Improving the Fatigue Lives of Fillet Welds by Shot Peening

Augmentation de la durée de vie des cordons de soudure par grenaillage

Erhöhung der Lebensdauer von Schweissnähten durch Kugelstrahlverfahren

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SUMMARY
Circumstances under which shot peening would improve the fatigue strength of attachment fillet welds in steel were investigated. The treatment was found to be more effective for transverse welds than welds around the ends of longitudinal attachments and the benefit increased with steel strength. However, it decreased with increases in stress ratio. Preliminary tests indicated that shot peening was still beneficial under variable amplitude loading. The benefit of shot peening varied with peening conditions and even for nominally identical conditions. In practice, the treatment is particularly effective in the high-cycle regime.

RESUME
Le grenaillage contrôlé peut améliorer la résistance à la fatigue de cordons de soudure en acier. Le traitement est plus efficace pour les soudures transversales que pour les soudures aux extrémités d'attaches longitudinales; l'effet bénéfique augmente avec la résistance de l'acier. Par contre, il diminue aver l'accroissement du rapport des contraintes. Des essais préliminaires montrent que le grenaillage est également bénéfique dans le cas de sollicitations d'amplitude variable. L'effet bénéfique varie avec les conditions de grenaillage voire même sous des conditions en principe identiques. En pratique, le traitement est particulièrement efficace dans le cas d'un nombre de cycles élevé.

ZUSAMMENFASSUNG
Die Verhältnisse, unter welchen das Kugelstrahlverfahren eine Verbesserung der Ermüdungsfestigkeit von Kehlnähten bringen kann, wurden untersucht. Das Verfahren erwies sich als vorteilhafter für Quernähte als für Schweissungen an den Enden von Längsrippen, wobei sich die Wirksamkeit mit steigender Stahlqualität verbessert, mit grösserem Spannungsverhältnis jedoch abnimmt. Versuche zeigten, dass das Kugelstrahlverfahren auch wirksam bei Belastungen mit variabler Amplitude ist. Die Wirksamkeit variierte in Abhängigkeit der Bearbeitung, auch unter praktisch gleichen Bedingungen. In der Praxis ist das Kugelstrahlverfahren speziell im Bereich der Langzeitermüdung vorteilhaft.

1. INTRODUCTION

One of the most effective techniques for improving the fatigue strength of welded joints which fail from the toe is the introduction of compressive residual stresses by peening [1]. For example, the fatigue strength of mild steel transverse fillet welds at 2 x 10^6 cycles can be raised by 91% by hammer peening along the weld toe [2]. Another method which is widely used to improve the fatigue strength of unwelded, and usually machined, components is controlled shot peening. Although the value of this technique has been widely demonstrated for such components (eg. [3]) surprisingly little work has been done in relation to welds, particularly steel fillet welds. However, some investigations have confirmed that shot peening of welds can effect an improvement, sometimes as high as that obtained by hammer peening [4,5], but usually less [5,6]. Even so, in practice shot peening may prove to be more convenient and cheaper than hammer peening, especially in the case of small components which could be treated in batches. Also, it may offer a particular advantage over other imrpovement techniques in terms of control of the process to ensure that the expected imrpovement in fatigue strength is actually realised.

The beneficial effect of shot peening is likely to depend on many factors and these must be appreciated before design recommendations can be made. Clearly, the peening conditions are important and some may not introduce any significant improvement in fatigue strength [5]. Equally, a method of checking that the required shot peening conditions have been achieved is required. At present, it seems to be assumed that the curvature introduced into an Almen strip by shot peening provides a satisfactory indication of the residual stresses produced, but reservations have been expressed about this [6]. The service loading conditions are also expected to be significant. Applied stresses are superimposed onto the compressive residual stress and clearly the effective (tensile) stress will increase with increase in peak applied stress. Thus, applied stress ratio R will be significant, such that the beneficial effect of shot peening will decrease with increase in positive R value but should increase for negative values, as has been found for hammer peened welds [7]. In addition, there is evidence [8,9] that the application of strains above yield, which could occur in the region of stress concentration at the weld toe under nominally elastic conditions, can relax the compressive residual stress due to shot peening. For this reason, there is concern that any improvement technique which relies on compressive residual stresses may be unreliable under random loading [1]. One factor which might enhance the benefit of shot peening is an increase in the tensile strength of the steel, due to a proportionate increase in the level of residual stress introduced. Certainly this has been confirmed for plain steel [3] and hammer peened welds [2].

