1992045

New Challenges for Shot Peening of Aircraft Gas Turbine Engine Components

by P. G. Bailey, D. M. Comassar and J. M. Whalen,
GE Aircraft Engines, Evendale, Ohio
and R. A. Thompson,
GE Corporate Research and Development, Schenectady, N.Y.

This paper was given by D. M. Comassar at the June 1992 SURFAIR IX Conference (International Conference on Surface Treatments in Aeronautic and Aerospace Industries) in Cannes, France.

New shot-peening requirements are emerging, driven by aircraft engine customers both in the military and commercial sectors. There is increased interest in improving the overall life of engine components to provide continuing gains in engine reliability, operating efficiencies and cost of ownership. The shot-peen process, which is applied to a high percentage of the engine components of interest, provides an avenue for such improvement. This report describes work that has been underway for several years at GE Aircraft Engines and GE Corporate Research and Development and will focus on fundamental process understanding and control strategies for the shot-peen process. In-depth process knowledge is an essential requisite for significant gains in process repeatability, reliability and process analysis. This work should thus allow the ability to determine quantitative benefits of the process that provide the foundation for achieving the long-term goal of improved component life.

PROCESS BENEFITS

Today, the typical benefit that peening provides the aircraft engine is improvement of fatigue life of the components to which it is applied. Benefits are seen in both low- and high-cycle fatigue environments by retarding crack initiation and growth. As applied today, these process benefits are qualitative in nature and are therefore not used directly in the calculation of component life. Peening is also used today to inhibit stress corrosion cracking, to reduce fretting of contact surfaces and to minimize the effects of severe machining—deterioration that is typically not quantified.

NEW MANUFACTURE AND OVERHAUL

Aircraft engine repair and overhaul facilities use peening to restore the repaired hardware to overhaul requirements. The requirements for application of the process at overhaul are often the same requirements that the aircraft engine manufacturer places on new components.

CURRENT APPLICATIONS

The shot-peen process is applied to a range of aircraft gas turbine engine components to enhance their ability to withstand physical damage as they perform in service and age. There are several peening processes used for the broad range of engine components peened; however, the majority of components are peened with steel shot; thus, that is the area of discussion in this report. Typical production peening processes are shown in Table I.

MEASUREMENT OF THE PROCESS

An Almen strip intensity is specified that indirectly represents the magnitude of the compressive stress imparted to the component when peened. This strip of AISI 1070 spring steel reflects compressive stress by the amount it curves (arc height), which is measured in thousandths of an inch or tenths of a millimeter.

Three designations of Almen strips are used in the industry. These designations are A, N and C. The three types differ in nominal thickness: A strips are 0.051 in. (1.28 mm); N are 0.031 in. (0.78 mm); and C are 0.094 in. (2.35 mm). Strip type is chosen on the basis of level of compressive stress desired; for deeper profiles, for instance, a thicker Almen strip would be used. Compressive stress increases with peening time as the impact dimples cover the area peened. "Saturation" is

Table I. Shot-Peening Applications

Typical Components[a]	*Material*	*Steel Shot Process at GE Aircraft Engines*[b]
Fan blades	Ti	Single nozzle stroked over manipulated part at intensity 0.003–0.005 in. A (0.08–0.13 mm)
Compressor and Turbine		
Disks	Ti, Ni, Fe base	Multinozzle and numerical control single nozzle oscillated across rotating part at intensity 0.004–0.008 in. A (0.1–0.2 mm)
Airfoils	Ti, Ni, Fe base	Indexed parts rotated in front of multinozzle fixed gun stations at intensity 0.003–0.005 in. A (0.08–0.13 mm)
Static structures (frames, static airfoils)	Ti, Ni, Fe base	Multinozzles oscillated across part at intensity 0.003–0.005 in. A (0.08–0.13 mm)

[a] Typical engineering requirements for the above components are the following: media size and type, S110 steel shot [cast steel shot with a 0.014-in. (0.35 mm) nominal diameter]; Almen intensity, 0.004–0.008 in. A (0.1–0.2 mm); number of nozzles, 2; nozzle position and angle, 4–8 in. (100–200 mm) from part at 45°; air-pressure range, 45–65 psi.
[b] A, Almen strip designation (see text for explanation).

