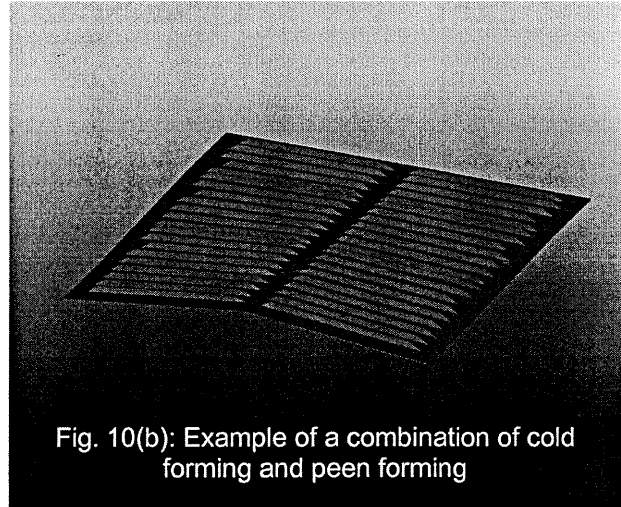


Fig. 10(b): Example of a combination of cold forming and peen forming

### Shot Peening Technology:

When hard spherical metal shot is impinged upon a target of elastic/plastic material, and the impact velocity is sufficiently high, the target material below each impact undergoes local plastic deformation. Upon rebound, the rest of the elastic material tends to push against the plastically deformed zone resulting in compressive stresses. Softer materials like aluminum alloy plate engender a relatively large plastic layer. Higher velocity or larger shot size increases the peening intensity, and the thickness of the plastic layer.

Saturation shot peening of both outer OML and inner IML wing plank surfaces with small shot at moderate intensities will typically induce a compressive stress layer of 0.005-0.010" deep with a maximum compressive stress of approximately 2/3 of the material yield strength. This compressive layer prevents initiation of fatigue cracks and SCC (stress corrosion cracking), possibly triggered from continuous excessive tensile stresses in the panel surface during service.

Older structural airframes and wings calculated on safe life design benefit from the increased fatigue limit imparted by shot peening. Damage tolerance calculations and tests now qualify modern airframe and wing designs. Parts are manufactured based upon durability and damage tolerant materials. While the calculations do not include a factor recognizing shot peening, materials and design rely less on the safety margin created by shot peening the surfaces; thus, slowing down crack initiation is recognized none the less. As a consequence saturation peening is included on all fatigue and fracture critical parts.

Peen forming involves the preferential stretching of one side of the work piece in order to induce a curvature to the panel. This may be accomplished in addition to saturation peening, by peening the outer OML side at a higher intensity than the inner IML side. Panels with integral stringers may remain straight in one axis while unreinforced panels may exhibit a natural spoon shape effect.

High aspect wing panels (ratio of length to width) will tend to stay straight in the long direction, although some curving of the corners will result. Prestressing the panel before peening can prevent most of the spoon shape effect. If pre-stressing is not possible or practical, peen forming (growing) the chordwise edges or peening the IML with narrow bands in the spanwise direction on the skin landing will correct this distortion.

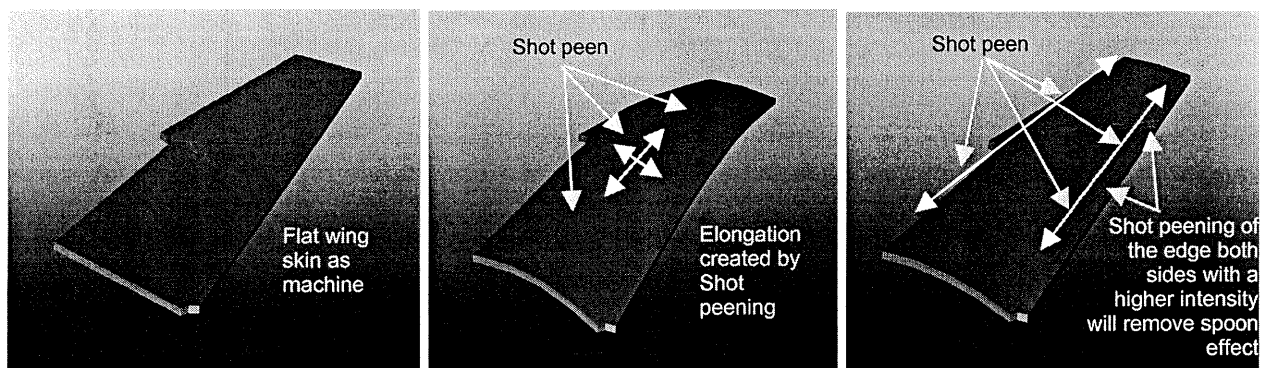


Fig. 11: Effect of shot peening on panel shape

Controlling the direction and degree of curvature by the peen forming operation may be augmented by pre-stress equipment. Subjecting the panel to a pre-load within the elastic limit (normally below 75% yield) followed by peening, will impart a deeper plasticised zone and compressive stress layer of higher intensity, with the result of greater material movement and panel curvature. Orientation of the elastic prestrain also suppresses unwanted curvature in the opposite direction.

