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Improving the fatigue strength of welded joints by peening

Peening of weld toes can be a considerably faster and cheaper method of improving the fatigue strength of welded joints compared with grinding or remelting to remove defects. **S J Maddox** reviews the results of investigations to examine the effects of peening on the fatigue strength of joints, and considers how these methods can be implemented practically.

The presence of a weld in a member can drastically reduce its fatigue strength, as illustrated in Fig. 1, and it is usually found that design stresses in repeatedly loaded structures are limited by the fatigue strength of welded details. Not surprisingly, fatigue is still the major cause of service failures.

Rules exist which enable welded structures to be designed to avoid fatigue failure[1-3] but circumstances can arise which make it necessary or desirable to increase the fatigue strength of a particular weld detail. One method of doing this is to introduce compressive residual stresses by peening in the regions where fatigue cracking could initiate. The effectiveness of peening as a means of improving the fatigue strength of welded joints has been demonstrated in a number of investigations (*e.g.* ref. 4-8), as reviewed by Gurney[9] and Booth.[10] However, the techniques are not widely used and are not included in any fatigue design codes. This may reflect doubts surrounding the possible detrimental effects of peening or its long term service reliability, but equally the lack of clear specifications regarding the application and inspection of the techniques could be the reason for this state of affairs.

In this article, investigations of the effects of peening on the fatigue strength of welded joints are reviewed and the scope for introducing specifications for their practical application is considered.

FATIGUE OF WELDED JOINTS

Depending on the nature and orientation with respect to loading of a weld, there are a number of possible sites for the initiation of fatigue cracking. By far the most likely site is the weld toe. This represents a severe stress concentration, partly because of the abrupt change of section it introduces but also because, in steels, there are sharp inherent defects, in the form of non-metallic intrusions, at the toe,[11] (Fig. 2). Fatigue cracks readily initiate from such defects with the result that, in contrast to the fatigue behaviour of plain material, fatigue crack initiation occupies a negligible part of the fatigue life of a welded joint failing from the weld toe. The consequences of this have been discussed elsewhere.[12, 13] Apart from the obvious consequence, that of a low fatigue strength and low fatigue limit, a particularly important one, which is relevant to the present article, is that the fatigue strengths of welded joints are independent of material tensile strength.

Fatigue failure in most of the lower fatigue strength weld details is by fatigue crack propagation from a fillet weld toe. There is little scope for influencing the fatigue strength of such details when the weld is made and therefore if an increase in fatigue strength is required, a post weld improvement technique must be used.

WELD TOE IMPROVEMENT TECHNIQUES

Most weld toe improvement techniques rely on two principles. Probably the first principle to spring to mind, in view of the conditions revealed in Fig. 2, is to remove the inherent toe defects and to improve the local profile. These aims can be achieved by machining, or by grinding, or by remelting the weld toe using TIG or plasma arcs whereby considerable increases in fatigue strength can be achieved.[9, 10]

The second principle is to introduce compressive residual stresses at the weld toe to reduce the effective (*i.e.* tensile) part of the applied stress. This can be achieved by peening such that the surface is plastically deformed. Compressive residual stresses arise because the elastic material sub-surface resists lateral expansion of the surface. If the peening operation actually treats the sharp discontinuity at the toe, it is possible that it also reduces the severity of the stress concentration by reducing the sharpness of the notch.

There is no doubt that improvement techniques aimed at removing weld toe defects are more widely used than those which rely on the introduction of residual stresses. This situation exists probably because the benefits of the former are more readily apparent and it is easier to check that a weld has been treated correctly. As will be seen later, it is less certain that peening will be effective. However, greater improvements can be achieved by peening than by grinding or remelting the toe and, in general, the techniques are cheaper and often easier to apply. For example, Knight[5] found that hammer peening was twelve times quicker to carry out than a grinding technique which actually resulted in a slightly lower improvement in fatigue strength. Clearly, the potential benefits of peening of weld toes with a view to establishing standard procedures related to fatigue strength improvement merit further consideration.

