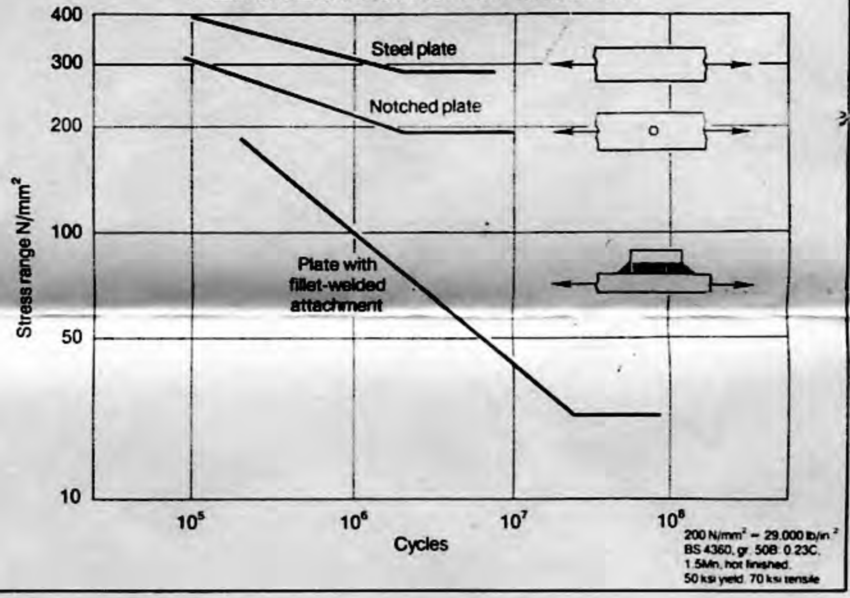
What we have learned about fatigue of welds

Welding Institute researchers look for improved understanding of fatigue failures and for ways to extend fatigue service

by ROSALIE BROSILOW, *editor*

Most industrial equipment—offshore platforms, earthmovers, cranes, and all rotating machinery—is subjected to repeated alternating loading, or fatigue loading. Because such equipment usually is of welded construction or weld surfaced, and because welds can seriously reduce the fatigue life of equipment, fatigue performance of weldments was the subject of a Welding Institute seminar held last October in Atlanta. Boosted by British interests in the North Sea, the institute has an entire research section devoted to applied research on weldment fatigue.

WELDED ATTACHMENT REDUCES FATIGUE STRENGTH



What welds do to fatigue life

As explained by Steve Maddox, head of the fatigue laboratory at the institute, the mere presence of a weld in a stressed member is enough to reduce fatigue strength drastically. In design, fatigue strength of welded details sets the limit on allowable design stresses for fatigue-loaded structures.

The villain is stress concentrations that inevitably accompany welds, due to the change in section thickness that welds introduce and, more importantly, due to discontinuities, sometimes very small, at the weld toe. The weld need not be a load-bearing one to have this effect: fatigue cracks often start at unloaded attachments that are welded to stressed members. Fatigue failures in transversely loaded welds and in short or discontinuous longitudinal welds, Maddox reported, normally occur at the weld toe. Continuous longitudinal welds, when they fail in fatigue, begin to crack at surface irregularities, such as ripples and start-stop points.

Like all failures, fatigue cracks have two stages—initiation and propagation. For plain unwelded base metal the fatigue life includes cycles required to start the crack and for it to propagate; the limiting stress is that required to start a crack.

When a discontinuity is already present, as in the case of a weld, initiation has, in effect, already occurred. Fatigue life is cycles required for the crack to grow to failure, and the limiting stress is that required to propagate the crack, much lower than that to initiate a crack.

About residual stress

Fabricators stress relieve to improve impact properties of weldments. Does stress relief improve fatigue properties as well? Not really, Maddox said. He reported that, for fully tensile fatigue loading, fatigue crack growth rate does not vary with applied mean stress. In the presence of tensile residual stress, applied compressive stress may be damaging, so stress relief to remove tensile stress should be helpful. However, Maddox questions the effectiveness of stress relief practice and therefore its value in improving fatigue life in compressive loading situations.

. . . and tensile strength

For unwelded material, fatigue strength increases with tensile strength. But for welded parts, failure has to do with crack growth rate, which has little to do with material strength. This fact is reflected in design codes which, for a given joint design, use the same S-N curve for steels of all strengths. In fatigue service then, high-strength material is useful only for sustaining few cycles of high stresses.

