Fatigue strength of shafts reclaimed by welding

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Abstract

Reclamation of components by welding is well established, and considerable work has been done previously on the fatigue strength of built-up shafts. The general conclusion of this work was that the fatigue strength was generally lower for a built-up shaft, although some work has claimed that mild steel shafts could give the same strength as the base metal if care is taken in welding. However, control of welding processes has improved over the last 20 years and welding consumables have been subject to ongoing development. Equally, for the case of cracked shafts, thick layers of weld metal may now be deposited. These factors have prompted a reassessment of the current situation, and the present study indicates that normalised medium carbon steels may show a higher fatigue strength than the base metal after weld build up, whilst quenched and tempered higher alloy steels may show only a small reduction in fatigue strength if post-weld heat treatment is performed.

Nomenclature

R	stress ratio $\sigma_{\mathrm{min}}/\sigma_{\mathrm{max}}$
S_{a}	variable normal stress
UTS	ultimate tensile stress
σ_{a}	allowable variable stress
σ_{m}	mean stress
σ_{min}	minimum tensile stress
σ_{max}	maximum tensile stress

Introduction

It is often desired to reclaim components, particularly shafts, by building up with weld metal, either because of wear or corrosion damage to the surface, or when a fatigue crack is detected during service. Justifications for reclamation, rather than replacement, include economic arguments, the time that may be required to obtain a replacement, downtime considerations (it may be advantageous to quickly repair the component and run it until the next scheduled maintenance period, when a replacement can be commissioned with minimum disruption) and the possibility of increased wear or corrosion resistance from the weld deposit.

Because of these advantages, and as shaft design is often fatigue dominated, a considerable amount of work was done on the fatigue strength of welded steel shafts from the late 1950s to the middle 1970s. The International Institute of Welding was particularly involved in these studies,[1; 2; 3; 4; 5] although other workers also contributed to the knowledge base.[6]

The paper by Dawes [3] is particularly useful, as it summarises the results of 16 studies conducted throughout the world and draws some general conclusions, which form the starting point of the present work. These studies covered both fusion welding and metal spraying and all reached the same general conclusion that the fatigue strength of reclaimed shafts is invariably reduced relative to that of the shaft in its original state. It is worth noting that Newman & Gurney [2] claimed that mild steel shafts could, with care, be welded to give fatigue strengths comparable with the unwelded shaft.

Reclamation by arc welding

Considering firstly reclamation by arc welding, fatigue strength reductions found with welded shafts ranged from 23% to 79% compared with the unwelded state. In all cases these low strengths were a result of crack initiation at weld defects, often associated with stop/start positions. Gas porosity was the most common defect, although slag inclusions, incomplete penetration, lack of fusion and heat-affected zone (HAZ) cracking were also observed. The worst strengths were always associated with manual metal arc welding. Automatic welding was the most reliable reclamation method, and little advantage was observed between gas shielded metal arc and submerged arc welding, provided that care was taken to ensure sound weld deposits.

The arrangement of weld beads was a strong influence on fatigue strength, as a result of the greater tendency for defects to occur at stop/start and overlap positions. Two- or three-start spiral welding was found to be preferable to either close spiral or longitudinal welding. Preheating of the shaft tended to reduce gas porosity, to lower the susceptibility to cracking of higher strength steels, and to reduce residual stress levels.

Post-weld stress relief by heat treatment appeared to offer only a relatively small improvement in fatigue strength (a maximum of 25% of that of the unwelded shaft, and often only 10%), whilst preheating medium carbon steel to around 300°C gave a marked reduction in residual stresses (50%).

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Reclamation by metal spraying

Metal spraying was found to give relatively small reductions in fatigue strength (~ 4% to 8%), provided that initial surface preparation was acceptable (which is reflected in adhesion bond strength).[5] Typical surface preparation involves shot blasting immediately after preheating and spraying with a bonding layer (usually molybdenum or a nickel-base alloy) to give better adhesion of the sprayed deposit. Plasma spraying appeared to offer a better combination of fatigue strength and adhesion strength than either electric arc or oxy-acetylene spraying.

Present work

Two factors prompt a reassessment of the current situation regarding reclamation by arc welding; firstly, the improved control of welding processes and ongoing development of welding consumables that have taken place over the last 20 years and, secondly, it is becoming more commonplace to reclaim cracked shafts of large diameter, in which a considerable depth of metal (~ 10s of millimetres) may have to be removed prior to building up of the shaft and machining back to the original size. Thus, in such cases, the weld layer may be much thicker than the typical sizes (1–3 mm) considered in the earlier studies.