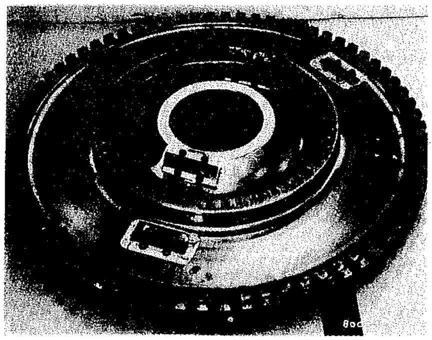


Fig. 1. Almen strip fixture high-pressure turbine disk.

Table II. Almen Strip Repeatability

Variable	Almen Strip A in.	Almen Strip A mm
Skilled operator repeatability	±0.0001	0.0025
Entrapped shot	±0.0015	0.038
Loose hold-down screw	±0.0002	0.005
Strip hardness specification limits	±0.0003	0.0075
Strip thickness specification limits	±0.0001	0.0025
Old method—no flatness compensation	±0.0008	0.02
New method—flatness compensation	±0.0002	0.005
Typical industry practice	±0.0005–0.001	0.013–0.025
Improved methods	±0.0003	0.0075

achieved when the Almen strip arc height stops increasing or, specifically, when doubling the peening time results in an arc height increase of 10%. Almen intensity is defined as the arc height at the saturation point. Normally, Almen strips are positioned on fixtures approximating the part configuration (Fig. 1) and are peened under the same process conditions. A typical process requirement for Almen intensity is 0.003–0.005 in. A (0.08–0.13 mm); this means that the Almen strip is nominally 0.051 in. (1.28 mm) thick and that the arc height at saturation is 3–5 mils (0.08–0.13 mm).

ALMEN STRIP REPEATABILITY

Improved practices when using the Almen strip can lead to reduced measurement variability. Table II and Fig. 2 list several parameters that affect the measurement and show how prepeen flatness compensation substantially improves strip reliability.

The experimental setup for the data summarized in Table II comprised a circular plate fixture with provision for circumferential mounting of Almen strips at each of the 12 "clock" positions at an 18-in. (46 cm) radius from the center of rotation (Fig. 3). A peening nozzle was positioned at 45° to the strip surface and aimed along the strip length at a 6-in. (15 cm) standoff distance. All data were taken on a 0.0001-in. (0.0025 mm) digital Almen gauge.

COVERAGE MEASUREMENT

Coverage is the term used to define the amount of peening applied to a component. Coverage is expressed as a percent of the total part surface area completely covered by an overlapping pattern of impact dimples—100% coverage indicates that the entire surface is covered; higher percentages are a multiple of the time required to achieved 100%.

Visual inspection is normally used to verify that the part has been completely peened. The visual inspection for coverage is done on the actual component but has limited effectiveness in areas that are not easily viewed, such as a deep bolt-hole, and would be very time-consuming if sampling methods were not used. Visual inspection can also be subjective; thus, different interpretations of coverage

