A SIMULTANEOUS METHOD OF IMPARTING COMPRESSIVE STRESSES ON VARIOUS SUBSTRATES WHILE MAINTAINING SURFACE INTEGRITY

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ABSTRACT

The investigations include the equipment and processes developed for the purpose of imparting compressive stresses in substrates while maintaining smooth surface finishes, particularly on gas turbine engine titanium airfoils. The equipment utilizes gravitational forces as an accelerant in a peening process. The kinetic energy contained in the peening media is closely controlled by requiring the media to pass through a labyrinth prior to falling on the substrate from specified heights. By using large (1mm to 2mm) hardened and polished steel balls as a peening media, surface finishes of less than 15AA microinches are obtained while peening in the range of 0.25mm to 0.38mm Almen "N" shot peening intensities.

KEYWORDS

Shot peening; finishing; titanium; airfoils; compressive stresses; fatigue life.

PURPOSE OF INVESTIGATIONS AND BACKGROUND INFORMATION

The present investigations were carried out for the purpose of obtaining improved surface finishes on gas turbine airfoils, thereby improving engine efficiency. This had to be done while retaining or simultaneously imparting compressive stresses on the surface in order to improve the fatigue life of the substrates.

Shortly after the introduction of axial flow jet engines, the need for improving the life of compressor airfoils became apparent. The obvious method was to impart compressive stresses to the surface.

This presented problems. The use of existing peening methods utilizing steel shot such as were applied to the roots would damage leading and trailing edges to the point of destroying the airfoils. Reduction of the intensity into the 0.08mm to 0.12mm Almen "A" arc height range using steel shot was not controllable.

About this time, a shot peening media consisting of small glass beads was utilized by Pratt & Whitney Aircraft to develop methods for low intensity peening of airfoils for improving fatigue life without damage. Special consideration was still required with respect to thin leading and trailing edges. Special protection or lower intensities are required to avoid stress concentrations, rolled edges or waviness.

During the course of developing wet and dry glass bead peening, the "N" strip was introduced by Pratt & Whitney Aircraft in order to better control the intensities in the low range of the "A" strip (0.008mm to 0.12mm) being a thinner strip which developed about three (3) times the arc height of an "A" strip with the same given intensity.

While glass bead peening imparts additional fatigue strength to thin airfoils, the process is not without problems. Peening with new glass beads at 0.25mm to 0.38mm "N" produces, at best, a surface finish in the range of 35AA surface roughness, and the glass has a tendency to fracture. Practically, dry glass bead peening equipment with some broken particles produces surface finishes of 35-45AA. Glass bead peening using a water-glass slurry improves the surface finish. However, maintenance of the equipment becomes more difficult and intensities in the range of 0.42mm to 0.48mm "N" are difficult to obtain. In addition, fines and broken particulates must be continuously removed by filtration.

Glass bead peening of titanium compressor airfoils in the range of 0.15mm to 0.48mm "N" has been standard procedure at Pratt & Whitney Aircraft for nearly twenty-five years. Glass bead peening has also been applied to vane and shroud assemblies, titanium rotating parts, vapor deposited coatings and other gas turbine engine hardware. Since the 1973 oil embargo and subsequent substantial increases in the price of oil, engineering departments all over the world have been striving to improve fuel consumption. This is particularly true in gas/oil based energy producing systems.

Definitive fuel savings can be realized by improving (making smoother) the gas path passages of gas turbine engines. Turbulence of air movement over airfoil surfaces can be shown by smoke trails as depicted in Fig. 1 and loss coefficients can be calculated from surface roughness and Reynolds number. The higher the cost of jet engine fuel, the more important fuel efficiencies become.

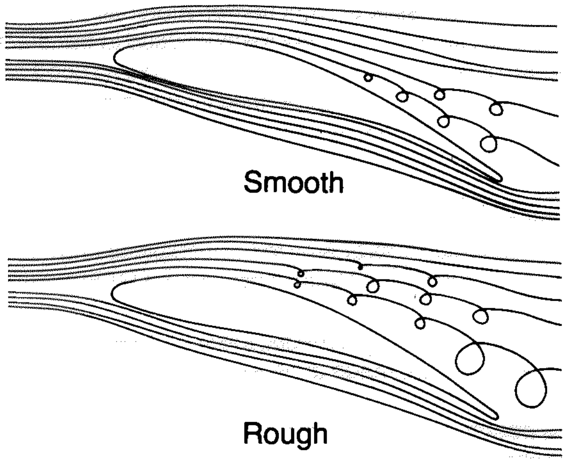

Fig. 1. Turbulence over smooth and rough airfoils.

