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WELD REPAIR OF CRACKED DEFA
CANNON MOUNT FRAMES

J.C. Ritter, R.H. Phillips and B.F. Dixon

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R.H. Phillips and B.F. Dixon.

1. Page 3, Paragraph 2 line 5. Delete "which" and insert "high"
2. Page 9, Paragraph 1 line 3. Delete "length" and insert "length"
3. Figure 10 has been printed upside down.

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ABSTRACT

The weld repair of fatigue cracks found in the mounting frames of the Defa gun pack, fitted to Mirage III aircraft, is described. These cracks, caused by normal gun firing stresses, occurred well short of the frame design life as a result of metallurgical degradation in the form of a decarburized layer on the surface of the cast steel frames.

Weld repair was by the Tungsten Inert-Gas process, using a low alloy Ni-Cr-Mo steel consumable. This produced a weld deposit with overmatching strength and toughness, with the aim of conferring a fatigue resistance at least equal to that of the sound parent metal, so as to prevent the recurrence of cracking. This performance was validated by laboratory fatigue-life (S-N) tests and fatigue crack growth measurements in weld metal and in sound casting. A detailed description is given of preweld preparation, the weld repair procedure, and postweld finishing including weld profile blending and surface protection.

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WELD REPAIR OF CRACKED DEFA

CANNON MOUNT FRAMES

PART I. INTRODUCTION

During the latter part of the 1970s, RAAF Mirage III Operating Units reported a number of instances of cracking in the front mount frames of the Defa gun pack. Investigations at MRL showed that these cracks were of the fatigue type [1]. In early 1980 there was a sudden increase in the incidence of reports of cracking, accompanied by observations of rapid rates of growth of those cracks under surveillance. This spate of cracking appeared well inside the planned service life of the gun pack, giving rise to concern that aircraft safety could be jeopardized, in addition to the prospect of rendering the whole class of gun unserviceable.

RAAF Headquarters Support Command therefore requested that MRL devise a weld repair scheme which would achieve a significant service life extension for this component.

This objective was achieved through a program of work involving several investigations. The principal task was the development of a weld repair scheme for this cast alloy steel component which could be undertaken by RAAF workshops to produce a metallurgically sound, defect-free deposit which would have a high degree of resistance to further fatigue cracking. In scope, this weld repair scheme began with in-situ inspection of operational frames, followed by the removal of cracks and weld preparation, welding by the Tungsten Inert-Gas (TIG) process, and postweld treatment and re-plating.

In order to demonstrate that a worthwhile extension in service life, possibly 30% or more, could be achieved by this weld repair, a detailed analysis was made of the nature and cause of cracking, using a combination of fractography and fracture mechanics [2]. It was found that cracking was related to metallurgical degradation and loss of strength in the frame arising from a decarburized surface layer, and that the normal gun firing stresses were the over-riding driving force causing cracking. This deduction was particularly important because it meant that no excessively severe cyclic

loadings were likely to occur during operation: such overloadings would have negated the value of any repair scheme, by damaging even metallurgically sound metal.

This analysis also gave an estimate of the level of cyclic stress causing the cracking. The value of stress was used as the basis for a laboratory fatigue test program which would demonstrate the likely service performance of a repair weld compared with metallurgically sound parent material in the mount frames. This fatigue evaluation centred upon the generation of fatigue life data for the weldment and for sound material, in the form of S-N data under stress conditions considered appropriate to the mode of stressing in the cracked regions of the frames.

Once it was demonstrated that the fatigue resistance of the repair weld metal was similar to that of the sound parent metal, it was reasoned that the fatigue life of the frames would then be restored to a level close to the design life of the component.

PART II. WELD REPAIR SCHEME

1. MATERIALS

The frames were low alloy steel castings, heat treated to achieve the required strength level. The components were made overseas and the details of manufacture were not known. The present spate of cracking followed the same pattern reported previously [1], namely fatigue cracking at three recurrent locations in the frame, as shown in Fig. 1, the most common sites being A and B. Similarly, metallographic examination revealed that the surface layer of the castings had been decarburized to a depth of approximately 0.3 mm during some stage of heat treatment (Fig. 2). This layer would have caused a marked reduction in resistance to fatigue crack initiation at points of stress concentration on the frame. Cracks in all cases were found to have initiated at machining grooves on the frame surface.

The weld repair filler metal, CIG Autocraft Ni-Cr-Mo steel wire, was selected on the basis of overmatching levels of strength and toughness, in order to confer a high degree of fatigue resistance upon the crack-susceptible regions. In this way it was hoped that any intrinsic geometric weakness in the frame, manifest as regions of high stress level at these recurrent sites, might be overcome. Chemical analyses of the frame and weld metal are given in Table 1, and their relevant mechanical properties are given in Table 2.