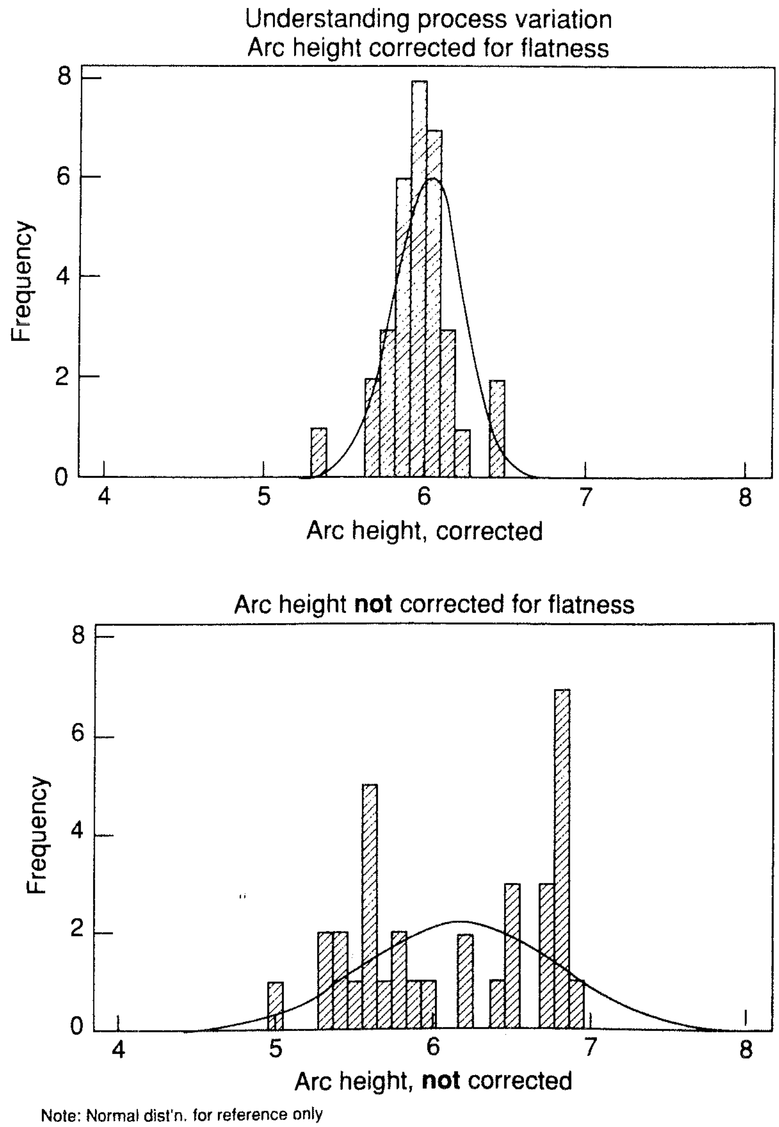


Fig. 2. Almen strip reliability.

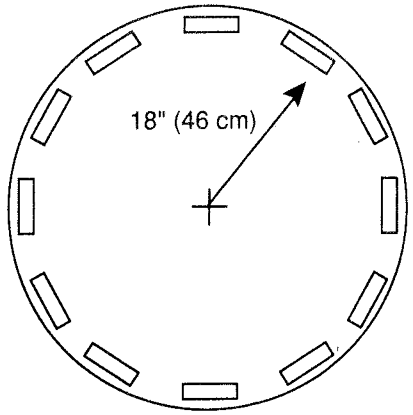


Fig. 3. Almen strip setup.

are probable. A fluorescent tracer material is also used to verify coverage. This material is painted on a component before peening. The component is then peened, and the part is visually inspected with a black light. If the component is completely covered, there will be no areas that fluoresce.

HISTORICAL PERSPECTIVE

Shot peening has progressed from manual controls in the 1970s to robotic nozzle motions and microprocessor controls in the 1980s. Required for the 1990s is the ability to quantify the process effects (e.g., the resultant compressive stress and surface effects that may degrade fatigue life). This requires building on today's best process by developing new capability to model the process and quantitatively predict resultant process effects. A control strategy for process repeatability and reliability can then be applied. Table III illustrates the type of equipment used in all of the stages of peening development.

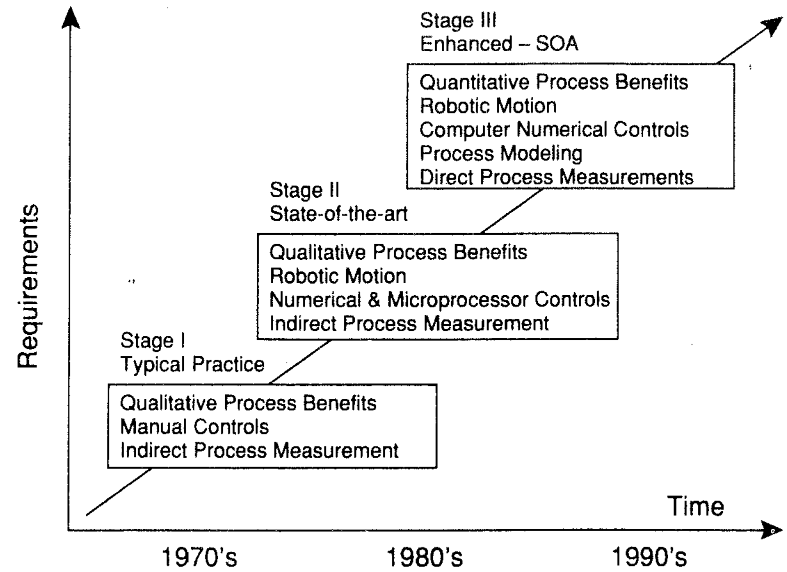


Fig. 4. Historical stages of peening; SOA, state of the art.

