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Peen-Forming – A Developing Technique

Peter O'Hara
Metal Improvement Co Inc, Newsbury, UK

1 Abstract

The application of Controlled Shot Peening to form or correct the shape of components has been in process for over 50 years. The extension of the principles of the Almen strip has been well applied through a range of industries although Aerospace has been the greatest user.

Shot Peen-Forming uses the compressive stresses induced by shot peening to alter the stress pattern, magnitude and depth, within a structure to deliberately create a change in product shape. Gentle curves, within the elastic range of the material, are regularly formed to consistent tolerances in to-day's peen forming facilities.

Changes to those induced stresses in magnitude or depth will alter the products profile. Consequently, the introduction of compressive stresses significantly deeper than can be achieved by conventional shot peening will extend the potential of using this forming method on a range of component parts.

Lasershot^{sm} Peening achieves that by introducing residual compressive stresses 3 to 4 times deeper than conventional shot peening. Thus opening up the Peen-Forming method to section thicknesses beyond present capability and producing tighter radii more consistently.

2 Introduction

The use of shot peening to forming the shape of components is not a new process but one that even today is finding new areas of application. For over 50 years large and small components using the basic principle that applies to the Almen strip have been formed successfully.

An Almen strip builds up a compressively stressed layer at the surface being shot peened. As this material is stretched, the Almen strip curves towards the direction of shot peening to a degree that varies with the intensity of shot peening, coverage and ball size used. Consequently with peen forming the same method applies and with the use of different parameters various shapes can be achieved. Generally cast steel shot is used to achieve the high strain required but other media, glass, ceramic etc, can be used for less demanding forming.

Lasershot^{sm} Peening is an alternative technique for the introduction of residual compressive stresses. It has the advantage over conventional peening in that it induces these stresses to greater depths, consequently a tighter radius of curvature can be achieved.

3 History

Shot peen forming was discovered and patented by Lockheed Aircraft Corporation in Burbank, California in the late 1940's. An engineer on their staff by the name of Jim Boerger was working on the development of a new aircraft. He recognised that with the desire to employ integrally stiffened wing panels as a weight saving measure for this aircraft that this presented some real challenges in creating the aerodynamic curvature.

Boerger working with an Almen strip realized that if a curvature could be induced in an Almen strip then it could be induced in a wing panel. Several sample panels were processed and it was proved that by peening on one side you could certainly induce a reasonable curvature. The first full size wing panels were selected but were quite distorted due to lack of machining knowledge on integrally stiffened wing panels. Fortunately, it was possible to bring them back to a reasonably flat shape and then further work proved that the required aerodynamic curvature could be produced. Lockheed Corporation granted a royalty free licence for the process and ultimately, once the patent expired, Boeing, McDonnell Douglas, British Aerospace and subsequently Airbus, as well as many of the smaller aircraft manufacturers employed this process as the most cost effective manufacturing technique for inducing curvatures in fully machined complex aerodynamic panels. Consequently the first aircraft to incorporate the peen forming technique was the Constellation shown in Figure 1, followed many others over the years.

