Shot Peen Forming - An Ecomonical Solution

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Theory

All metal forming methods require the inducing of permanent plastic strain within the component material. This is true of, for example, hot and cold techniques using punch and die presses, stretch forming presses, hydrostatic presses or simply a tinsmith with his hammer. In this respect shot peening is no different to any other metal forming technique.

Shot peen forming works by either stretching one surface and so causing the metal to bend or by stretching a complete section in relation to another and so inducing a compound 'barrel' or 'saddle' double curvature. A barrel shape is one which is convex in both 'x' and 'y' directions when viewed from one side and a saddle shape is convex in one direction and concave in the other.

An example of simple bending, and one that is familiar to those in the shot peening business, is that of the Almen Strip. In this case a thin steel strip is shot peened on one side only whilst held in a fixture. The action of the shot striking the surface stretches the material beyond its yield point . The material below the surface will be permanently stretched for a finite distance below the surface. The depth of stretched material will vary according to the part's material composition and hardness, the shot media used (steel, glass, ceramic) the size and speed of the shot etc. These factors will effect the size of the dimple which will give an indication of the depth of compression. (See Fig. 1).

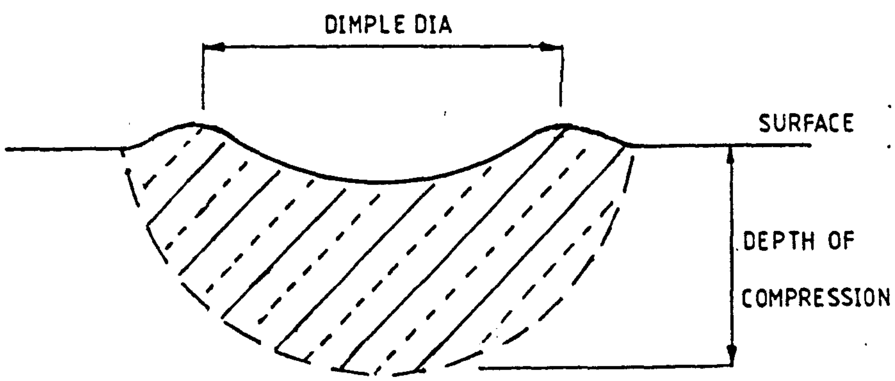

Fig. 1 Proportions of dimple diamater and compressive depth

There is some evidence to suggest that, for some materials at least, the depth of compression is approximately equal to the dimple diameter. By careful selection of the shot media, size and striking energy in relation to the component's size, thickness, material and required shape the necessary depth of compression will be induced so that the metal bends as a result of the change in balance of the internal residual stresses. Fig. 2 shows the residual stresses in a beam which has been shot peened on the upper surface, it is assumed that there were no residual or applied stresses in the beam prior to shot peening. As the shot peened beam is in equilibrium the areas between the curve and zero stress must be equal on either side of the zero datum. That is, the compressive forces are balanced by tensile forces. The sum of moments about the neutral axis must also balance, for equilibrium to be maintained.

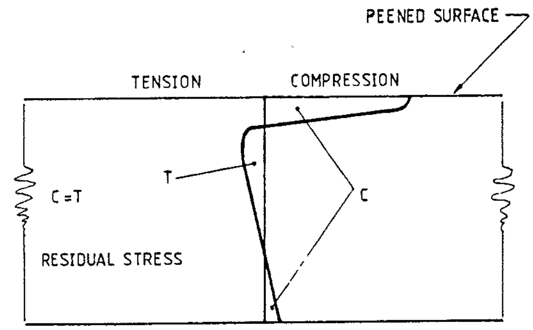

Fig. 2 Residual Stress Pattern in a Shot Peened Beam.

If the thickness of the beam is very large in relation to the depth of compression then little, if any measurable, bending will have occured. For thinner sections, where the depth of compression is in the order of 10% of the total thickness, a useful change in shape can occur.

The stress distribution described above will tend to apply in all planes perpendicular to the components surface. Consequently a panel which is wide and long in relation to its thickness will initially tend to have a barrel shape when shot peened uniformly on one side only. (See Fig. 3).