The above factors were investigated in the present work. Other factors which might prove significant, including working environment and original weld condition, are currently being investigated. The aim of the project is to establish design S-N curves for shot peened fillet welds in steel.

2. TESTING PROGRAMME

2.1. Test Specimens

Two types of fillet welded joint which normally fail from the weld toe were tested, plates with longitudinal attachments fillet welded to the surface with welds which continued around the ends of the attachments (Fig.1a) and plates with transverse fillet welded attachments (Fig.1b). The virtue of the former is that test data usually exhibit little scatter. However, the transverse weld probably typifies more fillet welded joints which arise in practice. The specimens were waisted to reduce the risk of failure in the grips. Both types of specimen were fabricated from structural steels to BS 4360, Grades 43A and 50B. In addition, the specimens with longitudinal attachments were fabricated using two high strength low alloy quenched and tempered structural steels, QT445A and RQT700. The chemical and tensile properties are given in Table 1. The specimens were welded by the manual metal arc process in the flat position using conditions appropriate to the parent steel. The welds to be shot peened were standardised by using batches which had similar fatigue strengths in the as-welded condition, as confirmed by testing.

Table 1. Material properties

Steel	Element, wt% C	S	P	Si	Mn	Ni	Cr	Mo	Nb	Al
BS 4360 Grade 43A	0.22	0.037	<0.005	0.04	0.86	0.01	<0.01	<0.01	<0.005	<0.005
BS 4360 Grade 50B	0.18	0.017	0.017	0.04	1.40	0.02	0.01	<0.01	0.036	<0.037
QT 445A	0.18	0.017	0.023	0.46	1.00	0.03	0.82	0.30	<0.005	0.072
RQT 700	0.19	0.014	0.010	0.42	1.28	0.02	0.14	0.16	0.036	0.105

Steel	Yield stress, N/mm^2	UTS N/mm^2	Elongation, %	Reduction in area, %
BS 4360 Grade 43A	262	472	38	60
BS 4360 Grade 50B	392	564	36	67
QT 445A	727	834	23	65
RQT 700	824	881	23	66

2.2. Shot peening conditions

The shot peening was carried out commerically under controlled conditions which complied with U.S. Defence Department Specification 'Shot peening of metal parts' MIL-S-131 65B, 1979. Most specimens were treated in the same way (condition A) but in three batches (A1,A2 and A3) and by two different companies (A1 and A2 by the first, A3 by the second. Two other conditions, B and C, were also used by the first company. Condition A used 0.6mm diameter shot to produce a peening intensity of 0.012 - 0.016 inches arc height in a type 2 Almen strip. Condition B gave the same intensity with 0.8mm diameter shot while condition C gave a higher intensity, 0.016 - 0.020 A2, with 0.8mm diameter shot. 55 - 65 Rockwell C hardness cast steel shot was used in every case and the operation was carried out in two passes (200% coverage) in order to achieve full coverage in the region of the weld toe.

Table 2. Test conditions

Joint type	Steel	R	Loading	Weld treatment: As-welded	Shot peened: A1	A2	A2 + stress relief	A3	B	C
Transverse non-load carrying fillet welded attachment	43A	0	constant amplitude	✓	✓					
	50B	0	"	✓	✓	✓	✓	✓	✓	✓
	50B	0	Random	✓				✓		
	50B	-1	constant amplitude	✓		✓				
	50B	0.5	"	✓		✓				
Longitudinal non-load carrying fillet welded attachment	43A	0	"	✓	✓					
	50B	0	"	✓	✓					
	QT445A	0	"	✓	✓					
	RQT700	0	"	✓	✓					

2.3. Test conditions

All specimens were tested axially under the conditions summarised in Table 2. Failure was taken to be complete fracture of the specimen.