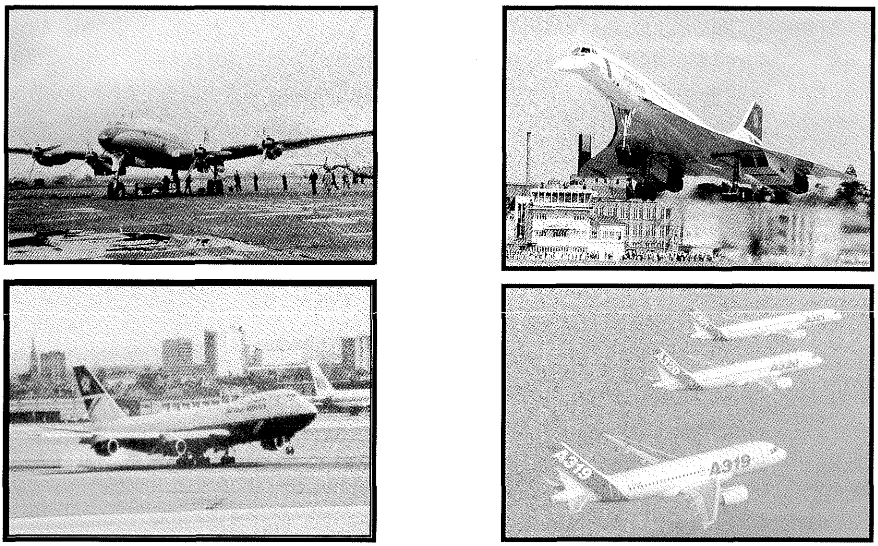

Figure 1: Super Constellation, Concord, Airbus and Boeing

4 Shot Peen Forming

Techniques for the forming of metals are many and varied, each having key features that endear them to specific materials and applications. Shot Peen Forming is a dieless forming process generally performed at room temperature, although certain applications require "warming" of the substrate for maximum benefit. During the process, the surface of the workpiece is impacted by pressure from small, round steel shot. Every piece of shot impacting the surface acts as a tiny hammer, producing elastic stretching of the upper surface. The impact pressure of the peening shot causes local plastic deformation that manifests itself as a residual compressive stress. The surface force of the residual compressive stress combined with the stretching causes the material to develop a compound, convex curvature on the peened side. When curvatures are being formed within the elastic range of the metal, the core of that metal remains elastic with a small, balancing, residual tensile stress. Other mechanical forming processes that require overforming with subsequent springback induce high tensile stress. Although high tensile stress can be minimized by stretch forming techniques, stretch forming is usually not performed on tapered or sculptured sections. Figure 2 demonstrates the type of section most suitable for the peen forming technique. The size, velocity, and angle of impingement of the shot as well as the distance of the wheels or nozzles (the wheels or nozzles propel the shot) from the workpiece are automatically controlled in specially designed machines. Peen forming can be performed with or without an external load applied on the workpiece.

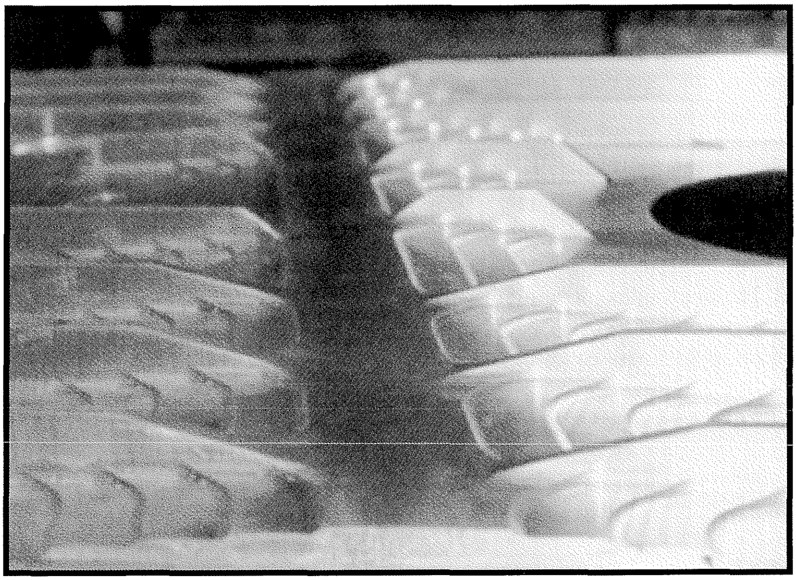

Figure 2: Complex multi-thickness ribbed structure

The non equal compressive residual stresses from shot peening on one side of the Almen strip, causes a degree of curvature, which is measured to give the intensity of controlled shot peening.