2. IN-SITU INSPECTION OF FRAMES

In order to refurbish defective frames in the most efficient manner it was first necessary to identify all the cracked frames in service, and instructions were issued to RAAF units operating with these frames to inspect them in-situ using the magnetic particle method of non-destructive inspection (NDI) [3]. The recommendation for inspection was made on the following grounds:

- (i) The known crack-susceptible sites were readily accessible for in-situ NDI, and cracks were readily identifiable using this technique.
- (ii) The removal and refitting of frames from the gun pack was difficult and time-consuming.
- (iii) As the cracks initially propagated at a relatively low rate, any incipient cracks missed in the first in-situ inspection would readily be identified at the next inspection interval.

As a result of the in-situ inspection, frames found to contain any evidence of cracking were removed from the gun pack for detailed inspection using the fluorescent magnetic particle penetrant method.

3. PREWELD PROCEDURE

Before repair weld could be commenced, several preparatory steps were required such as cleaning the frame, stripping the protective plating, grinding out the cracks, and ensuring against distortion and hydrogen-induced cold cracking during welding. The first step was to degrease all frames using trichlorethylene. The frames were then inspected for cracks using the fluorescent magnetic particle technique. This is an effective and sensitive technique for detecting surface cracks down to less than 0.5 mm long. The position and extent of cracking was recorded. After inspection the frames were demagnetized.

3.1 Grinding-out of Cracks

Previous inspection of cracked frames at MRL had shown that even the most severe cracks were repairable. All cracks in positions A, B and C (Fig. 1) were therefore weld repaired, regardless of size. Cracks were ground out using specially shaped tungsten carbide cutting burrs in a pneumatic rotary grinding tool. In this crack removal operation a 'U' shaped groove with tapering sides was required as the most suitable repair preparation. This geometry was chosen to minimize the possibility of lack of side wall fusion during subsequent welding.

The degree of crack removal depended on the location and extent of cracking as follows:

- (i) Cracks were totally removed where they had not propagated through a complete section. This situation commonly arose at position A, Fig. 1. During the process of crack removal it was frequently necessary to check for complete elimination of the crack using the fluorescent magnetic particle technique.
- (ii) Where crack had propagated through a section, as could occur in position B (Fig. 1), 0.5 mm of metal was left to help support the subsequent weld root run. The aim here was to completely fuse out the remaining crack in the first root pass. The weld preparation to achieve this is shown diagrammatically in Figs 3. A grooved copper backing strip, especially manufactured for this operation, was used for additional support during welding (Fig. 4).

The protective cadmium plating was chemically stripped from the frame, in accordance with Australian Air publication 7002.005-1, and the area around the weld preparation was then grit blasted with #200 silica grit. Immediately prior to welding the frame was again cleaned using trichloethylene.

3.2 Distortion Control

It was recognised at an early stage in devising the weld repair procedure that distortion arising from the welding could prove to be a

significant problem. The tendency for distortion in welding is an inevitable consequence of localized heating due to passage of the welding arc followed by quenching as the heat source moves away.

In the present case, a very close tolerance was called for in the alignment of bolt holes between the frame and the gun pack. If any significant distortion were to result from the weld repair, then refitting the frame to the gun pack might prove impossible. To prevent this problem from arising the frames were firmly bolted to one of two strong backing plates prior to repair welding. The first was designed to give access to cracks in position A, whilst the second was designed to give access to cracks in positions B and C.

4. WELD REPAIR PROCEDURE

4.1 Preheating

It was shown by preliminary welding trials that a hardened martensitic microstructure would inevitably form in the weld heat-affected zone (HAZ) if the weld repairs were not accompanied by some heat treatment procedure. This hardened HAZ microstructure could cause problems because it is susceptible to the formation of hydrogen-induced cold cracks. Such cracks are likely to form after completion of welding if the following conditions apply simultaneously:

- (i) A hardened (martensitic) microstructure forms in the HAZ.
- (ii) A sufficient concentration of hydrogen is present in the HAZ.
- (iii) Tensile stresses are present.
- (iv) The temperature is near ambient.

In this particular case, the control of microstructure was not a realistic option, so the most appropriate way to avoid cracking lay in reducing the hydrogen level in the HAZ. This could be best achieved by using a low hydrogen welding process, and by maintaining the frame at an elevated temperature for sufficient time to allow for most of the mobile hydrogen present to diffuse out of the frame. Accordingly a preheat temperature of 200°C was chosen for the repair scheme. Apart from reducing the hydrogen concentration, a further benefit of using this temperature was that it resulted in a slower cooling rate after welding, thereby allowing for some auto-tempering of the martensite formed in the HAZ. This auto-tempering also has the beneficial effect of reducing susceptibility of the microstructure itself to hydrogen induced cracking.

4.2 Process Selection

In choosing a welding process for repair of the Defa frame, the

important requirements were:

- (i) maximum control of the weld pool to ensure that there would be no lack of side wall fusion, that penetration of root runs could be closely controlled, and that there would be a minimum of undercut;
- (ii) a process having a low hydrogen potential; and
- (iii) a consumable giving the required mechanical properties of the weldment.

The two processes that best fill these requirements were Tungsten-Inert Gas (TIG) and Manual Metal-Arc. In this instance TIG was chosen because of its lower hydrogen potential and because it gives superior control of the weld pool.