This paper, then, reports the results of an investigation into the fatigue strength of normalised EN 8 steel (080M40 in BS 970 Part 1 1983) shafts reclaimed by submerged arc welding. EN 8 is a plain carbon steel often used for the manufacture of shafts. The cases of both thin and thick layers of deposited weld metal were considered.

Experimental details

Shafts generally experience bending and torsional loading. As the fatigue strengths in bending and torsion are simply related in steels and other ductile metal, specimens tested in bending will provide an adequate characterisation of the effect of weld build up on the fatigue life of shafts.

Economics dictated against the use of full-size rotating bend specimens, hence most of the tests were performed on small square section specimens tested in 4-point bend under tension–tension loading. These specimens were manufactured by depositing weld metal circumferentially onto a 100 mm diameter EN 8 bar over a length of some 120 mm. Initially 2 mm was machined off the surface of the bar, and then multipass submerged arc welding was used to build up a weld layer either 3 mm or 10 mm in depth.

In the case of the thinner layer, weld metal was machined off to just expose the weld metal/HAZ interface, whilst the thicker layer was only skimmed to give a smooth surface. These two different preparations were intended to provide specimens giving data on the fatigue strength of the interface region and of the weld metal; i.e. to be representative, respectively, of the case where superficial corrosion or wear damage is repaired with a thin built-up layer, and the case where a deeper weld deposit is required to repair a cracked component. The centre of the bar was then machined out to leave a 'doughnut' from which square section bend bar specimens about 10 × 10 × 80 mm could be cut.

Clearly this manufacturing sequence destroyed the residual stress distribution attendant on welding. Three steps were therefore taken to assess the residual stress effect on the fatigue strength:

1. Testing of the bend bars was done at a stress ratio of 0.1, rather than in reversed bending, as the main effect of residual stresses on fatigue crack behaviour is to raise the local stress ratio. Stress ratio R is defined as $\sigma_{\text{min}}/\sigma_{\text{max}}$ and is a measure of mean stress in the fatigue cycle, hence positive R values correspond to high mean stress levels.

2. Specimens were cut from built-up bars in both the as-welded condition and after post-weld stress relief at temperatures of 350°C and 650°C.

3. As-welded specimens 25 mm in diameter were tested in tension–compression loading at $R = -1$, in both the as-welded condition and after a 350°C stress relief heat treatment.

As well as showing the effect of residual stresses on the fatigue strength, these latter tests had an additional purpose; that of applying a uniform stress throughout the cross-section of the specimens, and thus providing a complete assessment of the influence of the weld layer in crack initiation. Bending, in contrast, produces a peak stress in the surface region and is likely to activate only near-surface defects. Welding on the tensile specimens was done after rough machining, and a single weld run was applied which started and terminated on the larger diameter ends. Final machining to size was then performed.

Specimen dimensions are shown in Figure 1. The small bend bar specimens were tested at 150 Hz using an Amsler Vibrophore eletromagnetic testing machine, whilst the larger tensile specimens were tested at 20 Hz using a servohydraulic testing machine in load control.

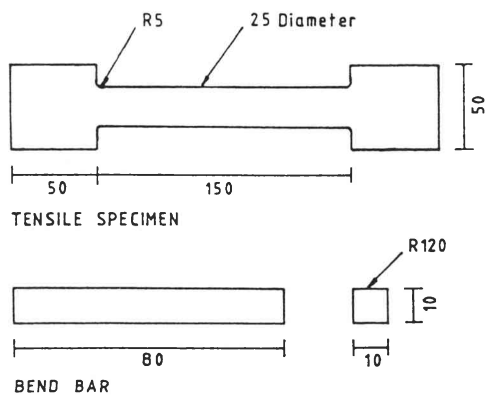

Figure 1

Welding details

These were constant for all the EN 8 specimens and are given in Table 1.

Table 1 Details of the welding process

Wire specification	AWS A5.28
Wire classification	ER 80 SG
Wire diameter	1.2 mm
Current	150 – 180 A
Voltage	26 V
Welding speed	25 mm/s
Preheat temperature	150°C
Maximum interpass temperature	300°C

Preheating was done by flame and extended approximately 100 mm either side of the region to be welded. Specimens were slowly cooled after welding under insulation.

Where post-weld heat treatment was used, the heating and cooling rates were 55°C / h and time at temperature was 1 h per 25 mm diameter.

