EFFECT OF SHOT PEENING VARIABLES ON BENDING FATIGUE

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ABSTRACT

A fractional factorial experiment was run to determine the effects of shot peening variables of shot size, wheel speed (shot velocity), and shot flow rate on the magnitude and distribution of residual stress, and on fatigue life of SAE 1074 steel.

Shot peening has a beneficial effect on fatigue life, increasing the $B_{63.2}$ life by about a factor of five over unpeened samples tested in three point bending. Highest fatigue lives were obtained when peening gave a high residual surface compressive stress for a shallow depth.

A total shot stream energy concept was developed as a characteristic parameter of the process and indicates that an optimum value of energy exists to obtain maximum fatigue life. Surface residual compressive stress reached a constant value at a relatively low shot stream energy while higher shot stream energy produced deeper and higher residual compressive stress levels.

KEY WORDS

Shot peening, fatigue life, residual stress.

INTRODUCTION

Effects of the peening process (Wheelabrator, 1965) on parts have been described and analyzed in terms of macro residual stresses and micro changes involving cold working (SAE; Mohamed, 1953; Pope, 1955; Polakowski, 1961). Both are present as a result of peening but differ widely in explaining fatigue properties. In some instances, particularly bending tests, macro residual stresses account for 80% of the effect, while for torsion tests, the entire improvement effect was attributed to micro physical change (Mohamed, 1953). Also, for steels in the range of R_C45 to R_C50, there is little physical change detected compared to the introduction of macro residual stresses during peening. Peening effects for materials in this condition have been ascribed to superposition of the macro residual stress on the loading stress (Pope, 1955) resulting in effectively lower stresses during load application. The present study was undertaken to provide quantitative data relating processing parameters to fatigue life.

EXPERIMENTAL PROCEDURES

Material and Heat Treatment.

SAE 1074 steel sheet, cut into samples .75 in. x .094 in. x 3.0 in. was heat treated to obtain an R_c45 to 50 range and to produce zero residual stress, Nominal heat treatment was 1500°F two hours, oil quench at 250°F, temper at 800°F for one hour. Slight tensile stresses were obtained, in the range of 65 to 7200 psi.

Shot Peening Parameters.

Major variables selected in the experimental design were: 1) shot size, 2) shot velocity as determined by wheel speed, and 3) shot flow rate. The machine used in this laboratory for shot peening was one in which a batch type work load is tumbled under a stream of shot coming off a rotating wheel.* Since only a very small sample lot was to be used, several attempts were made to restrict the samples to the "hot spot" region of the machine. When these were unsuccessful, the samples were run with a dummy load. Consideration of the physical effects during shot peening shows that the three parameters selected are interrelated when the kinetic energy of the shot blast stream is calculated. The experimental method used to determine the exposure times was found to result in the total kinetic energy of the shot blast being relatively constant for each size shot. In the 330 shot, the spread from high to low kinetic energy was within a factor of three; i.e. from 1.24 to 3.49 x 10^6 N-M for peening conditions of 1500 rpm at 4.8 lb/sec. and 2380 rpm at 2.0 lb/sec. respectively, as the shot size decreases on going from 330 to 110 shot averaging 1.08, 1.69 and 2.64 x 10^7 respectively, with overlaps in each group. These data are shown in Table 2 with correlations with fatigue life.

Fractional-Factorial Design.

The design evaluated effects of (a) shot size, (b) wheel speed, and (c) shot flow rate, at three levels; high, intermediate, and low. High and low levels were of primary importance with the intermediate put in to obtain an estimate of the response surface. Specific values are given in Table 1.

Stress Measurement - Fatigue Testing.

Stress measurements on both sides of each sample were made by use of the X-ray technique given in SAE TR-182. Measurements were made only in the middle of each sample. Representative samples were selected from each run for stress gradient measurements. In this process, stress measurements on both sides of the sample are made after removal of successive layers on one side by electropolishing, done in .0005 to .002 in. increments to obtain sufficient points to draw a smooth curve.

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* Wheelabrator Tumblast machine, Serial No. A122138.

Table 1. Test Conditions for Peening

Calculation Number	Level of Variables	Run No.	Calculation Number	Level of Variables	Run No.
1	-a -b -c	15	11	+a +b +c	7
2	-a +b +c	21	12	-a b c	19
3	+a -b +c	2	13	a -b c	9
4	+a -b -c	5	14	a b c	10
5	-a -b +c	17	15	a b c	11
6	-a +b -c	20	16	a -b -c	8
7	+a -b -c	1	17	-a b -c	18
8	+a b c	3	18	-a -b c	16
9	a +b c	13	19	+a +b c	6
10	a b +c	12	20	+a b +c	4

Level
+ = high value
No sign = mid value
- = low value

Variable
a = shot size
b = wheel speed
c = shot flow rate

Three point bending fatigue tests were used, with cyclical stress levels from 93,800 to 170,000 psi around a mean stress of 131,900 psi.

