Maximization of Flexural Fatigue Strength of Heat-treated Steel Specimens Using Multiple Peening Techniques

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Introduction:

Reliability is one of the most marketable characteristics of any manufactured item. Products known to be highly reliable have consumer acceptance, and can command a higher price in the market-place. Increasing reliability, therefore, is one of the major goals of the competent engineer.

In the case of cyclically-stressed metal parts, one all-too common way to achieve reliabiity is to size the component parts so that the maximum service tensile stresses do not exceed about 20 percent of the yield strength of the base metal. The resulting oversize, heavy, rigid and inflexible structures are expensive to build and to operate, but they do minimize or eliminate metal fatigue, a major cause of failure and low reliability.

Increasingly, however, the cost of all this excess weight is making products designed in this fashion non-competitive in the market-place. They are being displaced by lower-cost lighter items of equivalent performance with no sacrifice in reliability. Indeed, the latest fatigue design techniques can increase reliability by controlling and managing previously uncontrolled residual stresses.

Shot-peening is one of the ways we are learning to manage residual stress to make it work for us. The replacement of random uncontrolled residual stress with a thin, highly-compressed surface layer has gained acceptance as a viable and cost-effective design tool. In many studies and case-histories, traditional shot-peening has been shown to increase the fatigue strength of high-strength metals by about 35 to 50%.

Fatigue life improvements have been even more impressive. Automotive leaf and valve springs and crankshaft fillets are routinely shot-peened as part of their production process. Aircraft high-strength aluminum and titanium alloys are shot-peened to increase fatigue life and reduce scheduled maintenance or replacement frequency. The list of manufactured metal components which are impacted by spherical particulates is already long, and continues to grow.

In most accepted new technologies the initial gains are impressive, and may even be termed a "breakthrough". Further gains may come more slowly, and be of lesser magnitude, as the process becomes more fully understood. The same is true of shot-peening. The improvements in fatigue strength and fatigue life which are brought about by traditional peening are in many cases so remarkable that it is easy to forget that most of the elastic zone remains unused. In other words, even after traditional shot-peening, components still cannot be stressed beyond 40 or 45% of their yield strength without risking premature failure caused by fatigue.

Using more of the elastic zone in stress design is accomplished by increasing the fatigue strength. In addition to further reductions in weight and cost beyond those achieved by traditional peening, other benefits are obtained. For example, designing for greater elastic deflection improves the load-sharing aspects of the entire assembly and can reduce peak stresses in shock loading. In the case of automotive vehicles, the less-rigid design can be more satisfying to the operator. And, of course, each incremental improvement in fatigue strength increases reliability by decreasing the chance of early failure.[5]

Indications are that the traditional shot peening process may be improved to result in incrementally greater fatigue strength improvements. Areas of potential improvement currently being considered are:

1. Increasing the magnitude of residual compressive stress so that higher levels of service tensile stresses may be sustained. In typical traditional peening, the maximum RCS is no more than about 50% of yield.

2. Maximizing the residual compressive stress at the surface. Traditional peening results in a maximum stress a certain distance below the surface with a lesser amount at the extreme surface. In some cases, surface residual stresses may approach tensile even though they are underlaid with high levels of residual compression.

   In bending or torsion, applied tensile stresses range from zero at the neutral axis to maximum at the surface. Therefore, the need for the counteracting effect of residual compressive stress is greatest at the surface of the part.

Peening with smaller shot usually places the maximum RCS closer to the surface. However, total depth of compression may be sacrificed. The solution seems to be secondary or multiple peening operations, using successively smaller-diameter shot at lower intensities. The initial peening establishes the depth of compression. The subsequent peening is additive to the original and results in increasingly higher surface stress by decreasing maximum stress depth. Fig. 7 is a schematic representation of this phenomenon. Even though the maximum value for RCS is unchanged, successive peening increases the effective surface stress by decreasing penetration below the surface. The original depth of compression from the first peening is not affected.

Multiple peening may also increase the magnitude of RCS by compaction of previous layers, although this has yet to be determined.

The secondary peening effect on fatigue life was first reported in 1963, when a US patent was issued to J.J. Bush, R.L. Mattson, and J.G. Roberts of General Motors. The patent claims that secondary peening with smaller-diameter media at lower Almen intensities increased fatigue life from a figure of under 100,000 cycles for primary peening to over 300,000 cycles. Fatigue strength benefits were not stated.[1] A small amount of subsequent publication exists, some of which is found in References 2 and 3.

Of particular interest is the work of Hirose, et al, as reported at the second International Peening Conference in 1984[4]. By power brushing (after peening) with stainless steel filaments, and chemical etching to maximize surface RCS, they were able to effect a remarkable 98% improvement in the fatigue strength of carbon tool steel specimens. This is at least double the improvement by traditional peening, and serves as an indication of what might be possible by careful management of residual compressive stress. Peening has the advantage of being a low-cost, mature and widely-available technology.

