

Forecasting Fatigue Life of Peened Parts

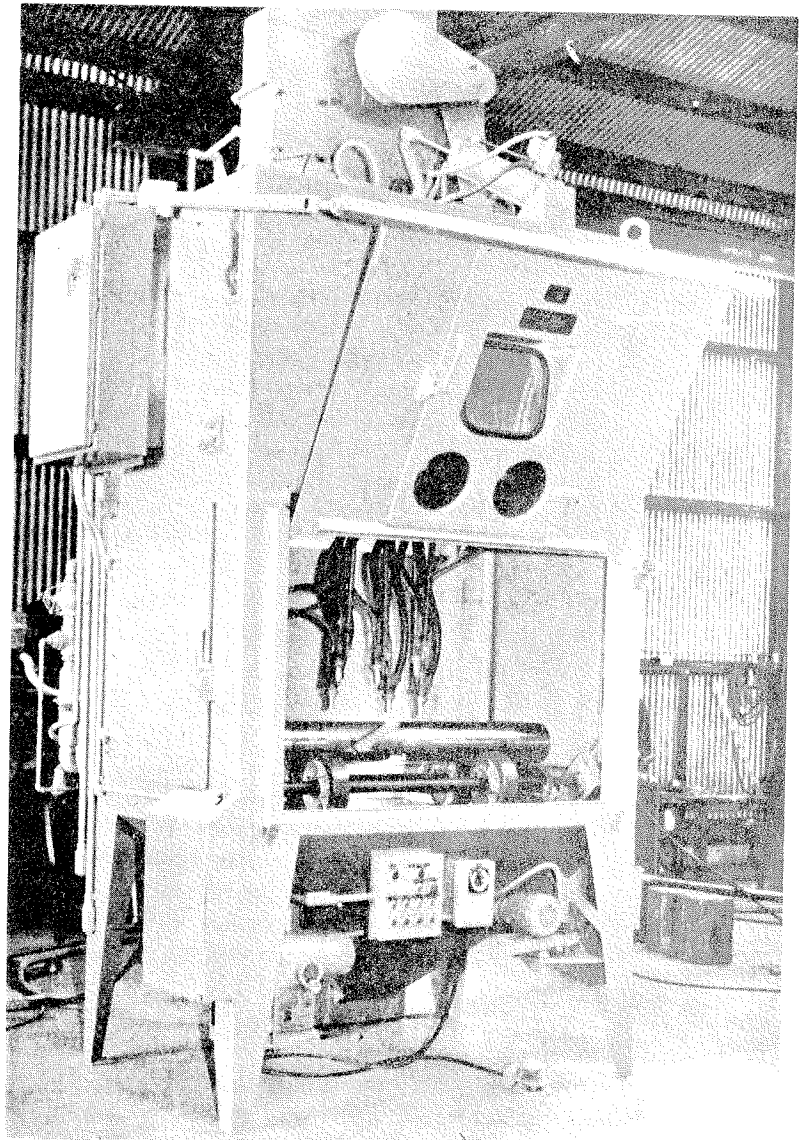
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Recent research on fatigue crack propagation provides a numerical tool for making forecasts of fatigue strength. Although precise predictions are not yet possible, this tool can be used to estimate the effects of shot peening accurately enough for design purposes.
(Q7, G23h, Q23b, Q26q)

THAT THE FATIGUE LIFE of metal parts can be increased by shot peening is now a well established fact. How much the life of a given part can be extended and how high the endurance limit of a part can be raised by peening are questions that are as yet open. The answers depend on stress distribution, mechanical properties of the material, surface conditions, ambient conditions, and shot peening specifications. In reversed bending, for instance, the endurance limit of Moore specimens made of mild steel can be increased only a few percent, but the endurance limit of automobile axles can be raised to over twice the original value by peening.