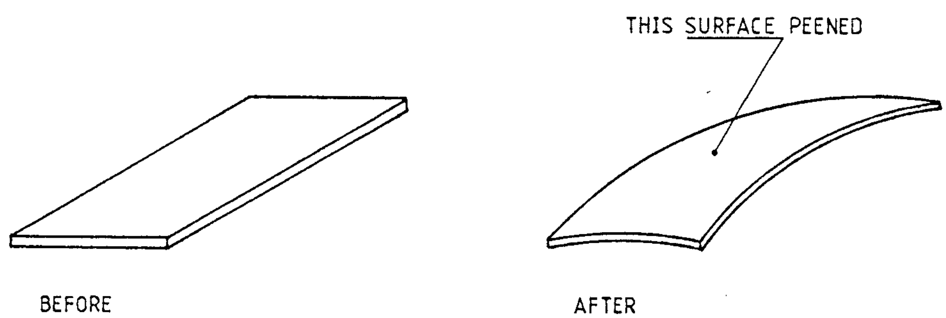

Fig. 3. Compound Shape Induced by Low Level Shot Peening.

A point may be reached however when the depth of the induced shape becomes large enough to cause it to be too stiff to take this compound shape. When this point is reached the panel will tend towards single curvature (Fig. 4) although the corners will try to 'curl' in.

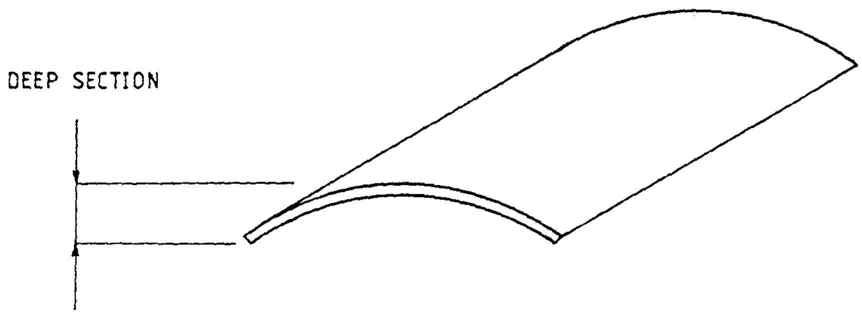

Fig. 4 Single Curvature from Heavier Shot Peening

The double and single curvatures described above are, however, uncontrolled with regard to the relationship of the induced radii in the 'x' and 'y' directions and would rarely match that desired in practice. The necessary control can be gained by stretching the full thickness of the metal in specific areas to induce the required compound shapes. By varying the shot energy when it strikes the part's surface the depth and intensity of the compressive stress can be varied accordingly. If both surfaces of the panel are shot peened so that the residual stresses are symetrical, or near to symetrical, about the neutral axis an overall increase in area will result with any asymmetry causing a bending action. If the area so worked is restricted to a specific area then a compound shape is induced.

A significant development in controlling the direction and degree of the stretching action of shot peening has been "Pre-Stress Shot Peening". It has been established that if the component surface is subject to a tensile stress whilst it is shot peened then the depth of the resultant compressive stress is increased. Control of the applied tensile stress provides control not only of the depth of the resultant residual compressive stress but also of its direction and thus control of the magnitude and direction of the degree of stretch apparent in the panel. It is essential that the applied tensile stress during pre-stress shot peening is within the elastic range of the material being processed. It is usual to have a safety margin well short of the yield point. It is emphasised that a permanent change in shape will only occur when the part is shot peened, and that if the part were to be removed from the pre-stressing fixture without being shot peened it would spring back to its original shape.

Practice

There are a variety of variables associated with shot peen forming. As the principles of the procedure are similar to other applications of shot peening there is a corresponding similarity in the controls and variables adopted for forming work.

As the shape induced in the part determines the amount of overall work applied to it the use of Almen Strips to control the process is not necessary though they may be used to establish datums in setting up a development programme or as a comparison of the characteristics of two machines. 100% coverage is not necessarily a criteria when shot peen forming, unlike most other applications of shot peening. Full coverage may be applied at comparatively low intensities, to enhance the components fatigue life, resistance to stress corrosion or other characteristics, in addition to the use of shot peening for forming purposes.

The depth, magnitude and direction of the compressive layers dictate the shape of the part, after shot peening, in relation to the overall dimensions, material and temper of the part. Various types of media can be used including glass, ceramic and steel shot. Cast steel shot is used in the majority of applications. It is essential that the media is of uniform size and is spherical. As in other shot peening applications too wide a variation in shot size inhibits control of the process. If too much of the shot is undersize the surface may be work hardened before the specified shape is induced conversely an excess of oversize shot may cause overforming of the part. The shot quality must be high to ensure that control of the process is maintained. Broken shot for example will cause sharp craters which will not only give an inadequate compressive stress but, in addition, result in stress raisers in the surface. (See Fig. 5)

