The Fatigue Strength of Non-Load-Carrying Fillet Welds

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Introduction

It is well established that when a welded structure is subjected to dynamic service loads, any fatigue crack initiation that may occur is invariably associated with the geometrical discontinuities or notches in, or near, welded joints. It is also well known that the fatigue limit of plain (i.e. smooth, unnotched) steel specimens is a linear function of the Ultimate Tensile Strength (UTS) of the material. For plain specimens, with a UTS less than about 1 500 MPa, a fatigue limit of UTS/2 is often used as a general "rule of thumb"; however, it should be noted that the actual fraction of the UTS can vary between 0,23 and 0,65 [1]. For notched specimens, on the other hand, the linear relationship between fatigue limit and UTS is strongly dependent on notch acuity and specimen size. Furthermore, this linear relationship will only be applicable up to a UTS of about 540 MPa [1]. Although this latter value may be appropriate to some of the lower strength, weldable structural steels, if a designer were to calculate permissible dynamic service stresses for a welded structure from the UTS of the parent material, such a structure would have a very low period of operation!

Large, all-welded steel fans are used extensively for ventilation purposes in mines and for the supply of air to, and extraction of gas from, boilers in conventional coal-fired power stations. The particular fans under consideration here may be double or single inlet, are typically 3 m in diameter, with a rotating mass of up to 30 tons and operate at speeds in excess of 700 rpm. The fans are fabricated by welding the blades to the shroud plates and "centre sheet" (or "back sheet" in the case of a single inlet fan), and are stress-relieved prior to transporting to the site of operation. Once in position, the fans are statically balanced, which involves welding "balance pads" to the periphery of the shroud plate. These mild steel balance pads are typically three quarters the thickness of the shroud plate, and may be up to 600 mm in length, depending on the mass required for balancing. The fans are then checked for dynamic stability, and if any further balance pads are required, these are generally much smaller than the static weights. It should be emphasized here that this particular sequence of operations may not be followed for all fan types, or by other fan manufacturers.

The fans are designed such that the only appreciable source of cyclic stresses arise from start-stop conditions, and the dynamic stresses during operation are widely presumed to be less than 20 MPa. However, following a catastrophic failure of one of these fans [2], a comprehensive series of long term strain gauge tests were carried out on a similar fan during operation [3]. Results indicated that the cyclic stress ranges experienced under normal operating conditions were indeed below 20 MPa, although they could, in certain circumstances approach 33MPa. The mean stress during operation was measured at 150 MPa.

Initially, the balance pads were regularly stitch welded in position, as shown in figure 1(a), but these appeared to act as sites of stress concentration, since fatigue cracking which occurred in some of the fans were seen to be associated with these welds [2]. Accordingly, the fan's manufacturers introduced a specification

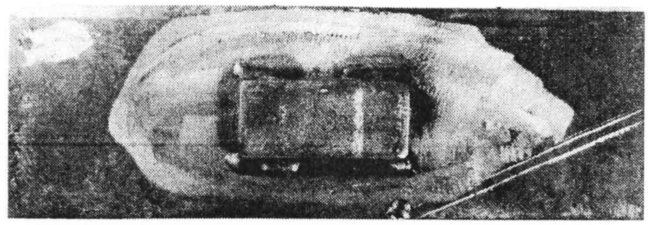

Figure 1 – (a) Specimen simulating the old stitch welded balance pad

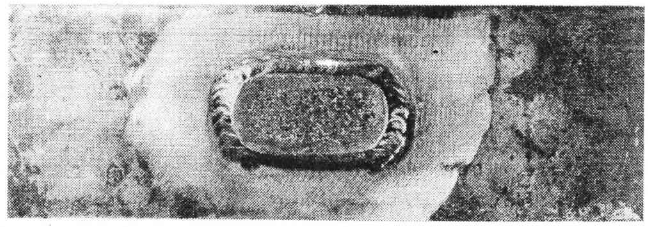

Figure 1 – (b) Specimen simulating the new continuous balance pad weld

for the welding of balance pads, which includes rounding the corners of the attachment, applying a local pre-heat of 150 °C, and welding continuously around the attachment, as shown in figure 1(b).

However, when applying the Welding Institute's Design Rules [4] to these two details, it was apparent that both welds would be classified as "G" type joints and were expected to have similar fatigue strengths. The graphical summary of these Design Rules is shown in figure 2, and it can be seen that at a stress range of 20 MPa, these G type joints would be expected to have a a fatigue life of less than 100 million cycles. Since in a year of continuous operation these fans can experience in excess of 300 million cycles, there was some considerable concern with regard to the origin of the fatigue cracking, and the fatigue behaviour of the balance pad weldments. An experimental test programme was therefore initiated to determine the fatigue strengths of the two details.

Experimental Procedure

Specimens were fabricated to simulate both the stitch and the continuous types of balance pad welds. The balance pad length was varied from 50 mm to 90 mm, since it has been shown [5] that the length of the welded attachment can affect the fatigue strength of the detail. The balance pad thickness and width were kept constant at 12 mm and 40 mm respectively, and the load carrying plates were 300 mm long, 100 mm wide and 16 mm thick. In all cases the welds were made using the Manual Metal Arc procedure, and a high tensile E7018 electrode.