4.3 Filler Wire Selection

In the selection of a filler wire the main requirements considered were:

- (i) The mechanical properties of the weld deposit. In particular, the weld deposit was required to have slightly overmatching strength at a high level of toughness. In this latter regard a low carbon level was clearly desirable.
- (ii) The weld metal chemistry was required to have a low susceptibility to weldment cracking.
- (iii) The weld deposit was to be readily machinable in order to assist in smooth blending of the weld profile; this in turn reduces the susceptibility to the initiation of further fatigue cracking.

The filler wire which best suited all these requirements was a low alloy Ni-Cr-Mo steel with a low carbon level. Specifically, CIG Autocraft Ni-Cr-Mo filler wire 1.6mm diameter was chosen. The composition of this filler is given in Table 1, and the mechanical properties are compared with the parent material in Table 2. This alloy has the advantage over the alternative type 312 stainless steel consumable in that machining is less of a problem.

4.4 Welding Procedure

The frame to be repair welded was bolted onto the strong back and preheated in an oven at 200°C for 30 minutes.

The TIG welding process was used with Argon shielding gas at 12 litres/minute flow rate. The TIG torch used had a 9.5 mm diameter ceramic nozzle with a 1.6 mm diameter electrode (W-2% Th). The electrode tip was ground to a needle point. DC straight polarity (i.e. direct current, electrode negative) transfer mode was used. The welding current used was in the range 70 - 100 ampere.

For the welding of through-section cracks, using the grooved copper backing strip, care was taken not to fuse the copper during welding. This was achieved by first fusing the remaining crack in a carefully executed root pass. The weld was then allowed to cool to about 200°C before the filling pass was deposited.

Welding was carried out using a minimum of heat input in order to minimize metallurgical damage and the risk of HAZ cracking. At the same time, care was taken to avoid lack of fusion in the root and in the side wall, and also to avoid undercut.

5. POST REPAIR PROCEDURE

Immediately after completion of welding, the frame with the strong back attached was transferred to an oven and held at 200°C for 2 hours. The frame and strong back were then removed from the oven and allowed to air cool down to ambient temperature before the frame was removed from the strong back.

The weld reinforcement was then ground off using tungsten carbide cutting burrs and the weld toe areas carefully blended out as shown in Fig. 5. A pneumatic rotary polishing wheel was used in the final blending-out operation. This polishing was done to minimize the propensity for crack initiation in the region of the weld toe, a common site for fatigue cracking, where the geometric notch effect of machining grooves and fusion boundary is compounded by the metallurgical notch effect of the weld.

All repair welds were then inspected for defects using the fluorescent penetrant method. MRL specifications [3] called for the blending out of shallow defects (up to 0.5 mm deep), and deeper crack-like defects were to be ground out and rewelded as before.

In the case where cracking had occurred at only one or two of the identified recurrent sites, preventative action was taken to delay fatigue crack initiation at the remaining sites (Fig. 1), by coarse polishing over an area about 30 mm across using a pneumatic rotary polishing wheel, followed by fine hand polishing. A final fluorescent magnetic particle inspection was then applied.

The final steps were to replate the frame with cadmium, and then passivate in a solution of sulphuric acid plus chromate according to the Ministry of Defence Standard 130. The post-plating heat treatment was 200°C ± 10°C for 16 hours (MOD Def. 03-4).

It was instructive to observe that no problems in alignment were encountered when the completed frames were bolted back onto the gun pack. Clearly the weld repair procedure had not resulted in significant distortion, and an important requirement of the procedure had been met.

PART III. VALIDATION OF REPAIR WELD

1. ESTIMATION OF CRACK DRIVING STRESS

1.1 Background

The rapid appearance of so many cracks at similar recurring locations in the frames pointed strongly to the cause of cracking being identical in all cases, most likely the result of the cannon firing forces. Given this assumption, the quantitative analysis of one typical crack would give a usefully accurate estimate of the crack driving stress representative for all.

Quantitative fractography was used in combination with fracture mechanics to obtain information about the nature and magnitude of the cyclic stresses causing this cracking. The analysis technique has been described elsewhere [2]. It involves measurement of striation spacings on a fatigue crack surface, then using fracture mechanics and a knowledge of fatigue crack growth characteristics to relate these spacings to the amplitude of applied stress which caused that crack to grow. While there are certain shortcomings and limitations with this technique [2], weapon systems tend to be amenable to such analysis, in contrast with the airframe flight loadings which are of random, variable amplitude. This is because the predominant fatigue stresses tend to be the uniform stresses from firing, associated with the use of fixed propellant charges, and the great difficulties of analysing random variable amplitude fatigue loading are eliminated.

1.2 Fractography

Analysis was undertaken on one crack, labelled B in Fig. 1, and shown more clearly in Fig. 6.

When broken open, the crack was found to extend some 8 mm into the section. It exhibited features characteristic of fatigue: at low magnification a generally flat, slightly fragmented surface (Fig. 7) with a few prominent progression markings. Scanning electron microscopy (SEM) at high magnification revealed many areas of striation markings relatively free from mechanical damage, and of noticeably uniform spacing (Fig. 8 (a)). A single origin at the surface of the section permitted reliable crack length measurement to any point.

