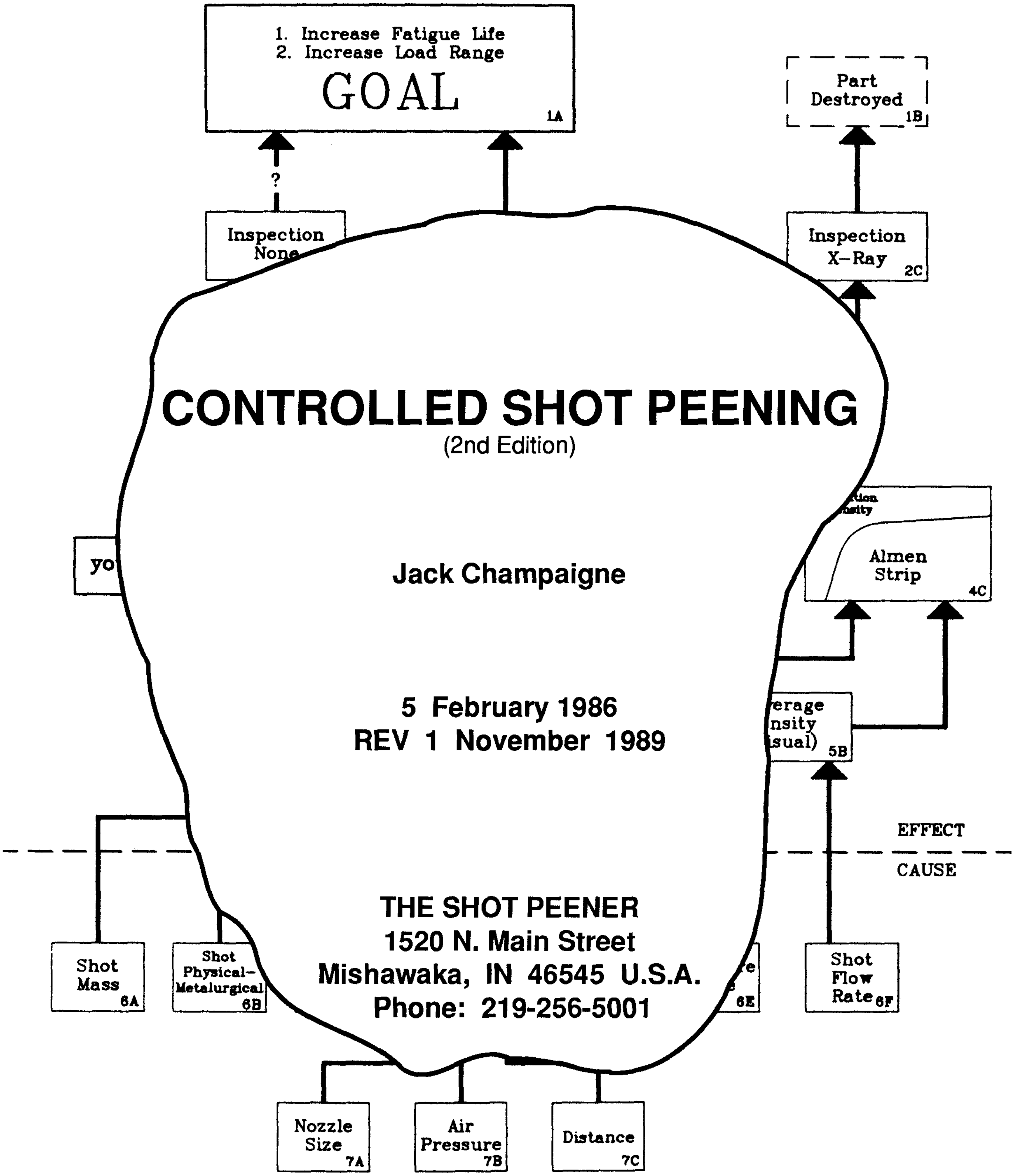
Controlled Shot Peening

THE SHOT PEENER



CONTROLLED SHOT PEENING

(2nd Edition)

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Controlled shot peening is the science of surface treatment to enhance fatigue life or load range by work hardening a surface and creating residual compressive stresses. By monitoring and controlling parameters of the process a consistent result can be obtained. This paper will discuss attributes and implications of the process elements.

Shot peening is useful in extending the fatigue life, stress corrosion resistance, and load carrying capacity of metal components. Peening variables affect workpiece performance. Uncontrolled peening results in a widely scattered range of component life, sometimes canceling out the benefits of shot peening. For this reason the designer of parts is reluctant to use the increased strength of a shot peened part and resorts to it only after field failures force engineering to go to shot peening for a margin of safety.