Originally, these fans had been fabricated from ROQ-tuf AD 690, a low alloy quenched and tempered, weldable steel. The fans are now also being fabricated from BS 4360 Grade 55E steel, which has a considerably lower yield stress, and is more easily formed. (The specified compositional ranges and mechanical properties are shown in table 1 for both steel types). Accordingly, test samples were fabricated from both these steels, in order to perform a full evaluation of the fan problem, although it was not expected that the different steels would affect the results to any great extent. (It has previously been shown [6] that even considerable variations in material yield strength have little effect on the fatigue properties of an as-welded joint).

It was thought that the service dynamic stresses were due to bending of the shroud plate about the blade welds; accordingly the specimens were tested under four point bending, with the balance pad weld on the tensile surface, as shown schematically in figure 3. All specimens were tested in a 100 kN Amsler Vibrophore, fitted with a Howden load controller. The Amsler is an electromagnetic resonance machine, and test frequencies of be-

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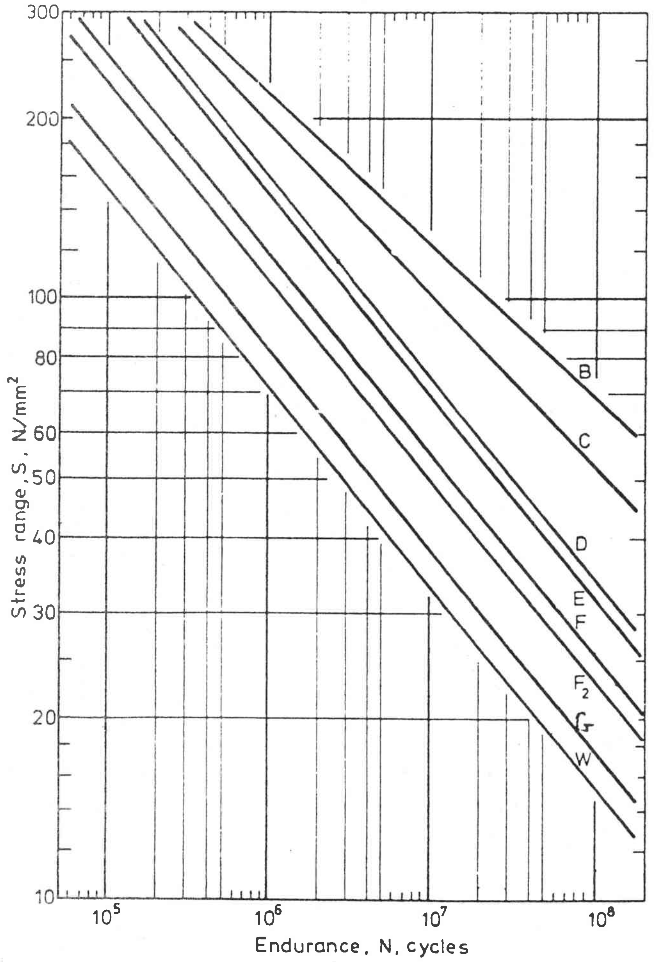

Figure 2 – A graphical summary of the fatigue Design Rules for welded joints, where each joint classification has a separate S-N curve

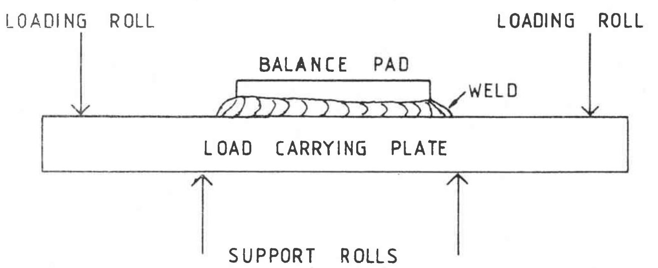

Figure 3 – A schematic diagram of the four point bend test fixture, note that the balance pad weld is on the tensile surface

tween 50 and 300 Hertz may be achieved, depending on the compliance of the specimen and loading arrangement. This "natural" test frequency can be decreased by about 40 Hertz by adding standard weights to the machine. The Howden control module will automatically maintain the required static load, and can be set such that it will trip out either after a pre-determined number of cycles, or due to a change in the test frequency. This latter feature was particularly useful since, as the fatigue crack initiated and grew in the specimen, the compliance of the specimen would increase, and the test frequency would decrease. Thus the test could be automatically stopped a short time after the initiation of the fatigue crack.

A typical test included an initial 50 000 cycles at a mean stress of 75 MPa and a stress range of 150 MPa, simulating the "start-stop" cycles experienced by the fan during commissioning and the subsequent service life-time. The mean stress was then increased to 150 MPa, and an initial dynamic stress range was chosen. The first test specimen (a stitch weld) was started at a stress range of 20 MPa, and after 10 million cycles (representing approximately 22 hours of testing at 130 Hertz) the stress range was increased to 30 MPa; this incremental increase in stress range was repeated every 10 million cycles, and cracking eventually initiated at a stress range of 120 MPa!

Quite apart from the unproductive nature of this extended test, it is likely that the large number of cycles at low stress ranges elevated the actual fatigue limit by the phenomenon of "coaxing". Thus, appreciable increases in the fatigue limits of strain-ageing materials have been observed after testing for long periods just below the fatigue limit [7]. Accordingly, in subsequent tests on as-welded specimens, an initial stress range of between 40 and 60 MPa was chosen, and this stress range was increased by 10 MPa every 10 million cycles until fatigue crack initiation occurred.

Initial results

The influence of weld procedure

Eight stitch welded specimens and ten continuously welded specimens were supplied for testing [8]. In this initial phase of the test programme, two stitch welded and two continuously welded specimens were strain gauged; these specimens were used to confirm that the magnitude of the actual stresses in the specimens, due to the applied bending loads, were consistent with those stresses calculated using beam theory [8].

