The challenge was the advanced compound curves of Boeing's new fuel-efficient 757/767 airplanes. The answer was a bold leap into contouring exotic wing-surface sections solely with peen forming. By combining CNC technology with empirical peen-forming data and experience, Boeing's Fabrication Div., Auburn, WA, with help from Wheelabrator-Frye and Allen-Bradley, has developed a unique patented forming process that has broad implications beyond its immediate applications in aerospace.

Compound curvature is not new; most current aircraft contours are a composite of transverse chordwise and spanwise curvatures to some degree. These compound curves, called saddlebacks, are generally produced by shot peening the more severe chordwise curvature and then draping the skin during wing assembly to achieve the much-larger-radius spanwise curvature. But for more extreme compound curves, both curva-

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tures must be formed. The methods used in the past include progressive bending in a press brake, the use of special fixtures to prestress the metal during peen forming, or more typically, creep forming—strapping the metal to large fixtures and "soaking" them at elevated temperature for extended periods of time.

Compared to creep forming, the new CNC shot-peening process cuts processing time by a factor of four. Creep forming a ship set of wing skins (1 plane's worth) takes about 8 hours plus an equal time for post-peening to relieve stress. Shot peening a ship set now takes about 4 hours and post-peening is not normally required.

Growth curves

Forming a flat sheet of metal to a single element of curvature is a simple matter of bending. Adding a second curvature requires some stretching. Figure 1. Distance $AB$ has to "grow" to distance $A'B'$, This growth, measured in inches per inch, is defined as $h/R-h$, where $h$ = arc or chordwise height (inches) and $R$ = lengthwise or spanwise radius (inches).

The standard method for measuring the intensity of the shot-peening blast is Almen intensity. In the Almen Test, a metal specimen $\frac{3}{4}\" \times 3\"$ is fastened to a block, placed horizontally and bombarded by a standard shot stream flowing vertically. The Almen value is the resultant bottom curvature of the specimen, $h$, measured in thousandths of an inch.

To develop an empirical data base for CNC, Boeing conducted a broad series of tests and created extrapolated growth curves, such as the one in Figure 2. This shows families of growth-rate curves, i.e., what Almen C intensity is required to achieve a desired growth rate for a given skin thickness of a given alloy. (For example, to achieve a growth of 0.001 ipi in a material of 0.2" thickness, the Almen C intensity required is approximately 0.006.) These curve families are stored in the computer data bank and are the basis for controlling the shot velocity and flow to produce the desired curvatures.

The Boeing tests covered aluminum alloys of 2024, 2324, 7050, 7075 and 7150; thicknesses of 0.18", 0.25" and 0.31"; and steel-shot diameters of 0.046", 0.125", 0.156" and 0.187". Because in the actual peening process skin thickness is constantly varying, the system automatically takes this into account so that contour requirements can be entered without respect to thickness.

The process

The process begins when the cut-to-size workpiece is CNC milled to a lengthwise taper, as it has in the past, for purposes of saving weight. It then moves via an overhead conveyor to a storage area adjacent to the two peen-forming units, one for chordwise curvature and one for spanwise curvature.

Within each machine are shot wheels, each with 20-hp DC motors, that eject shot horizontally at the vertically suspended workpiece. Each wheel produces a narrow rectangular shot pattern and both shot velocity and flow can be varied. All wheels are paired with identical wheels on the opposite side of the workpiece so that a net differential in Almen.
Peen forming becomes a CNC art

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3. In the chordwise shot-peening machine, wheel patterns are fixed.

intensity creates the desired curvature.

In the chordwise machine, Figure 3, there are six pairs of wheels in a fixed, staggered vertical array that covers the full height of the workpiece and accomplishes full chordwise forming in a single pass. The spanwise machine, Figure 4, has two mobile wheels on each side that follow the workpiece’s upper or lower edge, tilting their horizontal shot patterns up or down up to 30 degrees. Typically, three passes are required to cover six horizontal tracks, parallel to the edges of the workpiece. Thus, on this machine, the CNC control is essentially five-axis. The X axis is the conveyor’s horizontal movement through the shot-peening machine, the Y axis is the wheel’s vertical movement, the Z axis is the wheel’s ability to tilt rotation of the shot pattern in the plane of the workpiece, and the A and B axes are shot velocity and flow.

Surface areas of the workpiece are divided into segments, corresponding to the instantaneous shot-coverage areas.

The amount of growth required in each segment is determined by comparison with corresponding segments on the master mold for the wing prototype. By entering these dimensions of curvature into the system, the required Almen intensities can be computed from the empirical data bank.

Although it is theoretically possible to perform both chordwise and spanwise contouring in a single pass in a single machine, Boeing feels that that is not practical. The big difference in trans-

Wing skin emerges from the chordwise peening machine, right. The spanwise peening machine is on the left.
verse curvatures means that different shot size is required for each. Also, many more shot wheels and corresponding controls would be necessary.

Post-peening process options include facilities for sanding to improve aerodynamic smoothness and aesthetic appearance, and a finish-peening station to "fine tune" stress corrosion resistance and fatigue life. The latter is for use when the workpiece is very thick, requiring larger-sized shot for forming and smaller shot for finishing.

The controls

The shot-peening machines, wheels and recovery system were built for Boeing by Wheelabrator-Frye and the CNC controls are by Allen-Bradley. For the chordable machine, an A-B Series 7320 CNC operates in tandem 12 Type 1373 regenerative, field-reversing, variable-speed DC drives to coordinate and individually control each of the 12 wheelheads. The system selects the software for one of two sizes of shot used in this machine, precisely controls the volume and velocity of shot thrown and the speed of the wing skin as it passes through the machine. All the empirical forming data used to program the system is based on Boeing's research. An A-B 1774 PLC programmable controller controls the overhead carrier system that moves the wing skins from a staging area, through the CNC peening machines, the finish peener and the sanding machine.

For good quality control, a printout is generated by the CNC system for each workpiece, noting any exceptions to process parameters and providing a history for traceability and workpiece duplication. Sensors detect and record any deviation in shot wheel volume or velocity.

According to Boeing Development Engineer John Miller, one of the inventors, "Our monitoring system is creating a constant error signal. If system elements do not respond correctly to CNC commands, or if there is a runaway wheel from a control failure, we don't want to take a chance on overpeening, so shot flow is immediately shut off. The operator will then have to go back manually, pick up the cycle and complete it. But this is the extent of manual inputs and judgments. With our data base, we know exactly the response we will get by feeding in the desired Almen intensities and area coverages. One of our original decisions was that no operator could perform all these functions with the timing needed. CNC control was a must."

adds C H "Tom" Tombarge, director of facilities for the Auburn Fabrication Div, "Boeing is constantly pursuing improved productivity while enhancing product quality, and peen forming wing skins by CNC is a prime example. This CNC advancement means moving several steps ahead in precision forming of critical wing-surface configurations, with added benefits in repeatability, reduced stress, lower material-handling costs and savings in process energy.''

The process is certainly unique, and not just to the aviation industry. It has been in operation for over a year, and operator acceptance, after some initial anxiety, has been very good. Shaping, contouring and profiling had traditionally required a lot of hand work. CNC control is now clearly preferred over this prior degree of heavy manual involvement—working with gages and making a lot of manual adjustments for travel, wheel speed and other parameters.

The process is patented by Boeing. Although they have no licensing agreements at present, these are being pursued. For more information on the control equipment from Allen-Bradley, Highland Heights, OH, circle E33. 

Overhead storage areas, left, and control cabinets for the variable-speed shot-wheel DC-drive motors, right.