PEENING OF WELD TOES

Peening can be carried out by hammering the surface (hammer peening) or by directing a high velocity stream of particles at it (shot peening).

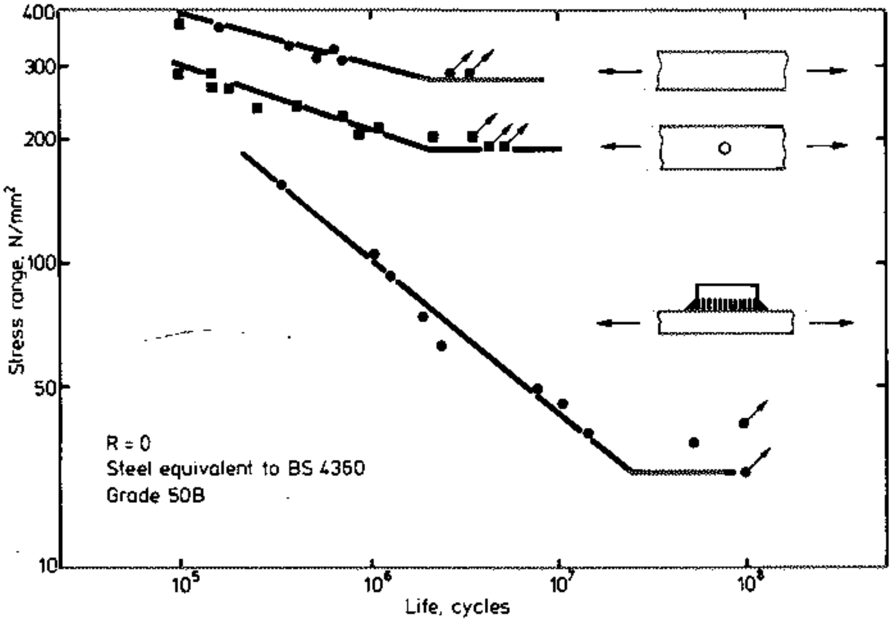
Hammer peening

Two hammer peening techniques appear to have been investigated, hammering with a solid tool and hammering with the ends of hard wires or needles bundled together, both hammers being operated either electrically or by compressed air. Recalling the sharp discontinuity at the weld toe (Fig. 2), a possible advantage of needle peening over solid tool hammer peening is that access to the toe would be more likely to be achieved with its smaller tip radius. Local treatment of weld toes was achieved by Nacher[14] using a needle peening tool composed of 3mm diameter wires. However, as discussed by Gurney[9] solid tool peening, carried out typically with a 12.5mm tip diameter tool, is usually found to be more effective because greater depths of deformation, and therefore higher compressive residual stresses, can be achieved. For this reason, the discussion that follows is confined to solid tool hammer peening.

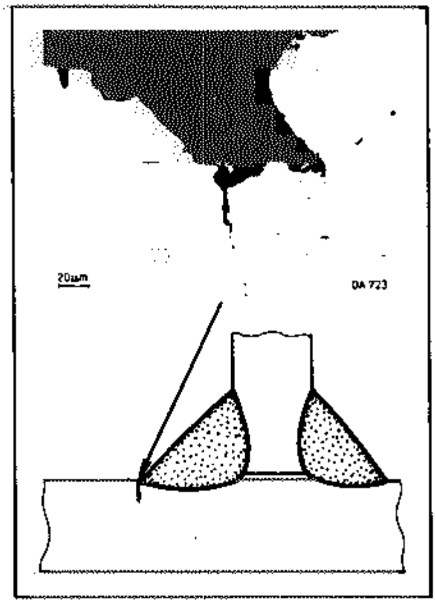
Shot peening

Strictly speaking, shot peening involves the battering of a surface with roughly spherical shot, typically 0.5-1mm in diameter, or short pieces of wire which become rounded during use, usually made of hardened cast steel, but possibly from stainless steel or glass.[15] Surface deformation can also be achieved by grit blasting.