Experimental Design:

Briefly, our experiment consists of the peening of specimens to various parameters after which the specimens are tested to determine fatigue strength, sometimes called endurance limit.

A. Specimen (see Fig. 8)

Test specimens are machined from SAE1070 carbon steel, then heat-treated and drawn to a hardness of 40-42 HRC. Tempering is fixture-controlled to maintain a flatness variation of no more than $^+$.002" (.05mm), measured with a dial indicator and surface plate. The two holes are for attachment to the test machine, whereas the other end is clamped in a vise.

Specimens are cut from 3/32" (2.38mm) flat steel sheet stock crossways to the direction of rolling. Sharp edges are hand-radiused to .010" (0.25mm) min. to avoid stress-risers. The remaining surfaces are as rolled after HT and prior to peening. Control (unpeened) specimens were not polished or hand-finished in any other way. Previous testing (x-ray diffraction) has shown that specimens prepared in this way may have a slight amount of RCS (about 10-15 ksi/maximum) (68-102 MPa) prior to peening.

The triangular shape of the specimen is to equalize stresses when the specimen is clamped at the large end and deflected from the small end. In other words, the stress applied in cantilever bending is constant along the specimen gauge length. This has the advantage of subjecting a significant bulk of metal to the test stress, which is not the case with rotating-beam fatigue machines, or tests using necked-down sheet specimens.

B. Test Equipment

Fatigue test machines (2) are of the flat-plate deflection type, using an eccentric crank arm to flex the free end of the specimen while the other end is firmly clamped in a vise. The proper deflection for any given stress is determined by actually hanging a weight on the specimen free end. The amount of weight is calculated so as to produce the required stress in the specimen. The resultant specimen deflection is measured with a dial indicator, and it is this amount of deflection (in thousandths of an inch) that is dialed into the adjustable crank arm on the test machine. When the machine is operated, the specimen is deflected alternately upward and downward at approximately 1750 total cycles per minute by an electric motor drive. When the specimen breaks, it actuates a micro-switch that shuts off the motor and counter.

C. Peening

All peening of specimens was accomplished in a suction/induction blasting cabinet using spherical glass peening media, ("glass beads") per MIL-G-9954A. Nozzle peening distance and angle were 6" (15cm) and 80°, respectively. Air pressure was adjusted to achieve the required Almen arc height peening intensity, using conventional techniques. The nozzle was fixed, and two specimens were peened at each set-up. Specimens were clamped to a fixture, and passed under the nozzle for the time calculated to achieve specified coverage (130%) on both sides. Specimen edges were also peened to the same intensity and coverage.

D. Testing Technique

Since we are interested only in the fatigue strength, we do not develop the traditional S-N curves (Wohler diagrams), but use the so-called "staircase" method to go directly to the fatigue strength value. To do this, we begin testing at a stress level below that which we expect will lead to fatigue failure. If the specimen "runs out" to 5 million cycles or more, the stress is incrementally increased (on the same specimen) and it is tested again. If a specimen breaks, it is replaced with a new specimen and tested at a stress level incrementally decreased by the same amount.

The increments used in our program were 4500 psi (31MPa), or approximately 2.5% of the yield point (0.2% offset) of the material. The results are reported as "percent of yield point" (rather than unit stress), a convention adopted to make it easier to compare results of future testing on various materials.

Staircase test results are reported in the manner of Dixon and Mood.[6] Approximately 10-15 specimens are run to eventual failure to establish each fatigue strength data base. From this type of data, it is possible to calculate fatigue strength quite accurately, and also to assign probabilities other than the 50% associated with the standard S/N curve. Therefore, for those engineers to whom a 50% probability of fatigue failure is too high, a lower figure of fatigue strength may be calculated which will provide a correspondingly lower probability of failure in fatigue. Reference (7) is a later work on this subject, with modifications.

Test Results: See Figs. 1 through 6

Discussion:

Test results on the unpeened control specimens, and the single-peened specimens, were more or less as expected. The 47% improvement in fatigue strength is on the high side, based on previous data. Even so, a significant additional improvement was noted for multiple peening.

Arc heights and bead sizes were chosen based on normal practice. The referenced patent suggests that the secondary peening be performed with media about 1/3 to 1/5 the diameter of the primary peening media.

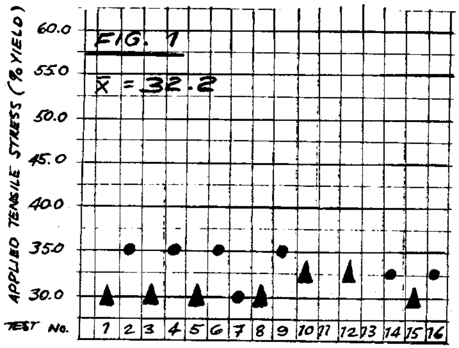
Seventy (70) specimens were run to eventual failure using the staircase method. 64 of these failures occurred prior to 10^6 cycles. and the other 6 between 10^6 and $2x10^6$ cycles. No failures were noted above $2x10^6$ cycles, although most of our runouts were extended to 10^7 cycles to investigate this possibility.