Forming of the complete wing skin shape is usually a multistage process. Following chordwise forming of the wing panel, shot size, pre-stress pattern and differential stretching techniques are adapted, to form the spanwise curvature and or dihedral bend angle of the wing skin.

The ability topeen form a given section depends on the ratio of the compression layer compared to local skin thickness. Thicker material, larger shot, higher velocities and greater prestress enable the forming of heavy sections.

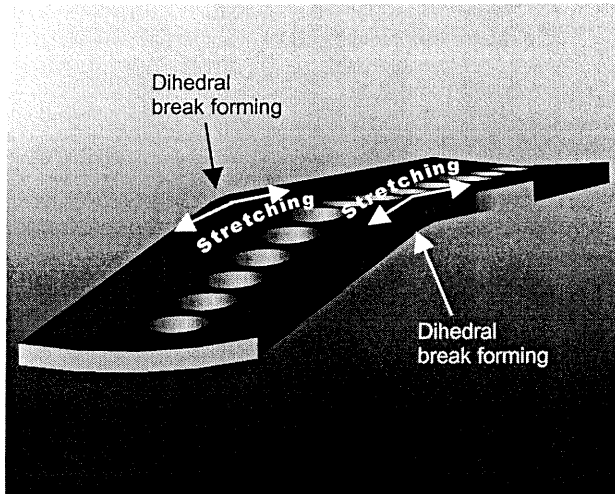


Fig. 12: Dihedral forming

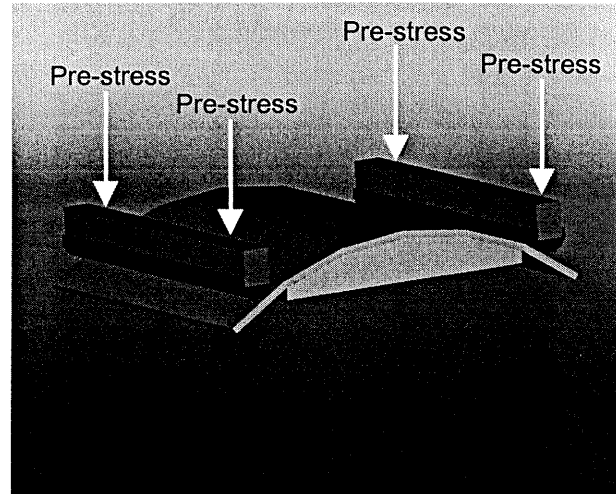


Fig.13: Dihedral forming pre-stress

Until recently, panels employing continuous stringers for spanwise stiffness could not be formed at the dihedral break without generating an interruption of the stringer (Figure 16). NMF has perfected the technique using the Formax® (Formage Axiale) technology. Chord forming followed by spanwise stretching and stringer growth results in the desired saddleback shape for integrally stiffened designs. Precise sequencing and control of these special-forming parameters is maintained in order to achieve repeatability from one panel to the next.

Correct forming of the dihedral wing break involves stretching the stringers without canning the thin OML skin. Formax® technology controls material movement and axis of curvature to retain a smooth outer wing skin surface.