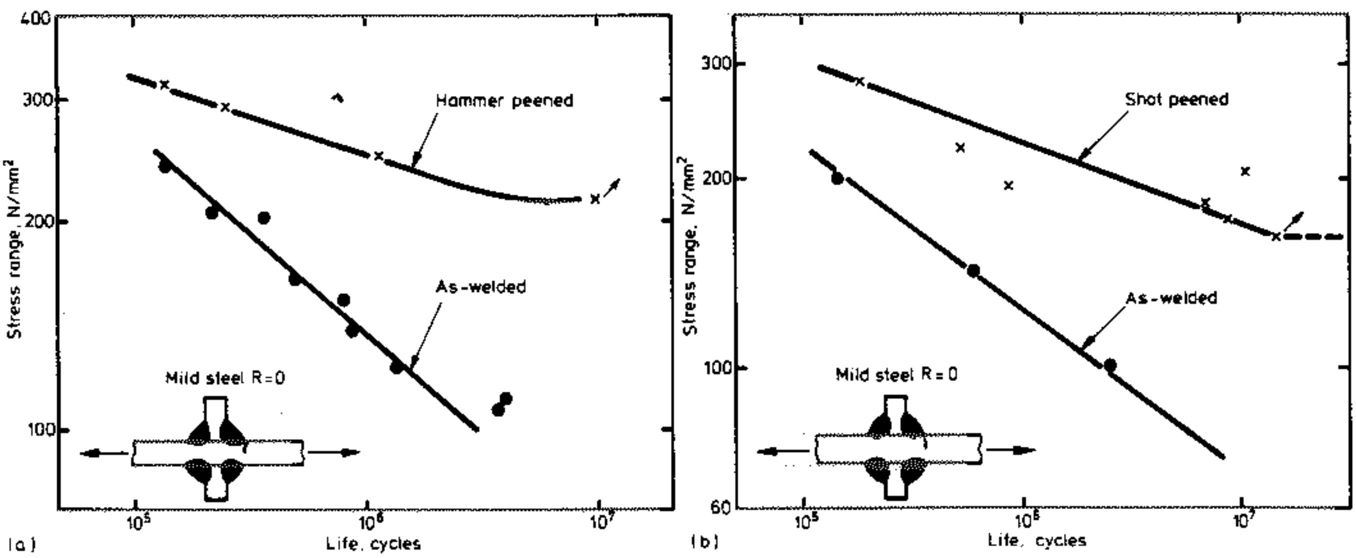
S J Maddox, BSc (Eng), PhD, DIC, CEng, MWeldI, MSEE, is Head of the Fatigue Department, at The Welding Institute, Abington.



1 Comparison between fatigue strengths of plain steel plate, notched plate and plate with fillet welded attachment.



2 Magnified view of toe of fillet weld in steel showing fatigue crack which has propagated from pre-existing non-metallic intrusion.



3 Effect of peening on the fatigue strength of a transverse non-load carrying fillet weld: *a)* hammer peening;[5] *b)* shot peening.[8]

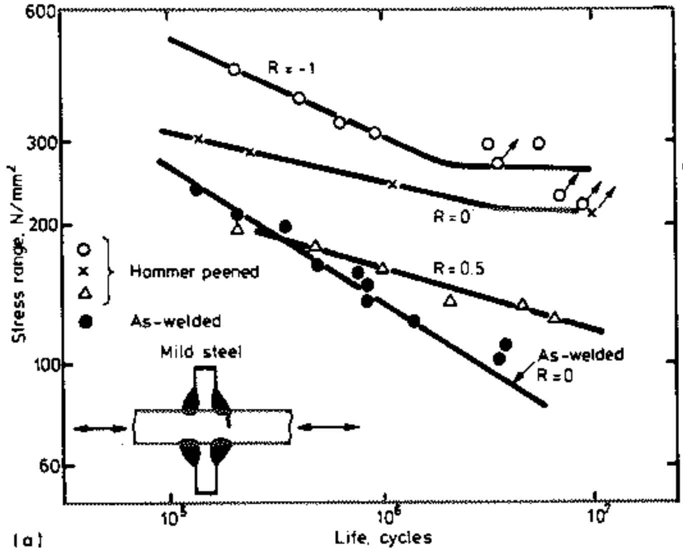
As with needle peening, shot peening should enable sharp discontinuities like the weld toe to be treated but, again, the degree of deformation achieved does not match that achieved by solid tool hammer peening.[9] However, shot peening may prove easier to control than hammer peening and, for repeated treatment of welded components in batches, partial automation should be possible.