68 out of the 70 specimens failed at 55% of yield or less. Only two specimens ran out at 55% of yield. Both were multiple-peened, and both failed at the next interval (57.5%). Curiously, both these failures were among the very few (6 out of 70) that exceeded 10^6 cycles prior to failure.

Conclusions and Recommendations:

The data show that secondary or multiple peening operations can produce a significant increase in the fatigue strength of heat-treated steel specimens. Although Fig. 3 shows only marginal improvements, Figs. 4,5, and 6 show fatigue strength increases of 28%, 19%, and 21%, respectively, when compared to traditional peening (Fig. 2).

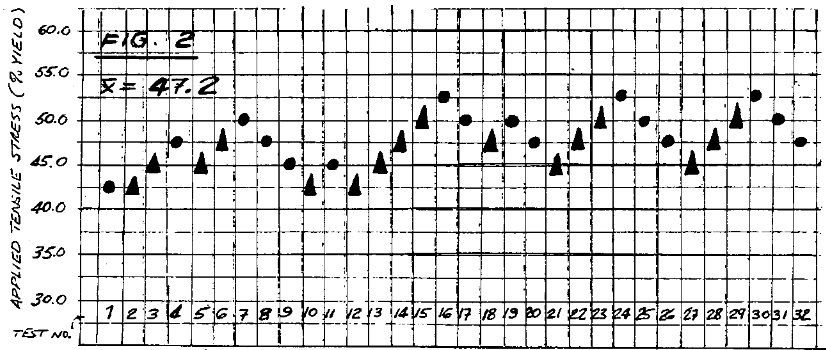
The best of our peening schedules (Fig. 4) showed a 60% improvement in fatigue strength when compared to the unpeened (control) specimens, (Fig. 1). The improvement for traditional peening (Fig. 2) was 47%.



UNPEENED CONTROL

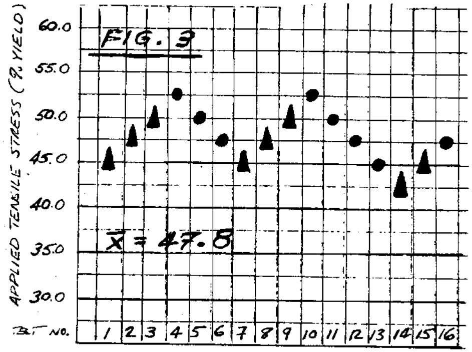
● BROKE
▲ RUNOUT

Fig.1



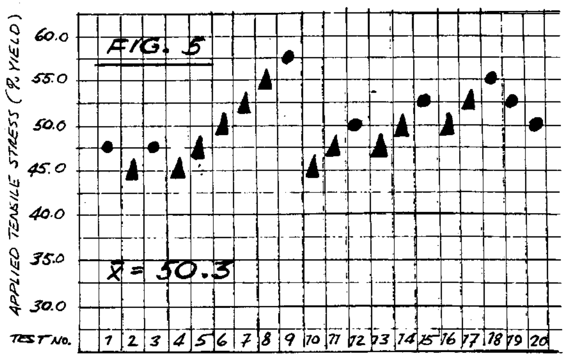
① 7A (.18 mm) MEDIA α

Fig.2



① 7A (.18 mm) MEDIA α
② 6N (.15mm) MEDIA β

Fig.3



① 7A (.18 mm) MEDIA α
② 9N (.23 mm) MEDIA β
③ 4N (.10mm) MEDIA γ

MEDIA	ϕ µm	U.S. SCREEN
α	425-300	(-40+50)
β	150-90	(-100+170)
Δ	600-425	(-30+40)
γ	<45	(-325)

