THEORETICAL AND EXPERIMENTAL STUDY OF COVERAGE IN MANUAL SHOT PEENING

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Abstract
This paper describes and quantifies a physically rigorous shot peening model relating coverage or the fraction of area peened to shot and target material properties such as yield strength, surface hardness and modulus of elasticity. The model presented is capable of characterizing the behavior of coverage at varying pressures and angles of impingement, parameters vital to manually or automatically peened surfaces. Model is verified with shot peening coverage by manual peening experiments on 7050-T745 Aluminum alloy and evaluated using optical micrographs to verify that 100% coverage was obtained.

Keywords Shot peening, Coverage, Intensity, Fatigue life, Work energy

Introduction

Shot peening is a surface treatment process that induces a compressive residual stress and cold works a surface with impinging shots typically made of steel, glass or ceramic. When the shot impacts the surface, large forces deform the material and a compressive zone remains after unloading occurs. The positive attributes of shot peening are regularly reported. For example, at 100% peening coverage a uniform residual compressive stress near 60% of the materials ultimate tensile strength improves the fatigue strength of high strength aluminum alloys by as much as 25 – 35% [1].

Shot peening researchers have invested a large amount of time, effort and money to find out what level of coverage is optimal for fatigue life, surface roughness, and residual stress development. Recently, Bae [2] indicates that coverage *must not* exceed a specified amount nor drop below a certain level for benefits to be optimal. Ludian and Wagner [3] perform a detailed study of what the effects of different coverage levels have on fatigue performance and residual stress development of the aircraft alloy AL 2024-T4. Ludian and Bae indicated a definite lower and upper bound to coverage control for shot peening to remain beneficial.

The purpose of this paper is to develop an analytical model for peening by considering the amount of kinetic energy absorbed by the shot peened surface. Fundamental contact mechanics parameters are utilized to calculate the amount of kinetic energy transferred to the surface by a pressure distribution from a spherical indenter i.e. the shot. Once the energy of impact is known it is used in conjunction with the total kinetic energy of the shots coming from the shot stream to obtain the fraction of area peened over a given time. This method of solving for coverage incorporates the functional dependence on many crucial parameters.

Theoretical Development

Figure 1 shows a schematic of the manual peening process with associated process parameters. The manual peening nozzle is held a specified distance (standoff distance) from the target at some impingement angle θ. The impact velocity of the shots is controlled by the machine supply pressure. However, the energy transferred to the surface not only depends on the velocity but is also influenced by the impingement angle. The shot spread area varies according to the diverging angle, α, of the flow and the standoff distance. Other parameters of importance considered in the theoretical development include the shot radius and combined modulus of elasticity of the shot and target surface.

Table 1. Shot peening parameters

Object	Quantity
Work Piece	ρ_w (work piece density, kg/ m^3) E_{eff} (effective modulus, Pa) E_w (work piece modulus, Pa) ν_w (Poissons ratio of work piece) σ_y (surface Yield Stress, Pa) W_{indent}(work to indent surface, Joules)
	a (indentation radius, m) A_{up} (unpeened Area, m^2) A_p (peened Area, m^2) A_{spread}(shot spread area, m^2) A_{indent}(indent Area, m^2) $A(t)$ (fraction of area peened in time t) z (indentation depth, m)
Shot	v (shot velocity, m/s) ρ_s (shot density, kg/m^3) r (shot radius, m) ν_s (Poissons ratio of shot) E_s (shot modulus, Pa) F (Hertzian load, N) KE_{stream} (shot stream kinetic energy, Joules) C_d (drag coefficient)
Nozzle	D (nozzle length, m) α (shot flow divergence angle) θ (angle of impingement) P (pressure, Pa) d (standoff distance, m) $\dot{m}$ or dm/dt (mass flow rate, kg/s) ρ_a(air Density, kg/ m^3) v_a (air Velocity, m/s)