It was found that the endurance limit of the stitch welded detail was 50 MPa for four of the six specimens tested. (The endurance limit is defined here as the lowest stress range that does not cause crack initiation in 10 million cycles). In the first specimen tested (T1), the atypically high initiation stress range of 120 MPa was most likely as a result of coaxing, as described in the preceding section. Specimen T13 also showed a slightly anomalous endurance limit of 70 MPa, this was ascribed to the inherent scatter in fatigue testing. The fatigue cracking in these six specimens occurred on both sides of the welded attachment, and initiation was typically subsurface, at the corner of the balance pad (as detailed in a companion paper to this [9]).

The results of the tests performed on the continuously welded samples indicated that there was some considerable scatter in the results, with four specimens (T2, T4, T10 and T12) having an endurance limit below 100 MPa, while the remaining four specimens (T3, T5, T9 and T11) showed an endurance limit in excess of 100 MPa. However, examination of the fracture surfaces indicated that the fatigue cracking in the four specimens with a low endurance limit had initiated from undercut defects at the weld toe [9]. The fatigue cracking in the specimens which had a relatively high endurance limit, on the other hand, was seen to initiate at several points, as evidenced by the presence of ratchet markings [9]. Such features are indicative of a low stress concentration, continuous around the weld toe, in relation to the very high, but localised, stress concentration of an undercut defect at a specific point along the weld toe. Unlike the stitch welded samples, fatigue cracking only occurred on one side of the balance pad in the continuously welded samples.

It was also evident from this series of tests that, whereas three of the four specimens in which undercut defects were seen to be present were fabricated from ROQ-tuf AD 690 steel, the four specimens which had endurance limits in excess of 100 MPa were all fabricated from the lower strength BS 4360 grade 55E steel. This could indicate that the 55E material is more weldable than the AD 690, but could also be entirely fortuitous. Thus, for the continuously welded samples, there are essentially two sets of results; those obtained from specimens that failed at low stress ranges due to the presence of undercut defects, and those which were defect free with a correspondingly higher endurance limit.

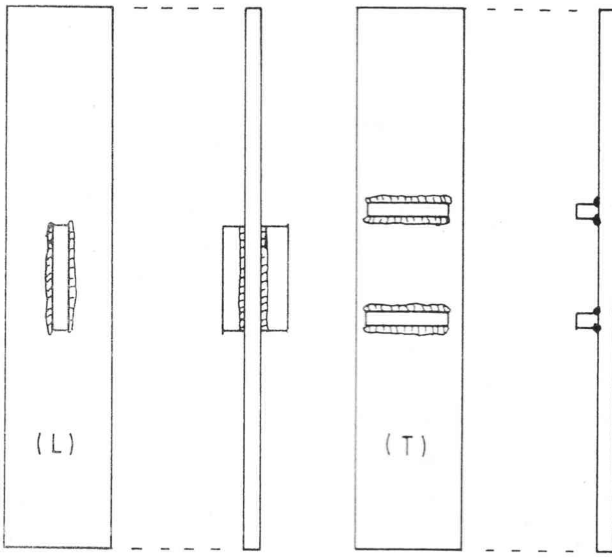

Figure 4 – The longitudinal (L) and transverse (T) welded stiffeners investigated by Gurney (12), note the similarity to the stitch and continuous type balance pad welds respectively

As early as 1960 it was shown that short sharp defects at the weld toe have a very significant effect on the subsequent fatigue life of a welded joint [10]. This early study investigated the fatigue strength of beams with stiffeners welded either transversely or longitudinally to the tension flange, as shown in figure 4. It was shown that for the longitudinal welds, the fatigue behaviour could be defined by a single S-N curve. For the transverse welded stiffeners, on the other hand, there were two discrete S-N curves, with weld toe undercut defects decreasing the endurance limit of this detail [10]. Comparing figure 4 with the welded details investigated in the present study (figure 1), it can be seen that the stitch welds have the same geometry as the longitudinal welded stiffeners. On the other hand, the weld in the transverse stiffeners is perpendicular to the applied stress direction, and therefore these specimens essentially have the same geometry as the continuous balance pad welds. Thus the present results are entirely consistent with this early work.

This effect was later examined in more detail, and in 1967 Signes et al. indicated that the presence of slag intrusions and undercut defects at the weld toe were responsible for the observed tendency of welded joints to exhibit a common fatigue strength, irrespective of base material yield strength. Indeed, this work [11] is regarded as the "classic" paper in this particular field of research. More recently, a stress concentration factor of 27 has been calculated [12] for undercut defects at the toe of a non-load-carrying fillet weld. Thus it was clear, both from the results of the present experimental work and from that of related work in this field, that the revised procedure for the welding of balance pads would only be effective in reducing the incidence of fatigue cracking if the continuous welds could be made without inducing undercut or slag intrusions at the weld toe.