Although the greatest emphasis has been on compressor airfoils, we will see gas turbine engine manufacturers making smoother all areas where gases move over surfaces, both stationary and rotating. These include components such as inlet nacelles, housings, cases, turbine blades and so forth.

One method of improving the surface finish of airfoils we have developed requires close monitoring and removal of broken particulates during the glass bead peening process in order to control surface roughness as much as possible, and subsequently following the peening operation by other specialized finishing methods. These processes are capable of producing surface finishes of 6-15AA on titanium airfoils. Some of these processes we have allowed our suppliers and customers to use in their operations. The major problem with this method is that it abrades surfaces after peening, which has the negative effect of removing desirable compressively stressed material from critical areas.

The second method, which is the subject of the following investigations, concerns the peening operation itself.

THEORETICAL CONSIDERATIONS

Peening intensity in critical applications such as aircraft engine airfoils must be closely controlled in order to produce compressive stresses of equal magnitude over individual substrates and of reasonably equal magnitude from part-to-part. The compressive stresses developed in the workpiece are related to the kinetic energy contained in the particular peening media, which of course is the product of one-half the mass and square of the velocity.

Partial velocities produced by conventional pneumatic peening systems vary considerably, as shown by Pangborn (not dated). These variations in particle velocities do not significantly extend saturation times in "N" intensity ranges due to small diameter shot at high velocity (approximately 60-90 m/sec) and the large numbers of particulates in the shot stream. Variations in particle size will effect saturation times similar to variations in velocity. The closer these two variables are controlled, the sharper the bend in a saturation curve tends to become.

In order to impart compressive stresses or work harden materials while maintaining smooth surfaces, several criteria must be met. First, the medium used to transfer the energy to the workpiece must be smooth or polished to the extent that it has as good or better surface finish than that desired on the workpiece, as is experienced in rolling or planishing. Secondly, the media must be or should be harder than the article that is to be work hardened, in order to keep the media from plastically deforming during processing and keep the transfer of energy to the workpiece at a maximum. The third criteria concerns the strength of the media, particularly in shot peening systems, where the presence of fragments or broken particulates would tend to increase surface roughness, impart less energy to the workpiece and increase the time required for complete saturation, as described by Metal Improvement (1980).

For a given intensity, the larger the peening media, the smoother the resultant surface finish is of the substrate. Initially, attempts were made to pneumatically propel larger shot of relatively low densities, such as glass and ceramics. The use of these classes of materials resulted in unsatisfactory control of peening intensity in the range of 0.25mm to 0.30mm Almen "N" intensities using pneumatic systems. Surface finishes were improved, but not to the extent required. This was due in part to the poor surface finish of the peening media and, in the case of less durable materials, the presence of fragments.

The lighter metals were not considered due to their lower hardness, durability and possible detrimental interactions with titanium. Preliminary investigations mentioned above also revealed that peening at lower intensities with the same media produces smoother surface finishes. This would suggest that in order to peen surfaces in the range of 0.25 to 0.30mm "N" strip intensities without substantially increasing surface roughness, relatively large size, high density media, propelled at low velocity would have to be used. The system would require very close control of the kinetic energy, i.e. particle size and velocity.

When peening at relatively low intensities with comparatively large dense media, gravitational forces may be employed as a shot propellant. In order to produce desired peening effects, shot of uniform mass with controlled initial velocity will accelerate by gravitational forces, resulting in consistent shot/workpiece impact velocity. The kinetic energy contained in each particulate can be altered by increasing or decreasing the starting height of the peening medium over the workpiece or changing particle size. The peening media must be densely populated and evenly distributed over the entire working area.

APPARATUS, MATERIALS AND TECHNIQUE

Apparatus

To fulfill these requirements, a laboratory peening machine was constructed (Fig. 2) consisting of a labyrinth (A) constructed so as to discharge the peening medium (shot) at a very low uniform velocity into the peening enclosure. A supply of shot is contained in a hopper (B) above the labyrinth. The spent shot is collected at the bottom of the apparatus and returned to the hopper via a bucket elevator (C).