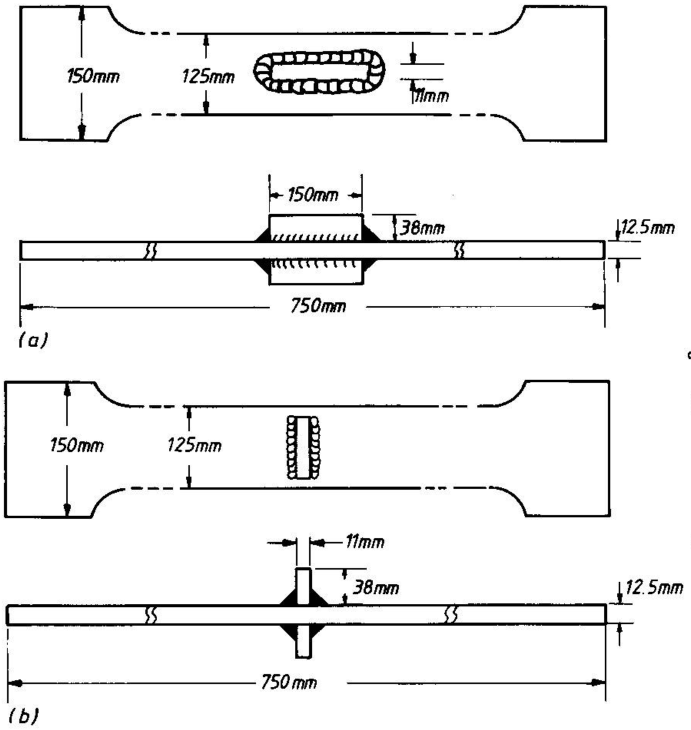

Fig. 1. Test specimens:
a) plate with longitudinal fillet welded attachment
b) plate with transverse fillet welded attachment.

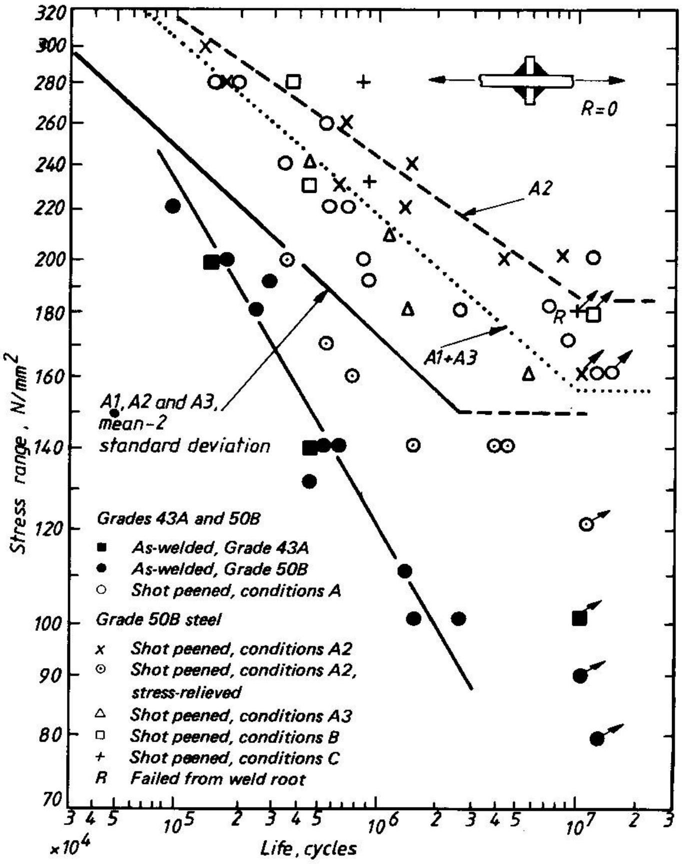

Fig.2. Fatigue test results for shot peened specimens with transverse fillet welded attachments.