When the Almen strip is shot peened, the top surface on which the peening has taken place is in a high degree of compression, stretching that surface to cause a change of shape. In so doing, there is also a slight compressive stress induced in the lower unpeened surface, of the Almen strip. Therefore, forming has taken place without the introduction of any tensile stresses at either surface. In order to gain strength, that type of design required a multiplicity of thicknesses of material at the locations where additional strength was necessary, the final assembly being riveted/bolted together. We are now beginning to realise, there was also another benefit in reducing doublers and treblers in panel design. Far less corrosion sites are created when fully machined wing and fuselage panels are used in an airframe construction. Previously corrosion attack was very difficult to detect between the many layers of this material jointed/bonded together. Shot peen formed fully machined panels do not suffer this problem. There was not only the weight penalty to consider with the number of fasteners and joints required, but it was also a very time consuming and expensive assembly process. This was probably acceptable in the days when aircraft were manufactured at the rate of one or possibly two a month, but at today's rates then the production engineering technology has to be improved in order to reduce the quantity of building fixtures and expense of assembly time required to produce the wings and other major structural components.

In the Lockheed application, the reduction of weight from using fully machined panels was the driving force. Single curvature panels were required, and these had integrally machined stringers on them. These stringers then precluded forming by the traditional pressing, rolling, stretch, creep forming or wheeling processes at that time.

The Lockheed panels had fully machined integral stringers that overcame one of the characteristics of shot peen forming that a piece of single thickness material does tend to go barrel shaped if it is peened on one side only. This meant it was a relatively simple peen forming process to give the Lockheed wing panels the shape required within the laid down straightness tolerance as the stringers tended to hold the panel true in the spanwise direction.

Today, however, whilst there are still peen forming operations carried out on panels that have fully machined stringers an them, it is equally typical to see panels that are fully machined without stringers but still incorporating such features as manhole reinforcements, fuel pump locations, structural thickness differences, where for example there are engines and under-carriage loads to be carried. The limiting factor being the size of material available.

This can give a very complex shaped wing panel that does not actually have integral stringers, but the variation in thickness can be as much as a ratio of 1–10 from the thickest to the

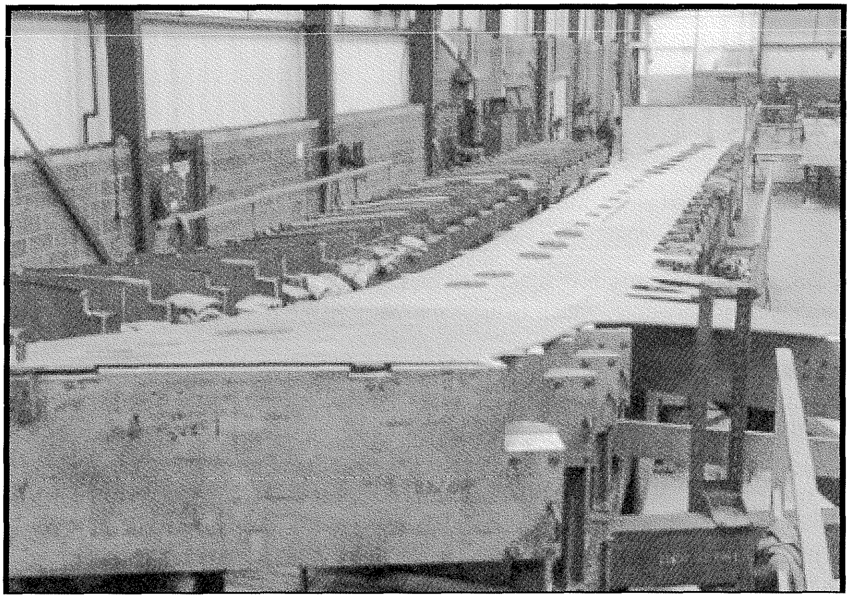

Figure 3: Wing skin panel on checking fixture

thinnest area of a shot peen formed panel. Typical of this complex peening process are the panels for the modern aircraft shown in Figure 3.

When it was decided to use the super-critical wing design, in order to improve efficiency and consequently save fuel, the design usually requires double curvature in the lower wing surface. This is double curvature in a fully machined panel, which means that neither the previous methods of pulling to shape in the build fixture, nor more conventional forming methods can be considered. Shot peen forming is the only method available to create such severe double curvatures consistently to the required accuracy in this type of complex machined panel.