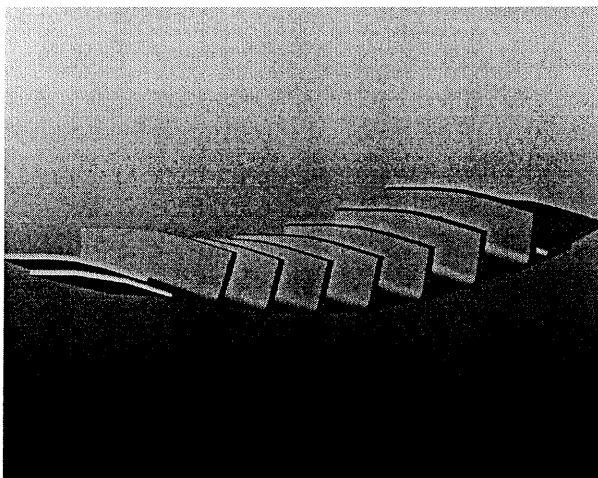


Fig. 14: Perfect dihedral without waviness between stiffeners

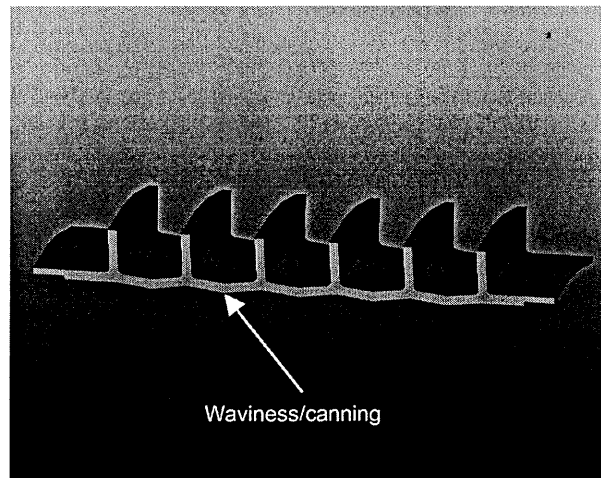


Fig. 15: Waviness or canning created by overgrowing stiffeners



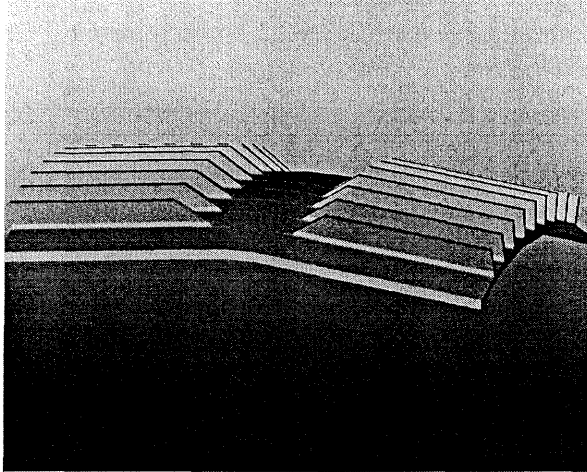


Fig. 16: Dihedral formed in conventional configuration

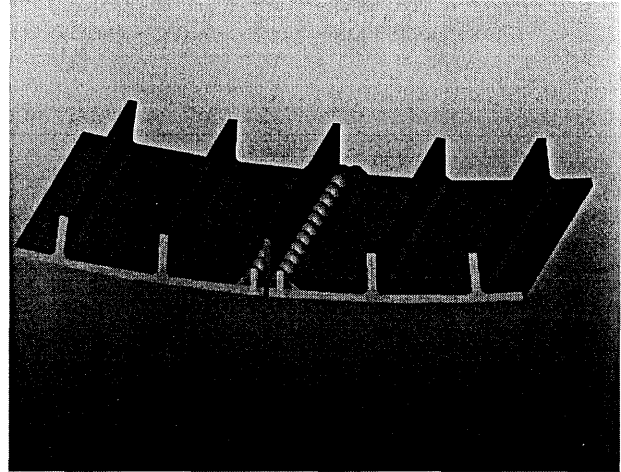


Fig. 17: Traditional splice joining of wing planks

A second advancement accomplished in peen forming was the ability for NMF to replace multiple wing panels with a single large structure. First realized on the Gulf-stream IV and refined on the Galaxy aircraft, the resulting reduction of weight, fasteners, doublers and fuel tight sealant has afforded the airframe manufacturer significant savings. Even though machining and forming time is slightly increased, the advantages during assembly stages are undeniable. These increases in performance and cost saving are so that they have become a key factor for the Galaxy aircraft development and performance rating.

#### Dimensional Control:

Shot peen forming is a progressive and calculated method of forming exotic wing configurations at room temperature. Formax® technology allows the repeatable forming of complex panels with the opportunity to return to the contour for additional dimensional refinement if necessary. The ability to refine the shape is advantageous as subtle changes in machined panel thickness and variation in raw material residual stress profiles may result in some small dimensional variations to be corrected, and may affect initial forming response. Concurrent engineering between designer and peen forming technology provider is highly encouraged to optimise the design. Height of integral stringer, thickness of chordwise rib landings, shape and location of integral stringers along common wing chord lines, section transition, tooling (datum) tabs, edge trimming and tolerances are but a few of the important features to consider in designing for manufacturability.

Achievable forming tolerances as measured in a template gauge are a function of panel thickness, size, and integral stringer reinforcement. Form compliance is measured in both the “free state” and an allowable “restrained condition” simulating the subsequent assembly operation of the skin to the wing box substructure. Both measures are important to ensure the quality of the peen forming applied to the parts. Free state will be a good indicator if the wing skin is sufficiently formed not only in the chord but in the span direction since weight, when applied may push the part to contour but also may be mis-indicating if a dihedral has been correctly formed.

Inspection of panel in the restrained condition is specified as a given weight per area of the panel area, and is limited in order to reduce the additional stress on fasteners in the assembled wing. Pre-load measurement will usually be a function of skin thickness. For example a thicker wing skin will tend to have a greater allowable pre-load at the pre-strained condition on the checking fixture (Table 1).

Inboard section landing thickness average	Free State	Pre-load condition	Weight allowed
.250 in.	.500 in.	.020 in.	15 pounds/sq. ft
.375 in.	.375 in.	.025 in.	20 pounds/sq. ft
.500 in.	.250 in.	.030 in.	25 pounds/sq. ft
More than .500 in.	.250 in.	.040 in.	35 pounds/sq. ft

Table 1: Allowable free state and pre-load conditions

As noted in Table 1, heavier/stiffer panels have limited free state gap allowance, in order to limit stresses on fasteners and distortion of the wing box upon final assembly.

Form tolerances are measured by a feeler gauge and expressed as a gap between the forming tool and the panel. The forming tool helps by providing data to record a Gap chart for inspection and certification purposes. Depicted at right is measurement of gap in the free state and restrained or “bagged” condition (Figures 18 and 19).