Microstructural and mean stress effects

When this initial phase of the work was completed [8], a fatigue crack which had initiated from a balance pad weld was discovered during a routine inspection of an induced draft fan in a power station. It was apparent that, although the welding appeared to be continuous around the balance pad, it was not performed to the manufacturer's specification. The cracked portion was therefore cut out of the fan, and submitted for investigation [13]. A hardness traverse was performed across the weld, and it was seen that the peak hardness in the near-heat affected zone was in excess of 400 Vickers microhardness (figure 5). In addition, it was seen that the near-heat affected zone had a coarse martensitic microstructure, indicative of very high cooling rates. For comparative purposes, two of the continuously welded samples that had been tested as described previously were sectioned, and a hardness traverse was performed across these welds. These results are also shown in figure 5, and it is clear that the peak hardness in the specimen weldments do not exceed 350 Vickers microhardness. Furthermore the near-heat affected zone microstructures in these specimens were not fully martensitic, indicating a slower cooling rate. Thus, the balance pad welding performed on the fan was not representative of the continuously welded specimens supplied for testing. Accordingly, test specimens were welded in such a way as to simulate the on-site welding, including the use of a high welding current to promote undercut, in addition to cooling the test plates prior to welding to simulate the rapid heat-transfer that would be achieved in a fan balance pad weld, if a local preheat had not been applied.

Due to the urgency of the initial phase of this investigation, a slightly different fatigue testing programme was used. Firstly, as in the previous tests, 50 000 start-stop cycles at a stress range of 150 MPa were applied, and then the stress range was decreased to 20 MPa for 3 million cycles. Thereafter, the stress range was increased in increments of 10 MPa every 3 million cycles, until a stress range of 50 MPa was reached. The tests were terminated after 25 million cycles at this stress range, and the samples fractured by sharp impact after cooling in liquid nitrogen, and the fracture surfaces examined for evidence of fatigue cracking. It was evident from the results of these tests that there is a synergistic interaction between undercut defects and a hard heat affected zone, such that the 10 million cycle endurance limit of this detail could be decreased to 40 MPa (i.e. below that of the stitch welds). However, specimens welded so as to contain either undercut or a hard heat affected zone only, did not show any fatigue cracking after the 34 million cycle tests.

This phase of the test programme was later extended to include an investigation of the effects of any residual welding stresses [14]. It is clear that the levels of residual stresses in the fans is much greater than those in the small test specimens, since although these fans are given a stress-relief heat treatment, the balance pads are as-welded, and there would be more restraint in the fans than in the flat sample plates. There was some concern about this aspect, especially with regard to the fact that high residual stresses would tend to elevate the nominal mean stress and hence the R-ratio (which is defined as the minimum stress in the fatigue cycle, divided by the maximum stress). The fatigue design rules for welded steel joints [4] do not account for the level of mean stress or the R-ratio, and this would seem to contradict the generally accepted view that high strength, low toughness microstructures (such as those found in the near-heat affected zone in steel weldments) are strongly influenced by changes in R-ratio. Thus, for high strength, low toughness alloys, an increase in the R-ratio has been shown to increase the incidence of "static" modes of failure, thereby increasing the rate of fatigue crack propagation [15, 16]. Clearly, tensile residual welding stresses will increase the mean stress level, and as the mean stress is increased, the R-ratio increases, and this could act to lower the fatigue life.

Therefore, in order to assess the effect of tensile residual stresses on the fatigue performance of the balance pad welds, a series of tests were performed at elevated mean stress, such that the peak stress in the fatigue cycle was equivalent to the yield stress (440 MPa) of the parent plate material. (i.e. for a stress range of 40 MPa, a mean stress of 420 MPa was applied). For this series of tests, after the initial 50 000 start-stop loading cycles, the stress range was decreased to 20 MPa, and this stress range was increased in increments of 10 MPa every 10 million cycles until crack initiation occurred.

As described earlier in this section, these specimens had been welded without a preheat, such that a hard near-heat affected zone was formed, and at high welding currents to deliberately