In the process of shot peen forming, there are three methods used to create panel curvature. Firstly chordwise curvature is achieved with peening on one surface only, as in Figure 4(a). In this instance, the compressive stress on the peened surface stretches the metal to cause the change in shape. The limitation of this forming method is that it is only within the elastic range that movement can take place, and therefore only shallow curvatures can be achieved. To obtain greater degrees of curvature, strain peening, Figure 4(b), is used in which the component is held in an unidirectional pre-stressed condition and then it is shot peened on the tensile stressed surface. This means that when the component is released from this stressed condition after peening, the compressive stress is greater in one direction than the other, and it is greater in the direction of curvature formed from the pre-stressing process. The third method of peen forming is by shot peening on the edges on both sides of a piece of material at the same time. This gives elongation to the component because of the stretched material on both faces overcoming the resistance of the core in elastic deformation. This is shown in Figure 4(c).

Selectively using two or more of these processes, different shapes with different degrees of curvature can be created using shot peening alone. These are only shallow curvatures, which

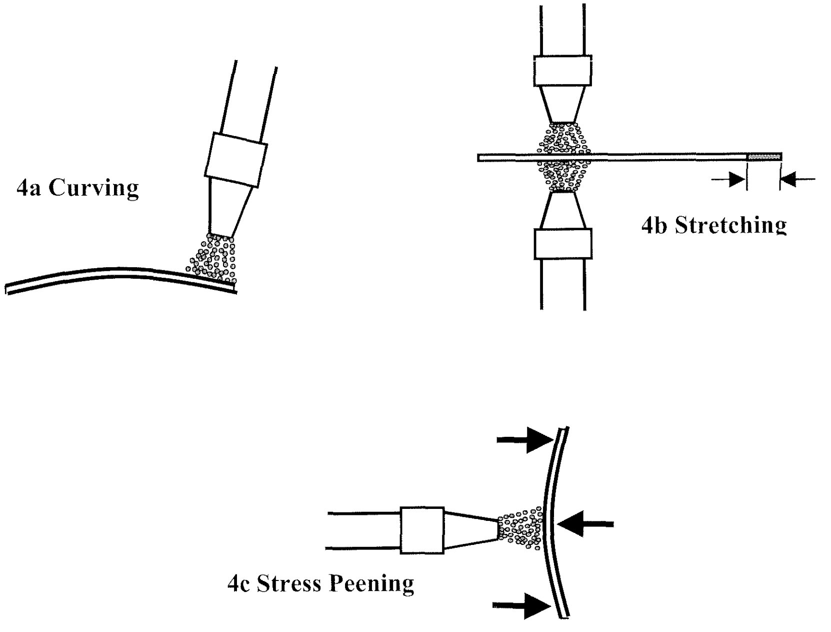

Figure 4: Peen forming methods

makes them particularly suitable for aircraft components, be they fuselage, wing, or tailplane items. They are however very accurate in their shape and because peen forming is carried out cold the reproducibility of forming is very good.

5 Super-Critical Wing Design

The super-critical wing design requires double curvature of the lower surface of the wing. On these designs, the double curvature is in the form of a saddle back shape, that is, the lower wing panel curvature is concave in the spanwise direction and convex in the chordwise direction.

The external surface of the panel is peened at comparatively high intensities to initiate the chordwise shape. The coverage and intensity in specific locations are varied to allow for differences in required curvature and component thickness. Subsequent to this peening, the double curvature is created using methods of pre-stressing the component, see Figure 4b. The double curvature shape begins to appear because the high degree of asymmetric stretching results from the localised pre-stressed peening.

This higher intensity shot peening means the edges are actually stretched Figure 4c, and the panel gains length at each edge and thus completes the double curvature shape. This double curvature once achieved is verified on a checking fixture, Figure 3. An accuracy of shape of 1 mm or better is quite usual for this type of forming, even with panels as large as 30 metres long.