The orientation of the crack, the direction of propagation, and the uniformity of striation spacings all pointed to the firing stresses being primarily responsible for cracking, assuming that random airframe loadings had not caused any obvious perturbations to the striation pattern. The assumption of a one-to-one relationship between striations and firing stresses is central to the following analysis.

1.3 Estimation of ΔK and $\Delta\sigma$

The spacing of striations was measured from SEM fractographs taken at intervals along a line from the origin of the crack. No clear striations were detected within the first 2 mm of crack length, because of secondary mechanical damage arising from crack closure effects. This 2 mm zone also contained the decarburised layer, so that striations measured on the remainder of the crack were representative of crack growth in sound material. All striation measurements were made using a normal incidence electron beam. Compensation was made for any significant tilt of hills and valleys on the surface, by taking stereo pairs where necessary. SEM stage co-ordinates gave a measure of crack length at the location of each fractograph. Resulting values of crack length, a , and crack growth rate, da/dN , are shown in Table 3.

Data on fatigue crack growth rate, taken from the literature, tended to be similar for both wrought and cast low alloy steels of the Cr-Mo type, provided that they were tempered to about the same yield strength and the fatigue tests were conducted in air and with similar R values*. Of the results used in Fig. 9 [4,5], the upper-bound curve (shown as a bold line) was adopted for analysis, to make allowance for significant shrinkage porosity in the casting (Fig. 10). The presence of such porosity would have had the effect of raising the overall macroscopic crack growth rate above that indicated by the striation spacings because of numerous local jumps across the voids.

For each spot measurement of striation spacing, this crack growth curve gave the estimate of cyclic range of stress intensity (ΔK) which the growing crack experienced at that spot (Table 3). The corresponding span of local stress ($\Delta\sigma$) driving the crack was obtained from the standard solution for stress intensity factor, K . For a through-thickness edge crack in the tensile side of a beam subjected to cyclic bending, the span of stress intensity factor (ΔK) is given by the following form of the Irwin solution (see ref [2]):

$$\Delta K = 1.12 \Delta\sigma \sqrt{(\pi a)} \quad \text{Equation 1.}$$

where $\Delta\sigma$ = span of applied stress = $\sigma_{\max} - \sigma_{\min}$, and
 a = depth of crack into the section.

Having established that $\Delta\sigma$ comes from firing recoil forces, it follows that σ_{\max} is the peak recoil stress and σ_{\min} is zero; that is, $\Delta\sigma = \sigma_{\max}$ and $R=0$.

The results in Table 3 are presented graphically in Fig. 11. Despite considerable scatter in fractographic measurements, a reasonably confident estimate of 300 ± 30 MPa for crack driving stress is obtained provided that two values from measurement at $a = 2$ mm (where measurement was more difficult) are given less weighting. The scatter bars in fact reflect

* R is the ratio minimum stress/maximum stress in the loading cycle.

the variation in measured striation spacing at each point. Strictly, these bars give the variation in $\Delta\sigma$ which the crack experienced in its opening, propagating mode [6]. Intrinsic errors arising from approximating assumptions made in the various steps of analysis would further expand these bars by a small but undetermined amount.

2. FATIGUE TESTING

The value of 300 MPa crack driving stress, and the stress ratio $R=0$ were used as a basis for designing fatigue test specimens and test load levels. The tests used cantilever bend specimens to simulate the loading on the bracket, and with transverse grooves to provide a known stress concentration factor of 1.6 [7,8]. Specimen dimensions are given in Fig. 12. Values of stress amplitude were obtained from surface strains measured under dynamic conditions by strain gauges bonded to the surfaces of a dummy test specimen.

Specimens were either of sound parent material, or had single-pass welds with the grooves along the fusion boundary to sample the most susceptible microstructure (Fig. 12b). In addition to generating conventional S-N fatigue life curves, tests were continued beyond the point of crack initiation in order to obtain crack growth data under known stresses.

2.1 S-N Curves

A second factor used in determining the bounds of fatigue test conditions for generating S-N data was the number of cycles to failure, N . Since the majority of cracks in the support frames had grown to significant size after $\sim 30,000$ rounds fired, fatigue tests were confined to the range $N = 10^4$ to $N = 10^6$ cycles. The point of failure in each test was determined by an automatic cut-off switch in the machine, triggered when a crack reached ~ 0.5 mm in length.

The number of test specimens was limited by the amount of material available from frames and, as a result, the S-N data are fewer than desirable for a high level of confidence. Nevertheless, the two bands of results (Fig. 13) show a high degree of consistency and overlap closely. The slight improvement apparent in the weld metal property is encouraging, but not experimentally significant.