RESULTS

Table 2 summarizes the experimental conditions, stress measurements and fatigue test data used in the statistical analysis to obtain the effect of each variable.

Fatigue Life

Results of fatigue testing are given in Table 2 in Cols. 10, 11, 12 and 13. Weibull analysis (Johnson, 1964) of the data was used to determine the B_{10} and $B_{63.2}$ lives. The high slope obtained indicates the relatively narrow band of lives obtained in each run.

Residual Stress

As mentioned earlier, stress measurements were made on each side of the sample after peening. Values for each run were then combined to obtain an average, a standard deviation, and a coefficient of variance as given in Columns 7, 8 and 9 of Table 2.

Regression Analysis

Limited regression analysis was run on the data with results indicating that best increases in fatigue life are obtained at low wheel speeds, low flow rates, and the smallest shot size. No sharp peaks were observed for any run when the results were plotted, with no indication of a sharp optimum in the range of conditions studied.

Calculations for variable effects showed at least one interaction effect larger than the main effect, especially for $B_{63.2}$ life where shot size - flow rate effect is more than twice as high as the flow rate alone.

Table 2 Master Summary of Factorial Experiment

1 Run No.	2 No. of Samples	3 Shot Size (10^4 in.)	4 Wheel Speed (rpm)	5 Shot Flow Rate (lbs/sec)	6 Peening Time (min.)	7 Stress* (psi)	8 Standard Deviat. (psi)	9 Coeff. of Variance (%)	10 B_{10} Life (10^3 Cycles)	11 $B_{63.2}$ Life (10^3 Cycles)	12 Weibull Slope	13 Correlation	14 Total Energy of Stream (Newton-meters x 10^6)	15 Total No. of Shot (x 10^7)
0	7					3,820	1,460	38.1	24.7	35.4	7.50	.956		
A1	5	330	1,500	2.0	112	-69,300	3,890	-5.61	60.2	81.3	7.49	.998	1.75	1.66
2	5	330	1,500	4.8	33.4	-67,700[1]	2,800[1]	-4.14[1]	44.5	91.2	3.13	.971	1.24	1.19
3	10	330	2,000	3.4	44.2	-70,900	2,800	-3.95	49.8	78.7	4.92	.938	2.00	1.11
4	10	330	2,000	4.8	26.4	-69,000	3,830	-5.50	54.1	96.5	3.88	.977	1.76	.94
5	10	330	2,380	2.0	88.9	-69,900	2,810	-4.02	53.4	81.3	5.36	.906	3.49	1.32
6	10	330	2,380	3.4	30.9	-68,800	3,470	-5.05	55.2	77.0	6.75	.981	2.06	.81
A7	10	330	2,380	4.8	17.1	-67,000	6,640	-9.91	53.8	83.1	5.18	.988	1.62	.61
8	9	230	1,500	2.0	53.4	-72,200	2,960	-4.10	45.6	107.8	2.61	.970	.829	2.74
9	10	230	1,500	3.4	15.7	-70,600	3,230	-4.57	53.7	128.3	2.58	.947	.416	1.37
10	10	230	2,000	2.0	49.4	-73,200	3,600	-4.99	57.8	110.3	3.48	.958	1.36	2.53
11	10	230	2,000	3.4	17.7	-69,500	5,250	-7.55	50.1	107.3	2.95	.984	.831	1.54
12	10	230	2,000	4.8	8.0	-69,300	3,600	-5.19	55.6	111.7	3.22	.980	.529	.98
13	10	230	2,380	3.4	17.4	-71,000	4,130	-5.88	64.9	95.5	4.87	.950	1.16	1.52
14	9	230	2,380	4.8	9.3	-71,100	4,010	-5.64	48.0	102.9	3.00	.929	.878	1.14
A15	7	110	1,500	2.0	17.7	-69,900[2]	3,400[2]	-4.87[2]	86.8	157.	3.80	.991	.275	4.23
16	8	110	1,500	3.4	5.5	-60,400[2]	11,400[2]	-18.9[2]	33.8	81.9	2.54	.946	.144	2.23
17	11	110	1,500	4.8	2.6	-45,500	14,900	-33.0	19.0	47.3	2.47	.901	.0978	1.49
18	9	110	2,000	2.0	15.9	-70,300	2,710	-3.85	46.0	169.1	2.61	.976	.438	3.80
19	11	110	2,000	3.4	3.5	-62,800	9,030	-14.4	35.5	83.1	2.64	.934	.164	1.41
20	18	110	2,370	2.0	16.0	-69,300[3]	5,400[3]	-7.74[3]	64.2	13.5	3.01	.886	.627	3.83
21	8	110	2,380	4.8	2.4	-70,500[4]	4,250[4]	-6.04[4]	51.6	85.8	4.42	.977	.227	1.37