With the lack of a non-destructive inspection for shot peening, one must have confidence in the process. To gain this confidence the process must be consistent, repeatable and uniform. Process parameters must be monitored and controlled.

Shot peening has evolved from a crude art initiated by an accidental discovery of the beneficial effects caused by creating compressive stresses on the surface of a part subjected to flexing. Fatigue failures always occur in areas of tension. By creating compressive stresses on the surface the fatigue life can be enhanced.

A process flow chart is shown in Figure 1 that represents the process of controlled shot peening. The chart is separated by a dashed line to denote process input ("cause") items below the line and process result ("effect") items above the line. This article will describe each box in the flow chart and show how consistency in "effect" can be achieved by maintaining consistency in "cause" (process control). All of the process inputs are directly and easily controlled and monitored by the machine operator. It merely remains a task of the process engineer to describe what final properties are required. Once the process inputs are identified they can be consistently maintained.

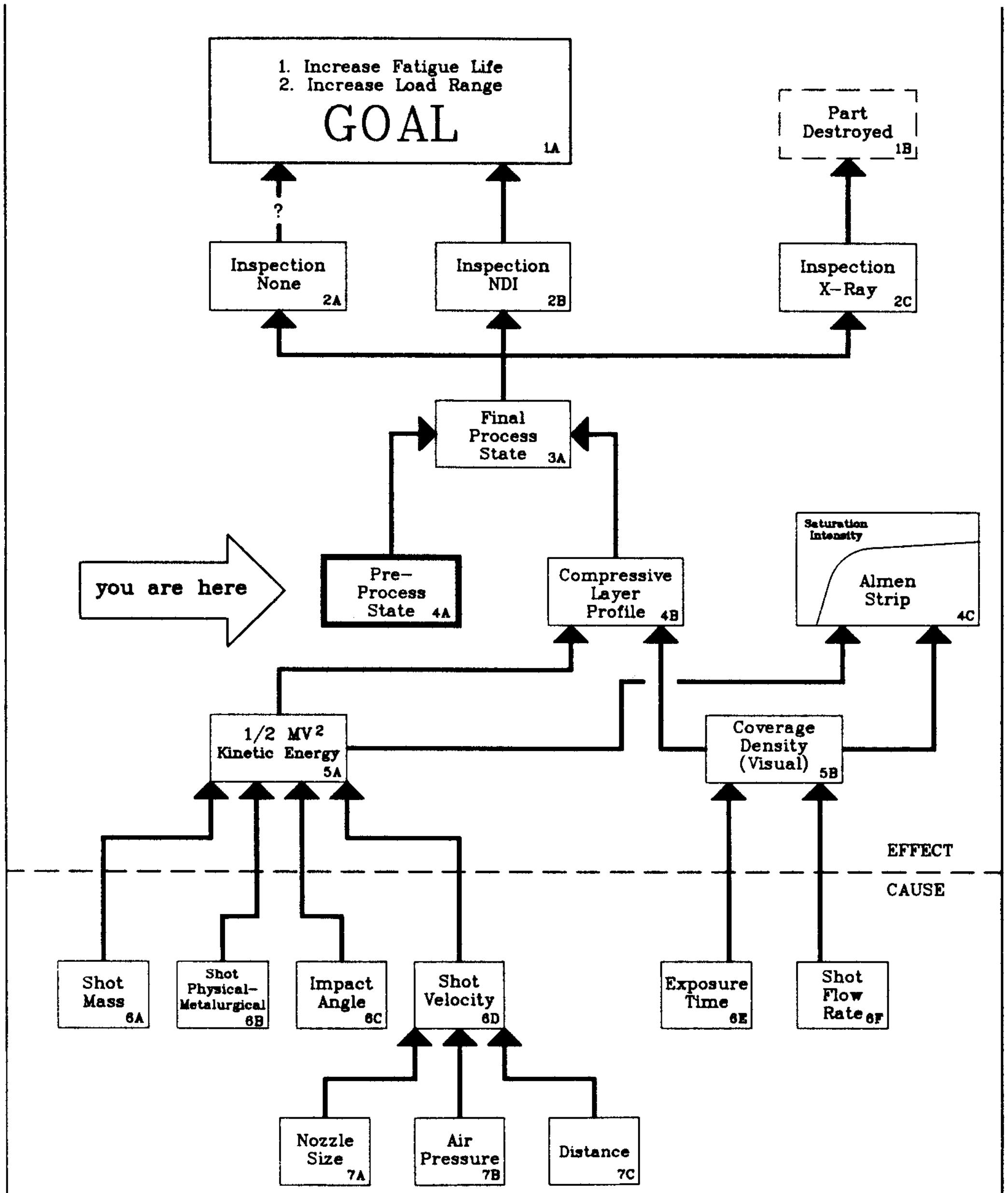

fig 1. Controlled Shot Peening Process

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<u>Almen Strip - 4C</u> Present shot peening practice utilizes the Almen strip method to describe the "intensity of peening". Many years ago, J.O. Almen of General Motors Corporation developed a method for quantifying all factors affecting the "intensity" of shot treatment. Figure 2 shows the principle. A flat metal strip is clamped to a test block and blasted with shot. Due to compression of the surface layer of only one side of the strip, the residual surface compressive stresses will make the strip bow upward in the middle when released. The height of this bowed arc is an index of the intensity of the peening.