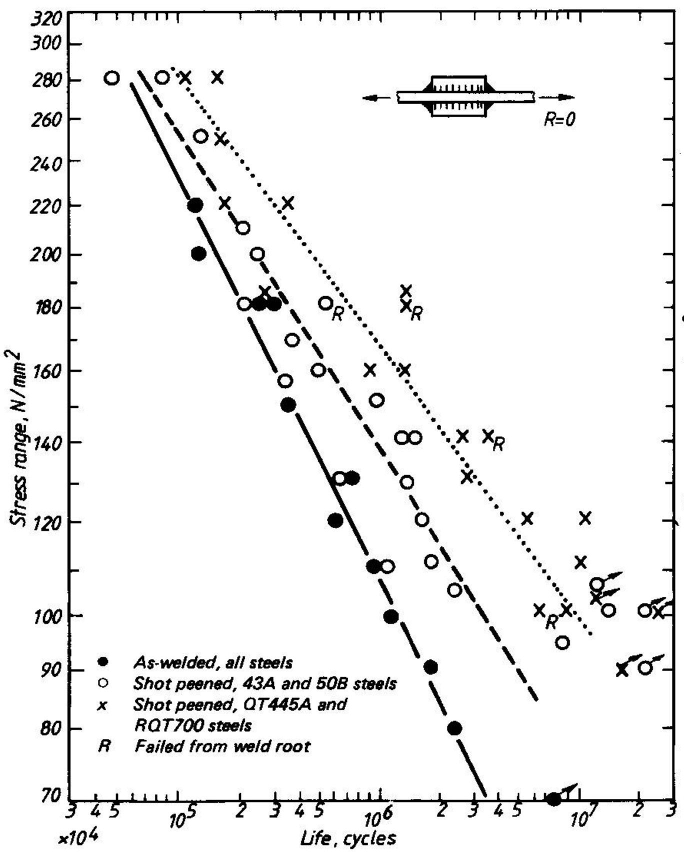

Fig.3. Fatigue test results for shot peened specimens with longitudinal fillet welded attachments.

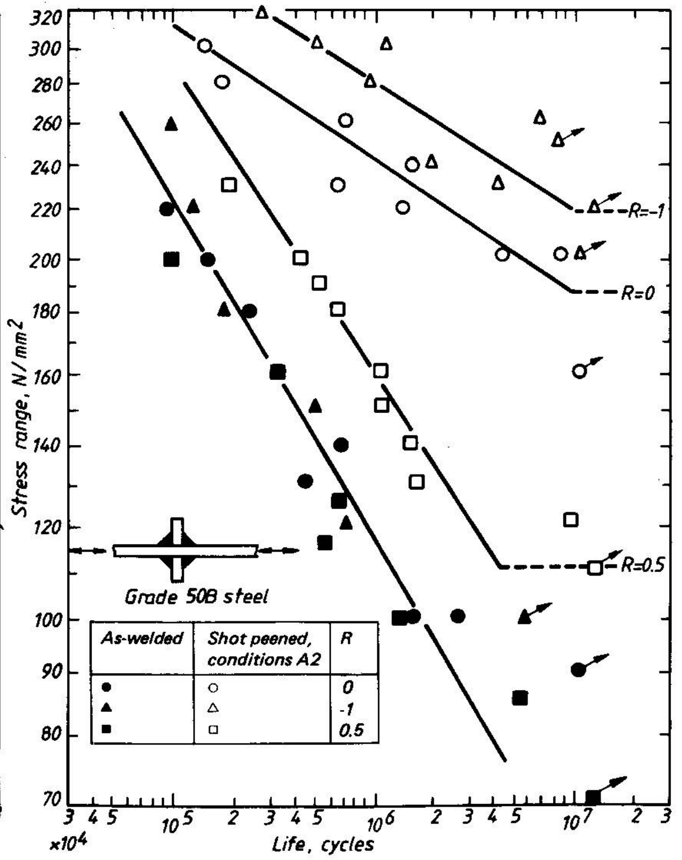

Fig.4. Effect of stress ratio on fatigue strength of shot peened specimens with transverse fillet welded attachments.

3. PRESENTATION AND DISCUSSION OF RESULTS

3.1. Effect of shot peening

The level and extent of compressive residual stress introduced by shot peening was checked on transverse weld specimens in 50B steel peened using A2 conditions by X-ray diffraction and by a relaxation technique [10]. Both methods indicated that compressive residual stresses close to tensile yield in magnitude were present near the surface. The relaxation technique further showed that they fell to zero 0.75mm below the surface.

The fatigue test results are presented in Figures 2 to 4 together with mean S-N curves fitted to the results from specimens which failed. Fatigue failure occurred from the weld toe unless otherwise indicated. It will be seen that shot peening usually introduced an improvement in fatigue strength, although the results for shot peened joints were more scattered than those for the as-welded joints and there was some overlap of results. As expected, the improvement increased with decrease in applied stress, so that the S-N curve was rotated. The fatigue limit was not clearly established in any of the test series but the indications are that it was increased considerably by shot peening.

Factors affecting the degree of improvement due to shot peening are discussed in the following sections. A number of variables were considered and in this respect it should be noted that the need for clarity in the figures and the shortage of space in the present paper have meant that in some cases results obtained under different conditions have been combined. However, these measures were taken only if analysis of the separate results showed that any differences between them were not statistically significant at the 99% level.