Thumb Rules

Can we foretell the results of shot peening? In trying to answer this question in the past we have used qualitative rules of thumb based



Large grooved shaft will be shot peened to increase fatigue life in service.

on experience and on J. O. Almen's† interpretation of experience. Recent research on fatigue crack propagation now permits quantitative estimates of the endurance of shot peened parts based on tests involving more fundamental properties of steel.

The qualitative rules of thumb are:

- Parts with section changes or other stress raisers can benefit more by shot peening than parts that are smooth.
- Parts with skins that are prone to fatigue damage (decarburization, corrosion attack, chromium plate) can gain far more than parts without such skins.
- Potential gains in fatigue life increase with the hardness of the steel, regardless of

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†See references.

Table 1—Comparison of the Predicted and Observed Effect of Peening on Bending Endurance Limit

Source*	Static Strength and Type of Test	Condition	Endurance Limit, Psi			Gain, %		
			Not Peened	Peened (Estimated)	Peened (Observed)	Estimated	Observed	Error
Harris (de Havilland)	130,000 psi tensile Rotating-bending	Smooth Round notch†	63,000	70,000	63,000	11	0	+ 11
			38,000	60,000	63,000	57	65	- 12
Mattson (General Motors)	Rockwell C 48 Flat bending, 0 to max	Slight decarburization	90,000	124,000	146,000	38	62	- 24
Takeuchi and Homma (Tohoku University)	200,000 psi tensile Rotating-bending	Smooth Round notch‡	84,000	100,000	86,500	19	3	+ 16
			43,000	90,000	57,000	109	32	+ 71
			27,000	90,000	47,000	220	74	+146

*See references at end of article.

†0.031 in. root radius; specimen peened with 0.031 in. diameter shot.

‡0.040 in. groove radius; specimen peened with 0.050 in. diameter shot.

§0.002 in. groove radius; specimen peened with 0.050 in. diameter shot.

failure can be shown in a single diagram, Fig. 1, in which the nominal alternating stress, S_A , is plotted against the steady or nominal mean stress, S_M . Such a diagram can be constructed if yield strength, unpeened endurance limit, and crack propagation stress are known or can be estimated.

The yield strength is usually available. The unpeened endurance limit may be available or may be estimated from the endurance limit of smooth polished specimens ($S_E = \frac{1}{2}$ ultimate tensile strength for steel) and fatigue strength reduction factors for shape (for example, from Peterson) and surface condition ($k = 2$ for either decarburization or chromium plate). Some data on crack propagation stresses have recently become available (Frost). For our purposes we use 5000 psi cyclic nominal tensile stress as the crack propagation criterion for steel. For other materials, zero cyclic tensile stress is a safe assumption.

To apply the diagram to peened parts we shall also need data on the residual stress produced by peening. For steel of 100,000 to 300,000 ultimate tensile strength this may be estimated as $S_R = 70,000 \text{ psi} + 0.2$ ultimate tensile strength. For other materials it can be estimated from analyses of the curvature and diameters of dimples on peened strips.

The diagram (Fig. 1) contains three sets of failure lines. The yield condition is indicated by the straight lines which join static tensile yield strength (A) and static compressive yield strength (B) to a pure alternating stress equal to the yield strength (C). The yield condition shows whether residual stresses

will fade out during cyclic loading and how much residual stress remains if some of it does fade out. This will be shown later in the example involving Fig. 2.

The crack initiation condition for smooth, unpeened parts corresponds to the fatigue failure condition for such parts because in them a crack will propagate very fast after it has been initiated. For uni-axial stress, this condition is represented by a line (D) which passes through the reversed endurance limit on the ordinate in Fig. 1; it slopes upward with increasing compressive mean stress, downward with increasing tensile stress. With equal scales for mean stress and alternating stress, we show a slope of 20% which represents many test data. As more detailed knowledge of different materials becomes available, this slope may be drawn more accurately for each material. For our purposes, the general trend of 20% is quite accurate.

It is interesting to note that the combination of the yield condition with this crack initiation condition, taken from Sines' recent work, conforms very closely to the parabolic diagram which Gerber established from Woehler's tests of a century ago, at least in the tensile range. Gerber knew that in the compressive range he was in error on the conservative side, but chose to neglect this in favor of the simple parabolic law.