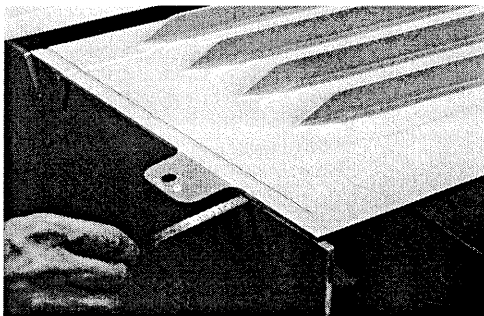


Fig. 18 : Free State

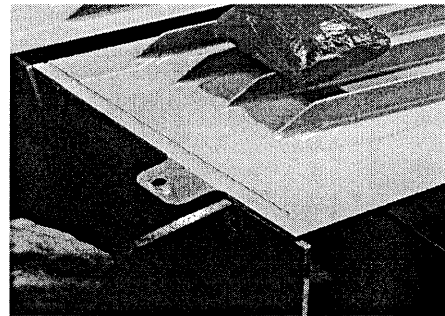


Fig. 19: Restrained

Depending on the configuration, panels may be trimmed to size on a fixture to strict assembly tolerances. Growth of the panel during forming is controlled by compensation in the initial machining design, in order to achieve a net shape after forming. Wing panels are frequently designed with tooling tabs and locator holes to position the part on the fixture during manufacturing inspection. After final inspection, a targeting operation consisting of drilling two locator holes in attached tabs, facilitates the transfer of the inspected geometry, to the wing box assembly jig. Single piece panels or multi-piece assemblies are commonly shipped with attached tool tabs to aid the location of the panel as it is affixed onto the wing box substructure. These tool tabs are located onto the forming fixture and have locator holes drilled to establish final panel datum system.

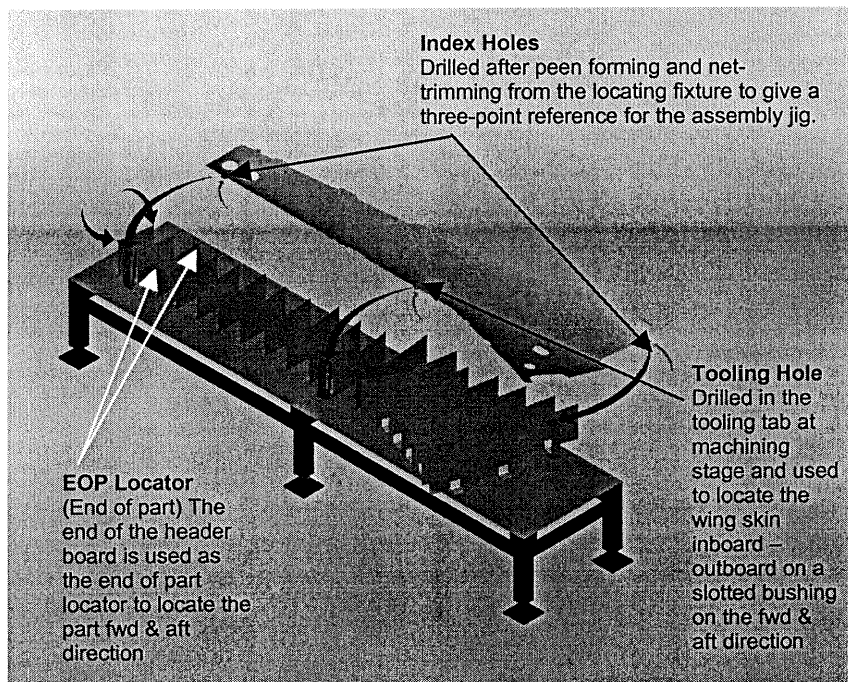


Fig. 20: Example of wing skin location to wing geometry after peen forming and indexation for next assembly.

Several designs also integrate panel edge machining templates into the jig, in order to trim excess material from the edges, further improving edge tolerances. Material removal is usually accompanied by florescent penetrant testing and re-saturation of the compression layer via peening of exposed surfaces. Wing skins on the Galaxy program have been engineered to include the growth factor at the machining stage so that the formed components requires no net-trimming operation prior to finishing and delivery to the wing box assembly area at IAI.

Material Transformation & Integrity:

Forming of single piece integrally stiffened panels requires significant material deformation via introduction of compressive stresses. While compliance to form is verified in a checking fixture, material integrity was investigated to see if any changes or knock down factors were appropriate in highly formed areas. Material properties were tracked from initial certification of plate through machining, saturation peening, peen forming, cold forming, and surface finishing. Results for tensile tests and residual stress measurements are summarized below:

Sample I.D.	Operation performed	Pre-Stress Imparted	Shot size	Intensity (Almen)*	Coverage (in percent)	Surface Sanding	Surface Finish after sanding
#1	As machined	No	N/A	N/A	N/A	No	63 RMS
#2	Saturation peen	No	SAE 230	4.5A	100	No	105 RMS
#3	Saturation peen	No	SAE 230	4.5A	100	No	105 RMS
	Peen forming	Yes	SAE 550	27-30A	80	yes	125 RMS
#4	Saturation peen	No	SAE 230	4.5A	100	No	105 RMS
	Peen forming	Yes	1/8 BB & SAE 550	18C & 27A	65	yes	125 RMS
#5	Saturation peen	No	SAE 230	4.5A	100	No	105 RMS
	Peen forming	Yes	1/8 BB & SAE 550	18C & 27A	65	yes	125 RMS
	Saturation peen	No	SAE 230	5.2A	100	No	115 RMS