TYPICAL PEENING PRACTICE—STAGE I

Shot-peening technology may be divided into three chronological stages, as shown in Fig. 4 and Table III. Stage I characterizes the stage of shot peening from the 1970s to the 1980s. At this stage, the component life benefit of peening is qualitative (e.g., the process benefit is recognized); however, this benefit was not substantiated with data and therefore not factored into the hardware life calculations. The equipment used to apply the process is highly operator dependent, with manual controls. The nozzle positioning is done manually, and nozzle motions are by simple oscillation. The operator is the only monitor of the process. Open-loop (manual) air pressure controls are used that may be very inaccurate and typically are not well monitored. The flow of shot is established by a fixed-orifice plate, which is open-loop controlled and cannot detect flow stoppages. Because the two critical parameters of air pressure and shot flow are open-loop controlled, variation in these parameters is likely, thus contributing to increased peening process variability. The operator is the key to process control; thus, the more knowledgeable and alert the operator, the more controlled the peening process. At this stage, the application of the process is measured with Almen strips, and the part surfaces are visually inspected to ensure process coverage.

Table III. Developments in Peening Equipment[a]

Peening Stage	*Nozzle Motion/Process Controller*	*Key Parameter Control*	*Process Analysis*
I. Typical peening	Simple nozzle oscillation/manual controls	Air pressure—manually set, open-loop control Shot flow—set by a fixed orifice, open-loop control	Almen strip used for intensity Visual inspection used for coverage
II. State of the art	Simple nozzle oscillation/microprocessor control Robotic motion/CNC	Air pressure—electronic regulator set by controller; closed-loop control Shot flow—electronic valve set by controller; closed-loop control	Almen strip used for intensity Visual inspection used for coverage
III. Enhanced state of the art	Simple nozzle oscillation/microprocessor control Robotic motion/CNC	Air pressure—electronic regulator set by controller; closed-loop control Shot flow—electronic valve set by controller; closed-loop control Shot velocity sensor with closed-loop control	NDT for intensity and coverage Analytical process model Computer work station for off-line analysis and process development

[a] CNC, computer numerical control; NDT, non-destructive techniques.

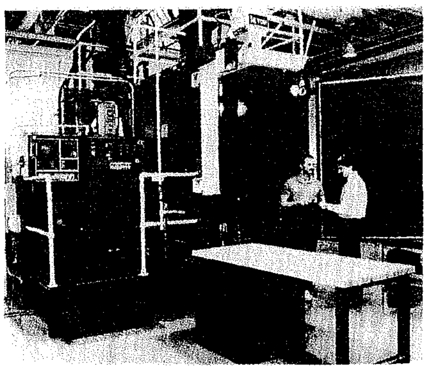


Fig. 5. Stage II robotic computer numerical control peening facility.

STATE-OF-THE-ART PEENING—STAGE II

The next stage of the peening process is considered state of the art (SOA) because it is representative of today's best practices. The process benefits are still qualitative, but today much of the equipment is either simple nozzle oscillation with microprocessor control or robotic nozzle motion with computer numerical control (CNC). The key parameters of shot flow and air pressure are set, monitored and controlled by the machine controller. Both of the devices used to set the air pressure and shot flow are automatic electronic valves, which are closed-loop controlled. When specified tolerance bands are exceeded, the valves trigger the machine to shut down. SOA robotic machines usually have one or two gantry robots with 4 or 5 degrees of freedom. Each robot manipulates one nozzle across the component surfaces. All nozzle movements are controlled by the CNC machine controller. In robotic motion machines, all of the nozzle positions are set very precisely and are very repeatable (position accuracy within approximately 0.10 in. or 2.5 mm). An example of a stage II robotic CNC machine is shown in Fig. 5. In the simple oscillation microprocessor machines, the nozzle-fixture motions are microprocessor controlled but without numerical control feedback. Therefore, the simple oscillation microprocessor machines do not place the nozzles as accurately (within approximately 0.100 in. or 2.5 mm) and are not as repeatable as the robotic CNC machines. The same indirect process verification using Almen strips is used here.

