A design guide: Preventing Fatigue Failures

Part 4—Surface Treatment and Environment

The designer of parts to be stressed in fatigue has to pay far more attention to surface condition than would be necessary for a “static” design of ductile materials. In addition, special consideration must be given to the environment in which the part or structure must operate.

Whether surface hardening is done by a metallurgical process, as outlined in Part 3 of this series, or by a mechanical treatment, as discussed in this article, considerable improvement can be obtained not only in fatigue properties, but also in resistance to abrasion. However, proper methods must be used. Otherwise, the treatment can do more harm than good.

The most common problems caused by environmental conditions are: Excessive heat, corrosion, and fretting. Any or all of these may be present, and will contribute to a reduction in fatigue strength.

Surface Treatment

Surface Protection: The belief has been expressed that the surface fatigue strength of a material may be only half of that of the internal fatigue strength.\(^1\)

\(^1\)References are tabulated at end of article.
PREVENTING FATIGUE FAILURES

This agrees with the hypothesis that since surface grains are not surrounded by other grains, there is less resistance to slip. At an edge, where a given grain is surrounded by even fewer grains than at the surface, this could account for some of the edge effect reported by some observers. However, in the last reference cited, the author thought that the low strength of his square specimens might have been caused by slight variations in the roughness of the sharp projecting corners, since most of the rectangular specimens failed through a fracture starting at a corner.

As further evidence of the existence of an edge effect, an improvement of 36 per cent has been reported in the long-life fatigue strength of a flat specimen of SAE 4340 steel when the edges were rounded to a relatively large radius. Of course, any stress raiser such as an inclusion close to an edge will reduce fatigue strength.

The surface of fatigue-stressed structural or machine parts must be carefully protected. It is clear that one important consideration in establishing a design-stress value is the deviation from surface conditions of the specimens used to establish fatigue-strength values. These deviations may be unavoidable in some cases, and intentional in others.

Surface Finishing: It is generally believed that the effect of mechanical surface finishing (polishing, grinding, etc.) on a structural part is largely dependent on residual stresses resulting from the finishing procedure.

Grinding may have one effect on long-life fatigue strength and an opposite effect on fatigue life at higher stresses. For example, it has been found that a ball-bearing steel of hardness Rc 59, when severely ground and hand polished, had a fatigue limit about 27 per cent lower than gently ground specimens. Yet, fatigue life at a fatigue stress of 120,000 psi was four times greater. On the other hand, tests on hardened 52100 steel flat-bending specimens seem to suggest that good commercial grinding does not reduce the fatigue life below that obtained by very gentle grinding.

In the case of fatigue strength in bending, some investigators believe that transverse grinding introduces minute scratches that act as stress raisers, whereas other investigators find no such evidence.

It is possible that grinding, polishing, etc., cause "plastic smearing" or microscopic tearing of the surface. This either sets up residual stresses or causes microscopic stress-raising notches. It is also possible that commercial grinding results in severe heating of the metal under the wheel, causing the metal to try to expand. This compresses the adjacent metal, sometimes above its compressive yield strength, so that plastic yielding occurs. This is followed by cooling and contracting, which results in residual tensile stresses.

Although electrolytic polishing is not a mechanical operation, it should be mentioned, since it is sometimes used in the hope of avoiding the uncertain effects of mechanical finishing. However, there is some difference of opinion as to whether or not these effects are in fact avoided. The relative fatigue limits shown in Fig. 12 (Part 3 of this series) show that fatigue limit is consistently lower where polishing is done electrolytically rather than mechanically. On the other hand, it has been suggested that where etching is used to remove successive layers of metal, compressive stresses of 10,000 to 20,000 psi might be introduced under certain conditions.

Because of these uncertainties, where unfavorable residual stresses could develop from surface-finishing procedures, stress relief of the finished part should be called for.

Surface Hardening: Peening, rolling, etc., will cause plastic deformation of a metal. If not overdone, this sets up compressive residual stresses and may increase hardness, thereby improving fatigue properties. If only the surface layers need such hardening, shot-peening is often used. This is done by bombarding the surface with small steel shot traveling at high speed, to produce minute surface pitting.