Mechanical properties

Average values of tensile strength and Vickers hardness (500 gf load) are given in Table 2.

Table 2 Average mechanical properties

EN 8	UTS (MPa)	Hardness (Vickers)
Normalised	625	175
As-welded (HAZ)	–	203
SR 350°C (HAZ)	–	191
SR 650°C (HAZ)	–	188
Weld metal		
As-welded	746	283
SR 350°C	726	266
SR 650°C	711	257

Results and discussion

The main results of this test programme are shown in Figures 2 to 5. Figure 2 compares fatigue strength data for all specimens, i.e. relating to the unwelded EN 8, the weld metal (relevant to thicker built-up layers), the weld metal / HAZ interface region (relevant to thinner layers) and the tension–compression loading. These latter data have been transformed to allow a sensible comparison to be made between $R = -1$ tensile loading and $R = 0.1$ bend loading.

In essence, a mean stress correction has been applied based on Goodman's rule, i.e.:

$$\sigma_a = S_a \left[1 - \frac{\sigma_m}{UTS}\right] \qquad (1)$$

For $R = 0.1$ σ_a can be replaced by 0.45 σ_{max} and σ_m by 0.55 σ_{max} and the equation rearranged to give:

$$\sigma_{max} = \frac{S_a}{0.45 + S_a\left(\frac{0.55}{UTS}\right)} \qquad (2)$$

This value of maximum stress is then multiplied by the stress concentration factor for the tensile specimen (as fracture always started at the shoulder), given as 1.56 in Peterson,[7] and by 0.9 to give the stress range at $R = 0.1$. Generally speaking, a correction factor would have to be applied to fatigue strength values in tension to convert them to bend, because of the greater volume of highly stressed material in the tension case. In the present situation, as crack initiation was invariably at the specimen surface, this is not required. Although only an approximation (as the Goodman relation is only approximately correct) this conversion technique should provide a reasonable gauge of the effect of residual stresses. Note that the tension–compression test data in Figure 2 relate only to the as-welded condition.

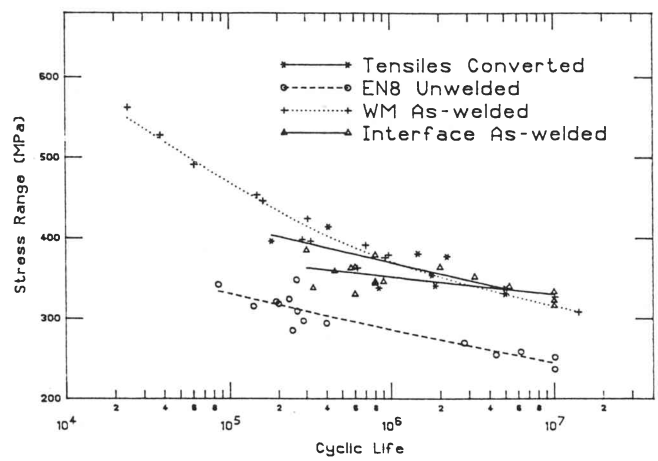

Figure 2

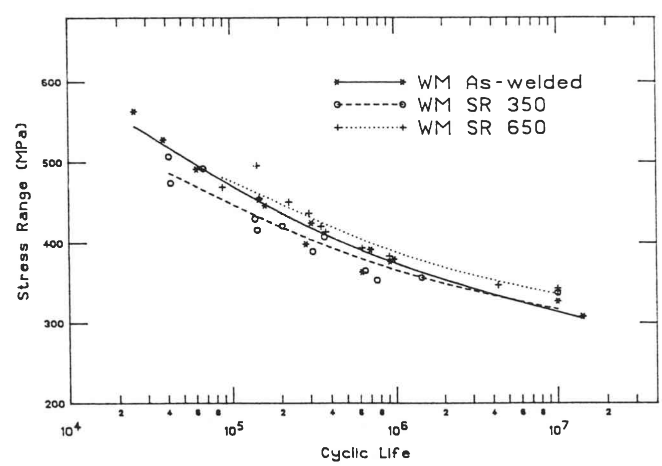

Figure 3

Trend lines have been fitted to the individual datasets in Figure 2, but it must be recognised that the number of data points is too small for these to be definitive. Nonetheless, two interesting conclusions can be drawn from this figure; firstly, for life values of service interest (> 10^6 cycles) the fatigue strength of all welded specimens is higher than that of the unwelded EN 8. Secondly, the fatigue strength of the interface specimens is generally lower than that of the weld metal specimens. Also, scatter appears to be more marked in the data from the weld metal / HAZ interface and tensile specimens. This presumably reflects the influence of the more variable microstructure in these specimens and, in the latter case, the presence of residual stresses. However, the converted tensile data lie in the same scatter band as those from the bend specimens, implying that the effect of residual stresses on fatigue strength is likely to be low for the given welding conditions.