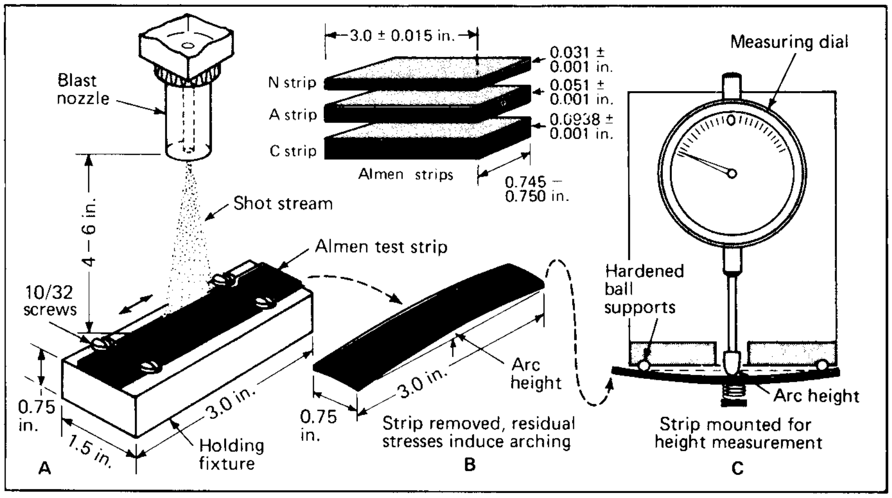


Fig. 2

The Almen strip test uses three standard size strips to measure ranges of peening intensity. All strips are 3.0" long and 0.75" wide. The thickness range is:

"N" - 0.031" - for low intensity
"A" - 0.051" - for average intensity
"C" - 0.0938" - for high intensity

The Almen strip is analagous to a thermometer used to indicate an over temperature. Placing the thermometer in the oven for a brief time may not be adequate to reveal the actual temperature. If subjecting the thermometer for a longer period results in an identical temperature reading, then the actual temperature is determined. If doubling the thermometer exposure time doesn't increase the reading by more than a few degrees, then the actual temperature is readily determined.

The Almen strip acts in much the same way. It must be exposed for an adequate time in order for saturation to occur. Industry accepted practice defines shot peening intensity has been determined if doubling the Almen strip exposure time results in 10% or less increase in curvature arc height. See Fig. 3 for a typical graph of arc heights achieved at increasing exposure times. The knee of the curve is referred to as "intensity".

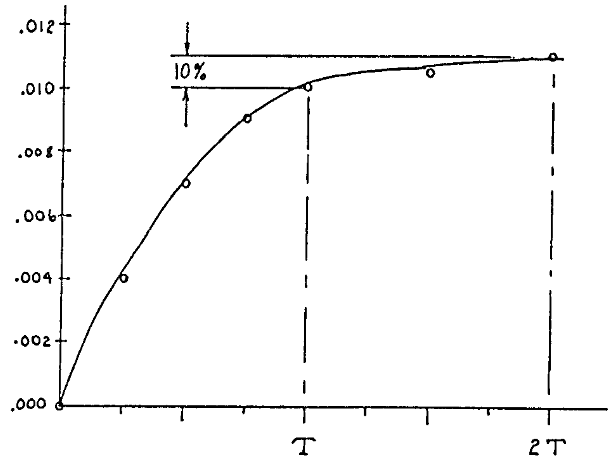


Fig. 3 Almen strip saturation curve

The most common Almen strip is the "A" strip used for average intensity. If the intensity indication is less than 0.006 A, then the "N" strip should be used. If the intensity indication is greater than 0.024 A, then the "C" strip should be used.

For critical part peening only premium grade Almen strips should be used. These should be accompanied by a valid certification that indicates compliance to either MIL-S-13165 for government peening, or SAE J442 for industrial peening. Attributes such as flatness, hardness, chemistry, size, surface finish and corrosion protection are commonly required.