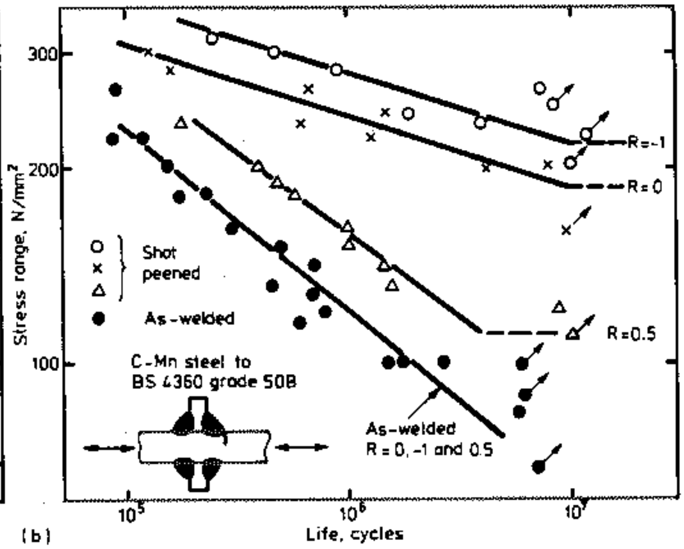
FATIGUE STRENGTH OF PEENED FILLET WELDS

An indication of the degree of improvement in fatigue strength resulting from solid tool hammer peening[5] and controlled shot peening[8] of transverse non-load carrying fillet welds in mild steel is shown in Fig. 3. In common with most fatigue strength improvement techniques, peening is most effective in the high cycle regime. Thus, it results in a rotation of the S-N curve for the untreated joint, the two curves converging at peak applied stresses near or above the yield strength of the material. This implies that, whereas the fatigue strength of as-welded joints (untreated and not stress relieved) is virtually independent of applied stress ratio, R $\left(\text{where } R=\frac{\text{minimum stress}}{\text{maximum stress}}\right)$, because of the influence of tensile residual stresses from welding,[9] the fatigue strength of peened joints depends on peak stress as well as stress range. This is confirmed in tests carried out at different R values (Fig. 4).[6, 8] Thus, peening is of particular benefit if the applied stress is partly compressive but may be virtually ineffective for fully tensile applied stresses at high values of R.

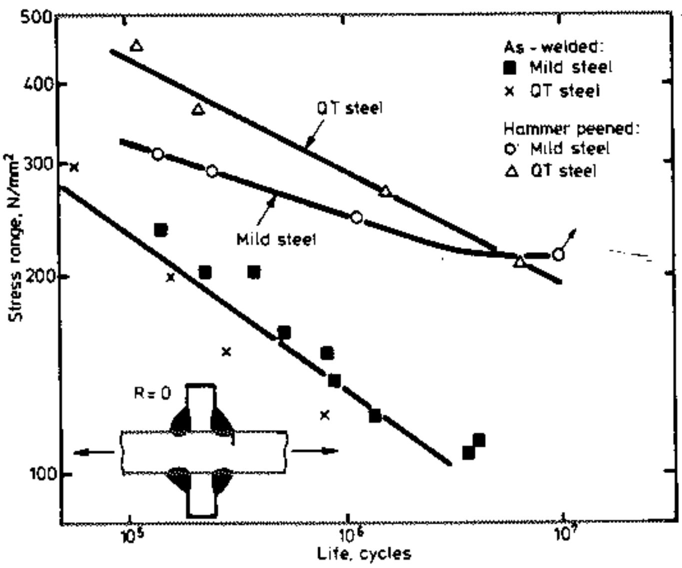
The above limitations, which suggest that peening will only improve fatigue strength significantly in the high-cycle ($>10^5$ cycles) regime for low positive or negative R values, should be less restrictive in the case of high strength materials, since peening should introduce higher compressive residual stresses than in low strength materials. This has been confirmed for both hammer[5] and shot[8] peening of steels, as illustrated for hammer peened fillet welds in Fig. 5. Thus, in contrast to the behaviour of as-welded joints, high strength steels offer some advantage from the fatigue viewpoint in the case of peened joints.