2.2 Fatigue Crack Growth Data

Using known stress intensity factor calibrations for a cracked cantilever bend specimen [9,10], Equation 1 was used to obtain values of ΔK at each discrete value of crack length. This analysis was confined to cracks having sufficient length to be clear of the influence of the machined groove, so that the stress intensity factor was in theory the same as at a

PART IV. CONCLUSIONS

1. The upsurge in the incidence of cracking in these front mount frames has been identified as fatigue cracking caused by the harmful effect of a decarburized layer on the surface of the heat-treated steel castings.
2. A weld repair scheme, involving the grinding out of existing cracks and use of the Tungsten Inert-Gas process to deposit a low alloy Ni-Cr-Mo weld metal of slightly overmatching strength and toughness, has been developed for this job.
3. The repair procedure also involves a careful blending out and polishing of the weld reinforcement and weld toe areas to ensure that fatigue cracking does not re-initiate in these areas.
4. Quantitative fractographic analysis of the fatigue cracks has been combined with fracture mechanics principles to establish that the driving stress for these cracks is the regular firing stresses of the gun, with an estimated peak cyclic stress of about 300 MPa acting in the critical regions of the frame.
5. Laboratory fatigue testing has demonstrated that the as-deposited weld metal has fatigue life and fatigue crack growth characteristics similar to those of the sound parent casting, so that the prescribed weld repair should restore the service life to the same order as the designed life for metallurgically sound frames.

ACKNOWLEDGEMENT

The 2AD RAAF base workshop at Richmond, NSW, manufactured the strong backs used successfully in these weld repairs. Charles Malmgren, now retired, provided valuable assistance in devising the weld procedure.

single crack having the same total depth. The results of five tests covering parent casting and weld HAZ, over a wide range of loads, are superimposed on Fig. 9.

Besides confirming the choice of estimated fatigue crack growth curve, these data show no real difference attributable to microstructures of parent and weld HAZ.

2.3 Fractographic Examination

The fracture surfaces of the cracks generated in fatigue testing were compared with those in the gun mounting frames using scanning electron microscopic examination. This revealed that, when comparing areas of crack surfaces reckoned to have been subjected to similar levels of stress intensity and crack driving stress, both the overall appearance at low magnification and the fine striations and details revealed at high magnification were very closely matching (Figs. 8 (a) and (b)). This is taken as evidence that there was no difference in the mechanism of fatigue crack growth between weld filler metal and sound parent metal.

3. DISCUSSION

The various analyses and tests have all shown that the overall fatigue resistance, and the fatigue crack growth characteristics are virtually identical in the repair weld metal and the sound parent casting. In addition, the magnitude and nature of the crack driving stress have been elucidated, firstly through the good agreement between the fatigue crack growth data and the representative curve taken from the literature (Fig. 9). Secondly, the close matching between crack surfaces of the laboratory test specimens with cracks in the failed frames lends further evidence that cracking was caused by uniform firing stresses rather than any random variable flight stresses or catastrophic overload damage.

Results from the fatigue S-N tests indicate that the weld repairs made in the crack-susceptible regions of the frame should confer the same fatigue life as if the frames were of sound material free from the harmful effect of the decarburized layer. That is, the fatigue life in the most susceptible areas should be restored to something approaching the design fatigue life. Whereas many cracks appeared in the mount frames after ~ 30,000 firing stress cycles, the fatigue curves in Fig. 13 indicate that sound metal should survive at least 10^4 rounds, with a fair probability of reaching 2×10^5 or 3×10^5 .

It may well be that, once these critical areas are weld repaired, the indelibly harmful effect of the decarburized layer will cause the initiation of further fatigue cracking in the next highly susceptible regions of mounting frames so affected. It is very unlikely that this cascading effect can be combatted; however, by further identical weld repairs as cracks appear, it should be possible to sustain the service life of the gun pack.

TABLE 1. CHEMICAL ANALYSES OF FRAME AND WELD METAL

Element	C	Mn	Si	S	P	Ni	Cr	Mo	V
Frame	0.25	0.68	0.16	0.003	0.01	0.12	1.06	0.23	n.d.
Weld metal	0.07	1.47	0.57	-	-	1.4	0.39	0.28	0.07

Analyses are in wt %.

n.d. = not detected.

TABLE 2. MECHANICAL PROPERTIES

Property	Frame	Weld metal (as deposited)
Yield Stress (MPa) (0.2 % P.S.)	670 (ps)	742 (ys)
Tensile Strength (MPa)	790	824
Elongation on 5d (%)	11	20
Hardness (HV30)	260	~300
Charpy impact energy (J)	-	129 at 0°C 47 at -40°C

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TABLE 3. ESTIMATION OF CRACK DRIVING STRESS

¹ Crack Length a (mm)	² Striation Spacing $\frac{da}{dN}$ ($\mu\text{m}/\text{cycle}$)	³ Stress Intensity Span ΔK ($\text{MPa m}^{1/2}$)	Driving Stress Span $\Delta\sigma$ (MPa)
2.04	0.25-0.36	30.0-33.5	240-378
2.08	0.19-0.28	27.3-31.5	307-353
2.92	0.25-0.33	30.0-32.5	285-308
3.69	0.33-0.39	33.0-34.8	279-294
4.90	0.50-0.63	37.5-41.0	275-300
5.36	0.69-0.97	42 -47	294-329
5.84	0.83-0.97	45 -47	302-315
6.05	0.78-0.92	44 -46	290-304
7.48	0.90-1.20	46 -50	273-297