An assumption is made that the curvature of the Almen strip will indicate the degree of compressive stresses and, hence, the resistance to fatigue failure or of stress corrosion cracking. However, there are various ways of exposing an Almen strip to a blast stream of high-velocity shot particles to obtain the same arc height. Factors influencing the arc height are shown as process inputs and are illustrated in Figure 1. These same factors determine the profile of the compressive stresses; and it will be seen that only a complex correlation between arc height and the desired goal of fatigue life, or load range improvement, exists. Fuchs (5) addresses some of the virtues and defects of the Almen strip.

It will become obvious that the connection between the "Almen Strip" [box 4C] and the "Goal" [box 1A], by necessity, is missing. Some testing [Niku-Lari (19)] indicates that, "For the same Almen intensity it is thus possible to cause in the material very different distributions of residual stress. To achieve effective control of the shot-peeping operation, therefore, it is necessary to examine the influence of each parameter on the generation of the residual stress".

The effectiveness of shot peeping is demonstrated in the final results when increased fatigue life, or greater cyclic load carrying capability, is achieved. These increased benefits occur because of the nature of the surface treatment. The surface profile of compressive stress versus depth is of primary concern. The ability to impact the surface in a manner that results in a consistently desirable stress profile will be addressed in detail.

Final process state - 3A. Referring to the chart we see that Final Process State [box 3A] is influenced by two factors, namely the Pre-Process State [box 4A] and the Compressive Layer Profile [box 4B].

Pre-processed State - 4A. The pre-processed state defines the metallurgical and physical properties of the part as received prior to shot peeping. Various pretreatment techniques, such as pre-stressing [Barrett (6)], may be utilized to enhance the treatment. Obviously, the sub-surface profile should be identified for the original properties and, conversely, it must be known for the final properties since this is the object of the impact treatment.

Compressive Layer Profile - 4B. The two contributors to Compressive Layer Profile [box 4B] come from Kinetic Energy [box 5B] and Coverage Density [box 5B]. Kinetic Energy (K.E.) will be discussed first.

Kinetic Energy - 5A. Surface treatment is primarily related to instilling a layer of residual compressive stress. The intensity of the compressive stress at the surface, and its subsurface profile, is directly controlled by the transfer of kinetic energy (K.E.) from a moving mass (the shot particle) into the surface and by the coverage of the surface.

The K.E. available to impart compressive stresses into the surface is governed by laws of physics, namely $1/2\ MV^2$ where "M" is the mass of the shot particle and "V" is the shot particle velocity. Less than maximum K.E. is transferred to the surface due to (a) elastic and inelastic collisions and (b) kinematic constraints due to angle of impact. The mechanics of the collisions involve the physical and mechanical properties of the shot -- such as its hardness, texture, shape, microstructure and chemical analysis -- and the surface properties of the workpiece.

Shot Mass - 6A. The mass "M" is defined by the size and density of the shot particle. The necessity for defining a shot particle of known mass is covered in many reference articles. Shot is described in size by its diameter in ten thousandths of an inch. The U.S. military specification MIL-S13165 and other documents describe acceptable ranges of size that qualify the shot. Schrama (3) shows effects of shot size on local peening. Simpson (14) suggests using the smallest shot size consistent with intensity requirements. To impart a homogeneous compressive layer the shot must have consistent mass.

Shot -- Physical/Metallurgical - 6B. The physical and mechanical properties of the shot determine the quality of the impact on the surface. If the shot is softer than the surface it is intended to compress, then the shot will be deformed and the full intended peening effect will not be achieved. Many peeners will work-harden "condition" a new batch of shot in a wheel machine to insure uniform hardness. Straub (13) describes a method of pre-conditioning the shot to bring it to a stable condition of hardness. The method is careful to prevent shot fracture in the conditioning stage. Other factors, such as roundness, broken or fractured particles and miscellaneous contamination, will strongly affect the treatment. Delitizia [1] shows effects of broken shot on peening. Simpson [2] shows additional effects caused by use of unqualified shot. Various materials may be used as the shot peening media for different effects, [Koehler C4)].

Impact Angle - 6C. The angle of impact of the shot with the target should be as close to normal (i.e., 90° impact) as practice will permit, with attention paid to effect of rebounding shot interfering with the impinging shot. The kinetic energy available will vary approximately with the sine of the angle of impact. Below 45° is considered to be detrimental practice for surface treatment for two reasons. First, the energy imparted is less than optimum and will not instill a deep compressive layer; and secondly, the phenomena called Peened Surface Extrusion Folds, PSEF, may develop, [Simpson (2)]. Some I.D. peening is done with ricochet shot. This method will not give consistent compression and, furthermore, will give a false indication of coverage. Happ (8) describes a patented process developed for I.D. peening. Ferrari [11] describes effects of nozzle angle and metal erosion rate.