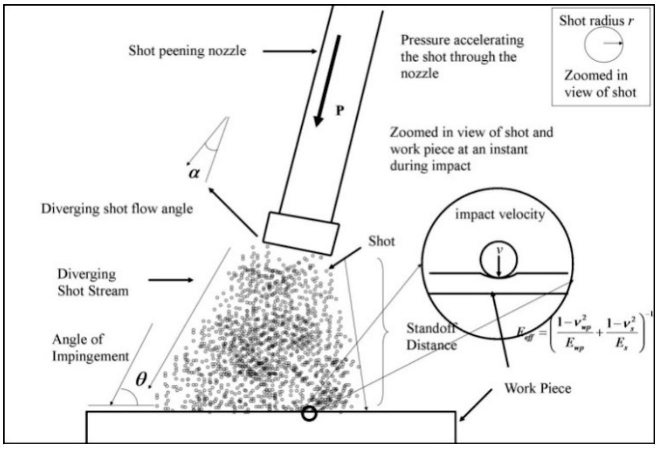


Figure 1. Schematic diagram of shot peening nozzle with relevant parameters.

Energy Based Coverage Model

The current work proposes a model based on the kinetic energy of the stream of shots coming from the nozzle and the energy of surface deformation. Parameters used in this analysis are provided in Table 1. Consider the number of shots impacting the surface as the quotient of the total kinetic energy of shots coming from the nozzle, KE_{stream}, and the energy transferred to the surface, W_{indent}, by an individual shot. Coverage can be written as

$$A(t)=1-e^{-\frac{KE_{stream}A_{indent}}{W_{indent}A_{spread}}} \quad (1)$$

This simple yet powerful equation makes it possible to derive an expression for coverage in as many ways as it is possible to derive expressions for the impact energy of the shot and energy of shot stream. With $A_{spread} = \pi R^2_{spread}$ and $A_{indent} = \pi a^2$; where R and a are the radius of shot spread and the radius of indentation respectively. The kinetic energy of the stream of shots is easily calculated. Let M be the total mass that comes out of the nozzle in a given time and v the average velocity of each of the shots:

$$KE_{stream} = \frac{1}{2}Mv^2 = \frac{1}{2}\frac{dm}{dt}tv^2 \quad (2)$$

The mass flow rate, $\frac{dm}{dt}$ or $\dot{m}$, is easily measured. The work energy theorem is used to calculate the amount of work to compress the surface. Hertzian contact theory [4] predicts the load for a spherical indenter and takes the form:

$$F = \frac{\frac{4}{3}a^3E_{eff}}{r} \quad (3)$$

with $E_{eff} = \left(\frac{1-\nu_{wp}^2}{E_{wp}} + \frac{1-\nu_s^2}{E_s}\right)^{-1}$. The work to compress the surface in terms of the indentation radius a is

$$W_{indent} = \int_0^a \frac{\frac{4}{3}a^3 E_{eff}}{r} dz = \int_0^a \frac{\frac{4}{3}a^3 E_{eff}}{r} a/r \, da = \frac{\frac{4}{15}E_{eff}a^5}{r^2} \tag{4}$$

from using $a^2 = 2rz$ to obtain dz. Substituting Eqs. (2) and (4) into Eq. (1) gives the fractional area peened:

$$\frac{KE_{stream}A_{indent}}{W_{indent}A_{spread}} = \frac{15\dot{m}tv^2r^2}{8R_{spread}^2E_{eff}a^3} \tag{5}$$

We can explicitly calculate the average velocity of the shots leaving the nozzle in terms of the pressure [5] from Bernoulli's equation. Geometric considerations yield the simple relation between the shot spread radius and standoff distance $R_{spread}^2 = (\tan\alpha)^2 d^2$ where *d* is the standoff distance. Inserting into Eq. (5) gives

$$\frac{15\dot{m}tv^2r^2}{8R_{spread}^2E_{eff}a^3} = \frac{45}{16}\frac{\dot{m}trC_dPD(\sin\theta)^2}{\rho_s(\tan\alpha)^2d^2E_{eff}a^3} \tag{6}$$

From this we can calculate the coverage of the surface:

$$A = 1 - e^{-\frac{45}{16\rho_s(\tan\alpha)^2d^2E_{eff}a^3}\dot{m}rC_dPD(\sin\theta)^2 t} \tag{7a}$$

We need not limit ourselves to eq. (7) to calculate the amount of work to compress the surface. Eq. (1) is highly modifiable and adaptable. To demonstrate this three more coverage models, see Table 2, were developed based on the energy of impact of the shots. Two are based on the work necessary to plastically deform the surface [6] and are functions of the yield strength, Y. The other model is a function of the Brinell hardness, HB, of the surface. An adjustment factor, β, for these expressions is used and kept constant while relevant parameters are varied. All four models are within 10% of experimental results see Figure 2.

