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THE LASER WELD REPAIR OF FATIGUE CRACKS IN SHIP STEELS

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The laser weld repair of fatigue cracks in 10mm thick S275J2G3 grade C-Mn ship steel has been investigated. Results indicate that helical laser weld repair is a viable alternative to conventional arc weld repair. One such repair exhibited a restoration in initial fatigue life of more than 500% and was associated with a repair time of approximately 20 minutes. This should be compared with an equivalent arc weld repair time of about 5 hours. It is envisaged that this technique has the potential to reduce the costs associated with the fatigue crack repair of maritime vessels. Partial and full repair of fatigue cracks was found to be ineffective in restoration of initial fatigue life because either repair techniques were unable to capture fatigue cracks in their entirety.

Key Words: Repair; Laser welding; Fatigue cracks; Shipbuilding; Fatigue strength; Carbon manganese steels; Comparisons; Arc welding

1. INTRODUCTION

Fatigue fracture is one of the most common modes of structural failure. In defect-free components a fatigue crack must first be initiated at a favourable site such as the toe of a weld run where the local stress intensity is high. In large structures initiation is frequently unnecessary as cracks are often introduced during fabrication. During service these cracks may experience a wide range of loading conditions and under the influence of a fluctuating tensile stress may start to grow. Given time they will continue to increase in length until the load bearing capacity of the remaining uncracked area of the component is exceeded. At this point catastrophic failure follows and the useful life of the component is over. To avoid this situation most large structures are regularly inspected. Cracks of an unacceptable size are normally removed by grinding and the resulting gap is filled with weld metal using a conventional arc welding process. Such repairs must be done correctly as the levels of distortion and residual stress associated with arc welding are not insignificant. These may act in combination with in-service stresses to re-initiate fatigue cracking from defects introduced during the repair process.

However, the low levels of distortion and residual stress associated with laser welding may offer an opportunity for improved fatigue crack repair. The process requires good component fit-up which is difficult to achieve in large structures. However, the fracture faces of fatigue cracks are normally separated by no more than 0.1 mm. On first inspection therefore, fatigue cracks would appear to be ideally suited to laser weld repair. This view is not reflected in the open scientific literature which contains no references relating to the laser weld repair of fatigue cracks. Because of the lack of research in this area "best practice" with regard to the successful laser weld repair of fatigue cracks is as yet unknown. The objective of this work is to present an account of research undertaken by DERA, Liverpool University and Aberdeen University into the laser weld repair of fatigue cracks in ship steels.

2. EXPERIMENTAL DETAIL

2.1. Test specimen design

A diagram of the test specimens used in this study is shown in Fig. 1. They may be classified as non-load carrying longitudinally stiffened F2 class joints [1]. The chemical composition and mechanical properties of the S275J2G3 grade C-Mn ship steel [2] from which they were manufactured

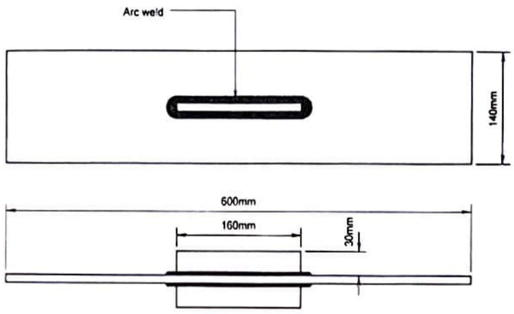


Fig. 1. Schematic representation of F2 class fatigue crack repair test specimen.

are presented in Table 1. Details of the arc welding procedure associated with their assembly is shown in Table 2.

2.2. Fatigue testing

Preparation

Prior to initial fatigue testing both weld toes at one end of each specimen were burr ground and polished to produce a smooth, rounded weld profile. This was done to reduce the stress concentration at this point in order to promote fatigue crack initiation at the opposite end of the specimen.

Initial fatigue testing

Each specimen was cycled at a fixed frequency of 30 Hz in a 600 kN "Schenck" resonance fatigue testing machine over a stress range of 95 MPa, at a mean tensile stress of 52.5 MPa and an R value of 0.05. Specimens were visually inspected every 15 minutes and cycling was allowed to continue until specimens developed a fatigue crack approximately 75 mm in length. Testing was then stopped, crack length was measured more accurately and the total number of cycles experienced by each specimen during initial fatigue testing, N_I, documented. Specimens were then removed from the test rig and prepared for laser weld repair.