Shot Velocity - 6D. The velocity of the shot as it impacts the surface is largely determined by three factors: nozzle size, air pressure (Fig. 4) or wheel speed, and distance to the work-piece. Shot projected by the centrifugal wheel method has the most consistent shot velocity; whereas, with all three air blast methods the velocity of the shot has a wide range. The surface compression seems to be particularly sensitive to shot velocity as reported by Baughman (7). Measure of velocity is also cited by Deloughry (9). The depth of compression is closely related to the speed of impact [Meguid, Duxbury (16)]. Shot flow rate will also decrease the shot velocity in air peening machines due to the limited air supply kinetic energy available.

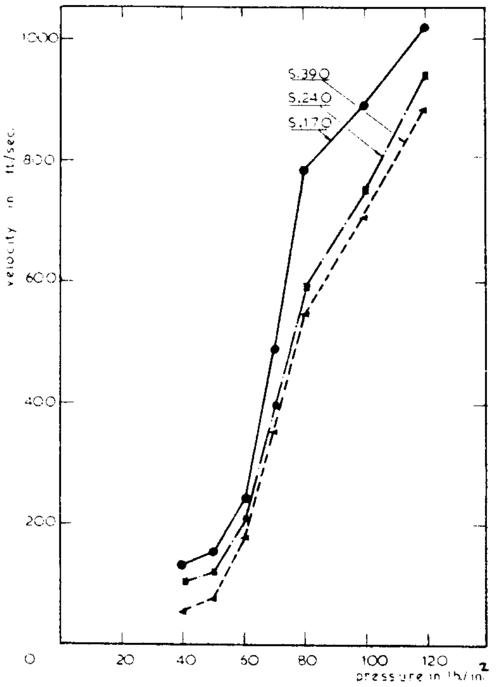


Fig. 4. Velocity-Pressure Relationship.

<u>Coverage - 5B.</u> Uniform and complete coverage of the surface is paramount if consistent results are to be obtained. Variations in coverage density will result in variations in depth of compressive stress and also the intensity of the compressive stress. The density of coverage is affected by both exposure time and shot flow rate. The most common method of coverage control, described in MIL-S-13165, is by visual examination using a ten power magnifying glass.

NOTE: In the U.S. military specification MIL-S-13165B item 6.10 reads, "Complete visual coverage is defined as a uniform and complete denting or obliterating of the original surface of the part of work..........". This is a correct reference to the concept of coverage.

<u>Exposure Time - 6E.</u> The coverage that is obtained may be the result of a fixed spray pattern or, more commonly , an oscillation or translation of either the shot spray or workpiece. The exposure time may be determined by the machine cycle timer or by completion of a fixed number of machine movements, either spray pattern or piece part, at a selected speed.

The exposure time should be sufficient to achieve desired peening coverage of the workpiece. Three common methods used to select exposure time are:

1. Almen strip saturation time
2. Workpiece denting (indentation) time
3. Tracer removal time

The second method gives the most accurate and repeatable performance. Using Almen strip saturation time can be misleading due to surface hardness differences between the Almen strip and workpiece. Material softer than Almen strip Rockwell C44-C50 will achieve coverage at a faster rate due to the larger impacts. Conversely, harder material will require longer exposure time.

Use of dye or chemical tracers for correct targeting is common. However, caution must be used for coverage control, since low intensity shot spray may not remove the tracer material during complete coverage. Also, it is common for broken shot to erode the tracer material while no indentation has occurred; and ricochet shot can cause removal of the tracer.

Direct visual examination is the best method available, but care must be exercised that only full impacts account for coverage. Smaller shot, lower velocity shot, and indirect impact angle shot can give a visible appearance of coverage that is incorrect. Use of a 5X or 10X magnifying lens will aid in revealing the nature of the coverage.

<u>Shot Flow Rate - 6F.</u> The shot flow rate needs to be set while considering several attributes. Ultimately, the surface must have sustained a certain density of impacts per square surface area. Figure 5 shows a graphic representation of shot flow rate versus air pressure settings. Fig. 6 shows the relationship of the shot flow rate to the wheel speed.