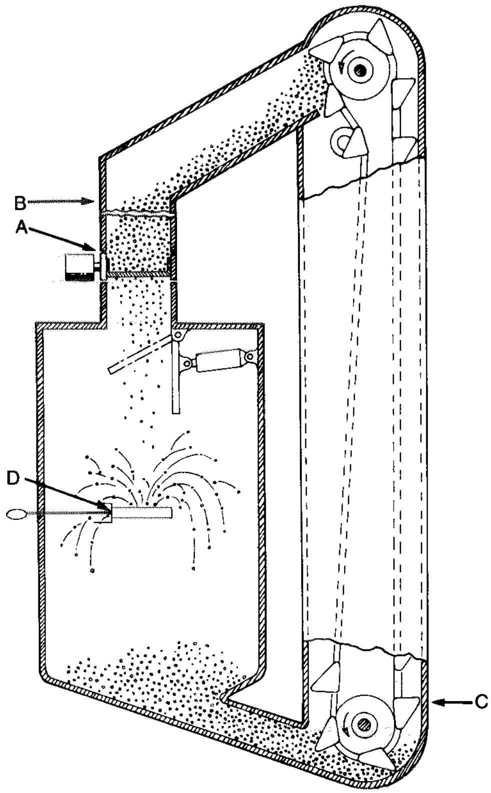

Fig. 2. Gravity accelerated peening apparatus.

The labyrinth was designed to uniformly distribute the media over the entire workable area, which was approximately 10 by 15 centimeters, and consisted of a series of closely spaced offset perforated metal plates of various sizes, depending on peening shot size. Media velocities above the labyrinth were calculated using the weight of media per unit volume above the labyrinth and weight/sec delivered to the substrates. The initial velocities varied during these investigations, depending on the media size and screens used, but in all cases were less than 0.01m/sec, which was considered negligible compared to typical impact velocities of 6m/sec. Shot impact velocities were changed by varying the vertical distance between the labyrinth and the workpiece (D).

Materials and Technique

The materials used in the investigations consisted of titanium gas turbine airfoils, titanium rolled sheet stock, and Almen "N" test strip specimens. The specimens were held in a clamping device (D) which had the capability of oscillating the workpieces in order to get adequate intensities on the leading and trailing edges of the airfoils and also had the capability of tilting up or down in order to investigate effects on fillet radii at either end of the airfoils.

The Almen "N" strips used in the investigations were made of rolled and annealed (SAE 1071) spring steel conforming to SAE specification J-442. Flatness of each test strip was measured on an Almen gage prior to testing and only those test strips that were perfectly flat were used in the tests. The same Almen gage was used for measurements after testing. Surface roughness tests were made on rolled annealed 6-4 titanium sheet stock conforming to AMS 4911 of approximately the same dimensions of Almen "N" strip specimens. Specimens below a surface roughness of 10AA were used for roughness testing. For smoothing tests, panels were roughened to the desired roughness using conventional air delivery blasting equipment. The surface roughness measurements were measured in AA microinches/inch – using a digital surface roughness measuring instrument equipped with an amplimeter peak counter, gated pilotor and diamond stylus tracers. The equipment was calibrated using a precision roughness specimen meeting American National Standards Institute Standard B46.1.

Parametric studies utilized the Almen "N" strip and the titanium sheet stock specimens which were fastened to a standard Almen test strip holder placed on a 25 x 50 centimeter steel plate with a cross section of approximately 2.5 centimeters. The steel plate was rigidly fastened to the floor of the apparatus.

Test media consisted of 1, 1.8 and 2.5 $\pm$0.05mm diameter hardened steel ball bearing stock conforming to AISI C-1013 with a hardness of Rc 60 minimum except for the 1.0mm size, which was Martensitic stainless steel ball bearing stock conforming to SAE 51440C with a hardness of Rc 58-65. The restitution values of the two materials was considered negligible.

DETERMINATION OF PARAMETERS

Intensity and Saturation

Several preliminary investigations were performed in order to determine the necessary relationships between shot diameter, shot density and velocities required to produce the intended surface finish at various "N" strip intensities. Titanium specimens with initial surface roughnesses of 8-35AA were peened with several sizes and densities of shot at a variety of velocities, producing a series of intensity levels for each size shot used. These investigations indicated that steel shot of diameters of 1mm to 2.5mm would produce final surface finishes of less than 15AA on titanium in the range of 0.25 to 0.30mm "N" strip intensities.