2.3. Laser repair

Three types of laser weld repair were investigated:

Partial repair

This involved the use of a low power laser (~ 1 kW) to weld shut the surface of fatigue cracks to a depth of approximately 2 mm to produce an embedded defect, Fig. 2.

Full repair

This required the use of a higher power laser (~ 5 kW) to weld shut the full thickness of fatigue cracks. This was achieved by welding specimens from both sides to a depth of approximately 6 mm, Fig. 2.

Helical repair

This was essentially the same as a full repair, except that the laser beam was made to follow a helical weld path. This allowed the laser to cross the line of the fatigue crack during repair to produce a wider weld, Fig. 2.

Table 1. Chemical composition and mechanical properties of S275J2G3 C-Mn ship steel from which fatigue crack repair specimens were made.

C 0.14	Si 0.32	Mn 1.13	P 0.017
S 0.007	Al 0.035		
0.2% proof stress			371 MPa
Ultimate tensile strength			502 MPa
Elongation			33%
Charpy impact at – 20 °C			134 J

All elements in wt %

Table 2. Arc welding parameters used to assemble fatigue crack repair specimens.

Welding process	Manual metal arc
Electrode	VODEX 4.0 mm
Position	Downhand
Amperages	160 A
Voltage	26 V
Heat input	1.7 kJ

Details of the laser welding equipment and process parameters used to effect each type of repair are presented in Table 3.

2.4. Resumption of fatigue testing

Following laser weld repair fatigue testing was resumed and allowed to continue until specimens developed a fatigue crack similar in size to that grown during initial fatiguing. Testing was then stopped, crack length was measured more accurately and the total number of post-repair cycles received by each specimen, N_R, documented.

Additional examination

On completion of fatigue testing specimens were sectioned and examined in order to determine the profile, hardness, weld metal microstructure and crack growth characteristics associated with each laser weld repair technique.

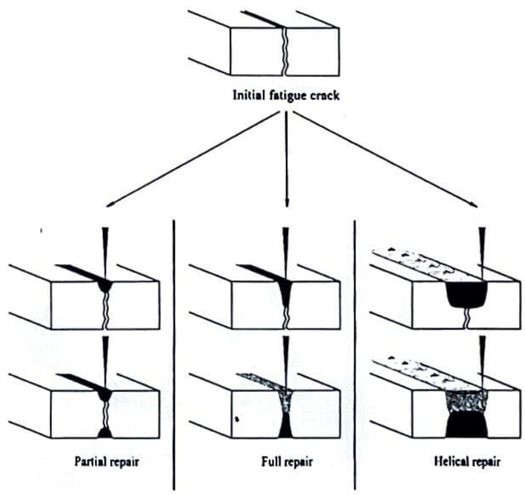
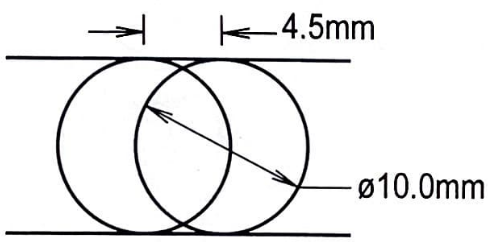


Fig. 2. Schematic representation of partial, full and helical laser weld fatigue crack repair techniques.

Table 3. Laser welding parameters associated with partial, full and helical repairs.

Partial laser weld repair	
Equipment	1.2 kW CO2 laser
Workpiece power	1.1 kW
Welding speed	0.5 m/min
Shielding gas	Helium at 30 l/min
Full laser weld repair	
Equipment	5 kW CO2 laser
Workpiece power	3.0 kW
Welding speed	0.6 m/min
Shielding gas	Helium at 50 l/min
Helical laser weld repair	
Equipment	5 kW CO2 laser
Workpiece power	3.3 kW
Welding speed	0.48 m/min
Shielding gas	Helium at 40 l/min



Detail of helical laser repair weld path.