3.2. Influence of weld type

The results obtained for the two weld types in the same steels, 43A and 50B, are given in Figures 2 and 3. As can be seen, the improvement was considerably greater in the transverse than in the longitudinal weld detail, particularly near the fatigue limit. Tests on grit blasted specimens led to the same conclusion [11]. Based on the mean S-N curves at 2 x 10^6 cycles, the improvement in fatigue strength for the longitudinal detail was 35% while that for transverse welds was 93%. There was still a 33% improvement at 10^5 cycles in the case of the transverse welds but virtually none in the longitudinal weld. A possible explanation for this difference is that the tensile residual stresses due to welding, which would have been higher in the specimens with longitudinal welds than in those with transverse welds [1], inhibited the introduction of compressive residual stresses by shot peening or reduced their beneficial effect. Alternatively, the weld geometry at the end of a longitudinal attachment is less amenable to shot peening treatment.

3.3. Influence of steel strength

The influence of the steel strength can be examined by reference to the results obtained from specimens with longitudinal attachments, in Figure 3. There was no significant difference between results obtained from the two carbon structural steels or for the two QT steels, perhaps because in each case the difference between the strengths of the two steels was not large. As anticipated the improvement obtained from specimens made from high strength QT steels appeared to be considerably higher than that obtained from carbon steels. At 2 x 10^6 cycles, the improvement was 70% compared with 33% for the lower strength steels, and at 10^5 cycles there was still a 25% increase. However, because of the scatter in the results, the difference between the S-N curves for the QT and carbon steels was not statistically significant above the 80% level.

3.4. Influence of shot peening conditions

Limited tests were carried out to investigate the effect of changes in the shot peening conditions but what proved to be of more interest was the opportunity to compare the results from welded joints shot peened under nominally identical conditions at different times and by different companies. All the results are given in Figure 2 where it will be seen that the selected variations in peening conditions had no consistent effect on the degree of improvement but there is a difference, which is statistically significant at the 90% level, between the results obtained from the batch of specimens shot peened using conditions A2 and the other two (A1 and A3). It is interesting to see that this difference did not arise as a result of a change from one shot peening company to another, A1 and A2 referring to the same company. From the practical viewpoint these results are important because they demonstrate that shot peening conditions which produce the same Almen intensity do not necessarily give the same fatigue strengths.

Examination of the shot peened welds indicated that conditions A2 had introduced a distinct improvement in the weld toe geometry whereas conditions A1 and A3 had not and this could explain the superior fatigue strengths for A2 specimens. The beneficial effect of the improved weld toe geometry in A2 specimens was demonstrated by testing specimens which had been stress relieved at 580 - 620°C for one hour, as seen in Figure 2.

Although there is scope for exploring other shot peening conditions, it would appear that of those used in the present investigation conditions A were the most suitable. Certainly the large number of failures originating at the weld root in QT steels (Figure 3) suggests that no further improvement in those joints is possible.

3.5. Influence of loading conditions

The results in Figure 4 shows that, as expected, there was an increase in the fatigue strength of shot peened specimens for $R = -1$ and a decrease for $R = 0.5$, compared with results for $R = 0$. Theoretically, assuming elastic conditions, the effective tensile stress resulting from the superposition of an applied stress range S and a residual stress S_{res} is $S_{max} + S_{res}$, where S_{max} is the peak tensile applied stress. But $S = (1-R)\ S_{max}$ and therefore the applied stress ranges which result in the same effective stress, and hence fatigue life, for the three R values should be in the ratio 1: 2: 4 for $R = 0.5$, 0 and -1 respectively. Clearly, these estimates based on elastic conditions will be most reliable at the fatigue limit. Referring to Figure 4, the actual values for $R = 0$ and 0.5 differ by a factor of approximately 1.7, but for $R = 0.5$ and -1 the factor is 1.95, about half that predicted. A possible explanation for this is that the application of a compressive stress during cycling under $R=-1$ relaxes the original compressive residual stress, an effect observed by Kodama [9]. To check this, residual stresses were measured in an unbroken specimen tested at ±100 N/mm^2 for 10^7 cycles. They were found to be between -50 and -100 N/mm^2, which represents a reduction of around 75% compared with the levels measured in untested specimens.