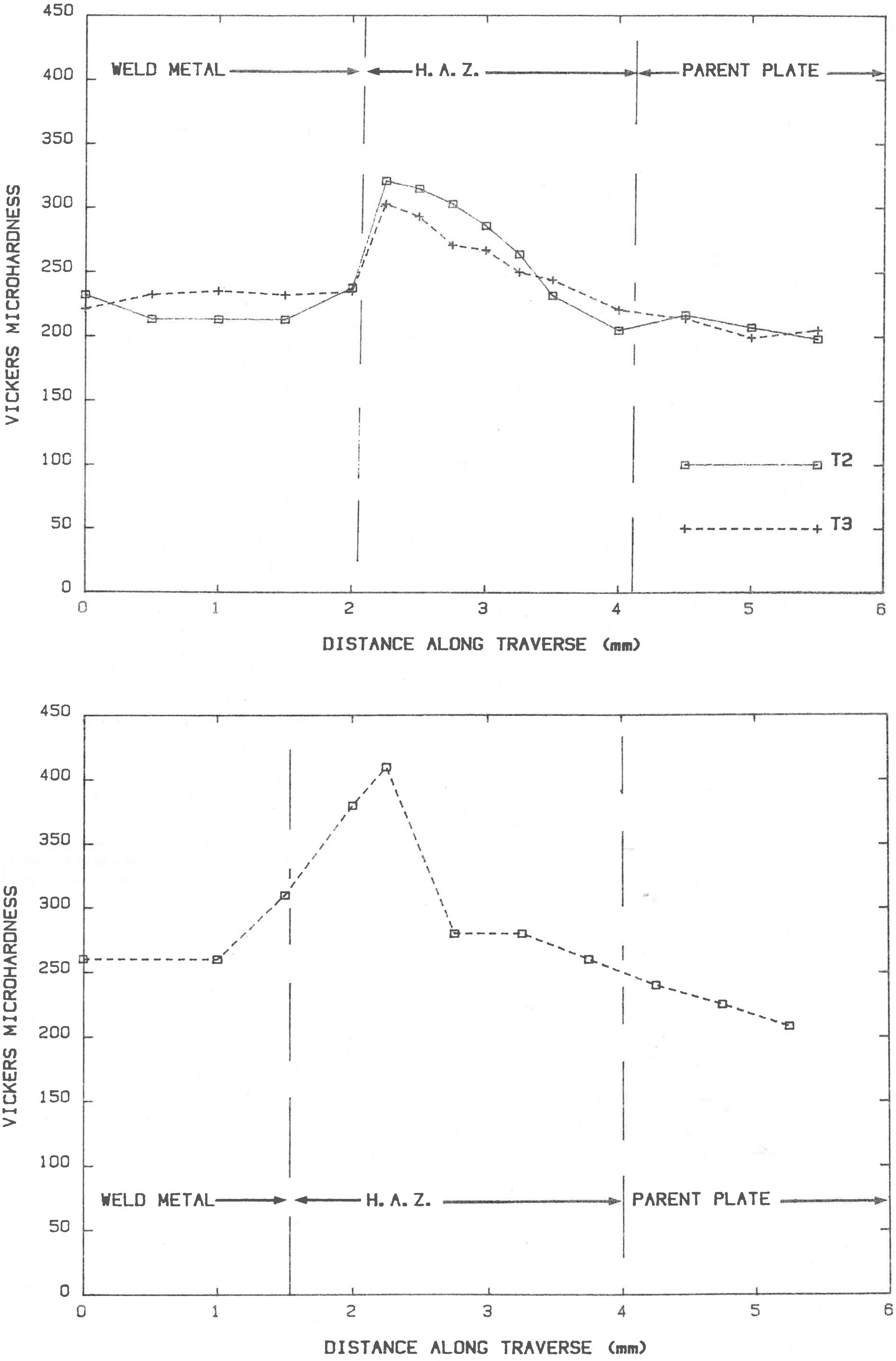

Figure 5 – A graphical summary of the results obtained in the microhardness traverses across (a) specimen balance pad weldments and (b) the service failure [13]

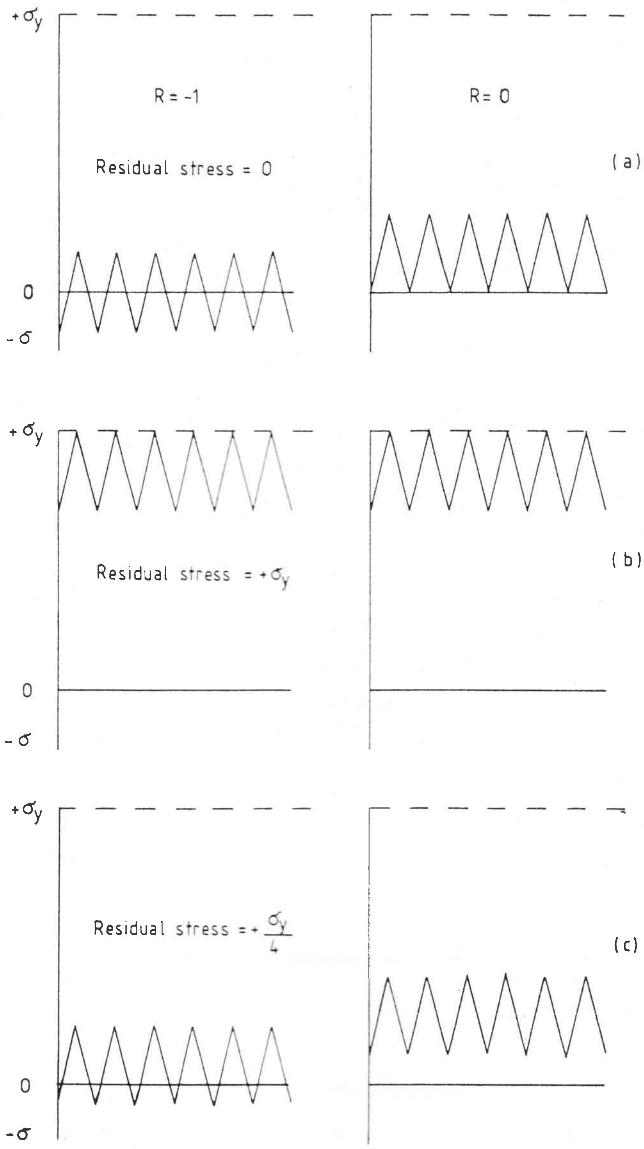

Figure 6 – A schematic illustration of (a) fully reversed and fully tensile loading, (b) the effect of a tensile residual stress and (c) the two loading conditions after a thermal stress relief

induce undercut defects. The results obtained in this phase of the test programme [14] indicated that, at high mean stress levels, the endurance limit of the (badly fabricated) continuous welds was 40 MPa. These results therefore confirmed the findings of the initial phase of this work; in addition to demonstrating that the high mean stress level (or magnitude of residual stresses) did not affect this endurance limit. Indeed, other researchers [17] have shown that the dominant parameter in the fatigue behaviour of a welded detail is the stress range, and that the mean stress does not affect the fatigue strength.

It is therefore pertinent to consider the advantages and limitations of stress relief by heat treatment. Two cases of fatigue loading are considered, as shown schematically in figure 6(a); fully reversed (R = −1), and fully tensile (R = 0). If the stress range is the same for the two different conditions, the fully reversed loading condition will be the least damaging, since the compressive portion of the applied loading cycle will not contribute to crack extension (figure 6(a)). However, it can be seen (figure 6(b)) that the effect of a tensile residual stress will be to increase the mean stress level, with the only limitation that the maximum stress in the fatigue cycle does not exceed the yield stress of the material. In this instance, the nominal fully reversed loading condition will be as damaging as the fully tensile condition.