Invariably the double curvature requirement is not uniform, in that the edges have to be stretched at different amounts on one side of the panel to the other. This means that in plan, the panel can change shape and create a slight banana configuration to the panel. This is usually not desirable, and one way that this can be overcome is that the panel, before shot peen forming, is machined with the banana shape in the opposite direction, so that when the forming operation is completed, the panel will be the correct shape for installation on the wing during production.

The process is only really limited by the size of material available. At present panels of 30 metres long by 3 metres wide are being produced to these high levels of accuracy that gives acceptable and consistent assembly.

6 Correction of Distortion

Shot Peening can be used not only to form panels to a given shape from an original piece of material that is flat but also can be used to create flat material from a component that has been distorted during manufacture or heat treatment. The raw material will have stresses of varying and generally unknown magnitude from the casting, rolling, forging, heat treatment and any other manufacturing process. If this stock material is then machined with the majority of the metal removed from one side only there will be a dramatic alteration to the stress pattern in the final machined part, and subsequently distortion could result.

Add to this the stresses induced by, perhaps, high speed machining with rapid metal removal and these are all factors that can give rise to distortion, Figure 5, which is usually of such a high magnitude that without remedial action, the component would be unsuitable for assembly. A very successful and metallurgically acceptable method of correcting this distortion is by using the principle of shot peening. This method involves the stretching of material on the concave side of the distorted component.

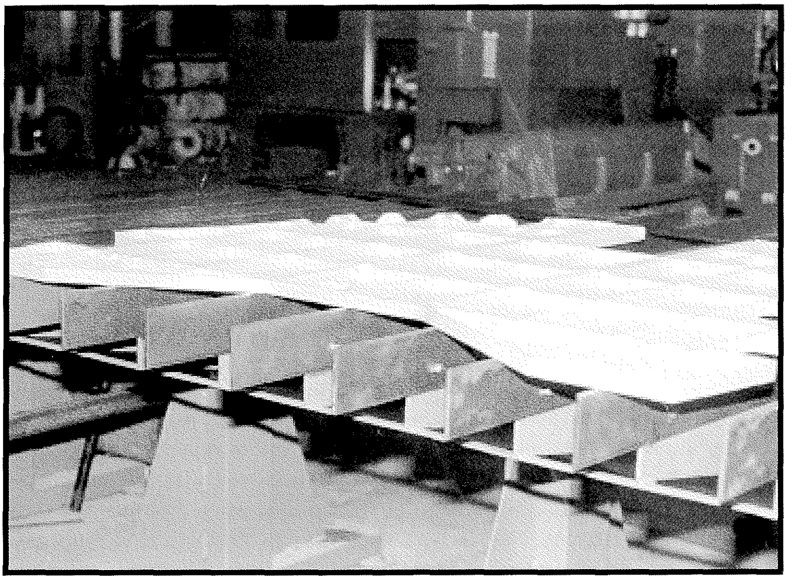

Figure 5: Bulkhead fittings for correction of distortion

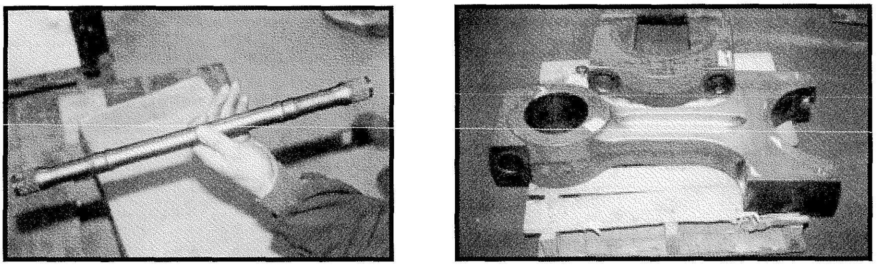

Figure 6: Industrial applications

Aircraft components are an extremely good candidate for this correction method as has been indicated previously, but the same technique can be used for industrial applications, Figure 6. Components such as steel drive shafts where they might distort during heat treatment, or even large marine connecting rods or crankshafts distorted through a service problem are both suitable for shot peen correction if their slenderness ratio is approximately 20:1 or greater. The same basic principles as with shot peen forming are followed during correction but it is always a very specialised operation for each distorted part. The very fact that in a batch of components machined on the same NC machine there can be significant differences in the degree of distortion does not make the correction task any easier. With particularly complex machined items even the direction of distortion may vary from part to part produced on the same NC machine.