3. RESULTS AND DISCUSSION

3.1. Restoration of initial fatigue life

Details of the post-repair fatigue performance of each type of fatigue crack laser weld repair technique investigated here are presented in Table 4. This demonstrates that helical repair gave an average restoration in initial fatigue life of 161% and was the only technique to offer a realistic alternative to conventional arc weld repair. It also demonstrates that helical repairs failed by crack growth in HAZ/parent plate material. This is in contrast to full and partial repairs which failed by weld metal crack propagation. More importantly, the initiation life for helical repairs was significantly higher than that recorded during initial fatiguing. This appears to be the principal benefit associated with the helical repair technique.

Further discussion of partial and full repairs is presented elsewhere [3]. Their inability to capture a fatigue crack in its entirety was considered to be the main cause of their poor fatigue performance. The remainder of this discussion will focus on the much better fatigue properties of helical repairs.

3.2. Laser weld repair profiles

A macrograph of a typical helical repair is presented in Fig. 3. The weld metal width of helical repairs at 11 mm was ~ 4 times greater than the 3 mm associated with full and partial repairs. The heat affected zone (HAZ) width of helical repairs at 3 mm was also considerably larger than

Table 4. Performance of fatigue crack repair test specimens before and after partial, full and helical repair.

		INITIAL FATIGUE DATA					POST-REPAIR FATIGUE DATA					
Specimen	**Laser repair type**	$_IN_S$ (cycles × 10^{-3})	$_IN_P$ (cycles × 10^{-3})	N_I (cycles × 10^{-3})	a_I (mm)	Crack location	$_RN_S$ (cycles × 10^{-3})	$_RN_P$ (cycles × 10^{-3})	N_R (cycles × 10^{-3})	a_R (mm)	Crack location	RIF (N_R/N_I)
LFA 2	Partial	–	–	1615	80	a	11	25	35	95	c	2%
LFA 6	Partial	–	–	1937	65	a	3	44	47	100	c	2%
LFA 9	Partial	–	–	1735	70	a	15	35	50	100	c	3%
LFA 10	Partial	–	–	1590	75	a	8	21	29	100	c	2%
LFA 11	Partial	–	–	1863	75	b	5	9	14	75	c	1%
LFA 12	Partial	–	–	1692	80	a	10	56	66	100	c	4%
Average				1739	74		9	32	40	95		2%
LFA 1	Full	–	–	487	70	a			53	95	d	11%
LFA 3	Full	–	–	1691	65	a	14	755	768	100	d	45%
LFA 4	Full	–	–	1437	95	a	135	270	405	95	d	28%
LFA 5	Full	–	–	2115	72	a + b	20	214	234	75	d	11%
LFA 7	Full	–	–	1256	75	a	1069	489	1558	90	d	124%
Average				1397	75		309	432	604	91		43%
LFA 14	Helical	2850	1162	4012	49	a	440	545	985	85	e	25%
LFA 16	Helical	1150	854	2004	48	a	2380	522	2902	90	f	145%
LFA 17	Helical	1050	560	1610	51	a	6728	1633	8361	90	f	519%
Average		1663	859	2542	49		3183	900	4083	88		161%

Key
$_IN_S$ = Cycles to initial fatigue crack initiation.
$_IN_P$ = Cycles to propagate an initial fatigue crack of length a_I.
$N_I = {_IN_S} + {_IN_P}$

$_RN_S$ = Cycles to post-repair fatigue crack initiation.
$_RN_P$ = Cycles to propagate a post-repair fatigue crack of length a_R.
$N_R = {_RN_S} + {_RN_P}$
N_R/N_I = Restoration in initial fatigue life.

a = Base of plate / stiffener arc weld.
b = Main body of plate / stiffener arc weld.
c = Contained entirely within partial repair weld metal.

d = Some deviation out of full repair weld metal.
e = Helical repair weld metal.
f = Along HAZ of helical repair.

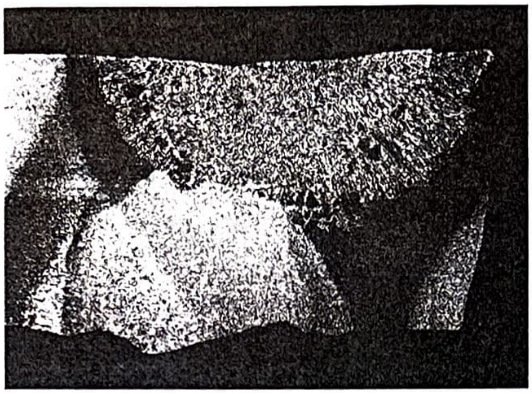


Fig. 3. Macrograph of helical laser weld repair. (× 6)