It is estimated that, even after a heat-treatment stress relief, 10 to 25% of the welding residual stresses remain in a structure [18]. Thus, as shown in figure 6(c), even after such a stress relief, the nominally fully reversed loading may still be as damaging as the fully tensile conditon. It has been shown that only for fully reversed loading, where the stress ratio is −1, (i.e. applied loads always compressive) will stress-relieved joints generally have higher fatigue lives than as-welded joints [6]. For positive applied stress ratios (i.e. fully tensile loading), on the other hand, a heat-treatment stress relief had little effect [6]. This is the main reason why the Welding Institute (UK) favour mechanical dressing procedures such as grinding or peening rather than a heat treatment stress relief (which for a large structure may be prohibitively expensive). It must be emphasized that this argument is applicable specifically to increasing the fatigue strength of a welded structure; a heat treatment stress relief is often an effective procedure when potential problems of brittle fracture are under consideration. In such a situation the stress-relief will act to increase the level of static stresses required for fast facture; however the influence of this tempering treatment on microstructure and therefore properties must also be carefully evaluated.

It should further be pointed out that, when testing these welded samples at a mean stress of 150 MPa and a stress range of for example, 40 MPa, the R-ratio is 0,76. On the other hand, at a mean stress of 420 MPa, and the same stress range, the R-ratio is 0,91. This relatively small increase in R-ratio would not affect the fatigue strength of the detail to any great extent. This effect is probably also influenced by the fact that the high strength, low toughness microstructure is only a very small portion of the total extent of the weldment.

The effect of post-weld mechanical dressing

Clearly, it would be virtually impossible to reproducibly fabricate balance pad welds on site (where there may be restricted access to the weld area) without introducing any undercut defects at the weld toes. However, by grinding or hammer peening the weld toes, the surface defects can be easily removed, and a smoother weld profile is obtained. In addition, peening introduces compressive surface residual stresses, which further improve the fatigue strength of the welded joint. The cost-effectiveness of these and other weld dressing procedures have been the subject of some considerable research [19-22].

The choice between grinding and peening is usually made on the basis of adequate access to the detail. The pneumatic hammer typically used for peening must be directed at the weld toe, and more than a single pass is necessary to achieve the required degree of weld profile modification. The peening tool is hard to control unless the operator can use his body weight to maintain the tool on the weld toe. A grinding operation on the other hand can be carried out in areas of restricted access, and the only limitation to this method is that the residual grinding marks must be parallel with and not perpendicular to the principal direction of the applied stresses. The effectiveness of these two mechanical dressing techniques are well illustrated in figure 7, which indicates that 4-pass hammer peening (with a single point tool) provides the greatest improvement in fatigue life [20]. However, it must be pointed out here that the degree of peening is difficult to quantify and should be determined by the depth of deformation achieved. It has been suggested that the number of passes required to achieve 0,6 mm ± 0,1 mm depth of deformation on a trial piece should be used on the actual weldments [20]. Such trial pieces are also of considerable use in post-fabrication inspections of the finished component, where they will provide an immediate visual comparison for the condition of the actual weldments.