Similar circumstances arise in aluminium alloys. For example, results obtained

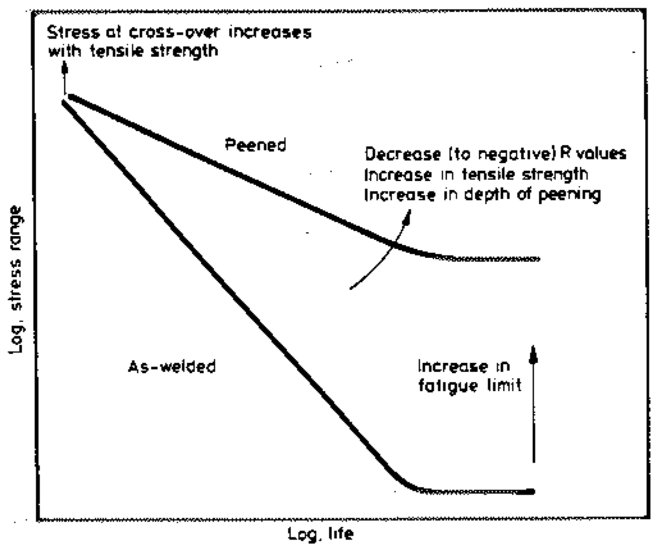




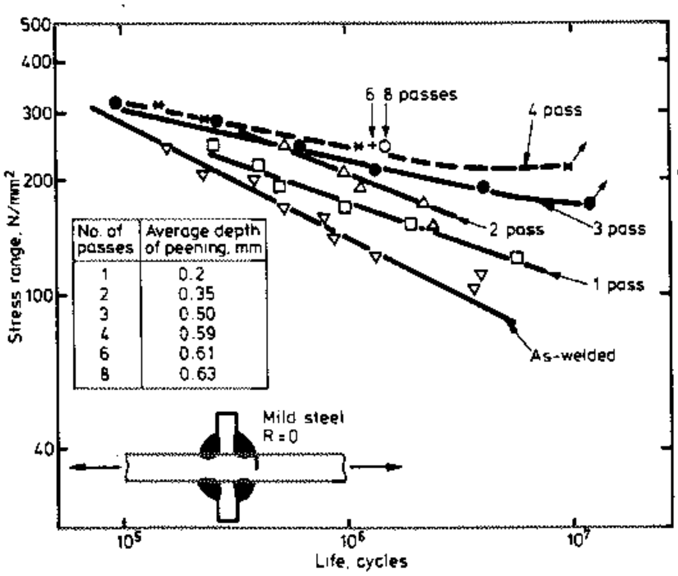
4 Effect of applied stress ratio (R) on fatigue strength of transverse non-load carrying fillet welds: *a)* hammer peened;[6] *b)* shot peened.[8]