After establishing these initial requirements, it was then necessary to determine the final parameters for use in a gravity accelerated peening system. The parameters required to produce the desired "N" strip intensities within reasonable peening times, would be governed by three distinct criteria:

1. Shot diameter (i.e. mass).
2. The kinetic energy contained in each particulate upon impact.
3. The number of particulates striking the workpiece per unit area per unit time (shot density or flow rate).

The flow rates and densities for the three sizes of shot used are as follows:

SHOT DIAMETER (mm)	FLOW RATE $kg/cm^2/sec$	DENSITY Impacts/cm^2/sec
1.0	0.009	2'136
1.8	0.011	420
2.5	0.019	281

Fine adjustments could have been made to the labyrinth for each size media in order to further optimize peening times. However, this was considered unnecessary for the purpose of this investigation. The 1.8 and 1.0mm diameter media were chosen for extensive studies.

The final parameters of the system were determined by constructing families of saturation curves using Almen "N" strip specimens at various energy levels, or vertical distances, of the labyrinth over the workpiece. Surface roughness measurements on titanium were also made by peening titanium panels at these energy levels. The optimum parameters for each shot size were determined from plots of the saturation times (T) and the energy levels (Height) vs intensity (Fig. 3 and Fig. 4). Fine adjustments were made to the system as necessary. The resultant heights for the 1 and 1.8mm diameter shot were found to be 1.83 and 0.45 meters, respectively. Less thorough investigations were made for 1.5 and 2.5mm diameter shot to determine saturation times and effects on surface roughness on titanium for 0.25 and 0.30mm "N" strip intensities.

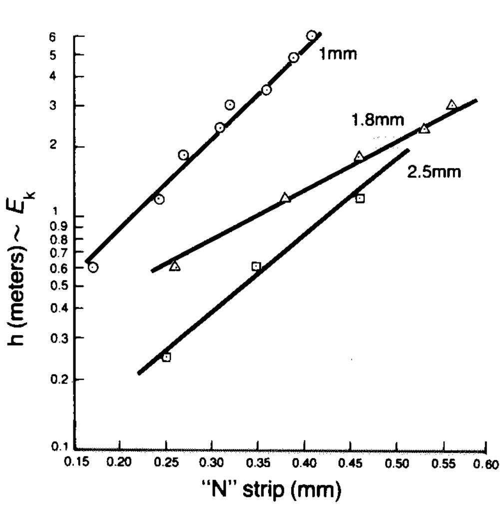

Fig. 3. Height ~ (E_k) vs intensity.

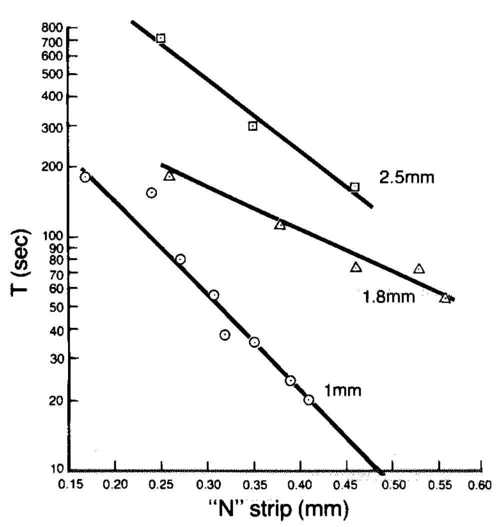

Fig. 4. Saturation time vs intensity.

Surface Roughness

The resulting surface roughness of smooth (8-10AA) and rough (30-40AA) titanium panels peened at various intensities and shot sizes are graphically illustrated in Fig. 5 and Fig. 6.