Parts distorted in heat treatment, from the same batch in the same oven can show considerable variations and also service damaged items, like the connecting rods mentioned above will also show indeterminate amounts of distortion. The stresses that cause these distortions are combined with the stresses in the material from original casting, forging, rolling etc. to give variation on a piece by piece basis and the need, therefore is for these distorted parts to be treated individually.

7 Peen Forming Machines

Peen forming is usually performed within a cabinet enclosure by automatic machines. When close tolerances are required, some forming may be performed manually by skilled technicians. Two basic types of machines are used, differing only in how the peen forming media is delivered to the part being formed.

In nozzle-type machines, compressed air or gravity is used to propel the steel shot to the workpiece. These machines may have as many as 20 nozzles, and each nozzle is capable of delivering 25 kg of shot per minute to a specific location or area of the workpiece. Pressure gauges, control valves and monitors can independently control each nozzle. The nozzle direction is adjustable so that the optimum angle of impingement can be achieved when the workpiece contains surface areas with unusual geometry. Nozzle-type machines can automatically compensate for varying curvature requirements along the workpiece length or width. Thickness variations, cutouts, and reinforcements, as well as distortion caused by machining stresses or heat treatment, can also be compensated for with these machines. Figure 7a shows a nozzle-type, gantry peen forming machine. In this machine design, the gantry, which houses the nozzles, traverses over the workpiece while the workpiece is stationary. Another machine design, using nozzles or wheels, has the workpiece moving through the stationary machine that houses the nozzles, Figure 7b.

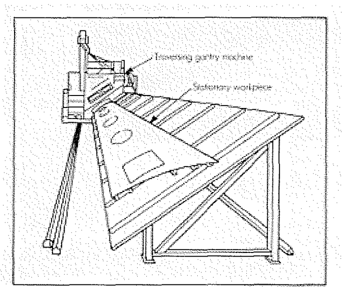

Figure 7a

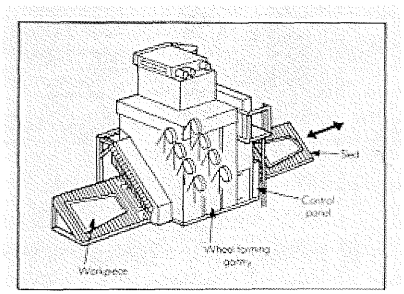

Figure 7b

Centrifugal wheel peen forming is another method by which the shot media is delivered to the workpiece. These machines use electronic controls to regulate rotating speeds of a paddle wheel, which accelerates the shot at the workpiece. A typical wheel can deliver 136 kg of shot per minute. Production-type centrifugal wheel machines may have 6-8 wheels, providing the machine with a capacity to peen form using more than 900 kg of shot per minute. The ability to deliver shot media at a controlled velocity in such large volumes permits higher production rates on these machines than obtainable on nozzle-type machines. Components formed by centrifugal wheel machines are usually of broad, uniform cross section, with all areas accessible to the shot stream. Indexing the position of the shot delivered to the wheel paddle can make minor changes to the shot stream direction.

8 Lasershot^{sm} Peening and Peen Forming

Conventional Peen Forming is used today on many aircraft, however it has limitations primarily in the thickness of metal that can be altered by the peening effect. Ball sizes up to 6mm can be used but the practicality of throwing, containing and grading this media on a routine basis is difficult. The introduction of Lasershot^{sm} Peening, which has the ability to induce depths of compressive stress 3 to 5 times the depth of conventional peening, with virtually no surface roughening, expands the potential of using this method on a wider range of structures.

Laser treatment of metals is not a new phenomenon. Laser cutting, shaping and laser thermal methods are some of the developing techniques, which are finding new applications in many industries. Indeed the principle of peening with lasers has been around for several years. What is relatively new is the speed at which this can be applied, i.e. at last it is a production technique rather than a laboratory tool restricted to exotic applications. Today the speed of processing is achieved using a solid state laser employing Nd:glass slabs and phase conjugation.