1 for 10 samples 2 for 11 samples 3 for 24 samples 4 for 11 samples

DISCUSSION

Surface stress as measured by X-ray techniques is related to the total energy of the shot stream as shown in Fig. 1. A saturation value is reached at a value of about 0.5 x 10^6 Newton-meters, corresponding to a stress level of about 70,000 psi.

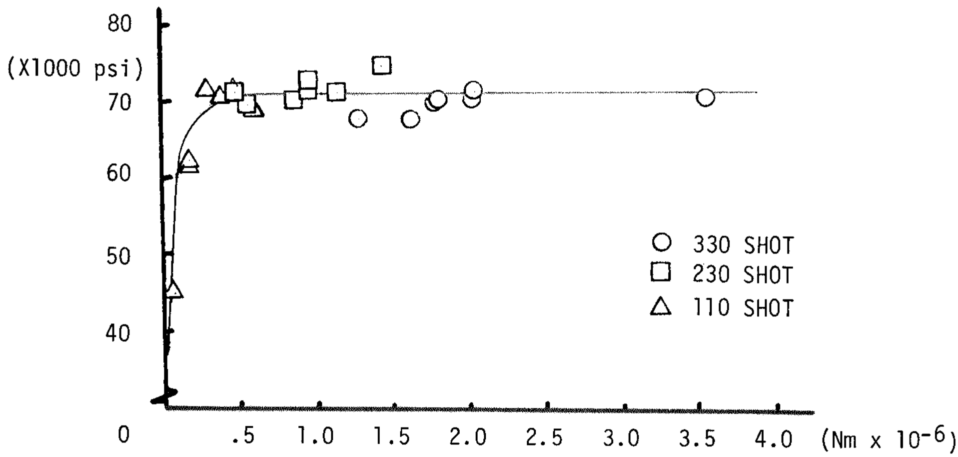

Fig. 1 - Total Energy of Shot Stream vs. Average Surface Stress

The plastic deformation, which occurs during peening results in residual lattice strain. Two types of stress have been proposed by Greenough (1951) for explaining residual strain due to plastic deformation, the first being microstress, the second a macroscopic stress system due to the differing plastic behavior of grains at the surface, i.e. those which are not constrained by their neighbors for some part of their surface area. Of the two stress types, the microstress system is probably the one holding the key to a satisfactory explanation of fatigue failure.

Fig. 2, a plot of the $B_{63.2}$ life is shown vs. the total energy of the shot stream. This is somewhat related to Fig. 1 where the total energy is plotted vs. the residual compressive stress. One interpretation would be to draw a curve as shown with a peak at about .03 N-M of energy.

Here the peening of Runs 16, 17 and 19 produced a low surface stress, significantly lower than the other runs on the average. Comparison with the stress gradient results for these runs becomes difficult because the stress gradient results are from a single sample while the surface stress values are averages for all the samples in the run.

Comparing the stress gradient values with the $B_{63.2}$ life shows that in general, if there is a high residual stress value close to the surface which does not extend too deep, there is also a high $B_{63.2}$ life. The lowest $B_{63.2}$ lives were found in Runs 1 through 7 where high residual stress values extending to depths of 0.10 in. to .012 in. were found. Fig. 3 shows depth vs. stress curve drawn from the composite collection of each shot size.