that of full/partial repairs. The advantage of a wide repair is that it enables fatigue cracks to be "captured" in their entirety. The penalty for generating such a large volume of weld metal is an increase in repair time. Partial and full repairs were achieved in under 1 minute. Helical repairs took ~ 20 minutes. Nevertheless, when compared to an equivalent arc weld repair time of ~ 5 hours the potential cost savings associated with helical laser weld repair become clear. Although the travel speed of the laser during helical repair was similar to that used for full and partial repairs, i.e. ~ 0.5 m/min, the need to follow a longer helical weld path effectively reduced helical repair welding speeds to ~ 0.01 m/min. Consequently, the heat input associated with helical repair at ~ 20 kJ/mm was extremely high. This should be compared to a heat input of < 1 kJ/mm for partial and full laser repairs and ~ 2 kJ/mm for a conventional arc weld repair. As a result helical repairs cooled very slowly allowing residual contraction stresses to be more easily accommodated.

3.3. Microstructure

A weld metal micrograph of a typical helical repair is presented in Fig. 4. Because of their slower cooling rate the microstructure of helical repairs was characterised by a complex mixture of higher temperature transformation products such as Widmanstätten, acicular and polygonal ferrite. Although not equilibrium decomposition products

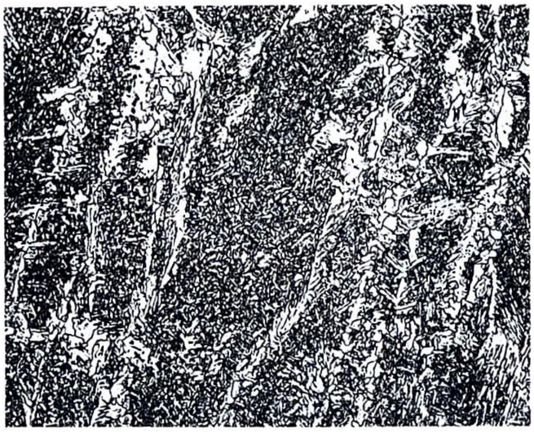


Fig. 4. Weld metal micrograph of helical laser weld repair. (× 200)

their ferritic nature was similar to that of C-Mn steel arc welds. Unlike conventional single pass arc and laser welds, helical repairs did not exhibit a centreline, although a columnar solidification sub-structure was observed. This was attributed to the refinement of initial weld metal deposits by successive passes of the laser in response to the selection of a helical weld path geometry. The absence of a centreline should be regarded as advantageous as it can act as a source of weld metal imperfections.

3.4. Hardness

A Vickers hardness (Hv_{1kg}) profile for a typical helical repair is presented in Fig. 5. This demonstrates an average weld metal hardness of 226 which is comparable with a parent plate hardness of 208. This is consistent with their ferritic microstructure.

3.5. Post-repair fatigue crack characterisation

Details of the post-repair fatigue crack initiation and growth characteristics associated with each repair technique are presented in Table 4.

Initiation

For the majority of specimens crack initiation occurred in the weld metal or HAZ region of laser repairs near to the toe of plate/stiffener arc welds, Fig. 6. The most notable exception to this was helical repair LFA14. To facilitate helical repair, following initial fatigue crack growth from the toe of plate/stiffener arc welds most of the arc weld was removed by rough grinding. This significantly impro-

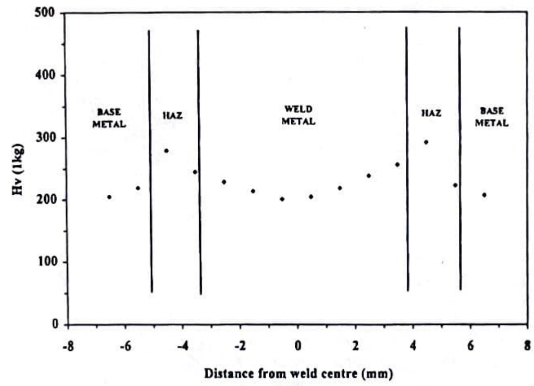


Fig. 5. Microhardness profile of helical laser weld repair.