From an equipment standpoint, robotic nozzle motion machines with CNC represent the best approach for controlled application of the peening process. The nozzle angle and distance to the surface are significant factors affecting the end result of the peening process. Robotic control of the nozzle reduces the variability of nozzle position and improves the process consistency. In addition, robotic machines also offer a manufacturing cost benefit in that process setup is faster because all the nozzle positions are stored electronically. Also, the commercially available robotic machines are superior in rigidity and precision motion control to the available simple nozzle oscillation microprocessor machines. SOA robotic equipment also lends itself to further automation when coupled with the right material handling, part fixturing and factory computer system.

CNC robotic equipment offers the opportunity for improved process control and consistency to satisfy emerging needs; these needs will be likely to require more precise application of the process, including impingement angles, surface area coverage and other surface effects currently under study.

ENHANCED STATE OF THE ART—STAGE III

The next stage of peening, shown as stage III, may be labeled enhanced SOA peening. This is the next-generation peening process that is emerging in the 1990s. The baseline equipment established for today's SOA process services this new need well. This baseline equipment, coupled with new process enhancements, is needed to raise the level of process understanding and assurance.

The ability to obtain quantitative benefits through enhanced SOA peening requires advances in several areas. Increased reliability and control of the process itself is the first step. To that end, new equipment and process control requirements are being implemented. The following are new peening specification requirements being implemented across GE Aircraft Engines:

1. *Machines are required to have sensors that shutdown* if air pressure, shot flow, table rotation or nozzle motions vary from prescribed limits.
2. *Almen strip reliability* controls include tighter initial flatness requirements and flatness compensation methods.
3. *Intensity variations* allowed from part to part have been reduced.
4. *On-machine shot separators* are required to ensure removal of broken shot particles.
5. *Part and nozzle fixtures* are required to be used to ensure positional repeatability.
6. *Almen fixture controls* require that difficult peening access areas are accurately represented.
7. *Operator qualification* is improved through new provisions that require training and certification of operators.

IMPROVED SHOT QUALITY

Improved quality shot is another imperative for enhanced SOA peening. Wrought (conditioned cut wire) shot is the preferred candidate for the following reasons:

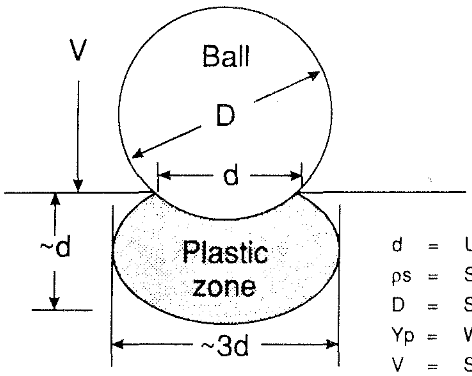
1. Wrought shot is produced from wire drawn to specification for tensile/hardness.
2. Cylinders cut with a length/diameter ratio of 1 can be peen conditioned to spherical shapes.
3. Size uniformity is 5% (versus 50% for cast shot).
4. Wear is by "onion peeling" rather than fracture.
5. The cost is twice that of cast shot, and the lifetime claimed is six times longer.

Shot material characteristics evaluated for improvement over cast shot were propensity to fracture, hardness range and ability to reduce hardness maximum but keep hardness minimum harder than most engine components. Also evaluated were size range capability and ability to improve roundness in conditioning of shot cut cylinders.

Wrought shot has been introduced at GE Aircraft Engines and is meeting expectations relative to low fracturability; thus, it is proving to be cost effective.