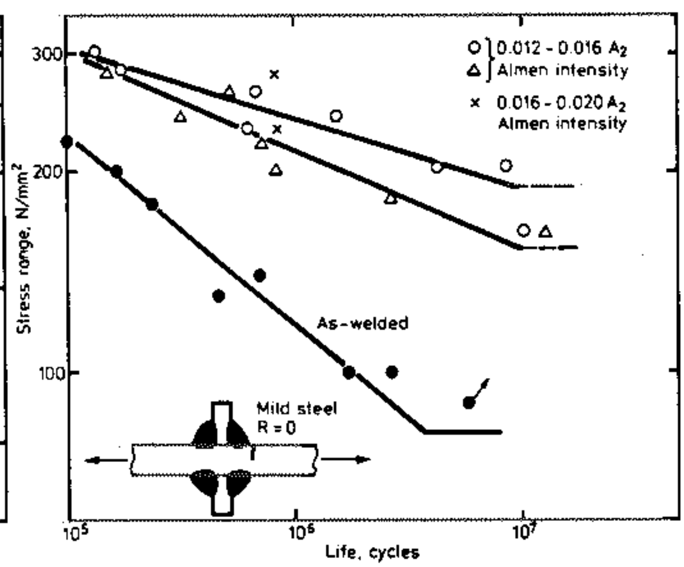
5 Fatigue strength of hammer peened transverse non-load carrying fillet welds in mild steel (245 N/mm² yield) and a quenched and tempered (QT) steel (685 N/mm² yield).[5]



6 Characteristics of the S-N curves for welded joints improved by peening the weld toes.



7 Effect of number of passes on peening depth and fatigue strength of hammer peened transverse non-load carrying fillet welds.[5]



8 Fatigue test results obtained from shot peened transverse non-load carrying fillet welds.[8]

under tension-tension loading from high strength Al-Zn-Mg alloy fillet welds[16] showed that hammer peening introduced significant benefits at endurances as low as 10^4 cycles since the applied peak stress was still only approximately 60% of proof stress.

Finally, referring to Fig. 3-5, it will be seen that if peening increases fatigue strength in the finite life regime, the fatigue limit is also increased. From a practical viewpoint, this may be the most significant benefit to arise from peening. The fatigue limit for as-welded fillet welds is so low that design for infinite life is rarely practicable. However, for conditions under which peening is effective, substantial increases to values which are effectively above the static design stress limitations for many structures can be achieved.

The features of the fatigue behaviour of peened welds described above are summarised in Fig. 6. Similar characteristics are found for peened aluminium alloy welds.[9, 16] A practical consideration which should be mentioned concerns the mode of failure of improved welds. As noted earlier, there are a number of potential sites for fatigue crack initiation in a welded joint, the weld toe being just one of them. Improvement of the toe does not necessarily guarantee improvement of the joint since failure may simply be transferred to another site with little improvement in fatigue life. This is especially true for load carrying welds, where fatigue cracking may initiate from the weld root or from buried defects, but even non-load carrying joints (*e.g.* attachments to stressed members) can fail from features other than the weld toe.[8, 16]

It will be clear from the results presented above that peening, particularly hammer peening, can bring about considerable improvements in the fatigue strength of welded joints. However, before advantage can be taken of such improvements, it is necessary to establish peening procedures which can be related reliably to improvement gained and quality control and inspection criteria which ensure that the required standard of treatment is achieved. Some factors which can influence the efficacy of peening are considered in the next section.

PRACTICAL APPLICATION OF PEENING TO IMPROVE FATIGUE STRENGTH

Hammer peening

To achieve full benefit from hammer peening it is necessary to ensure that the whole surface in potential regions of fatigue crack initiation is hammered. Pneumatic and electric hammers are usually heavy and cumbersome, and some physical effort is needed on the part of the operator to control their positions. As a result, the tool tends to jump and miss some regions, so to ensure full coverage, it is necessary to peen over a given area several times. Combined with this, repeated peening seems to influence the depth of deformation which, in turn, affects the level of compressive residual stress introduced. The effect of inadequate peening, which is reflected by the depth of deformation achieved, is illustrated in Fig. 7.[5] Based on these results, it would appear that the optimum conditions for hammer peening mild steel fillet welds are those which result in 0.6mm depth of penetration. In ref. 5 this was achieved using four passes of a 12.5mm tip diameter tool in a pneumatic hammer with a 40mm diameter piston operating at a pressure of approximately seven bars. Different conditions may be required for other steels or materials. For example, considerable benefit was obtained using three passes of a 12mm tip diameter tool in a pneumatic hammer with a 17.5mm diameter piston operating at seven bars, which resulted in approximately 0.3mm depth of deformation, on Al-Zn-Mg alloy fillet welds.[16]