Table 2. Coverage models based on Eq. (1)

Eqn. #	Alternate forms of Eq. (7)	Adjustment factor (β)
7b	$1 - e^{-\frac{\beta .05\times 3\dot{m}C_dPD(\sin\theta)^2}{2.8\rho_s(\tan\alpha)^2d^2Y\pi a^2}t}$	.2
7c	$1 - e^{-\frac{90\beta .05\times\dot{m}C_dPD(\sin\theta)^2}{\rho_s(\tan\alpha)^2d^2Y\pi a^2(13+20\ln(\frac{aE}{Yr}))}t}$	.2
7d	$1 - e^{-\frac{\beta 1.5a^2\dot{m}C_dPD(\sin\theta)^2}{2r\rho_s(\tan\alpha)^2d^2\pi HB(2ra^2-\frac{1}{6}((2r)^3-((2r)^2-4a^2)^{1.5}))}t}$	2

From Eq. (7) by using the work energy theorem

$$\frac{\frac{4}{15}E_{eff}a^5}{r^2} = \frac{1}{2}m_{single}v^2 \tag{8}$$

And relating the pressure back to the shot velocity, expressing the standoff distance in terms of A_{spread} and substituting we obtain [7]

$$A = 1 - e^{-\frac{s\dot{m}ta^2}{4A_{spread}\rho_s r^3}} \quad (9)$$

From the physical methodology used Eq. (9) is a specialized case of Eq. (7). Therefore, all coverage models can be deduced from this analysis. A fundamental physical connection between coverage and all peening parameters has been created to provide a truly robust model.

Experimental

The experimental setup consisted of a manual shot peening vacuum-blasting system from Vacublast with a 6 mm diameter nozzle. The type of shot used was cast steel S230, per MIL-S-13165, with a nominal diameter of 0.58 mm. Mass flow rates were also recorded from the Vacublast system. In general, a higher mass flow rate was recorded for higher pressures. At a pressure of 82,700 and 241,000 Pa the corresponding mass flow rates recorded were .033 to .045 Kg/s respectively.

A total of fourteen test specimens were fabricated from Al 7050-T745, each specimen has dimensions 100mm x 100mm x 35mm. Four Al 7050-T745 plates polished to a mirror shine were shot peened to obtain indentation measurements for the analytical model. The plates were shot peened at parameters provided in Table 3 along with measured indentations. Experimental results suggest the following linearity relationship for an extrapolated indentation diameter

$$2a_{ex} = 245 - \frac{90-\theta_{applied}}{15} \times 10 \pm |25 - P_{applied}| \times 5 \quad (10)$$

where $\theta_{applied}$ is the angle of impingement and $P_{applied}$ is the applied pressure in Psi. If the applied pressure is less than 25 Psi then the minus sign is used and if it is greater the plus sign is used. Indentation sizes used in Eq. (7) are within 10% of the experimental or extrapolated indentation radii due to the large variation in indentation size involved in shot peening with variable pressure and angle of impingement. Table 4 provides a summary of the experimental times to reach 100% coverage. Experimental results of fourteen plates shot peened at varying impingement angles, stand-off distances and pressures were used to verify and validate the analytical model described by Eq. (7). Table 4 also provides corresponding experimental and theoretical coverage and time.