1 Measured from point of initiation.

2 Measured from fractographs, compensating for local surface tilt.

3 Estimated from published fatigue crack growth data (Fig. 9).

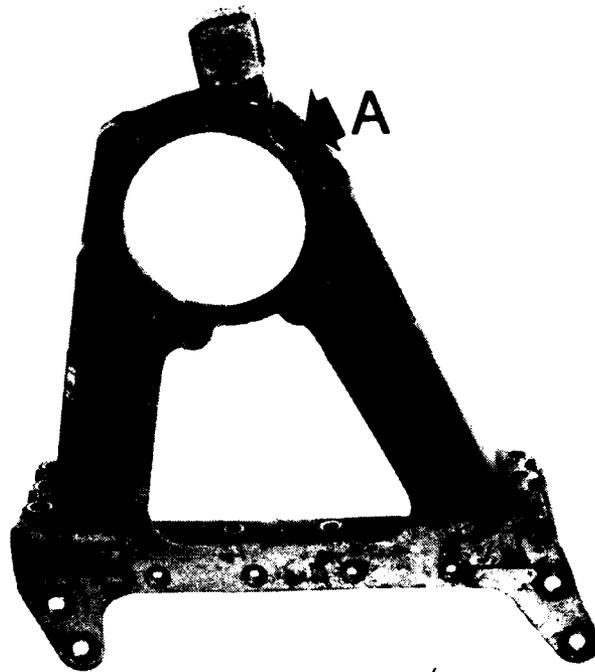


FIGURE 1

Location of cracks in Defa front mount frames. Cracking was most common in sites A and B.

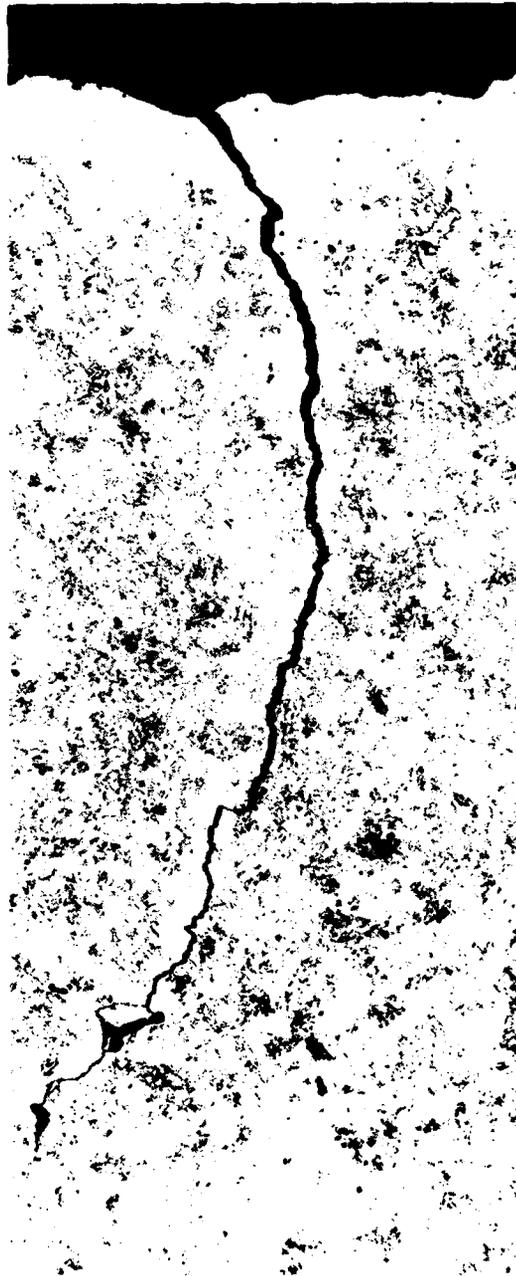


FIGURE 2

Initiation of a fatigue crack in the decarburized surface layer of a frame.

2% Nital etch. X100.