Thus, the present results indicate that the fatigue strength improvement due to shot peening depends on the magnitude and type of loading, both from the point of view of the dependence of the effective stress on the peak applied stress and the possible reduction in residual stress. In practice, this could be particularly important if shot peened joints operate under a spectrum of loads, especially if it contains high tensile stresses and compressive stresses.

An investigation of the fatigue behaviour of shot peened transverse fillet welded joints under random loading is in progress and preliminary results are presented below. Initially use was made of a spectrum based on the highway bridge axle load spectrum in BS 5400 which, from tests on as-welded joints, was known to produce fatigue lives up to double those estimated using Miner's rule, an indication that some crack growth retardation occurred as a result of high tensile stresses in the spectrum. It was:

Applied stress/ Max. applied stress	1.0	0.94	0.88	0.78	0.72	0.66	0.61	0.56	0.50	0.44	0.39	0.34	0.22	0.17
No. of occurrences in $\sim 5 \times 10^5$ cycle repeat block, kilocycles	44.0	58.7	11.0	11.0	33.0	11.0	30.4	53.5	27.3	22.0	58.7	69.7	11.0	66.1

The results obtained with R = 0 from 50B steel specimens were as follows:-

Condition	maximum stress range in spectrum, N/mm^2	Life cycles	actual life / predicted life
as-welded	211	690,000	1.4
shot peened (A1)	211	5,467,422	1.1
as-welded	188	2,063,085	2.8
shot peened (A3)	188	14,425,000 unbroken	> 1.4

As will be seen, shot peening still improved the fatigue lives of joints tested under random loading. The 8-fold increase in life obtained under the higher stress was approximately that expected from the constant amplitude results at 0-211 N/mm^2 (see Fig.2), suggesting that the highest stress in the spectrum might determine the degree of improvement due to shot peening. The actual lives all exceeded those predicted using Miner's rule in conjunction with the appropriate mean constant amplitude S-N curves, although it would appear that the margin is less with shot peened joints than as-welded.

4. CONCLUDING REMARKS

This work has confirmed that under some conditions the fatigue strength of steel fillet welds can be improved by shot peening. However, it has also shown that the degree of improvement can vary significantly depending on the loading conditions and shot peening conditions. An increase in positive R value, with the corresponding increase in peak tensile stress and hence increase in effective stress, reduces the benefits seen under R = 0. The application of partly compressive loading leads to an increased benefit but not as great as expected, probably because the compressive residual stresses are partly relaxed. It was feared that some relaxation would also occur under random loading but it was encouraging to find from preliminary tests that this will not necessarily happen. It is possible that such a problem will only arise if compressive stresses occur. Although high tensile stresses might relax the compressive residual stresses due to shot peening, they should then leave a new compressive residual stress field which will still reduce subsequent fatigue damage (the crack growth retardation phenomenon). The effect of the known variation in shot peening conditions was not so significant and a more striking variation was that seen between different groups of specimens shot peened under nominally, the same conditions. This finding, together with the fact that overall the scatter obtained in the results for shot peened specimens was large, suggests that the current method of assessing the effect of shot peening, the Almen strip, is not sufficiently sensitive, or that the anticipated reproducibility of a given set of peening conditions cannot be realised. In practice, it may prove to be unrealistic to expect greater consistency, in which case due account will need to be taken of the wide scatter in test results when design S-N curves are derived. As an illustration of the consequences of such an approach, the mean -2 standard deviations S-N curve from regression analysis of all the results from specimens peened using condition A for R = 0 is shown in Figure 2. Clearly, the full potential of shot peening would not be achieved using such a curve. Even so the improvement over the as-welded joint is still considerable, particularly in the high-cycle regime. More work is required before firm proposals can be made, particularly to ensure that qualifications (eg. relating to loading conditions, weld type and condition, environment) to be placed on the applicability of such proposals are fully appreciated.

The increased benefit observed in high strength steels suggests that further work using transverse fillet welds, which derive greater benefit than the longitudinal weld details used so far, would be worthwhile.

ACKNOWLEDGEMENTS

The author is glad to acknowledge the work of the Fatigue Laboratory staff under Mr. R. A. Males and his colleagues J. G. Summers, B. J. Fitzpatrick and G. Slater. The project was financed jointly by Research Members of The Welding Institute and the Engineering Materials Requirements Board.

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