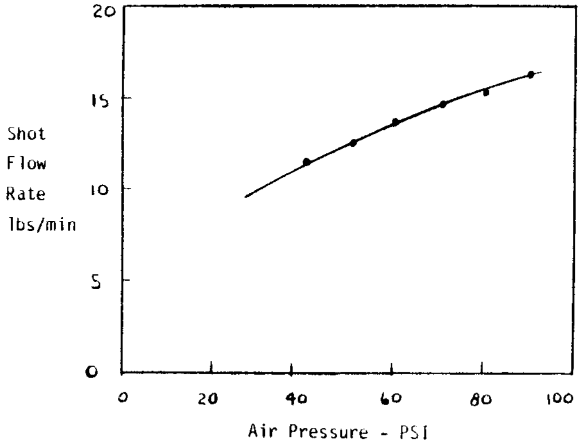
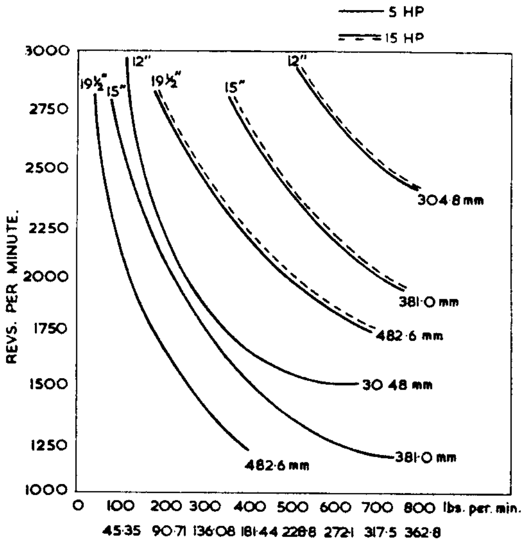


FIG 5. Shot flow rate vs. air pressure in direct pressure system with fixed feed rate orifice.



WHEEL SPEED vs. ABRASIVE FLOW.
FIG. 6

For wheel applications the maximum shot flow rate is determined by motor size and wheel characteristics. However, the maximum shot flow rate may be greater than the optimum shot flow rate. If too much shot is projected, then interference may occur at the surface. Also, rebound or ricochet shot may have enough kinetic energy to cause surface damage due to improper angle of impingement. For air blast machines the maximum shot velocity will occur at a lean shot flow rate while maximum coverage will occur at a rich shot flow rate.

A simple, and misleading, assumption on shot flow rate setting is common. Most operators adjust for the maximum shot flow rate obtainable that doesn't cause surging. The assumption is that this will minimize production cycle time by causing the greatest number of impacts for a given time. While this may be true, there are adverse side effects. In air peening machines the shot velocity falls drastically as the shot mass volume is too great to be conveyed by the available air supply. Since the available kinetic energy is a function of velocity squared, the effective compression of the workpiece surface changes dramatically. You may get a particular Almen arc height; but the compressive stress, and depth of compressive stress, can be significantly altered by variations in the velocity and coverage. To obtain a particularly high compression that isn't very deep may require small shot size propelled at high velocity and a lean flow rate. To get a deeper compression may require use of a larger shot size and lower air pressure.

The shot flow rates in the three types of air peening machines -- gravity, pressure, and suction -- each requires special attention. Generally speaking, gravity-fed nozzles tend to be self-regulating and don't suffer shot flow rate pulsation or wave effects; while the shot flow rate in suction-type machines tends to be quite sensitive to hose movement.

The gravity fed nozzle method of propelling shot is the simplest, but less efficient than suction or direct pressure in terms of accelerating mass to a given velocity. Shot flow rate is usually set by an orifice in the nozzle; but a regulating valve may be installed to meter the shot down to the nozzle. This allows for shot flow rate programmability to suit various requirements and also allows the use of continuous monitoring equipment.

Suction blast nozzles can be overloaded with a rich shot flow rate mixture. The conventional method of regulating suction shot flow rate is analagous to a carburetor. To increase the mixture richness the aspiration air inlet is choked, causing more shot to be sucked into the system. The system is limited when the air supply kinetic energy is insufficient to convey the shot to the nozzle. Shot flow rate then becomes erratic and the shot velocity drops. A preferred method of metering shot is analagous to electronic fuel injection, where the aspiration air inlet is continuously left open while shot is metered into the mixing chamber. This assures maximum availability of air supply for all shot flow rates. The shot flow rate is then remotely set to provide proper coverage. A magnetic servo valve ("MagnaValve") and controller is available for ferrous media flow rate control. Non-ferrous flow monitors are also available (9) and they may be used in conjunction with mechanical valves.

Pressure blast systems achieve the highest air peening machine efficiency at the cost of added complexity. Direct pressure produces the highest velocity and shot flow rate and is the only method that can move shot through long lances and side-shooting nozzles to peen deep holes or cavities. These systems require a pressurized vessel and associated flow regulators. Conventional shot flow rate regulation may utilize a fixed orifice, an adjustable grit valve, or MagnaValve. The fixed orifice is simple and relatively maintenance free; however, shot flow rate will vary with pressure (Figure 6).