DISCUSSION

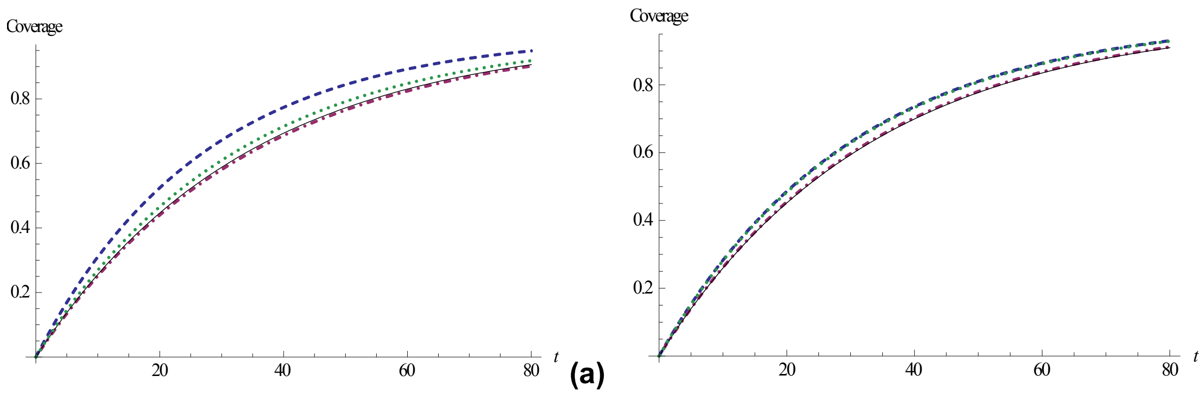
Theoretical coverage predicted at experimental times corresponding to 100% visual coverage from Eq. (7) are given in Table 4. Predicted values are within 10% of coverage measured using optical micrographs. From [8] a common efficiency coefficient assumes 80% of the impact energy is elastic. The remaining 20% contributes to thermal dissipation and plastic deformation. We assume 5% of the impacting energy constitutes plastic deformation. Typically, analytical coverage of 98% is interpreted as 100%. Our predicted coverage is in the range of 92% to 99.9%.

Table 3. Specimens shot peened at varying parameters

Specimen	Angle of Impingement (Degrees)	Stand-Off Distance (in)	Pressure (Psi)	Sample Size	Average Indentation Diameter (μm)
1	30	12	8	59	122
2	45	12	8	58	133
3	60	12	8	51	142
4	90	9	25	59	245

Table 4. Parameters and experimental time to obtain 100% coverage for all 14 Al 7050 specimens.

Air pressure (kPa)	Sample#	SOD (mm)	Angle of Impingement (degree)	Time to reach 100% Coverage (sec)	Coverage at corresponding experimental time	Predicted time to 98% - 99.9% coverage (s)
82.7	13	304.8	90	120	99%	64 - 113
68.9	7	203.2	90	130	99%	67 - 119
103.4	6	152.4	50	110	99%	80 - 141
	12	228.6	60	110	99%	76 - 134
137.9	5	228.6	30	110	97%	126 - 222
	14	304.8	50	90	98%	78 - 138
172.4	1	304.8	30	110	97%	118 - 208
	2	152.4	90	35	93%	51 - 90
	3	304.8	70	50	98%	50 - 89
	4	228.6	30	80	94%	113 - 200
	9	228.6	90	40	94%	57 - 100
	10	152.4	30	80	96%	100 - 178
	11	228.6	60	50	98%	50 - 90
241.3	8	152.4	60	35	92%	55 - 97



(a)
(b)

Figure 2. Each plot provides coverage vs. time of Eqn.'s (7a-d) (Eq (7a)-dash/blue, (7b)-dot/green, (7c)-solid line/black, (7d)-dot-dash/red). (a) Parameters corresponding to specimen #14 in Table 4 and (b) parameters corresponding to specimen #1 in Table 4.

This is very good given the uncertainty in the shot peening process, especially manual peening. Table 4 also provides a comparison of analytical and experimental times to achieve 100% coverage.

Figure 2 shows the simulation of coverage model results listed in Table 2 in addition to Eq. (7). 100% coverage predicted by each model compares well with experimentally obtained coverage. However, for pressures of 241300Pa and 82700Pa the predicted coverage is 92% and 99% respectively at experimental times corresponding to 100% coverage. These values are still reasonable but it appears predictions start to deviate from experimental results. This may result from using Bernoulli's principle to relate the pressure to the velocity of the shots; which is likely too simple to model the pressure at the instant of impact.

Summary and Conclusion

Models based on Hertzian theory, Brinell hardness and contact mechanics relate coverage to pressure, impingement angle, modulus of elasticity, yield stress and surface hardness. The theoretical coverage was verified by analyzing the experimental coverage of the 14 shot peened surfaces with optical micrographs. The comparison between theory and experiment show good agreement. There exists some variation between the experimental and analytical results but this is to be expected given the uncertainty of manually peening a part.

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