Table 2: Processing details of wing panel sections used in study

\* Peening intensity measured on standard test strips per SAEJ442

<u>Sample properties</u>	<u>Area</u>	<u>Tensile (psi)</u>	<u>Yield (psi)</u>	<u>Elongation</u>
Alcoa 7150-T7751 per AMS 4252				
Guaranteed prop. LT direction UTS		82,000	75,000	6.0%
1) After machining panel	-Plate area	82,400	79,900	8.5%
	-Stringer	86,500	82,100	9.5%
2) After saturation peening	-Plate area	83,800	79,000	9.5%
	-Stringer	83,600	78,500	10.0%
3) Saturation & peen forming	-Plate area	83,700	79,800	9.5%
	-Stringer	88,800	79,100	11.5%
4) Saturation & dihedral forming	-Plate area	84,300	80,100	9.5%
	-Stringer	87,100	82,400	8.5%
5) Saturation, dihedral forming and final Saturation of surface	-Plate area	82,300	78,400	10.5%
	-Stringer	84,000	79,300	8.5%

Table 3: Sub compact tensile specimens tested per ASTM B557

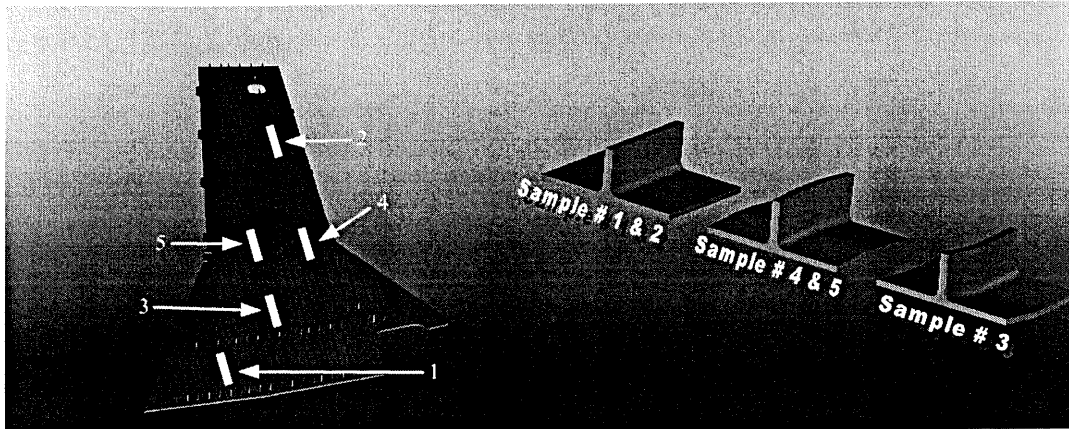


Fig. 20: Test sample locations

Although the extraction process of cutting test bars from the formed panels will relieve some of the imparted residual stress, the above tests demonstrate that static material properties were not degraded in the most extensively formed areas of the wing panels. Additional tests were conducted on the above samples (Figure 20) to look for evidence of micro cracks or damaged surface fibers of highly formed areas, which might otherwise result in crack failure initiation during the component's service life.

Optical and scanning electron microscopy was used to inspect sectioned samples near the formed panel surface. As anticipated, depth of the plastically deformed material and resulting compressive stress layer, is proportional to applied peening intensity. Good material integrity and absence of surface tearing was confirmed even in heavy peened formed areas.