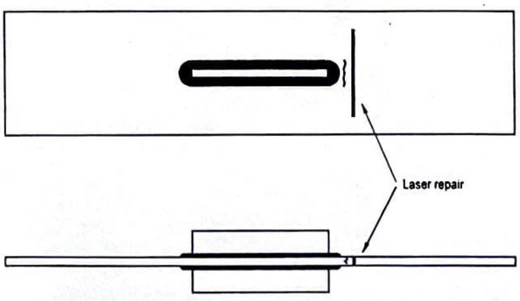


Fig. 6. Schematic representation of the site of post-repair fatigue crack initiation for a majority of laser weld repair test specimens.

ved laser beam accessibility during repair. However, the internal structure and profile of the remaining portion of ground arc weld was still considered to be an area where stress concentrations might arise, Fig. 7. In spite of this, during post-repair testing crack initiation occurred in the run-off area of helical repair LFA14, Fig. 8. During repair of this specimen laser beam stability was poor. This was eventually attributed to a defective focusing mirror which caused the beam to cut-out and then re-ignite unpredictably. Just such an event occurred at the end of the repair cycle in the repair run-off area. This momentary re-ignition of the laser produced a weld metal blemish, Fig. 9, which was found to contain a large defect, Fig. 10. That post-repair fatigue crack initiation also occurred at this point is an important observation and will be discussed later.

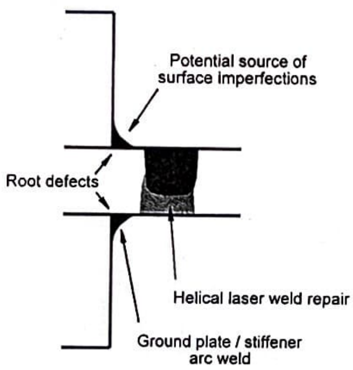


Fig. 7. Schematic representation of the profile of ground plate/stiffener arc welds associated with helical laser weld repair.

Growth

With the exception of specimen LFA14, helical repair crack growth occurred in the HAZ/parent plate region of such repairs, Fig. 11.

Fractography

Analysis of the post-repair fatigue crack fracture surface of helical repair LFA16, Fig. 12, shows that crack initiation occurred at a surface imperfection. This was located at the interface between ground arc weld and helical repair weld metal. However, examination of the fracture surface of helical repair LFA17, Fig. 13, demonstrates that cracking initiated from a lack-of-penetration defect at the root of a plate/stiffener arc weld.

3.6. Additional comment

The data in Table 4 shows that the restoration in initial fatigue life (RIF) associated with helical repair had an average value of 161%. A single poor result, LFA14, with an RIF of 25% was caused by a weld blemish which formed as a result of accidental laser re-ignition during repair. This demonstrates that helical repair weld metal deposits do

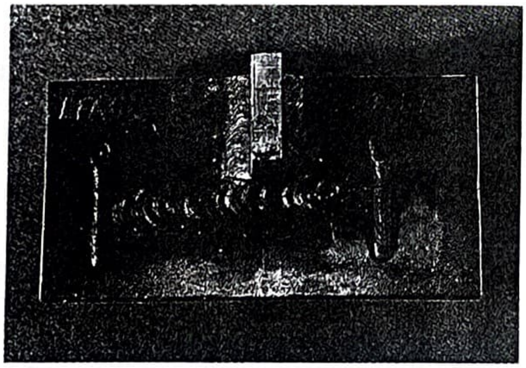


Fig. 8. Weld metal fatigue crack which initiated in the run-off area of helical repair LFA14. (× 1)

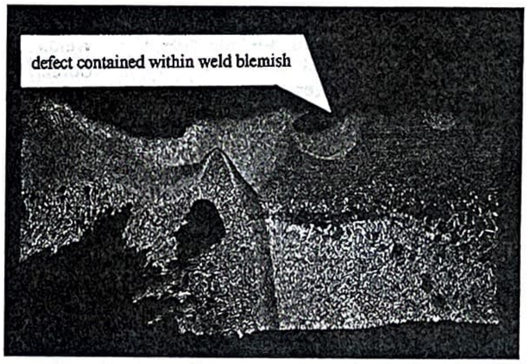


Fig. 10. Micrograph of weld metal "blemish" in the run-off area of helical repair LFA14. (× 5)