Depth of deformation together with a visual check on coverage would seem to be the most practical method of checking hammer peening. Such inspection should also ensure that peening has not resulted in unfavourable features at the weld toe such as cracking or lapping. The latter has been experienced at The Welding Institute and resulted in a reduction in fatigue strength.

The fatigue test results quoted earlier were all obtained from transverse fillet welds. However, the technique could also be applied, perhaps more easily, to transverse butt welds. Greater difficulty is encountered if the ends of short or discontinuous fillet welds are to be treated, partly because the local weld shape tends to be less favourable but also because access may be restricted, for example at the end of a web to flange weld at a cope hole. The peening operation is facilitated if the weld is continued around the ends of the attachment plate.

Hammer peening trials have tended to be confined to downhand operations where the weight of the operator can provide assistance. Positional operation, which may be required for the treatment of structures in service, could prove to be more difficult. Another factor which might inhibit the application of the technique is the noise produced.

Shot peening

Much of the early work carried out to investigate shot peening of welded joints as an improvement technique was confined to grit blasting and the treatment conditions were not well defined.[17, 18] In those cases, the treatments did not prove to be particularly beneficial, the improvement in fatigue strength for R=0 being typically 30-40% at 2×10^6 cycles for transverse fillet welds and as little as 17% for the ends of longitudinal welds. These results did not encourage the use of grit blasting as an improvement technique. However, more recent work (unpublished) in which particular attention was paid to the grit type and peening conditions indicated that, potentially, grit blasting might be able to match shot peening; further work is needed to confirm this.

Controlled shot peening, on the other hand, has been found to be effective in producing significant improvements in the fatigue strength of butt[19] and fillet welds[8] in structural steels. Investigations at The Welding Institute are still in progress, one aim being to establish the peening conditions which introduce the greatest benefit. Work so far has highlighted the potential variation in benefit which can arise and has brought into question the value of the Almen strip as a means of describing the intensity of peening[8, 19] (see below).

Shot peening does not give rise to the readily measurable depths of deformation produced by hammer peening so another technique is required to check that particular conditions are correctly reproduced. Two factors are important: the intensity of peening and the coverage.

As with hammer peening, full coverage is usually achieved by shot peening over the surface more than once, the actual conditions being established by trials. Initially, full coverage can be checked by applying a dye, possibly one which is sensitive to ultraviolet light, to the surface before peening. Full coverage removes all traces of the dye so incomplete coverage can be detected visually.

The traditional way of expressing shot peening intensity is by the Almen strip. This is a strip of steel which is shot peened on one surface under the selected conditions. As a result of the deformation of that surface, the strip bends. The curvature induced, expressed in terms of the height of the arc, is assumed to be proportional to the intensity of peening. By standardising on the size of strip and the type of steel used to make it, it is assumed that the curvature is reproducible and can therefore be used as a quality control check on the intensity of peening.

The Almen strip is certainly attractive as a quality control aid because of its simplicity. However, recent work suggests that it may not be sufficient as a means of describing the required peening conditions. The results shown in Fig. 8 were obtained from similar welded joints shot peened at different times under conditions which gave the same Almen strip intensity of 0.012-0.016 A2 arc height, yet the improvements in fatigue strength were different. Results from welded joints shot peened to a higher Almen strip intensity, 0.016-0.020 A2 are also shown in Fig. 8, indicating no apparent additional benefit in terms of fatigue strength.