Nor does weld microstructure have much to do with fatigue strength: rate of crack growth in steels is insensitive to microstructure.

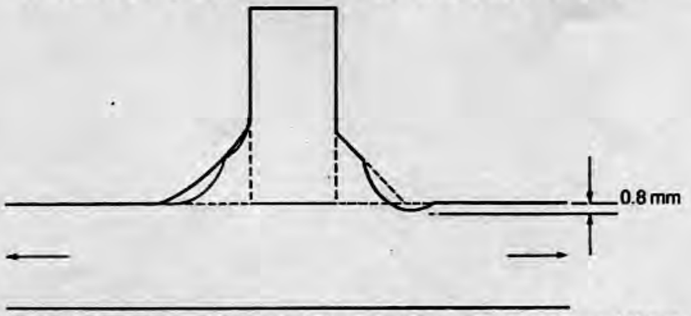
Does the welding process influence fatigue life? Only as it influences the factors already mentioned. For example, shielded metal arc welds normally have smoother contours than do submerged arc welds; therefore, their fatigue strength is likely to be higher. Flat-position welds have smoother profiles than overhead welds do, hence higher fatigue strength. Maddox recommends that for best fatigue performance the angle between the base material and butt weld reinforcement, the toe angle, not exceed 140 degrees.

Size effects count: the thicker the member, the lower the fatigue strength; and the smaller the weld relative to base plate thickness, the less this effect.

Keeping track of failures

A good way to check design practice is to follow service performance and to analyze causes of failures. The International Institute of Welding has been collecting data on failures since 1954. In a report to the Atlanta seminar, John Harrison, head of engineering research at TWI, reported results of this work, a study of 98 failures.

GRIND FILLETS TO IMPROVE FATIGUE LIFE



Specification for weld toe grinding and peening to improve fatigue strength, published by the Welding Institute, recommends grinding of the weld toe to 0.8 mm (0.03 in.) below the plate surface. The slight reduction in plate thickness is insignificant for plate thicker than 10 mm (0.4 in.).

The overwhelming number of these failures, Harrison found, occurred in rotating shafts where worn journals or corroded shafts had been machined down to a reduced diameter, built up by a weld overlay sometimes with a hard-surfacing finish, then remachined to the original diameter. IIW work shows that a weld-overlayed shaft suffers a 30-percent reduction in fatigue strength compared to a new shaft. Plasma spraying gives a much better result, reducing fatigue strength by only 4 percent.

FM predicts fatigue life

Geoff Booth, a senior research engineer in the fatigue section, reported on application of fracture mechanics principles to fatigue design, pointing out some of the limitations of fatigue design practice: S-N curves cannot help to determine the significance of a defect and whether it requires repair, nor can they provide a means of analyzing the process of fatigue failure. Fracture mechanics can do both, defining a tolerable flaw size, and therefore enabling assessment of the seriousness of a defect: it can determine reliable intervals for inspection. Booth's work applies fracture mechanics to fatigue life, treating small pre-existing discontinuities at the weld toe as the initial crack size and considering the fatigue stress range as the operative stress variable, to predict the service life of a joint in fatigue service.

What fabricators can do

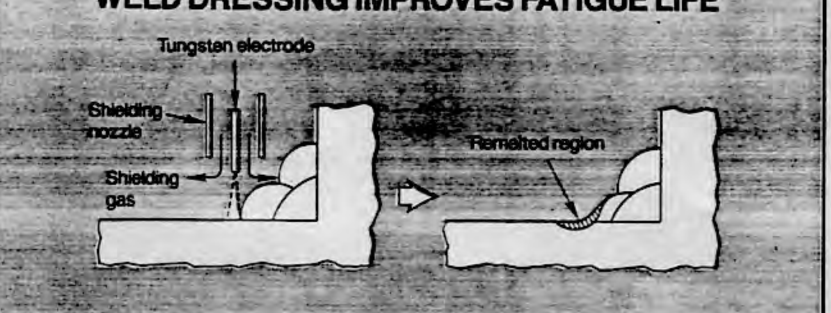
Knowing the general causes of fatigue failure, fabricators can treat welds to improve fatigue performance, as reported by Booth. Since the source of the trouble is at the weld toe, improvement techniques remove discontinuities there and smooth the transition between the weld metal and the parent plate.