Here again, there are differences of opinion as to why shot-peening, properly done, is capable of improving fatigue properties. In the case of shot-peened coiled springs wound from cold-drawn wire, where the failure criterion is maximum shear, the influence of the compressive residual stress has been questioned. On the other hand, the opinion has also been expressed that the improvement found in torsional fatigue strength of four spring steels under test was caused by compressive residual stresses. Whatever the reason, an increase of 25 to

![Fig. 15—Effect of shot-peening on fillet of SAE 1045 steel. Curve A is for the polished, unpeened steel. Curves B and C are for the steel after shot-peening with two different sizes of shot.](image)
30 per cent has been reported in shot-peened springs of 0.9 per cent carbon manganese steel (hot-coiled in as-received condition).\textsuperscript{12} Heavier peening—to get completely below the decarburized layers—could show an even greater improvement.

Shot-peening can improve fatigue properties, if size of shot, velocity, and time are suitable. The $S$-$N$ curve\textsuperscript{13} in Fig. 15 illustrates what might happen in cases where the optimum size of shot is not used. Curve $B$ indicates that long-life strength is improved but short-life strength is not, whereas curve $C$ implies that the use of a different-size shot from that used for curve $B$ resulted in little long-life improvement but a possible improvement in short-life strength. However, only two or three specimens were tested at short-life stresses, and the apparent difference between curves $B$ and $C$ could be due to scatter.

One of the most comprehensive studies of shot-peening effects has been reported by Lessells and Broderick.\textsuperscript{14} They found significant improvement in the fatigue strength of SAE 4340 steel specimens whose surfaces were peened, then blasted with shattered glass to simulate surface damage from abrasion. Benefits became even more marked as the hardness of the steel was increased. The observers made numerous measurements of the residual stresses left in the specimens as a result of the peening. Fig. 16 shows typical curves of residual stresses found at various depths in the steel specimen.

The previous discussion has concerned steel. However, similar effects—although not necessarily of the same magnitude—have been obtained by shot-peening aluminum alloys. As a matter of fact, any material having the property of elasticity and the ability to deform plastically should respond to shot-peening.

Rolling: This has much the same effect as shot-peening; that is, it cold-work-hardens the surface and induces compressive residual stresses. Some remarkable results from rolling have been reported in fatigue literature. For example, rolling of the fillet connecting the web and crankshaft (flake graphite iron) of an automobile, gave a 100 per cent increase\textsuperscript{15} in repeated bending-moment strength for a life of one to ten million cycles. Rolling the fillet of a stub axle showed an improvement of 35 per cent for 20,000,000 cycles, 20 per cent for 100,000 cycles, and 3 per cent for 100,000 cycles of reversed-bending moment. In another case, the fatigue life of a shoulder fillet was increased 500 per cent by surface rolling.\textsuperscript{16}

Although the literature contains fewer cases of rolling than of shot-peening, the instances cited here suggest that rolling should be given serious consideration, particularly in places where shot-peening is difficult to carry out.

Hammering: In places where surface effect must be
highly localized—particularly in gear teeth—hammering has been successfully used. However, where there is a need for controlled localizing of surface hardening and setting up compressive residual stresses in gear teeth, care should be taken that in the core of the tooth a sufficient part of the cross section remains free of hardening so that relatively low tensile stresses in the core can balance high residual stresses in the surface.17

Surface Covering (Plating, Cladding, etc.): Surface covering is sometimes used in an attempt to protect fatigue-stressed parts from the damage caused by corrosion. When corrosion is expected, design stress must be greatly reduced if the material is unprotected.