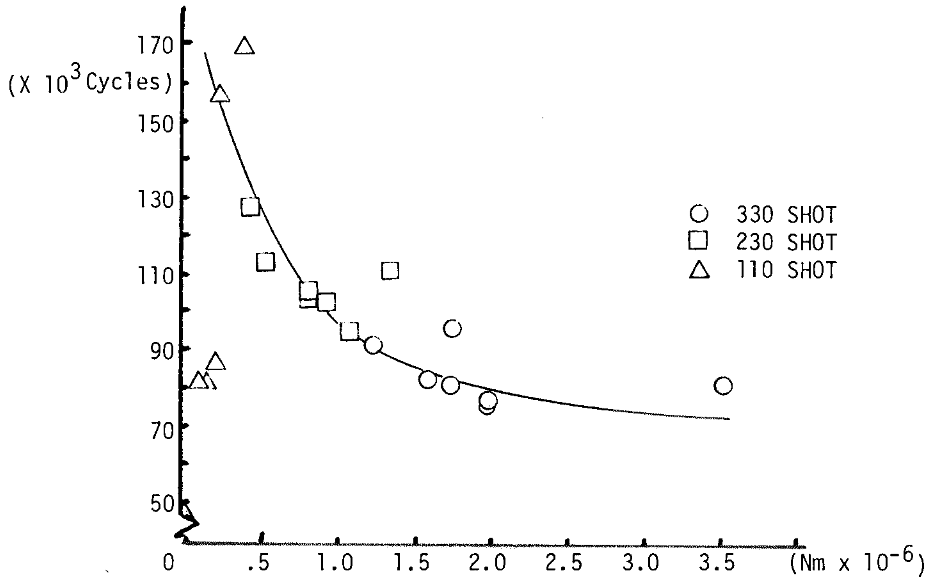

Fig. 2 - $B_{63.2}$ Fatigue Life vs. Total Energy of Shot Stream

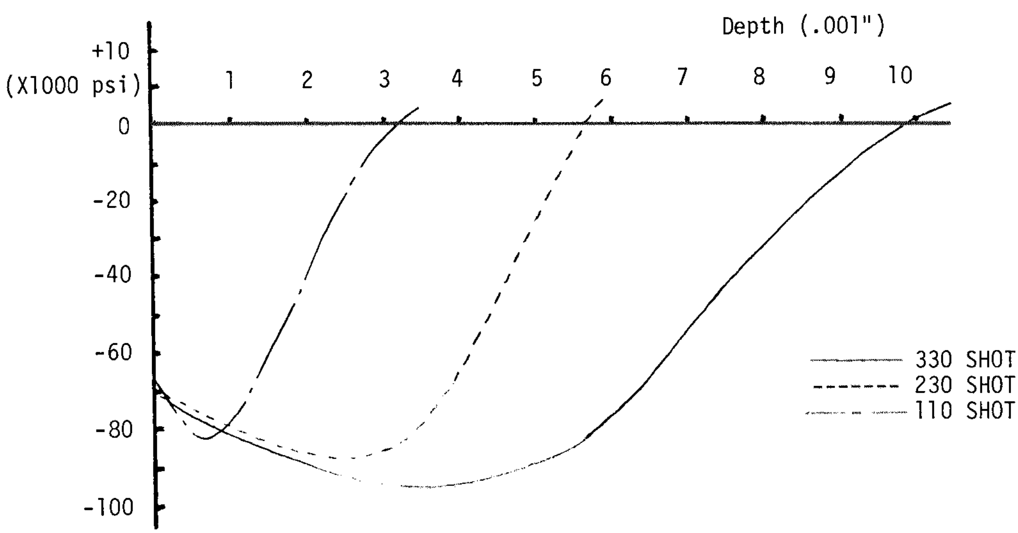

Fig. 3 - Stress Gradient for Various Shot Sizes

CONCLUSIONS

Shot peening has a beneficial effect upon fatigue life, increasing the $B_{63.2}$ life by about a factor of five over unpeened samples tested in three point bending.

Highest fatigue lives were obtained with peening conditions giving a high surface stress value for a shallow depth.

Regression analysis of the factorial experiment shows a peak in fatigue life for small shot size, low wheel speed, and low flow rate of shot.

Analysis of the shot peening variables in terms of the total energy of the shot stream shows that for a given material being peened, a maximum value of surface stress is reached and stays constant over a wide range of energies.

An optimum value of shot stream energy exists to obtain maximum fatigue life. This is related to shot size and flow rate through the physical effects of the shot impacting the work surface.

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REFERENCES

Wheelabrator Corp. (1965), Shot Peening, Eighth Ed., Chap. IV.

SAE Information Report, TR 182, Measurement of Stress by X-Ray.

Mohamed, A.K., Coombs, A.G.H., (1953), Experimental Study of Residual Plastic Strains Produced by Spherical Impact, J. Iron & Steel Inst., 175, 5-9.

Pope, J.A., Mohamed, A.K., (1955), Residual Plastic Strains Produced by Single and Repeated Spherical Impact, J. Iron & Steel Inst., 177, 285-297.

Polakowski, N.H., (1961) Softening of Metals During Cold Working, J. Iron & Steel Inst. 169, 447-456.

Greenough, G.B., (1951) Macroscopic Surface Stresses Produced by Plastic Deformation, J. Iron & Steel Inst., 173, 235-241.

Johnson, L.G., (1964) Statistical Treatment of Fatigue Experiments, Elsevier Publishing Co., N.Y.