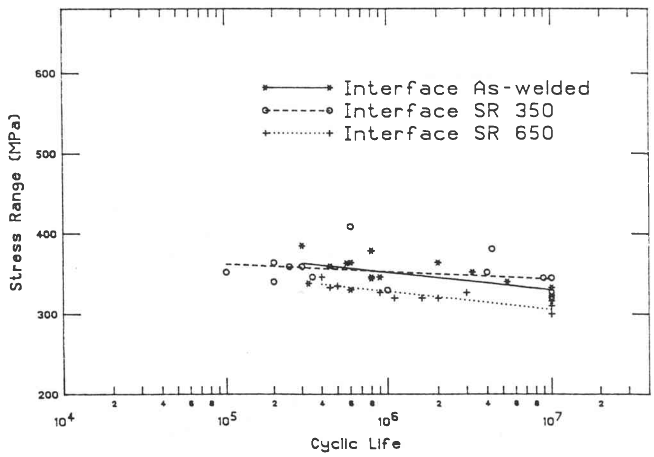

Figure 4

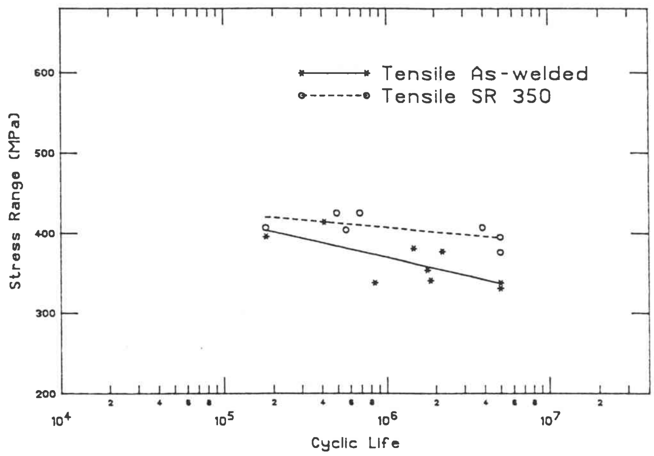

Figure 5

These observations can be related to the tensile strengths of the various specimens. Crack initiation was either from inclusions or porosity in all these specimens and sizes of initiating defect were generally less than about 20 μm, as seen in Figure 6. Under these circumstances the fatigue strength of a steel will increase with tensile strength and, as demonstrated by the data in Table 2, all the as-welded specimens were stronger than the original normalised EN 8 steel.