Metals are usually protected from corrosion by a coating, such as plating, cladding, etc. Some of these platings or coatings may cause a substantial loss in fatigue strength.18 The pure aluminum which is used to coat aluminum alloys is relatively weak in fatigue resistance, Fig. 17. However, although fatigue tests indicate a reduction—for a stress life of 500,000,000 cycles—of about 25 per cent, the elimination of intergranular or localized corrosion of the basic alloy compensates for this effect.19

For steels, numerous coatings and platings have been used. Very little quantitative information is available in the literature, but it has been found that electrodeposits of tin, lead, zinc, cadmium, copper, or silver will, if correctly applied, improve the corrosion-fatigue resistance of steels without reducing the normal fatigue properties. However, this is not true for nickel or chromium plate.20

To offset the reduction in par fatigue strength of chromium-plated steel, shot-peening before plating has been tried. Tests of this treatment of SAE 4340 steel of 200,000 and 280,000 psi ultimate tensile strength have been reported. From these tests it was concluded that shot peening prior to chrome plating is very effective in reducing the harmful effect of chrome plating on fatigue21 and that fatigue strength might even be raised above that of unplated and unpeened specimens. Similar results22 are reported in tests of SAE 4340 steel of 140,000 and 260,000 psi ultimate tensile strength, shot-peened, then cadmium-plated. Mean strength values were 7 to 10 per cent higher than those for unpeened, unplated specimens. Apparently, in both these cases peening raised the par fatigue strength, while plating lowered this value back to the original, but gave a certain amount of protection against corrosion.

Anisotropy: Anisotropy in a structural material is the property that manifests itself as a difference in fatigue strength to resist stresses parallel to the direction of rolling or forging from the strength to resist stresses that are transverse or diagonal to the direction of rolling. Considerable quantitative information is available concerning the effect of anisotropy on the static strength of various materials, but relatively little about its effect on fatigue strength. In addition, no correlation has been shown between anisotropic effects on static strength and on fatigue strength.

Most materials that are forged or rolled into bars or sheets show some anisotropy when fatigue tested. The grains are somewhat elongated in the direction of rolling or forging. In steels, the same thing happens to any impurities (inclusions) that are malleable.23 Manganese sulfide inclusions, which

Fig. 18—Effect of anisotropy on fatigue strength of aluminum and steel alloys in, a, bending and, b, torsion. Curves A are for a steel alloy of Rc 25; B and C are for aluminum alloys 765T-61 and 255-T6, respectively. Tests were conducted only at 45 and 90 deg; intermediate points are not necessarily accurate.
are malleable, usually appear as stringers, whereas silicate inclusions are affected little, if at all, and retain their more or less spheroidal shape. The degree to which inclusions cause transverse anisotropy depends upon their type, shape, and size. No general reduction factor can be assigned.

Malleable, stringer-type inclusions cause a serious reduction in transverse fatigue strength. However, in SAE 4340 steel (aircraft quality high-strength steel) containing nonmalleable silicate inclusions, tests have indicated only a 5 to 10 per cent reduction in transverse fatigue strength over longitudinal strength. Only a 10 to 20 per cent reduction was noted in the strength of specimens cut from a large forging. This indicated that nonmalleable inclusions in present-day steels are not important causes of anisotropy. Another interesting point is that transverse anisotropy in rolled parts could very well be caused largely by the rolling itself.

These conclusions are based on anisotropic effects at 90 deg to the direction of forging or rolling. Fig. 18 shows the relative effect of anisotropy on fatigue strength at 45 deg and 90 deg for a steel and two aluminum alloys. It is interesting to note that the right-hand chart indicates that torsional fatigue strength may be reasonably constant regardless of the anisotropic effect on fatigue bending strength. For bending-fatigue anisotropy, the values range in the neighborhood of 10 to 20 per cent reduction, for completely transverse stressing.

In addition to the effect of anisotropy at 90 deg with the direction of rolling or forging, the effect at intermediate directions should be looked into when combined stresses occur, since the resulting principal stresses will usually act in directions between the longitudinal and transverse.