The correct shot flow rate and air pressure (or wheel speed) must be determined empirically. By using the correct shot flow rate and air pressure or wheel speed the correct exposure time for the Almen intensity saturation and surface coverage can be determined. Experiment with air pressure (or wheel speed) and shot flow rate settings to determine minimum cycle time that will provide the desired compressive stress profile. For additional data on maximum shot flow rate and shot flow rate at maximum intensity in air peening machines see Table 1 in the Appendix A.

It is also interesting to notice some hidden interactions on the process flow chart of Fig. 1. Shot flow rate (box 6A) in air peening systems may be influenced by nozzle size, air pressure, and hose orientation unless a shot flow rate monitor/ controller is used. Conversely, shot velocity (box 6D) may be affected by shot flow rate variations, and it is therefore necessary to monitor or control shot flow rate to establish consistent operating conditions.

Assuming we have sufficiently discussed the process input "cause" items below the dotted line, let's turn our attention to the "effect" items above the line. Notice that the kinetic energy and coverage go to Compressive Layer Profile [box 4B] and also Almen Strip [box 4C]. The Almen strip is not cognizant of the Pre-processed State [box 4C]. Furthermore, it would be quite uncommon that the workpiece material would be the same as the Almen Strip - SAE 1070 cold rolled spring steel with a Rockwell "C" hardness of 44-50. The Almen strip is a measure of the performance of the shot blast. Caution must be exercised in making implications about what that shot blast will do to your work piece (see SAE J808a). In addition, any parameter changes (below the line) that may occur during the processing of the workpieces will not be detected by the Almen strip. To assume that the blast stream intensity used to develop the Almen strip is constant (and consistently repeatable) for your workpiece processing is valid only as long as <u>all</u> process inputs ("causes") are consistent.

If all of your processing has been consistent, then a consistent result at Final Process State [box 3A] should result. This is verified by Inspection [box 2C], or in actual test loading. Since there is no present method of non-destructive testing, arrival at Goal [box 1A] is never really assured; however, the probability can be quite high.

Things that can be done to raise your confidence level are listed as follows:

1. Closely control <u>all</u> process inputs ("causes") and provide out-of tolerance alarms.

2. Periodically inspect equipment and shot quality and provide training and operating procedures.

3. Perform Almen strip tests at regular intervals and present the data graphically for analysis. Use of SPC type control charts will demonstrate in-control/out-of-control.

4. Utilize dye tracer at regular intervals to assure correct targeting.

5. Perform manual visual inspection of workpiece for proper coverage.

6. Use strip chart recording or data logging methods to document process inputs.

7. Keep abreast of new process developments and methods and study available literature on Shot Peening (21).

One method useful in obtaining consistent shot peening results is to use a standard "menu" to define job processing requirements. A sample menu is given in the Appendix B.

Eventually, a non-destructive inspection method will be available to assure arrival at the Goal [box 1A] Presently, research is being conducted to nondestructively determine the depth of compression using a novel sub-surface profile technique. A change in the profile at the plastic deformation interface is expected to reveal the compressive stress depth and hence provide a measure of shot peening quality. In the meantime, it is important to measure and control all of the shot peening process inputs to assure consistent product performance.

APPENDIX A

Table I

VACU-BLAST CORPORATION

X- 106
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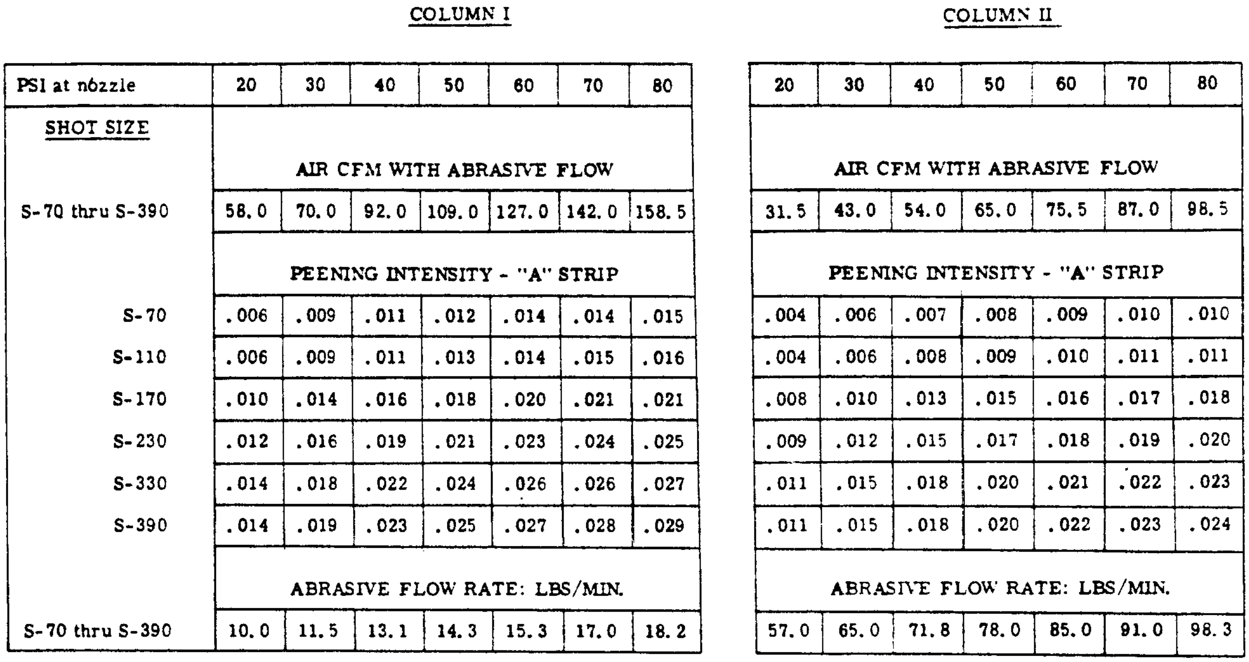
ENGINEERING SPECIFICATIONS