The comments made above about the hammer peening of longitudinal fillet weld ends also apply to shot peening. In fact, even if the weld is continued around the ends of the attachments, shot peening is not found to be as effective for treating this weld detail as when it is applied to transverse fillet welds.[8]

FUTURE DEVELOPMENTS

Additional work is required to establish quality control methods for ensuring that peening is carried out correctly, optimum peening conditions and the beneficial effects of peening. Existing knowledge is probably sufficient to enable recommendations for solid tool hammer peening of butt and fillet welds in structural steels to be established; however, further work is needed to ensure that the full potential of shot peening has been achieved.

Although fatigue tests have clearly demonstrated that both hammer and shot peening can introduce significant improvements in the fatigue strengths of welded joints, there are a number of aspects of peening and the behaviour of peened joints in service which require attention.

Behaviour under service loading

Virtually all investigations of the beneficial effect of peening on welded joints have been conducted under constant stress range loading. In practice, most real structures experience random loading. It is known that high stresses in a spectrum can cause modifications to the residual stresses in the vicinity of notches and, later, at the tip of the propagating fatigue crack; therefore compressive residual stresses introduced by peening could be partly relaxed under such conditions. Limited results obtained from steel fillet welds indicated that there is still an improvement in fatigue life from shot peening, the benefit appearing to depend on the maximum stress in the spectrum.[8] However, further work is needed in this important area.

Similarly, compressive residual stresses may be relaxed as a result of other factors associated with loading. An investigation into the effect of applied stress ratio on the fatigue strength of shot peened fillet welds[8] indicated that at high tensile mean stresses the residual stresses were relaxed. Thus, occasional increases in mean stress in a spectrum could reduce the benefit of peening. Sustained loading may also have the same effect; unpublished work at The Welding Institute has demonstrated this in relation to crack propagation across a cold-rolled steel plate.

Effect of corrosion

Both peening techniques rely on surface treatment and only a thin surface layer is affected. This is particularly true of shot peening, measurements indicating that the compressive residual stress only extends to a depth of around 0.5mm.[8] Thus, loss of material from the surface by corrosion could relax the residual stresses. Based on present knowledge, improvement techniques should only be applied to joints which can be adequately protected from corrosion.

Increased susceptibility to fracture

Hammer peening introduces considerable plastic deformation and concern has been expressed[20] that this will lead to a reduction in fracture toughness. Certainly, there is evidence of an increase in the brittle to ductile fracture transition temperature after heavy peening. The significance of this has not been investigated; considering the fact that compressive residual stresses are introduced, which will be beneficial from the point of view of both fatigue and fracture, it may not be a problem. However, in view of the risk, hammer peening should be applied with caution to structures likely to operate at low temperatures.

CONCLUSIONS

Both hammer and shot peening of weld toes can introduce significant increases in fatigue strength and fatigue limit, the benefit increasing with reduction in applied stress range, reduction in R (especially to negative values) and increases in material tensile strength. Hammer peening is usually more effective than shot peening.

Hammer peening seems to be easier to check than shot peening, on the basis of depth of deformation. Tests on mild steel fillet welds suggested that a depth of approximately 0,6mm would be sufficient and that this could be achieved using four passes. Shot peening introduces less deformation and another criterion for quality control checks will be required. The Almen strip intensity presently used may not be adequate.

There are still many gaps in the knowledge and further work is needed to determine suitable peening techniques for different weld details and materials. Also, factors which might inhibit any benefits of peening, particularly load spectrum and corrosive environments, must be investigated.

Acknowledgement

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Author Maddox S J

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A review of investigations on effects of peening to improve the fatigue strength of welded joints by introducing compressive residual stresses at the weld toe. Two techniques are described: hammer peening and shot peening. Data including S-N curves are presented to show effects of peening and applied stress ratio on fatigue strengths of transverse non-load carrying fillet welds in mild steel, quenched and tempered steel, and aluminium alloys. Practical applications of peening are discussed. Other aspects covered include behaviour in service, corrosion and increased susceptibility to fracture of peened welds.