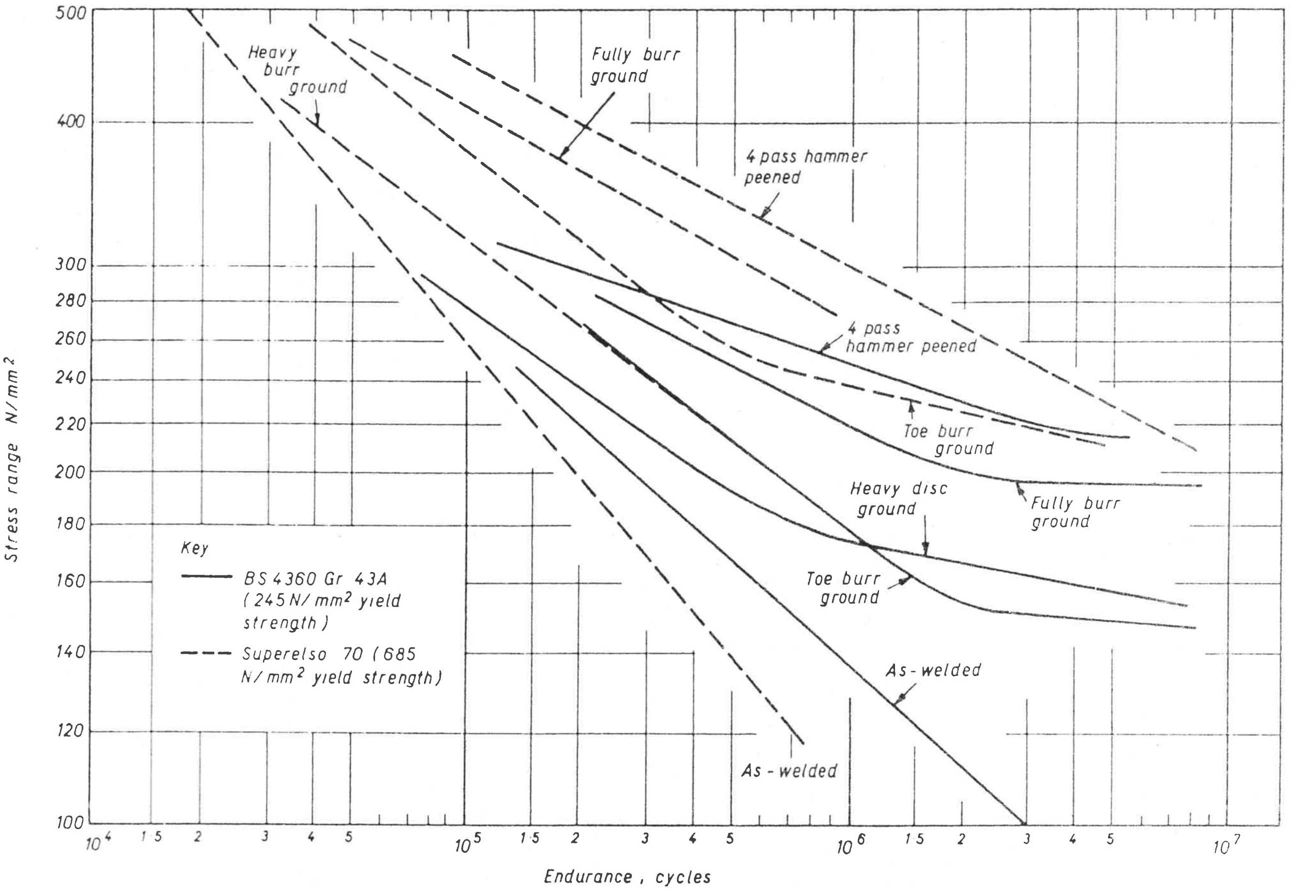

Figure 7 – A comparison of the effects of grinding and peening on the fatigue strength of fillet welded joints (from [20])

Ground specimens

A total of six specimens, in which the continuous welds had been burr-ground, were supplied for testing. Three of the test specimens were fabricated from BS 4360 grade 55E, and three from the higher strength ROQ-tuf AD 690. It had been proposed by the fan manufacturers that a weld fabricated using a 309 L austenitic stainless steel electrode would help eliminate any potential hydrogen pick-up by the carbon manganese base material. Accordingly, two of the ground specimens (one 55E and one AD 960) were made using the 309 L electrode such that the fatigue strength of this detail could be evaluated.

The results of the fatigue tests performed on the six ground welds showed that the 10 million cycle endurance limit was more than 150 MPa, thus there is a significant improvement in fatigue strength, compared to the as-welded specimens. It was also evident that the 309 L welds did not have a great effect on the fatigue strength of this detail although one of the 309L welds (specimen T27) recorded the lowest crack initiation stress range of 150 MPa. However, examination of the fracture surface indicated that initiation had occurred from a small surface defect near the weld toe, whereas in the other five ground specimens, the initiation site was removed from the weld toe to the weld root [9]. This is considered a crucial point; if the weld dressing is not adequately performed, the fatigue strength of the detail may not be affected. However, an endurance limit of 160 MPa can be obtained if the welds are properly ground. The anomalous result obtained for specimen T15 is due to the fact that this test was started at a stress range of 60 MPa, and the actual endurance limit of the detail was most likely enhanced by coaxing. (Subsequent tests on the dressed specimens were started at an initial stress range of 150 MPa).

Peened specimens

A total of nine continuously welded specimens were supplied for testing; the weld toes of these welds had been peened using three passes with a single point (10 mm diameter) pneumatic hammer. Five of these specimens were fabricated using the E7018 electrode (three from 55E and two from AD 690), and four using the 309 L electrode (two 55E and two AD 690). These tests indicated that cold-working of the weld toe has a very significant effect on the subsequent fatigue strength of this detail, such that the endurance limit was increased to at least 200 MPa. It was also evident that the peening operation must be carried out with some considerable care; if the tool is not directed accurately onto the weld toe, initiation can still occur from weld toe defects, as was the case in specimens T23 and T29 [9]. However, at the high stress ranges applied to some specimens (eg T22 and T24), crack initiation was observed to occur from the flame cut edge of the load bearing plate, remote from the weld. (It has been shown [1] that micro-cracks can originate at plate edges from even high quality gas-cutting).

However, the fatigue strength of the peened detail was shown to be well in excess of that obtained for the as-welded specimens, provided the weld toe is sufficiently cold worked, and that there were no other preferential crack initiation sites in the vicinity of the weld. Anomalously high values recorded for specimens T19 (250 MPa) and T20 (280 MPa) were again due to a large number of cycles below the endurance limit of the detail. The results of this series of tests also indicated that the 309 L stainless steel weld (specimens T24 to T29) does not affect the fatigue strength of this detail to any great extent.