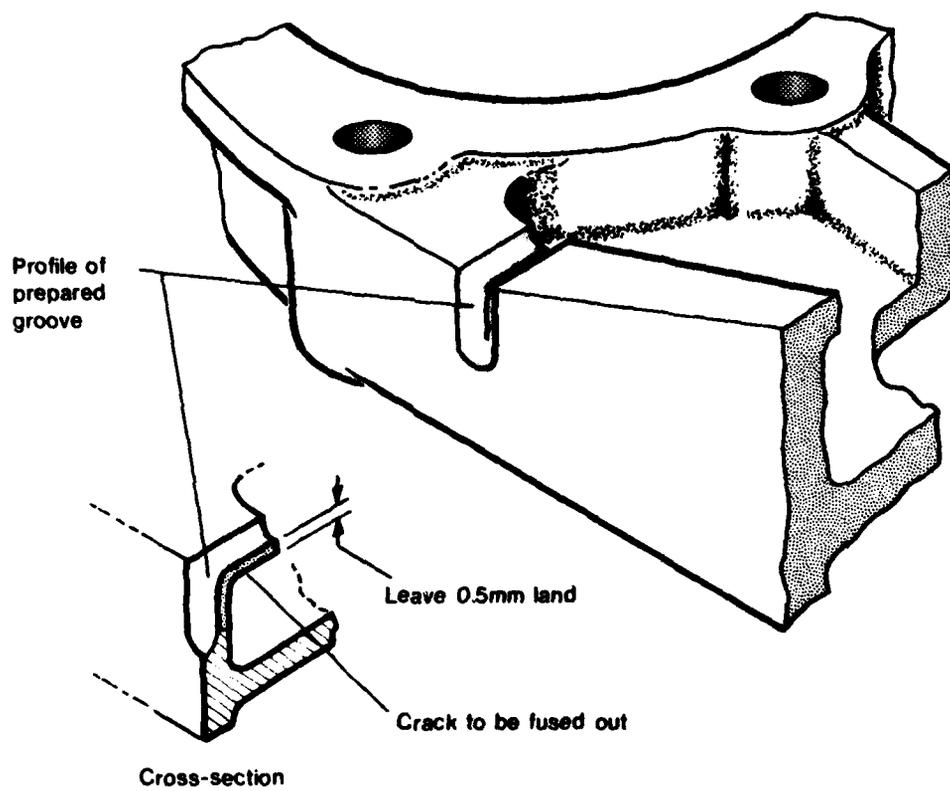


FIGURE 3

Recommended weld preparation for through-thickness cracks in position B, shown in Fig. 1.

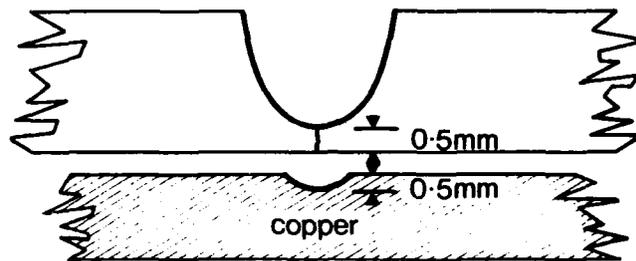


FIGURE 4 Schematic diagram of weld preparation and copper backing strip for through-section cracks.

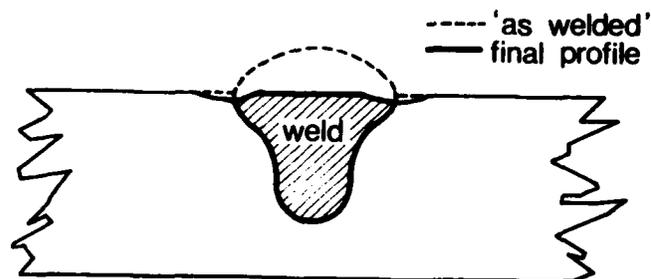


FIGURE 5 Schematic diagram showing blending out in weld toe areas.

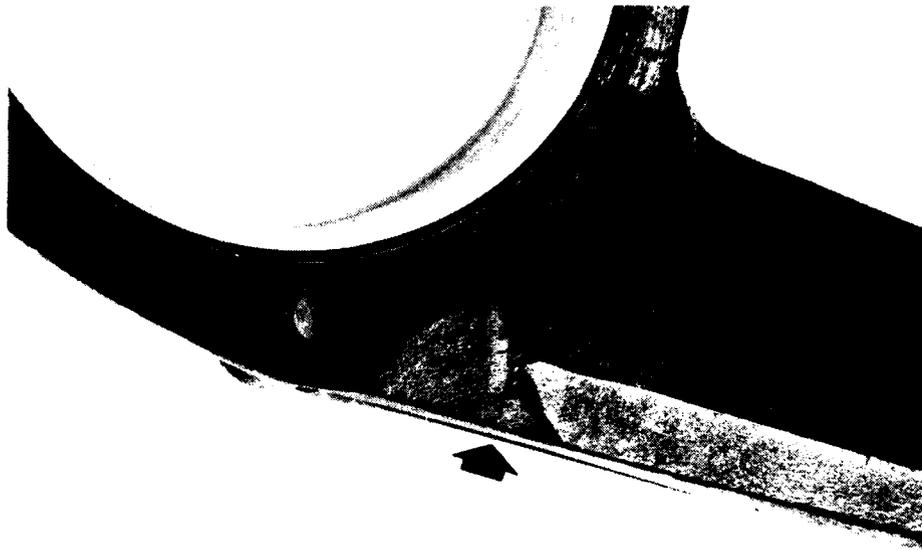


FIGURE 6

Detail of the crack shown at B in Fig. 1. The section shown had been subjected to bending stresses across the crack (arrowed), causing flexure convex to the plane of the page. The crack initiated at a machining groove, at the periphery of the machined surface.