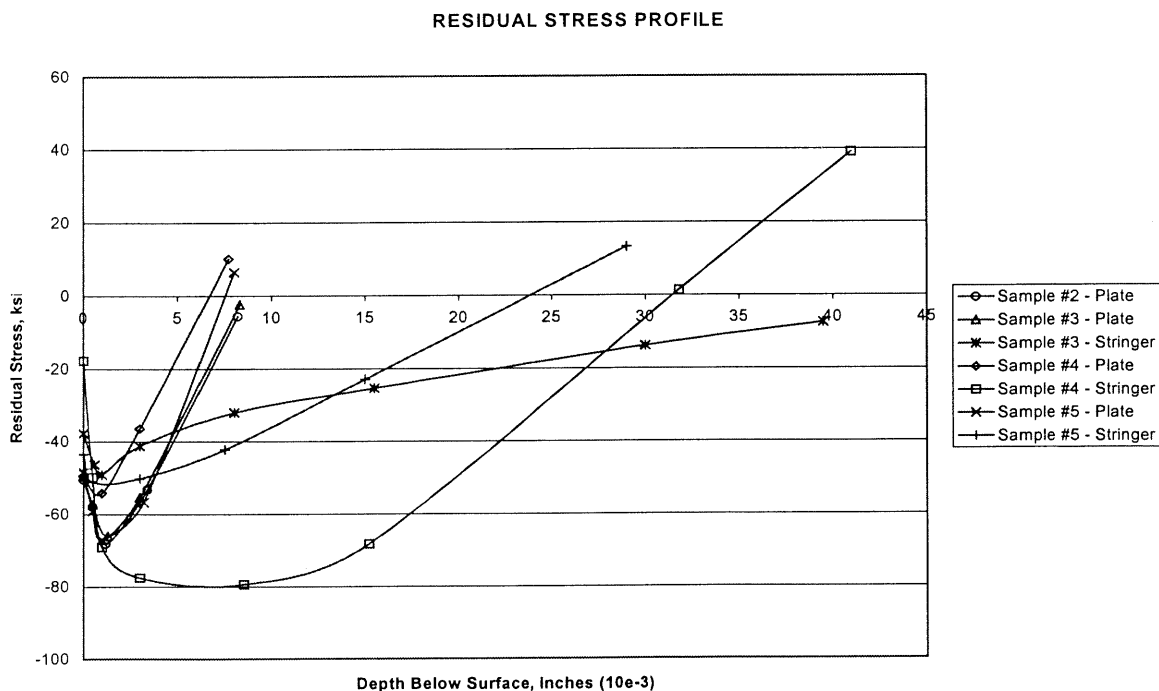
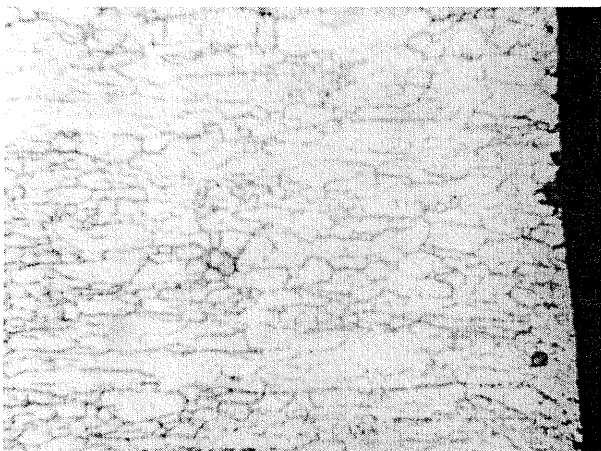


Fig. 21: Residual Stress Profile of samples as measured by the X-Ray diffraction technique.

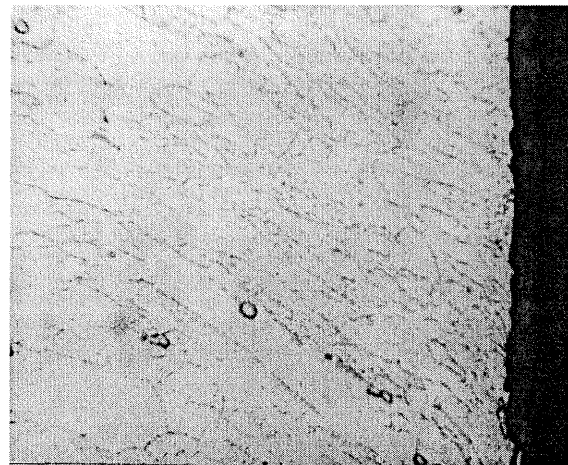
Observations of the studies are summarised below:

- Panel stringers, which were stretched or compressed by pre-stress and forming operations, exhibited high residual stress in magnitude and depth as anticipated.
- Depth of the compressive stress layer in all samples exceeds any material removal operation needed to improve surface finish.
- Surface integrity of the formed surface, especially after sanding to remove the rough dimpled surface of peen formed areas is maintained.
- Use of a second saturation peening after sanding of heavy peen formed areas, required by some specifications, may not be necessary to maintain the desired compressive stress layer in the panel.
- Depth of compressive stress layer measured in thousandths of an inch, is roughly comparable to units of Almen "A" scale shot peening intensity.
- Compressive stress magnitude can move from 60% of material yield strength for saturation peening to nearly 100% of the materials yield strength in stress peen forming.



**Fig. 22: Sample #2**

Saturation shot peened surface. Plastic deformation 0.0004 in. @ 500X



**Fig. 23: Sample #5**

Peened formed stringer surface. Plastic deformation 0.004 in. @ 500X

The above study concludes that normal manufacturing practice has very little chance of removing the compressive stress layer making it a very safe method of manufacturing and providing enhanced protection against in flight damage with a very tolerant level of flexibility.

## Surface Finish:

Shot peening produces a textured surface. While the saturation shot peening applied to both sides of most wing panels produces an aesthetically pleasing matte finish, rougher surfaces resulting from more intensive peen forming will need to be dressed. Scuff sanding with several abrasive grits, followed by acid or caustic etching and chromic acid anodizing restores these areas to 60-125 RMS surface finish as required. Aerodynamic OML surfaces have finer finishes as opposed to the internal IML fuel tank side, which may exhibit acceptable finishes of up to 180 RMS.