**Environment**

Elevated Temperature: Although this article has been limited to a discussion of fatigue properties of materials at room temperature, the fact that elevated temperatures change those properties must not be overlooked. Strictly speaking, any temperature at which a material shows a decrease in tensile and yield strength, or fatigue strength, is for that material an elevated temperature. However, most of the steels do not show such losses unless stressed while at temperatures well above 200 or 300 F. Thus, the designer need not worry about the complications of combined fatigue and creep in steels at those temperatures. However, this does not apply to the light alloys.

It should be kept in mind that at elevated temperatures, not only are fatigue stresses continuously damaging the material in a part, but creep may be adding to the damage. The relative damage differs with the material temperature, total elapsed time, and other variables.

In some cases, temperatures have been found at which fatigue stresses superimposed on creep seem to have no effect on the total service life of the material.

Corrosion: Perhaps the worst environmental condition affecting fatigue strength is corrosion. A hard steel having a long-life fatigue strength, under normal conditions, of 90,000 psi may lose as much as 90 per cent of that strength when tested in a stream of fresh water. As another example, marine propeller shafts are known to have very low fatigue strength and service life. Tests on the steel of marine shafts, Fig. 19, showed some small loss of torsional strength in fresh water, and almost complete loss of strength in both torsion and bending after 40 or 50 days in salt water.

Nonferrous structural materials are not as seriously affected by corrosion as are structural steels. The so-called stainless steels, which should more properly be termed corrosion-resistant, may lose half or more of their normal strength in salt water.

As noted previously many of the protective coat-
ings employed to reduce the effects of corrosion may reduce the par strength of a structural material. However, where the fatigue strength of unprotected materials is likely to be seriously reduced by a corrosive environment, the relatively small effect of a protective coating can usually be tolerated.

Fretting: When the surfaces of two metals are held in close contact and one of the metals is subjected to fatigue stressing, fretting occurs causing a marked reduction in fatigue strength. Cyclic stressing causes cyclic strain, and even if the relative movement of one surface over the other is as small as 0.001 in., fretting will still occur. Fretting failures are usually easy to detect because of the presence of finely divided material that has been removed from the metal surfaces by the friction and oxidized in the air.

Fatigue-strength reductions have been reported ranging all the way from 5 to 80 per cent. In one case26 nine 1/4-in. steel shafts were tested as cantilever rotating beams. Because of fretting, their "smooth" fatigue strength for 85,000,000 cycles was reduced from about 50,000 psi to about 10,000 psi. A subcritical quenching of the steel brought the strength up to nearly 20,000 psi, presumably by setting up compressive residual stresses in the surface layers of the steel.

Similar improvements have been obtained27 by prior shot-peening of contact surfaces. Surface rolling affords a substantial improvement in fatigue strength under fretting conditions, although it does not alleviate the fretting itself. Other devices used to reduce the destructive effects of fretting are: Soft gripping pads, prior oxidation of surfaces, interposition of soft metal screens, surface plating, etc.

In tests, molybdenum disulfide, MoS₂, bonded to the hot metal surface by corn syrup, was found28 to provide protection for millions of cycles of 0.001-in. vibratory motion of a 1/4-in. 52100-steel sphere (surface finish 3 or 4 mu rms, against glass, under a 0.2-lb load at 7000 cpm). Similar results were obtained with two plates of Swedish steel (0.003-in. motion at 600 cpm under a 20-lb load).

The intersurface materials will, of course, wear through in time. But even the number of fatigue cycles required to wear them through is a gain over the cycle life of unprotected materials subjected to fretting.

Part 5 of this series will discuss the factors involved in calculating fatigue strength or life.

References

They Say . . .

"Each of us, as the handiwork of the Creator, must be creative—give of our mind, emotions, and physical being—if we are to fulfill our potentialities. And this includes concern for our fellow men. One of the effective means for satisfying this need and acting upon this concern is pursuance of the natural sciences and of research as an activity in them. Physically, through research we help to establish a better life for our fellow men. Spiritually, the receptiveness and purposefulness implicit in research strengthen our faith—in the improvability of society, and in a future that will give meaningfulness to our lives."—WILLIAM H. BROWNIE, Mgr., Mechanical Engineering Dept., Battelle Memorial Institute.