PROCESS UNDERSTANDING AND CONTROL

Work in fundamental process understanding and control is proceeding in several areas including process fundamentals, shot velocity measurement, process modeling, process workstation modeling, and nondestructive testing.



$$d = 1.28 \left(\frac{\rho s}{Yp}\right)^{1/4} V^{1/2} D$$

d	=	Upset depth	Must control
ρs	=	Shot density	Known
D	=	Shot diameter	Known
Yp	=	Workpiece yield	Known
V	=	Shot velocity	Must measure

Fig. 6. Predicting instantaneous intensity from on-line measurements (shot velocity being most significant).

PROCESS FUNDAMENTALS

The following summarizes work accomplished to date and is in varying stages of implementation at GE Aircraft Engines. To understand peening fundamentals, the process was studied as a single-ball impact dent whose variables were ball density, diameter and impact velocity. These were related by energy and momentum relationship to the workpiece yield strength and hardenability. The following equation resulted:

$$d = 1.28(\rho_2/Y_p)^{1/4}\, V^{1/2} D$$

This is shown pictorially in Fig. 6, which also defines the variables. It shows clearly the significance of shot velocity as the critical process variable.

SHOT VELOCITY MEASUREMENT

Once the importance of shot velocity is established, the need to measure this critical parameter is indicated; direct measurement with a sensor is desired. Such a sensor could also detect nozzle and hose wear as well as incorrect air pressure or shot mass flow rate.

A shot velocity sensor comprising a nozzle-measuring coil has been developed and patented. The ability to directly measure shot velocity is a major advance in controlling the peening process in real time. The device compares the nozzle coil signal with the shot mass flow coil signal whose velocity is controlled by gravity fall in that coil and thus directly calculates shot velocity in the nozzle.

PROCESS MODELING

Knowledge about process variables, how they interact and how they ultimately contribute to achieving the desired result is essential. This knowledge includes the specific and combined effects of the process parameters of shot size, shot velocity and impingement angle and the nozzle spray characteristics of particle and velocity distribution. Application of this knowledge to specific hardware can best be handled with process models that take into account such things as nozzle-to-part distance and angle variations across part features. This results in the ability to design efficient, technically sound peening processes with tight tolerances, as well as analyze and improve existing processes.

SHOT-PEEN WORKSTATION/ PROCESS MODELING

A major improvement in the application of shot peening will be through the use of a process simulation workstation. The workstation will combine the new process understanding (developed for simple geometries) with the ability to handle real, complex shapes. It will allow the shot-peen specialist to acquire a three-dimensional model of the part from the engine archives. From this, one can create a shot-peen application pattern either analytically or through a "teach" system and simulate and evaluate the peening process. The end product will be an analytical prediction of local plastic flow with resultant residual stress. Once a satisfactory result is obtained, the application path and vectors will be downloaded to a CNC robotic peening machine.

The immediate benefits of this approach are the following:

1. Shot-peening patterns will be tailored to the compressive stress needs, with predictable coverage.
2. Application repeatability will be improved through use of CNC control and the shot velocity sensor.
3. A database consisting of part geometry, shot-peen path and predicted compressive stress and strain values will be created for subsequent engineering analysis.

The workstation effort represents the beginning of an orderly, systematic approach to create and refine algorithms to allow precise application of shot-peening enhancement with quantifiable benefits.

There are other less obvious benefits to the shot-peen workstation. By virtue of its installation on a modern high-speed computer, the specialist will be able to study many variations in path and shot energy, allowing generation of optimal surface properties. The workstation is planned for installation on the plantwide computer network. Therefore, the design and manufacturing engineers can concurrently develop the product, making design/manufacturing tradeoffs as necessary, jointly developing a logical quality plan. All this will result in a predictable product.

NONDESTRUCTIVE TESTING

Nondestructive techniques for measuring the magnitude of residual stress in production hardware are needed. GE Aircraft Engines has been exploring several nondestructive evaluation techniques, but more work is needed before they can be introduced.

SUMMARY

In summary, new shot-peening requirements are emerging that are driven by interest in confidently applying a repeatable, reliable process, and, longer term, achieving improved part life. Recent progress in shot quality, shot delivery control and current production practices has heightened that interest and moved the process toward better understanding and control. Work remains to complete the development and reduction-to-practice of the concepts reported here. Once that is accomplished, the stage is set to take full quantitative advantage of the benefits of this process.