NOZZLE PERFORMANCE

COARSE ABRASIVE: Steel Shot
PRESSURE NOZZLE: 3/8"
FEED VALVE: Adjustable

COLUMN I: At maximum intensity

COLU16IN II: At maximum flow rate



COLUMN I

PSI at nozzle	20	30	40	50	60	70	80
SHOT SIZE	AIR CFM WITH ABRASIVE FLOW						
S-70 thru S-390	58.0	70.0	92.0	109.0	127.0	142.0	158.5
	PEENING INTENSITY - "A" STRIP						
S-70	.006	.009	.011	.012	.014	.014	.015
S-110	.006	.009	.011	.013	.014	.015	.016
S-170	.010	.014	.016	.018	.020	.021	.021
S-230	.012	.016	.019	.021	.023	.024	.025
S-330	.014	.018	.022	.024	.026	.026	.027
S-390	.014	.019	.023	.025	.027	.028	.029
	ABRASIVE FLOW RATE: LBS/MIN.						
S-70 thru S-390	10.0	11.5	13.1	14.3	15.3	17.0	18.2

COLUMN II

PSI at nozzle	20	30	40	50	60	70	80
SHOT SIZE	AIR CFM WITH ABRASIVE FLOW						
S-70 thru S-390	31.5	43.0	54.0	65.0	75.5	87.0	98.5
	PEENING INTENSITY - "A" STRIP						
S-70	.004	.006	.007	.008	.009	.010	.010
S-110	.004	.006	.008	.009	.010	.011	.011
S-170	.008	.010	.013	.015	.016	.017	.018
S-230	.009	.012	.015	.017	.018	.019	.020
S-330	.011	.015	.018	.020	.021	.022	.023
S-390	.011	.015	.018	.020	.022	.023	.024
	ABRASIVE FLOW RATE: LBS/MIN.						
S-70 thru S-390	57.0	65.0	71.8	78.0	85.0	91.0	98.3

Vacu-Blast Corporation (12)

(For additional charts contact THE SHOT PEENER and request ANC176)

APPENDIX B

CONTROLLED SHOT PEENING MENU

A. Customer Identification

B. Customer Requirements
    1. Purchase order numbers
    2. Part number
    3. Part name
    4. Order date - due date
    5. Quantity and schedule
    6. Part fixture serial number
    7. Masking/peening requirements
    8. Peenscan requirements
    9. Almen strip requirements
        a. Type (N, A or C)
        b. Location (photo or drawing)
        c. Intensity (w/tolerance)
        d. Coverage (w/tolerance)
        e. Frequency
        f. Disposition (save, discard, graph)
    10. Reference to applicable specifications
    11. Fatigue life or load range requirements
    12. Desired compressive stress profile
    13. Documentation requirements
        a. Almen set-up (photo or drawing)
        b. Automatic alarms for out-of-tolerance
            1. air pressure
            2. shot flow rate
            3. conveyor or lance speed
        c. Almen strip saturation graph
        d. Shot size and quality
        e. Machine certification (gages, etc.)
        f. Operator proficiency certification

C. Vendor Performance
    1. Machine type or serial number
    2. Nozzle (wheel) quantity, size, location, attitude
    3. Shot type and size (include specifications)
    4. Air pressure at nozzle (and tolerance)
    5. Shot flow rate (and tolerance)
    6. Exposure time/cycle time
    7. Turntable/conveyor speed
    8. Lance speed and travel
    9. Strip chart or compouter record
    10. Photograph Almen strip set-up

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