During the sanding operation, no more than 15% of the compression layer shall be removed, in order to retain the desired compressive stresses. Control of this operation is evidenced by leaving the center of the dimples produced by peening, visible under 10X magnification. Panel areas with a saturation layer extending say 0.008" would be reduced approximately 0.001" in thickness. The rule of thumb (in specs as well) is 10% of the Almen "A" intensity may be removed. Heavier peen formed areas employing larger shot at greater velocities, result in both a deeper compressive layer (0.015 to 0.040") and rougher surface. It may be commonplace to remove 0.002 in. to 0.005 in. of material during sanding of these areas. Coordination between the wing designer and forming engineer will ensure that material removal areas and panel thickness tolerances are coordinated to yield a well-dimensioned component.

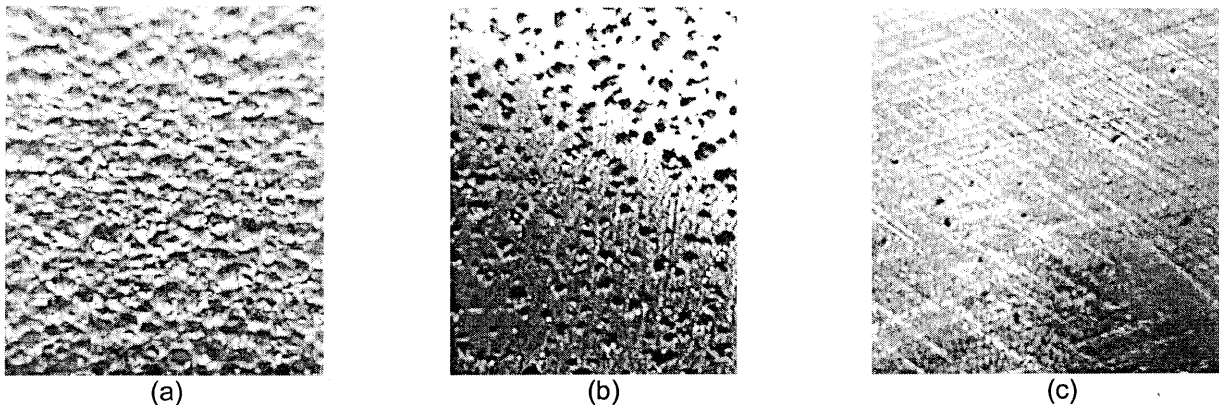


Fig. 24: (a) Shot peened surface (20X), (b) Properly sanded surface (20X),  
(c) Oversanded surface (20X) (very few shot dimples)

While care is taken not to remove excessive material, this operation is also self regulating. Excessive material removal would reduce compressive stresses and cause the panel to relax and be underformed. Re-forming and deepening of the compressive layer would then be needed to restore the panel to the required curvature.

As evidenced in a previous section, removal of a controlled amount of surface material via surface finish improvement will keep a significant portion of the compressive stress layer intact. While some designers request a final saturation shot peening after sanding operations to augment compressive stress, tests have shown that this procedure may not be required. In fact, additional saturation shot peening after light sanding may upset the delicate balance of stresses and panel curvature, resulting in dimensional deviations.

### Additional Work:

Success in combining 3 wing panels into one integrally stiffened structure (Figure 25) encouraged IAI and NMF to work together and build on past successes. Work is underway to combine small inboard lower wing skin extensions to the main wing panel in order to save weight, assembly costs and improve structural integrity. Another successful example includes the carry through structure (CTS) skin, joining both wings. The upper CTS wingbox skin previously formed in three individual segments has been successfully combined into one component as seen below.

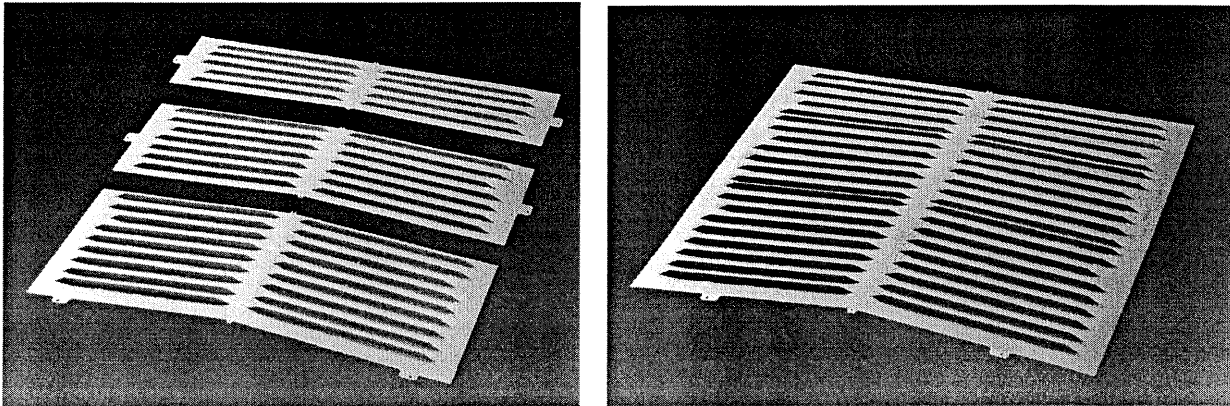


Fig. 25: Traditional 3-piece configuration and newly developed 1-piece configuration

### Industry Trends:

Integral (stiffened) metallic structures are replacing built up structures, according to recent studies conducted by Boeing and NASA. The Integral Airframe Structures (IAS) Program evaluated replacement of built up skin stringer structure with large monolithic machined/formed structures. Full scale trials on fuselage sections demonstrated favorable results with respect to: **1) Crack containment, 2) Residual strength, and 3) Fatigue** during cyclic loading of 7050 and 7475 aluminum alloys. Cost savings of over 40% are cited for integral structures over conventional built up structure. As the cost of assembly labor continues to rise year by year, savings afforded by large monolithic structures will become increasingly popular.