Fig. 9. View of weld metal "blemish" in the run-off area of helical repair LFA14 caused by accidental laser re-ignition. (× 2.5)

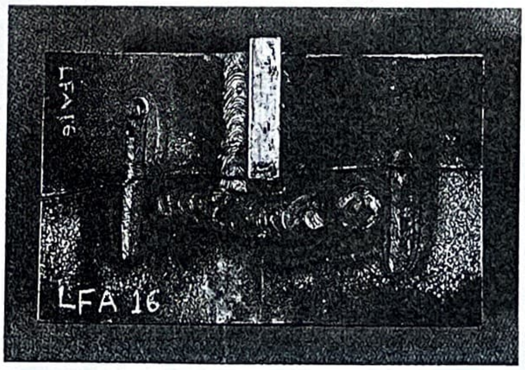


Fig. 11. A typical helical repair fatigue failure showing crack propagation in parent plate/HAZ material. (× 1)

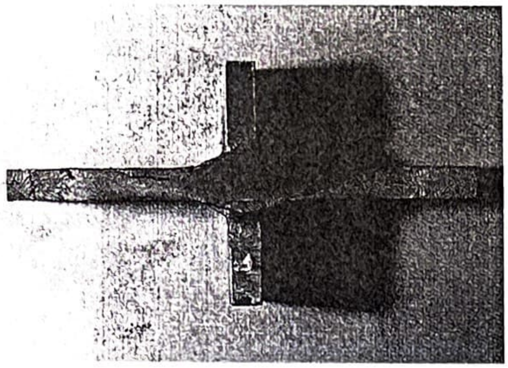


Fig. 12. Fatigue crack fracture face of helical repair LFA16 showing crack initiation from a surface defect. (× 1)

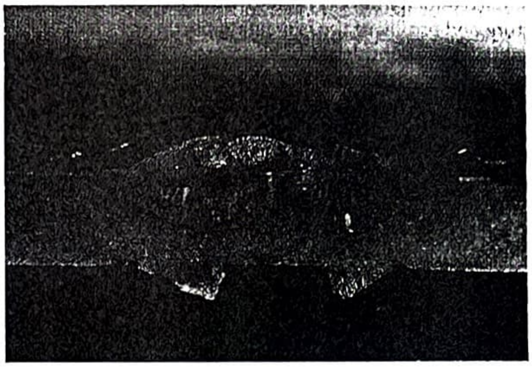


Fig. 13. Fatigue crack fracture face of helical repair LFA17 showing crack initiation from a plate/stiffener arc weld root defect. (× 2.5)

not have an especially high resistance to fatigue crack propagation. If the performance of helical repair LFA14 is discounted on the basis of faulty repair, the average RIF associated with the remaining helical repair specimens (LFA16 & LFA17) rises to 332%. Closer analysis of Table 4 reveals that the post-repair performance of these specimens was dominated by crack initiation. Only a small proportion of their repair life, ~ 20%, was devoted to crack propagation. This demonstrates that helical repair acts by retarding the onset of fatigue crack initiation. It should also be noted that both of these specimens failed by the initiation and growth of a fatigue crack in HAZ/parent plate material, i.e. away from helical repair weld metal deposits. This leads to perhaps the more important statement that helical repair is effective because it alters the site of fatigue crack initiation.

That helical repair LFA17 exhibited an RIF of 519% is remarkable. If this level of performance could be achieved consistently the costs associated with the repair of fatigue cracks in ship structures would be dramatically reduced. The British Standard S-N curve for F2-class joints [1] is reproduced in Fig. 14. For the stress range and specimen geometry investigated here this estimates a mean fatigue life of 1.5×10^6 cycles to failure which compares well with a value of 1.6×10^6 cycles recorded for specimen LFA17 during initial fatiguing. This demonstrates that fatigue testing was carried out correctly and that the RIF recorded for helical repair LFA17 at 519% was valid. This extention in fatigue life is partially explained by the observation that post-repair fatigue crack initiation occurred at a lack-of-penetration defect at the root of a plate/stiffener arc welds. This would not normally be considered a serious defect. However, it should be remembered that after initial fatiguing plate/stiffener arc welds were ground back to a concave profile to facilitate helical laser weld repair, Fig. 7. Under these conditions fatigue performance is governed by less potent flaws such as weld root defects and surface imperfections.