Fig. 5 - Shot Quality is Important

Different shot sizes may be used according to component thickness and required curvatures. Typical cast steel shot sizes vary from 0.44mm up to 9.61mm though smaller and larger sizes can and have been used. Steel shot is usually the preferred media due to its high density when compared to most other practical media. Cast steel shot is available in a wide range of well controlled sizes at economical prices. Ceramic and glass media have the advantage of being inert when in contact with most metals although are restricted to thinner components due to their low density and availability in relatively small sizes. Shot is propelled onto the surface through a compressed air nozzle or by a centrifugal wheel. In the case of the former, shot is ejected from a nozzle at high speed by compressed air and in the latter by being flung off 'paddles' on a wheel rotating at high speed. The speed of the shot is controlled by varying the air pressure or wheel speed as appropriate.

Unlike other applications of shot peening, and as stated above, 100% or more coverage is not necessary for shot peen forming a component. One individual component will vary from another in various respects including proof strength, hardness, thickness etc. These variations will be within design specification but may, in aggregate, vary each part's response to the same shot peen forming parameters. If coverage is at something less than 100% and the part is slightly underformed it is comparatively simple to increase the coverage and so attain the required curvature.

It is important, however, that the coverage, within the specified area, is uniform. Uniformity may be monitored by use of 'Dyescan'. Dyescan is a fluorescent material in a volatile carrier that is sprayed or brushed onto the part and allowed to dry before shot peening. The residual fluorescent varnish adhering to the component surface is brittle enough to break away when struck by a particle of shot but leaving the Dyescan intact elsewhere. The appearance of the shot peened surface when examined under an ultra-violet lamp quickly and easily shows if the coverage is uniform.

The design of Metal Improvement Company's shot peen forming machines allow changes in parameters to be made during the processing of a panel. The majority of applications of shot peen forming have been in the aerospace industry in Europe and North America (as will be discussed later in this paper). Many of the skin panels, both fuselage and flying surfaces, on an aircraft will require shaping to the appropriate aerodynamic profiles. These shapes will have varying thicknesses. By adjusting the parameters to accommodate these variations a precise shape conformity can be achieved.

The shape of the panel can be checked either with hand templates whilst the panel is still on the machine or, for more complex parts, with a checking gauge. The gauge can be a simple template mounted on a stiff portable box structure or, for larger parts, be a series of templates on a rigid frame permanently fixed to the factory floor. As many templates, in whatever direction, can be fitted as is required and is consistant with accessibility to the areas being inspected. The templates used can be simple sheets cut to a scribed line or metal boards which have been precisely machined using numerical control machining techniques.

Applications

As previously indicated shot peen forming has been developed mainly in the aerospace industry in Europe and North America. One of the earliest applications was on integrally machined aluminium alloy wing skins on the Lockheed Constellation. This was a fairly simple case where a panel had been machined from a billet of aluminium alloy so that the stiffening spanwise stringers and chordwise rib lands were an integral part of the panel. The panel was to be straight in the spanwise and so the only shape was chordwise, at right angles to the stringers. The panel was shot peened on the smooth outside face to induce the chordwise shape whilst the spanwise stringers held the panel straight in that direction. These panels were in the order of 1m wide by 12m long.

Since then the process has been developed to shape fuselage, wing and empennage surfaces, usually from complex machined panels for a large variety of aircraft, including most Boeing jet transports, Lockheed C130, L1011, McDonnell Douglas DC9, DC10, MD80, F-15, Fairchild A-10, Vickers VC-10, BAC1-11, Concorde and Airbus Industries A310 and A320 aircraft. The latest designs call for complex panels of constantly changing sections, with or without stiffening stringers, with integral doublers reinforcing lands etc., which are machined on 5 axis numerically controlled machines. In many cases, shot peen forming has been the only acceptable method of forming as other methods were impractical, unacceptable due to the associated residual tensile stresses or involved other severe penalties.

Aluminium alloy wing panels in particular continue to be a major application for shot peen forming. Different types of wing will require various combinations of single or double curvatures. The curvatures will usually be with a chordwise convex shape when viewed from the outside. Examples exist, such as A310 and A320 lower wing surfaces, where the chordwise shape changes from convex to concave near the rear edge and so forming a lazy 'S' shape. Spanwise shape will be determined by the overall geometry of the wing.

Most wings will have a dihedral angle, that is, the plane of the wing slopes upwards away from the fuselage. More rarely the opposite, anhedral angle will be designed. The dihedral angle may vary along the span. In addition the chord thickness may not vary uniformly. In these cases the spanwise shape may vary from straight to curved, either convex or concave within the length of the panel. In some cases the changes in the dihedral angle may be fairly sharp such that a dihedral break, or aerobreak, is required. This break may result in either a saddle or barrel shape to the wing skin panel. These specific shapes will be induced by stretching the skin locally as required, either at the panel edges or centre.