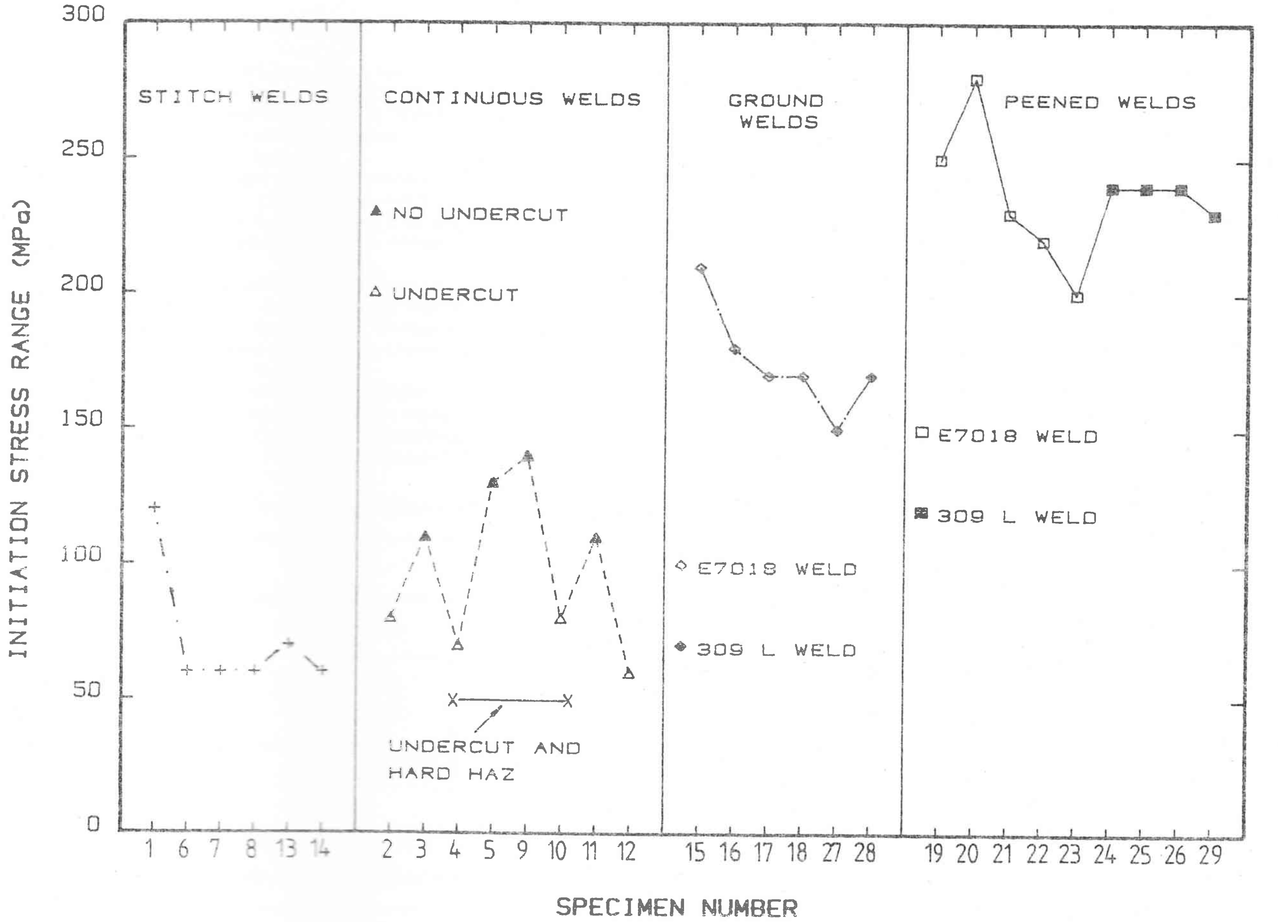

Figure 8 – A graphical summary of the results obtained in the fatigue tests, clearly illustrating the beneficial effects of post-weld mechanical dressing

Concluding remarks

This paper has shown how the fatigue strength of non-load carrying fillet welds can be significantly improved by cost-effective procedures such as grinding and hammer peening. The results obtained in the test programme are summarised in figure 8, where it can be seen that the endurance limit of the stitch and continuously welded specimens is 50 MPa. In the case of the continous welds, which were thought to represent an improvement over the stitch welded detail, small undercut defects at the weld toes led to fatigue crack initiation at relatively low stress ranges. If these welds are poorly fabricated, i.e. using high welding currents and welding without pre-heat, a hard near-heat affected zone acts synergistically with the undercut defects to lower the endurance limit to 40 MPa. This endurance limit was not further decreased by testing at a high mean stress level, thus indicating that welding residual stresses have little effect on the fatigue life of structures. However, reducing the level of the residual stresses by heat treatment may be an effective method of increasing the tolerance of a welded structure to brittle fracture.

Effective removal of the preferential crack initiation sites at the weld toes by grinding increases the endurance limit of this detail to 160 MPa. If the weld toe is effectively cold worked by peening, such that the preferential crack initiation sites are removed and a residual surface compressive stress is generated, the endurance limit is increased to more than 200 MPa. At these high stress ranges, however, cracking can initiate from flame cut edges remote from the weld.

Both mechanical dressing techniques should be implemented with care, however. In the limited number of specimens tested in this work, two peened specimens and one of the ground specimens failed early on in the tests; with fatigue cracks having initiated at defects still present at the weld toes after the dressing procedures had been carried out. This therefore indicates that the practical implementation of these dressing techniques must not be followed by an arbitrary increase in the operating stresses, without appropriate controls and periodic in-service inspections.

Acknowledgements

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Table 1 (a) Specified compositional ranges of ROQ-tuf AD690 and BS 4360 grade 55E steels.

Steel	% Composition (maxima unless range stated).							
	C	Mn	Si	P	S	Nb	V	Mo
ROQ-tuf AD 690	.12-.21	.45-.70	.20-.35	.035	.04	–	–	.50-.65
BS 4360 55E	.22	1.6	.10-.60	.04	.04	.003-.10	.003-.20	–

Table 1 (b) Specified mechanical properties of ROQ-tuf AD690 and BS 4360 grade 55E steels.

Steel	Specified properties (minima unless range stated).		
	Yield Stress (MPa)	Tensile Strength (MPa)	Charpy Impact Energy (J)
ROQ-tuf AD690	690	760-895	
BS 4360 55E	450	550-700	61 (at −20 °C)