Older alloys such as 2024-T3, 7075-T6, 7178-T6 and 7079-T6 developed for fuselage and wing structures for aircraft developed in the 1950's, focused largely on strength. Experience with aging aircraft problems has encouraged the industry to develop more corrosion resistant and damage tolerant alloys. Today, a very large scientific knowledge base, tighter chemistry and process controls has yielded spectacular improvements in material performance. Modern alloys such as Al 7150 alloy used on the upper Galaxy wing skin were designed for high compressive loads, exhibiting excellent durability, damage tolerance, and corrosion resistance. Lower wing skins are made of modern alloys, including alloys 7475 T351, 2324-T39 and 2224-T3511 are optimized for high tensile loads combined with high durability, damage tolerance, and resistance to stress corrosion cracking.



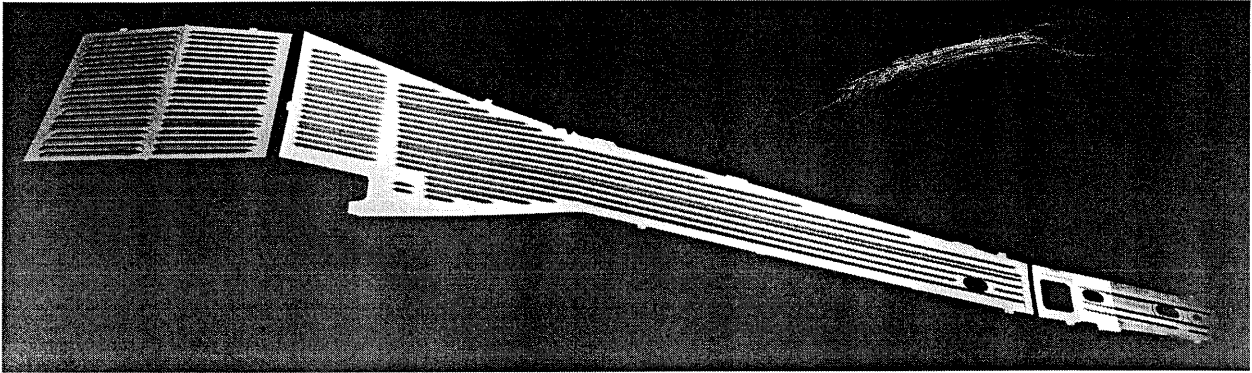


Fig. 26: Galaxy aircraft upper wing skin structures including central CTS panel, wing skin, and removable outboard tip extension

### Conclusions:

The large integral wing skin structure development on the IAI Galaxy program is a benchmark within the forming industry, and a model to be adopted on future wing designs. By combining conventional forming practices with advanced peen forming Formax® technology, NMF has developed a system to produce extremely complex, integrally stiffened, single piece wing skin structures. Avoidance of heat treat operations, required in creep or hot forming operations, facilitates the use of today's modern stretcher plate advanced aluminum alloys and heat treatment tempers. Tests have shown that material integrity is maintained or improved in all areas of the wing skin structure, including areas of high deformation. Structural engineers now have the freedom to optimize wing designs, reducing joints/fasteners, while saving weight and final assembly cost.

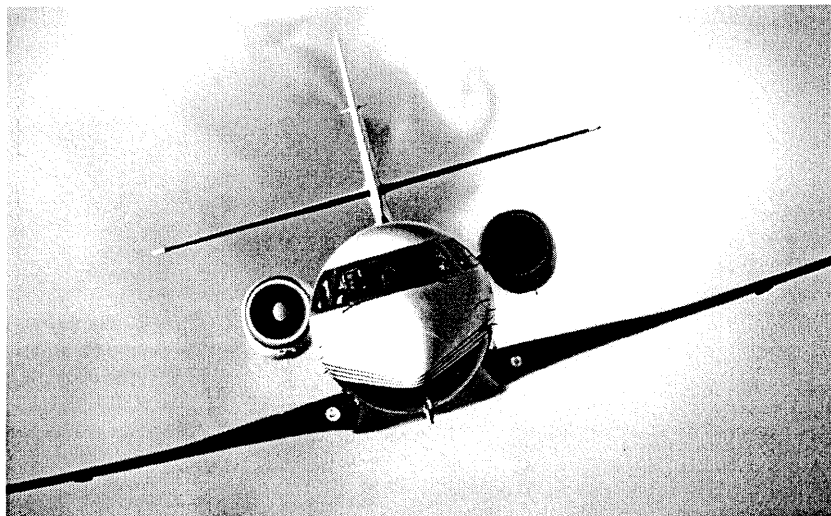


Fig. 27: Galaxy aircraft in full flight