Fig.5

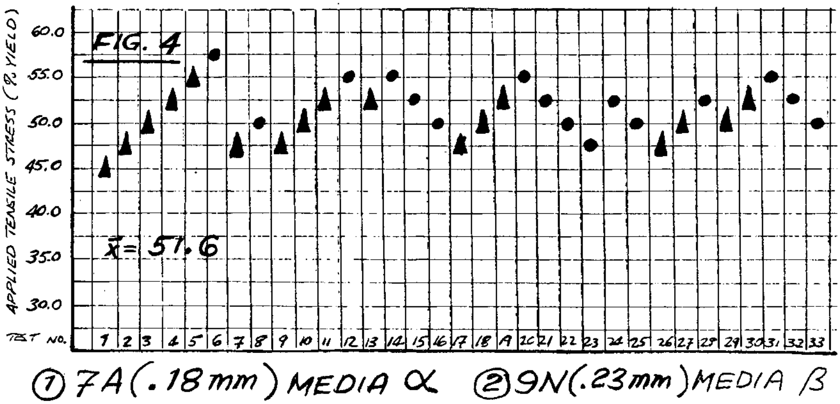


Fig.4

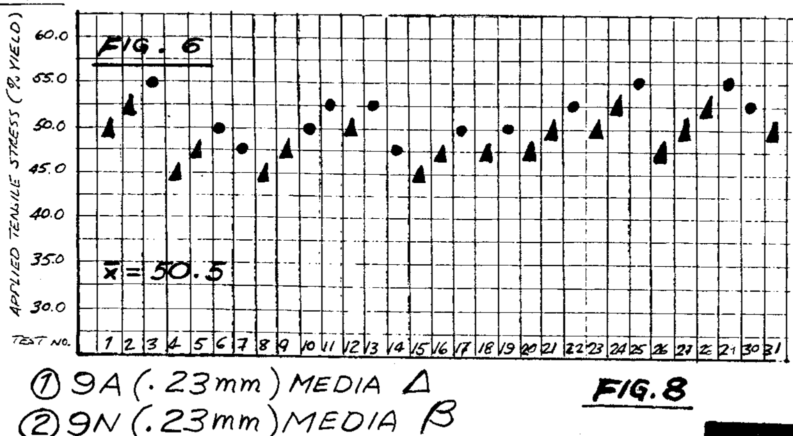


Fig.6

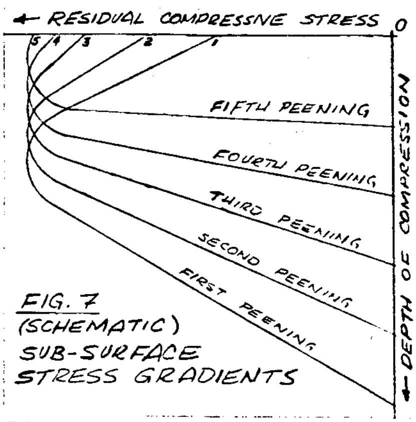


Fig.7

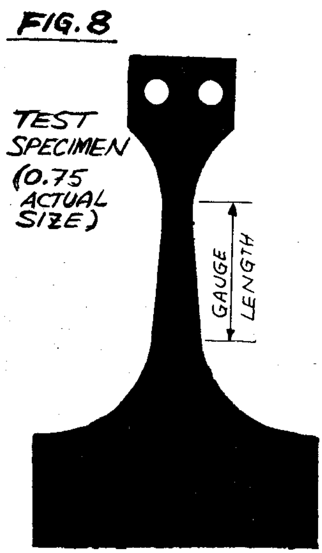


Fig.8

A total of 32 tests of traditional peening (Fig. 2) produced no runouts above 50% of yield. 100 tests of multiple-peened specimens (Figs. 3 through 6) produced ten (10) runouts at 52.5% of yield, and 2 at 55% of yield.

Of course, we still have much room for improvement before the peening process can produce the 98% fatigue strength improvement reported by Hirose, et al. Based on these results, however, we believe further peening experimentation may be warranted. Many areas remain to be investigated, for example:

1) Testing of a significant number of variations in media diameter, Almen intensity and percent coverage, to optimize these factors.
2) Effect of different media.
3) Different specimens (material, hardness, thickness).
4) Fractographic analysis of fatigue nucleation and propagation.
5) Crack growth rate determination.
6) Studies of residual stress gradients associated with maximum fatigue strengths.

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References:

1. Bush, J.J., R.L. Mattson, J.G. Roberts; U.S. Patent 3,073,022 (Jan. 15, 1963): "Shot-Peening Treatments"
2. Bell, R.A. (1984): "Shot-Peening Techniques for Greater Fatigue Life in Springs" Springs, May 1984
3. Delitizia, A.T. (1984): "Improving Fatigue Life through Advanced Shot Peening Techniques" Manufacturing Engineering, May 1984
4. Hirose, S., H. Moriya, S. Harada, A. Yamada (1984): "Combined Surface Treatment by Shot-Peening and Power Brushing" Proceedings of Second International Conference on Shot-Peening (Chicago) Available from SAE.
5. Tirey, C.J. (1986): "The Utilization of Fatigue Life Prediction Techniques in Support of a Major Vehicle Project" Proceedings Inst'n Mech. Engrs. Vol. 200, No. D5
6. Dixon, W.J., A.M. Mood (1948): "A Method for Obtaining and Anlyzing Sensitivity Data" Journal of the American Statistical Association (43)
7. Huck, M. (1983): "Ein Verbessertes Verfahren fur die Auswertung von Treppenstufenversuchen" Z. Werkstofftech 14,406-417