Panels currently being formed by Metal Improvement Company include McDonnell Douglas DC10 and Airbus Industries A310 and A320 wing skins. These panels are large - up to 2.9m wide and 25m long - with thickness's varying from 2mm in pockets, up to 35mm. The lower surfaces have saddle back shapes in either aerobreak configeration (DC10) or a general spanwise curve over approximately 5m of the panel length (A310 and A320). These panels are shot peen formed with a general accuracy of better than 1mm with tighter tolerances specified when necessary.

These skin panels when joined together and attached to a framework of ribs and spars form the main load carrying structure of the wing. The 'box' so formed also serves as the main fuel tanks for the aircraft. Not only does the wing provide the aerodynamics lift for the aircraft but will also be required to absorb loads from the undercarriage on take off, landing and taxiing and the thrust and reverse thrust from the engines. It can be seen therefore that the machined and shot peen formed wing skins serve a variety of load carrying purposes. To ensure that the technical requirements are consistantly met the peen forming process along with all other critical manufacturing processes must be carefully controlled. To this end the following documents and equipment will be employed:

- Engineering Drawings
- Process Specifications
- Loft Data
- Tool Data Sheets
- Checking Gauges
- Process or Technique Sheets

Much of the above will be generated during the design of the aircraft and will be used for purposes other than shot peen forming. The Engineering Drawings, for example, will provide data regarding the material to be used and its temper, machining dimensions, tolerances and other criteria, surface finishing and assembly together with the shot peen forming specification.

Process Specifications will have specific chapters devoted to shot peening, shot peen forming and its control.

Loft Data used to be composed of full size drawings acting as the master reference for the exterior shape of the aircraft. More recently this data will be stored in computer files and be produced on hard copy either as lines or dimension numbers as required.

Tooling Data Sheets give additional information such as tooling holes and trim allowances.

Checking Gauges are used to inspect the shape of a peen formed panel as previously described.

An individual Process or Technique Sheet will normally be drawn up for each panel. The precise sequence of forming operations will be defined, as will any intermediate inspections and other quality control activities. The instructions will include shot size, coverage, dimple diameter, pre-stressing parameters, wheel speeds, air pressure to nozzles, masking and sanding requirements. In addition the Technique Sheet will carry any saturation shot peening instructions which are deemed necessary to improve the panels resistance to fatigue and stress corrosion cracking failure.

Usually the operation to induce the chordwise shape and spanwise curves or aerobreaks will be carried out sequentially. Pre-Stressing and the larger sizes of shot will be used for the spanwise work, and the thicker areas of the panel. Once the basic sequence of forming operations is complete the panel is located on the checking gauge for the profile accuracy to be inspected. Minor deviations can be corrected with the panel on the gauge using portable shot peen forming equipment.

Once a satisfactory profile has been achieved it may be necessary to improve the surface finish in specific areas where large shot has left a dimpled surface. Aerodynamic requirements on exterior surfaces and stress requirements on inside surfaces where high load transfers occur between panel and substructure will determine the surface finish requirements.

When all shot peening operations (both forming and saturation for fatigue enhancement) are complete, aluminium alloy panels need to be cleaned either chemically or abrasively to remove iron contamination left on the surface by the steel shot to avoid subsequent corrosion problems. If the panel is not to immediately receive its permanent protective finish (anodise paint etc.,) it should be lightly oiled.

Development Problems

Apart from determination of shot peening parameters and methods in the initial development phase there are some problems which will become apparent on the formed panel. On large long panels two particular problems are overall stretch and 'fanning' both of which can be countered.

When the panel which, as stated, can be up to 30m long has had its surfaces stretched to varying degress there may be a resultant increase in its length in the order of 0.02 to 0.04%. That is up to 12mm over 30m. If the datum for assembly is at one end of the panel this can clearly give fit-up problems at the other end as machined features of the panel will not match up to the substructure within specified tolerances. If these errors are unacceptable then changes will have to be made to the machining of the panel to anticipate the growth. The growth will be reasonably constant from one panel to the next.

Fanning is caused by one edge of a panel requiring more stretching than the other when the aerobreak or spanwise curve is not constant across the width of the panel. This may cause the panel to curve in plan shape along its length - See Fig.6. Once again these variations can be compensated for by changing the machining parameters.