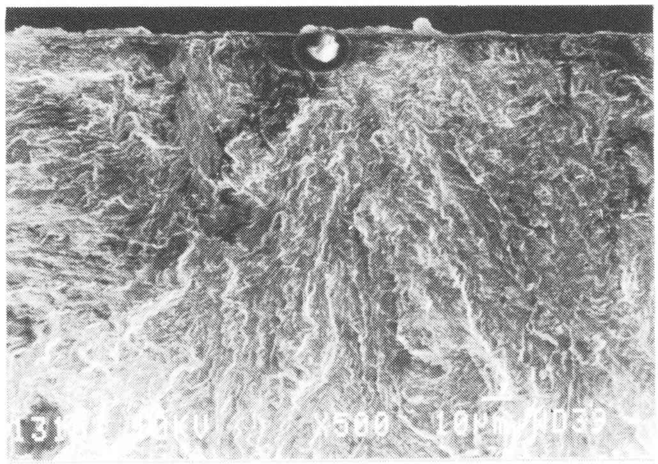

Figure 6a

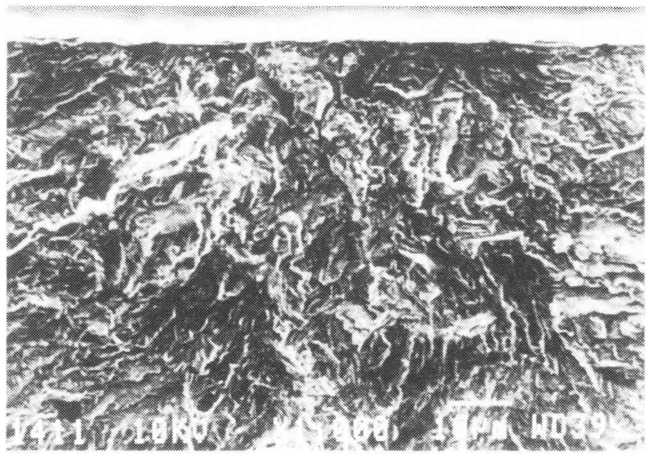

Figure 6b

Fatigue data for stress relieved weld metal specimens are compared with the as-welded data in Figure 3. Little difference can be seen, although it appears that the 650°C stress relief may have improved the fatigue strength slightly. All the data lie within a fairly small scatter band reflecting the fairly homogeneous microstructure and the fact that the residual stress field is largely destroyed by the specimen manufacturing route.

Slightly more scatter is evident in the data for the interface region, shown in Figure 4, and this is thought to be the result of the greater microstructural variability in these specimens. Again, no clear evidence for a significant residual stress effect can be seen in the data. Fatigue strengths for 650°C stress relieved condition appear to be slightly lower as a result of the lower tensile strength.

In the case of the tensile specimens, where the full effect of residual stresses should be apparent, Figure 5 indicates that a 350°C stress relief increases the fatigue strength by perhaps 20% at a life of 5×10^6 cycles. Even if the fatigue strength data for the bend bars in Figure 2 are lowered by this full amount, they still lie slightly above that for the original metal.

The conclusion to be drawn from these results is that the fatigue strength of a shaft manufactured from normalised EN 8 steel, built up by submerged arc welding, may well be better than that of the original shaft if gross welding defects are absent, even in the as-welded condition.

The situation for an initially quenched and tempered shaft may, however, be different. Some limited data were acquired using similar bend specimens, for quenched and tempered EN 24 steel. In this case the tensile strength of the unwelded metal was higher than that of the weld metal. Interestingly, although more scatter was evident in the data than for the EN 8 specimens, the reduction in fatigue strength of the as-welded specimens was only some 10% compared to that of the original steel. No significant change in strength of the bend bar specimens was observed after 350°C or 650°C stress relief heat treatment, probably because any reduction in remaining residual stress or improvement in cracking susceptibility of the microstructure is offset by the lower tensile strength. However, if another 20% reduction to account for the likely effect of residual stresses in the as-welded condition is considered (based on Figure 5), it is clear that post-weld stress relief would be mandatory on such shafts.

Conclusions

This study of shafts reclaimed by submerged arc welding has indicated the following:

1. For a normalised medium carbon EN 8 steel the fatigue strength may be higher than the original steel provided that gross welding defects are avoided. This appears to be the case for either thick or thin weld deposits, even in the as-welded condition. Statistically, however, thicker deposits of weld metal are more likely to contain a defect deleterious to fatigue strength and this should be borne in mind.

2. A 350°C post-weld stress relief heat treatment may increase the fatigue strength by around 20% in EN 8 steel.

3. For quenched and tempered steels a reduction in fatigue strength will occur in a reclaimed shaft and post-weld stress relief would be mandatory. After a suitable heat treatment process, however, the reduction in fatigue strength may only be of the order of 10%.

Acknowledgements

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References

[1] Anon. Tests to determine the influence of building-up with low-hydrogen electrodes on the fatigue strength of medium carbon-steel shafts. *International Institute of Welding Report*, XIII-162-58.

[2] Newman RP & Gurney TR. The fatigue strength of reclaimed ferritic steel shafts. *International Institute of Welding Report*, XIII-214-60.

[3] Dawes MG. A review of research on the fatigue strength of steel shafts built-up by welding and metal spraying techniques. *International Insitute of Welding Report*, XIII-314-63.

[4] Anon. Report on the influence of building-up on the fatigue strength of carbon-steel shafts, when using austenitic stainless-steel electrodes. *International Institute of Welding Report*, XIII-318-63.

[5] Thomas H. The influence of building up on the fatigue strength of carbon steel shafts. *Welding in the World*, 1975, **13**(1/2), pp.49 – 53.

[6] Ohuchida H, Nishioka A, Kitamura I & Kuboki E. Fatigue strength of steel shafts built up by welding. *Bulletin of the JSME*, 1972, **15**(85), pp.777 – 785.

[7] Paterson RE. *Stress Concentration Factors.* John Wiley & Sons, New York, 1974.