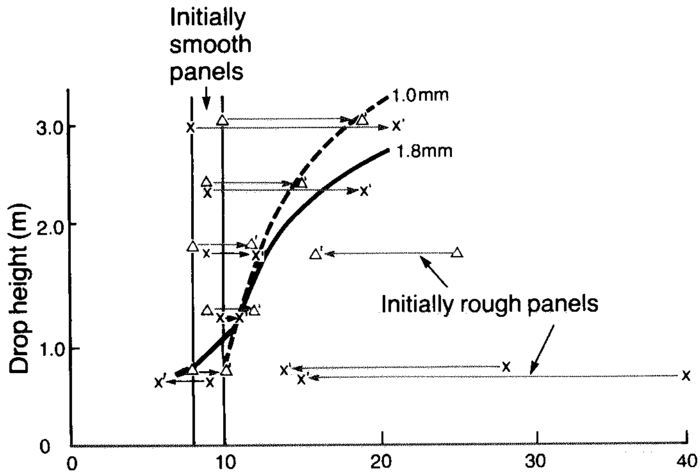

Fig. 5. Surface roughness at various drop heights

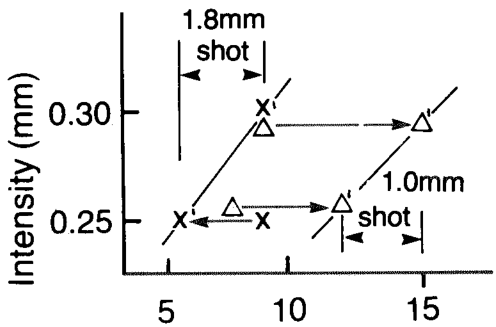

Fig. 6. Surface roughness at various intensities.

The data reveal that in the range of intensities desired, a media diameter of greater than 1mm results in surface finishes below 15AA, providing the initial surface roughness is below 35AA.

Shot diameters below 1mm peened to these intensities produced a surface finish roughness greater than 15AA even though the initial workpiece roughness was relatively smooth (8-10AA). The higher energies required to produce the desired intensities in the range of 0.25 to 0.30mm "N" with shot less than 1mm diameter also involve undesirable labyrinth to workpiece distances, in excess of three meters.

As the media size increases, the energy level increases, consequently the labyrinth-workpiece distance (velocity) must be reduced for a given intensity. At lower velocities, the time required for saturation increased dramatically.

Media sizes larger than 2mm diameter required over eight minutes for saturation, thereby lowering equipment utilization in a production operation. Small labyrinth-workpiece distances also limit the positioning of the workpiece. Small changes in workpiece position result in large variations in intensities. Consequently, the preferred media sizes for use in gravity peening systems in the intensity/surface finish ranges set forth lie between 1 and 2mm diameter.

Coverage

Coverage when peening with shot that results in surface finishes below 20AA cannot be determined by visual means, as is normally done in conventional peening operations. During the course of investigating gravity peening, it was found that by accurately monitoring saturation times at desired intensity levels was an effective method of ensuring adequate coverage. This method of control was substantiated by fatigue tests performed on gravity peened, glass bead peened, and unpeened titanium test specimens.

Treatment of Radii

Special consideration was given to the peening requirements of leading edge and trailing edge radii and fillets, but will not be addressed at this time.

Depth of Compressive Stress

Previous studies by Pope and Mohamed (1955) indicate that for a given intensity the depth of penetration increases with peening media size. This was confirmed by x-ray diffraction studies on titanium test blocks. Gravity peened blocks using 1.8mm diameter steel media and conventionally peened blocks using 0.25mm diameter glass beads were analysed for the level and depth of residual stress. The depths of stress were 0.152 and 0.110mm, respectively. Surface stresses were slightly higher on the glass bead peened specimens. Since erosion is a factor in gas turbine engine operation, it is generally felt that a deeper compressively stressed layer is more beneficial.

INTENSITY, ENERGY, AND IMPACT RELATIONSHIPS

Synopsis

During the course of determining the parameters for optimum gravity peening operations, peculiar relationships were observed between saturation times, energy requirements and total particulate impacts. A review of the literature revealed basic peening studies by Pope and Mohamed (1955). The basic factors were considered to be the amount and depth of residual plastic strain. The variables considered in their studies were the diameter, kinetic energy, number of impacts and the velocity of the peening medium. The medium was of relatively large size (18-56mm diameter).

These studies concluded, in general, that for mild steel:

a. Increasing the energy of impact increases the maximum plastic strain and its penetration.

b. For the same number of impacts, the effect of increasing the energy per blow is to increase the maximum increase in hardness and its penetration.

c. For the same number of impacts, the effect of increasing the ball diameter is to decrease the peak hardness and to increase its penetration.

d. Increasing the number of impacts tends to spread the plastic region further beyond the rim of the indentation rather than deeper.

e. The effect of velocity of impact is too small to be significant.

Energy, Time and Intensity

The kinetic energy contained in each particulate in a gravity accelerated peening system is directly proportional to the height from which it is dropped. The increased kinetic energy should also have an effect on increasing the diameter and depth of the impression, thus shortening the number of impacts required for a given intensity, or times to reach saturation (T). These two functions were plotted vs intensity and used to define the final parameters as shown in Fig. 3 and Fig. 4. These data appear to follow the studies and equations developed by Pope and Mohamed for maximum strain and penetration. The efficiencies in the slopes of the curves are not fully understood, but may be related to the efficiencies of each diameter of shot and the characteristic stress imparted to the workpiece. The efficiencies of each media were determined by rebound tests. These tests were made by measuring several rebound heights of individual particulates dropped from various heights onto Almen test strip specimens and are illustrated in Fig. 7. The Almen fixture was rigidly mounted as were the specimens used for intensity measurements.