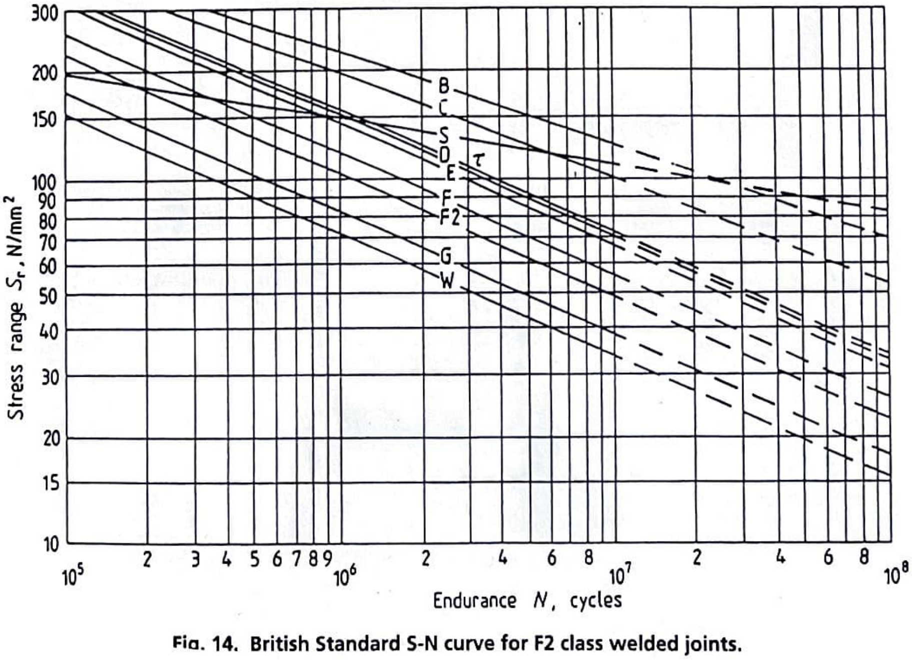


Fig. 14. British Standard S-N curve for F2 class welded joints.

Thus far, it would appear that the longevity of helical repairs has more to do with the grinding of plate/stiffener arc welds than it does with the helical laser weld repair technique *per se*. In reality precisely the opposite is true. By completely removing the most obvious defect source, i.e. the initial fatigue crack itself, helical repair forces other less potent mechanisms to operate.

As has been mentioned, prior to initial fatigue testing both arc weld toes at one end of each specimen were ground and polished to promote fatigue crack initiation at the opposite end. Although this approach was successful, crack initiation did occur in these polished arc welds during post-repair testing. These cracks were then subjected to conventional arc weld repair to allowed the fatigue testing of laser weld repairs to continue. In broad terms the grinding and polishing of plate/stiffener arc welds increased their fatigue life by a factor of ~ 250%. As a consequence the performance of helical repair LFA16 (RIF = 145%) could be accounted for solely in terms of the beneficial effects associated with arc weld profiling. However, although plate/stiffener arc welds were *roughly* ground to facilitate helical repair they were *not* polished. It is therefore doubtful that any significant benefit resulted from this operation. Even if this were the case it is still not an argument which can be invoked to account for the performance of helical repair LFA17, (RIF = 519%).

4. CONCLUSIONS

The laser weld repair of fatigue cracks in 10 mm thick S275J2G3 grade C-Mn ship steel has been investigated. The principal findings of this work are summarised below:

1. Partial and full repair of fatigue cracks was ineffective, resulting in an average restoration in initial fatigue life (RIF) of only 2% and 45% respectively. This was attributed to the inability of either repair technique to capture fatigue cracks in their entirety.

2. Helical laser weld repair of fatigue cracks *was* effective and was associated with an average restoration in initial fatigue life of 161%. When an RIF of 25% recorded for one specimen is discounted on the basis of faulty repair, the average RIF for helical repairs rises to 332%. The high performance of the helical repair technique was attributed to its ability to reliably achieve complete fatigue crack capture.

3. Helical repair of fatigue cracks took ~ 20 minutes. This should be compared to an equivalent arc weld repair time of ~ 5 hours. It is envisaged that the helical repair technique has the potential to dramatically reduce the costs associated with the repair of fatigue cracks in ship structures.

5. REFERENCES

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