Crack Propagation and Nominal Stress

The crack propagation condition in Fig. 1 (line 3-A) shows a sharp break at the point corresponding to 5000 psi alternating stress and

mating method to rotating-bend tests on smooth and on notched specimens (Fig. 2), we find that the peening stress of 95,000 psi together with a small alternating stress of 15,000 psi equals the estimated yield strength of 110,000 psi.* The peening stress will fade back by the amount the alternating stress exceeds 15,000 psi. The points C and D which represent the limiting conditions for the peened parts are located along the compression yield line.

Comparison of Forecasts and Observations

This method of forecasting endurance limits of peened parts was applied to published fatigue test results for which the details of material and stress concentration were given. No effort was made to "adjust" the forecasting method to obtain improved matching with observations. The results are shown in Table I. We draw these conclusions from the comparison:

- The proposed method correctly forecasts the different order of magnitude of improvement for smooth parts and for parts with notches of varying severity.
- With good peening, the amount of improvement can be forecast within about 20%.
- Where the observed improvement differs unfavorably from the forecast improvement by more than 40%, we have reason to suspect special conditions.

This is clearly brought out by the data reported from Tohoku University. The shot (which was 0.050 in. in diameter) never hit the bottoms of the V-grooves which had a radius of 0.002 in. The observed improvement of 74% is remarkable in indicating how far beyond the area of direct impact the favorable effect of peening can extend. Even in their round notches, they probably

*These specimens were made of steel with a 130,000 psi tensile strength. Applying our rule, we obtain a residual stress produced by peening of $70,000 + 25,000 = 95,000$ psi. The alternating stress (or maximum compression) is $95,000 + 15,000 = 110,000$ which equals the estimated yield strength.

did not obtain full saturation peening.

Multi-Axial Stresses

For stresses in more than one direction — torsion, for instance — the three criteria can no longer be represented in one simple diagram, but the same reasoning can be applied. Hot wound steel coil springs (Bhn 444) tested from zero to maximum load may have an endurance limit, without peening, of 60,000 psi torsional stress. At this hardness, the tensile strength is about 210,000 psi and the yield strength in tension is about 190,000 psi. The torsional elastic limit will be about 105,000 psi.

The torsional stress corresponds to numerically equal tension and compression at 45° to the bar axis. Peening supplies a compressive mean stress of

$$70,000 + (0.2 \times 210,000) = 112,000 \text{ psi}$$

in both directions.

In the direction of the compression component of torsion, this will yield back as in the example of Fig. 2. In the direction of the tensile component of torsion, the crack propagation condition of 5000 psi alternating tensile stress is reached when load stress cycles from zero to +122,000 psi are added to the peening stress to give a total stress cycle from +10,000 psi to -112,000 psi. These load stresses, combined with numerically equal compressive load stresses at right angles, would exceed the torsional elastic limit of 105,000 psi. Observed data show that shot peened compression springs indeed fail by yielding.

For notched parts with multi-axial stresses, the analysis follows similar lines but is somewhat more complicated. The excellent results of peening splined shafts and crankshaft fillets are known. To avoid the more complicated analysis, one may start by assuming that good peening will produce a part as strong as if it had no stress concentrations.

Finite Life

An estimate of the endurance limit of shot peened parts can be obtained

by the methods outlined above. In many instances only a finite life, for instance 400,000 cycles of load, is required. To estimate the effect of shot peening on the extension of finite life we refer to a sketchy forecast of an S-N curve, Fig. 3, which consists of two straight lines in a plot of log-load or log-stress versus log life. One line goes from yield strength at 1000 cycles to endurance limit at one million cycles. The other lines goes horizontally at the endurance limit from one million cycles on out.

With the endurance limit estimated as shown, the S-N lines can be sketched and the extension of life at various levels of load or stress can be predicted.

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