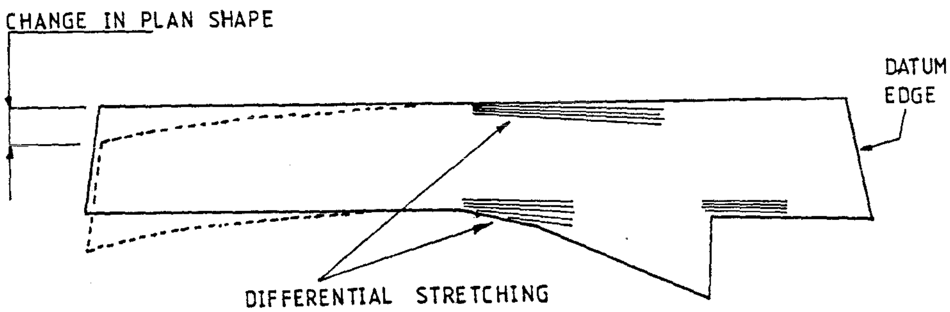

Fig. 6. - Fanning of a Wing Skin from unequal stretching of edges

Distortion Correction

In the last 20 years there has been a significant change in the methods used to manufacture the parts making an aircraft sub-structure from fabricated sheet metal to fully machined parts. Such parts include stringers, ribs, brackets etc. These machined parts may, however, suffer from distortion due to residual stresses within the raw material from forging, extruding, heat treatment and/or from the machining operation itself.

This distortion is not evident, however, until after the machining operation is complete and a considerable investment in time, material, machining costs etc has been made. In the case of special forgings or where exotic alloys have been used it may be some time before a replacement part can be produced - with the possibility of similar distortion occuring.

Most conventional straightening methods involve bending the part to shape which will induce a residual tensile stress on one face or another and require complicated and expensive tooling. Shot peening can often solve the machinists problems when properly applied. As reference back to Fig. 2 will show both sides of the part will be in compression and so the part's fatigue life should be unaffected - if not actually improved!

Economy - Shot Peen Forming v Conventional Forming

Size

Shot peen forming can be applied to virtually any size of part which will exclude conventional presses, pinch rollers or stretch presses - assuming such methods were practical on, for example a large machined panel.

Non-uniform Sections

Varying material thickness is readily accommodated by shot peen forming unlike press or stretch forming. Packing pieces or post machining operations are eliminated - if they are practical in any event.

Shape

Shot peen forming works well on compound shapes where radii of curvature, (as a guide), are within the elastic range of the material at that thickness.

Design Changes

Changes can be accommodated quickly and ecomonically with changes to peening parameters and alterations to check fixtures.

Short Runs

First articles may be used on an aircraft. No tool tryout is necessary after tool modifications as is necessary with press or stretch forming. Shot peen forming is a dieless process and so no die proving work is necessary.

Net Size

No need for metal to be left on parts as a forming aid as, for example, for the gripping jaws when stretch forming. Considerable savings, therefore to the manufacturer who has a reduced amount of material to purchase. Further savings from elimination of post forming machining or trimming operations.

Heat Treatment

Press or stretch forming require greater ductility than is required for shot peen forming and so very often expensive post forming heat treatment is necessary. The heat treatment can cause distortion which may be countered by careful use of expensive fixtures to hold the part's shape during heat treatment. As shot peen forming can be applied to the fully machined, fully heat treated part all these problems and expenses are eliminated as the raw material may be purchased in the fully heat treated condition.

Fatigue and Stress Corrosion

When post forming processes are required to induce either fatigue life improvement or stress corrosion cracking resistance in parts the additional operations will add to the manufacturing costs - if the part is formed by techniques other than shot peening. Material handling is a cost factor in any process and it is eliminated by the shot peen forming process as the parts are saturation shot peened on the same machines as do the shot peen forming. Savings in the order of 20 to 30% can be made by combining shot peen forming with shot peening for fatigue enhancement

Fatigue Life Improvement

Tests have been made by several aircraft companies comparing press forming only with press forming followed by shot peening for fatigue life improvement and with shot peen forming. In all cases the shot peen formed parts showed the best fatigue life.

Conclusions

- Shot Peen forming is a well established technique for forming complex load carrying components for structures requiring a very high level of integrity.

- Shot peen forming is an economical process when correctly and carefully applied.

- Shot peen forming can economically save expensive distorted parts.

- Shot peen forming is a reliable process - a major aircraft manufacturer has stated that they have excellent manufacturing experience with this technology and has no known service related difficulty with shot peen formed aircraft wing skins.

References

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