Most commonly, workers grind the weld toe. The institute has quantified this operation, having published a *Specification for weld toe grinding and peening to improve fatigue strength.* The spec gives directions for burr and disc grinding and for hammer peening.

Grinding is effective enough to move full-penetration butt welds made from both sides, ground flush, up a rating or two in design codes. Fillet welds do not allow the same result, but following the TWI procedure improves fatigue service considerably.

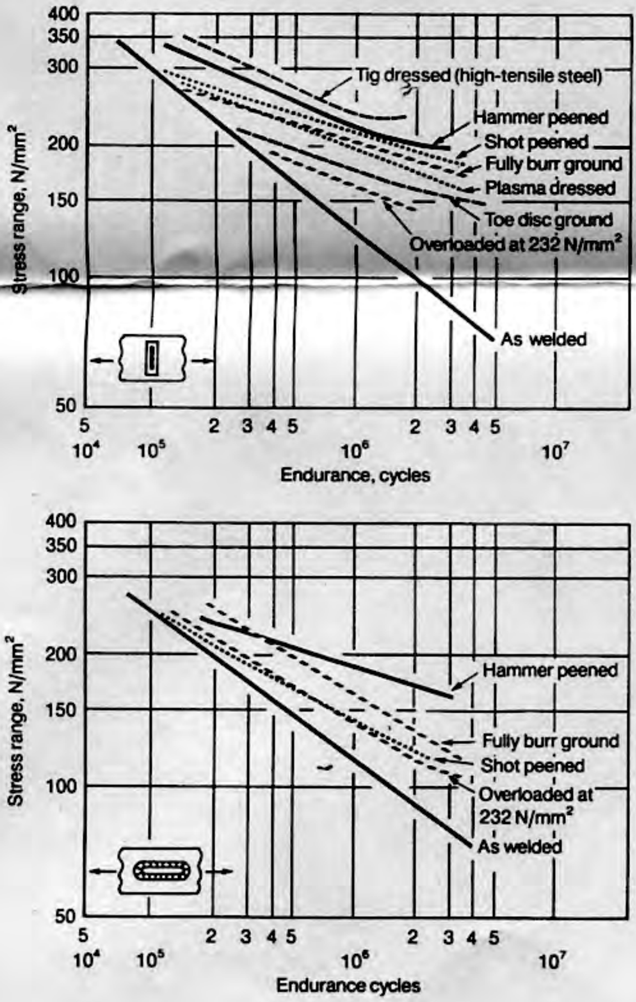
A more costly improvement

WELD DRESSING IMPROVES FATIGUE LIFE



Remelting weld metal to a shallow depth along the weld toe removes discontinuities and improves weld shape, to extend fatigue life. Plasma arc and gas tungsten arc are the processes used.

HAMMER PEENING BOOSTS FATIGUE LIFE



Test results show relative effectiveness of weld improvement methods. Hammer peening proves most effective. TWI cites four passes with a peening hammer along the weld toe as the best compromise between processing time and improvement in strength. The procedure should produce an indentation of 0.6 mm. (200 N/mm^2 = 29,000 lb/in.^{2})

procedure is remelting of the weld metal in the weld toe by gas tungsten arc or plasma arc. This removes intrusions and smooths in the toe contour. Applied to welds made by gas metal arc, submerged arc, or manual metal arc, this method requires careful positioning of the remelting arc. The GTA arc must come to within 1 millimetre (0.04 in.) of the toe; the PAW arc can be at plus or minus 3 millimetres (0.12 in.) of the toe.

Another way to improve the weld is to use special manual metal arc electrodes, made with a flux cover formulated to improve wetting of the metal, for final-pass welding of high-strength steel. Such electrodes, used widely in Japan, may not be suitable for out-of-position welding.

Modifying residual stress

Residual stress modification to improve fatigue life relies on the creation of compressive residual stress in the regions where fatigue cracks are likely to start. For tensile stress cycling, stress relief has no effect on fatigue life. Where at least part of the applied stress cycle is compressive, some improvement occurs after stress relief.

Peening is a proven fatigue-service-improver. Geoff Booth covered various methods of peening, including shot peening, needle peening, and hammer peening. This last has proven to be the most effective of the mechnical improvement methods and is even better than plasma dressing.

For any of these methods, improvements are greatest at low stresses, decreasing as stress level increases. However, for high-strength steels large improvements are possible because these steels can support high compressive stresses and therefore a larger part of the applied stress cycle can effectively be compressive. ■