Prototypes of laser peening machines were developed in the 1970's and there have been later versions over the last 30 years, but were very much restricted to laboratory processing and were not cost effective techniques as they lacked the high repetition rate required for treating parts in a cost effective manner. A laser appropriate for peening at an industrial level requires an average power in the multi-hundred watt to kilowatt range and an energy of around 100J/pulse and pulse duration of 10's of nanoseconds. The peening effect generated by the laser is fundamentally introducing a shock wave into the surface and this can, at present, only be achieved by means of tamped plasmas, which are generated at metal surfaces by means of high energy density lasers.

The improvements in fatigue performance over conventional shot peening are significant in low cycle/high stress application and where damage tolerant surfaces are necessary. The gain in these situations is primarily due to a greater depth of compressive stress although lack of cold work also plays a part. Figure 9 shows the comparable effect.

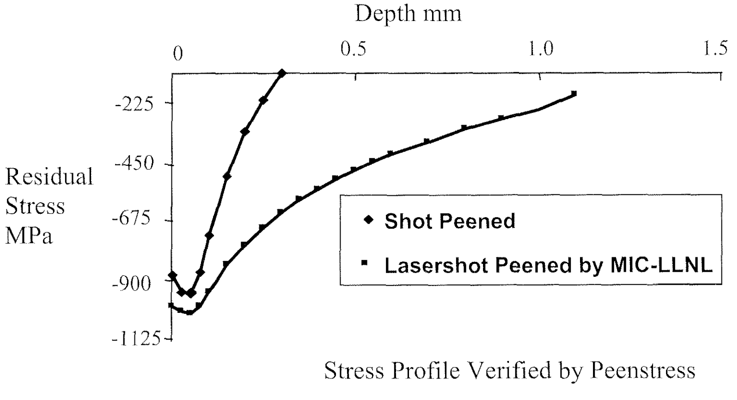

Figure 9: Lasershotsm peening against shot peening (Inconel 718)

When applied to Peenforming applications the results have indicated tremendous potential. However, it is not only the greater section thickness that can be formed, it is also the consistency and "cleanliness" of the technique. Trials to date indicate a repeatability of the shape, perhaps because of the greater depth achieved, not seen to date. In addition the lack of shot flying in all directions within an enclosure enables the forming, measurement and control all to occur in the same area and at the same time. Robotic equipment using iterative techniques are being viewed which should enable formed structures to be developed to precise shapes with no decontamination or surface refinement techniques, which today are time consuming and costly.

Figure 10: Lasershot^{sm} peen formed sections

Material	Thickness	Radius of curvature attainable by processes		
		Laser peen forming	Shot peen forming	Age/creep forming
Al 2024 - T3	16 mm	1.57 m	12.7 m	Cannot form 2000 series Aluminium
Al 2024 - T3	19 mm	2.85 m	20.3 m	Cannot form 2000 series Aluminium
Al 2024 - T3	25 mm	4 m	38.1 m	Cannot form 2000 series Aluminium
Al 2024 - T8	25 mm	6.1 m	30.5	Cannot form 2000 series Aluminium
Al 7000		As in Al2000 series	As in Al2000 series	As desired in Al7000 series

9 Summary

The conventional Peen Forming technique has developed significantly over the 50 years since the first application on the Constellation commercial aircraft. The process is today employed on most commercial aircraft and is part of the myriad of manufacturing techniques perfected and tailored to produce the complex products on those aircraft. However, although the process is getting close to its limits of performance, the introduction of Lasershot^{sm} Peen Forming will extend the envelop of performance and possibly one day replace the conventional technique

10 References

[1] Shot Peening Applications, *Metal Improvement Co Inc,* 2002.
[2] Barret, C., "Peen Forming" SME Handbook 1984
[3] Dane, B., et al, "Laser Peening of Metals – Enabling Laser Technology"