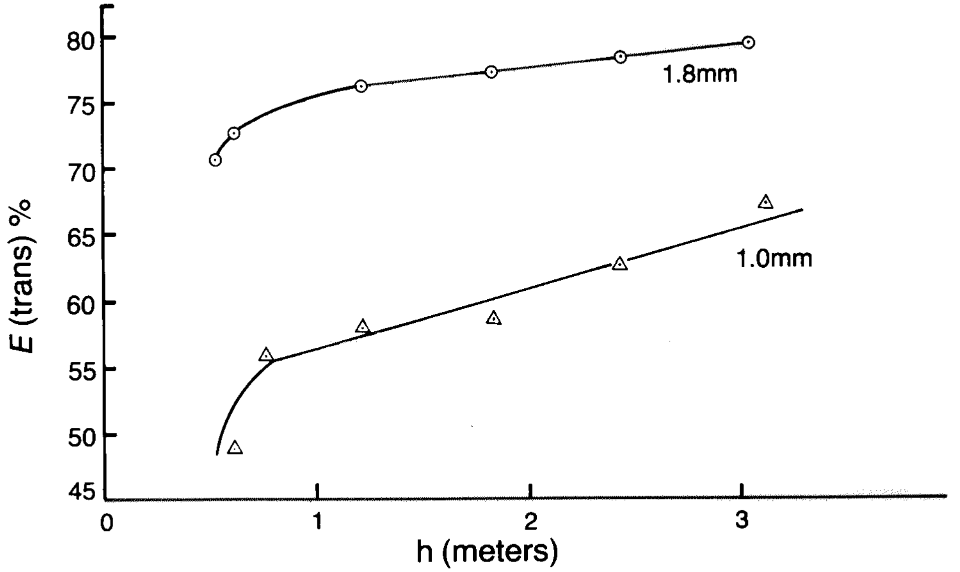

Fig. 7. Energy transferred vs height

The total energy and impact requirements for various intensities were calculated from the particulate kinetic energy, flow rates, and saturation times. These appear in the following table.

TABLE 1.

Intensity "N" (mm)	h (m)	T (Sec.)	E_t (Joules)	Total Impacts (Cm^2 X 10^4)	Eff. (%)	E (Trans.)	Surface Roughness (AA)
			1mm diameter media				
0.17	0.61	180	9.7	38	49.2	4.25	10
0.24	1.22	120	12.9	25	57.9	7.48	12
0.27	1.83	80	12.9	17	59.6	7.77	12
0.31	2.44	55	11.8	12	63.6	7.55	15
0.32	3.05	38	10.3	8.1	66.5	6.90	19
0.36	3.66	32	10.9	6.8	(68.5)	7.46	19
0.39	4.88	24	10.4	5.3	(71.0)	7.38	21
0.41	6.10	20	10.8	4.3	(73.5)	7.83	21
	(5.8)		10.2			7.50	
(0.46)	(9.2)	(13)	10.6	2.8	(75.0)	7.90	
			1.8mm diameter media				
0.26	0.61	184	12.1	7.7	72	8.71	6
0.30	0.74	165	13.2	6.9	74	9.76	9
0.38	1.22	113	14.9	4.7	77	11.47	11
0.46	1.83	84	16.6	3.5	78	12.95	12
0.53	2.44	74	19.5	3.1	79	15.41	19
0.56	3.05	55	18.2	2.3	80	14.56	21
	(2.80)	(56)	17.2	2.4		13.80	
0.60	(3.45)	(47)	17.5	1.9			
			2.5mm diameter media				
0.25	0.25	720	32.4	20			6
0.35	0.61	300	33.0	8.4			
0.46	1.22	165	36.3	4.6	99	35.9	12

Parentheses ( ) indicate values taken from graphs; other values are from experimental data.

These results reveal some interesting observations:

a. Efficiency (transferred energy vs total energy) increases with media diameter and kinetic energy of the particulate.

b. The total energy required to produce a given Almen strip intensity increase with media diameter.

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