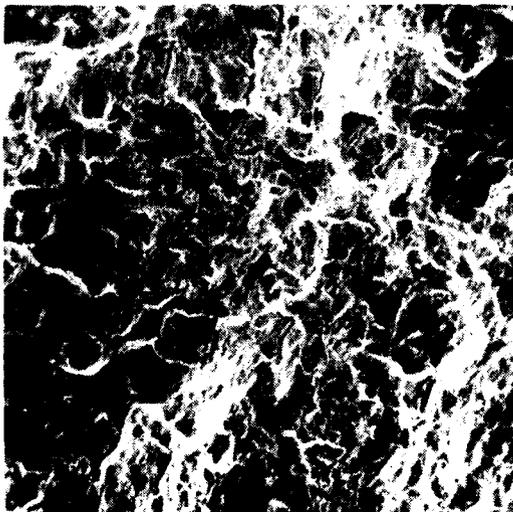


FIGURE 7

Fatigue fracture surface from support frame. Although flat in appearance, the crack is fragmented and broken up by branch cracks. Direction of growth is upwards.

SEM X360.



FIGURE 8 (a) Detail of fracture in Fig. 7 showing distinct striation markings. Local tilting of the surface away from normal creates the illusion of close spacing of striations. Propagation is from left to right. $\Delta K \approx 50 \text{ MPa m}^{1/2}$ at this point.

SEM X1400.

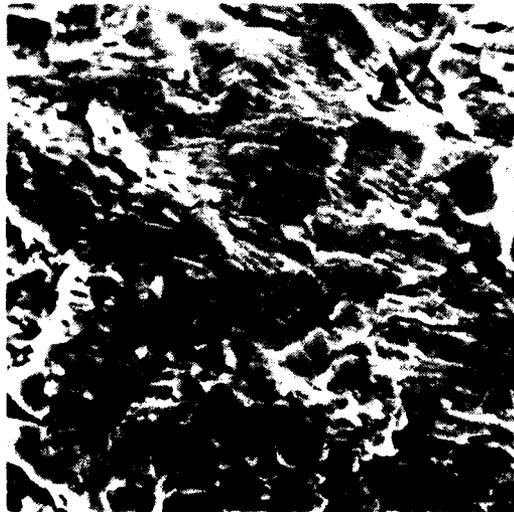


FIGURE 8 (b) Corresponding fracture from Laboratory test on a welded specimen, showing features identical with the service crack in Fig. 8(a). Direction of growth is upwards. $\Delta K \approx 55 \text{ MPa m}^{1/2}$.

SEM X1400

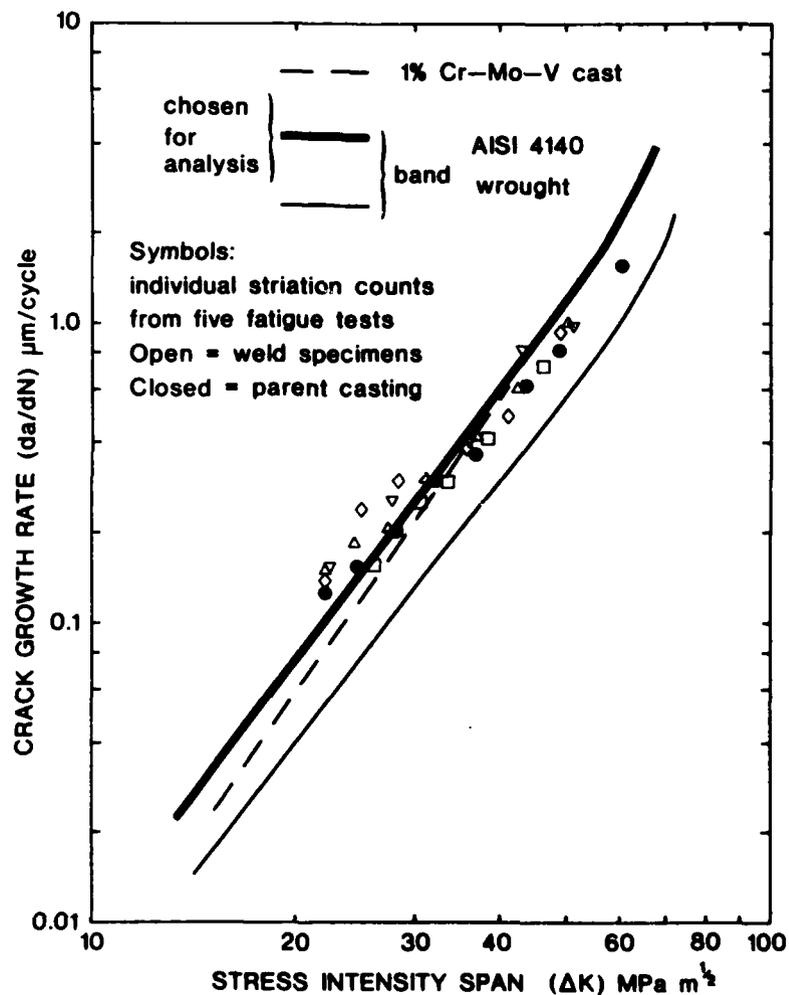


FIGURE 9

Fatigue crack growth rate data for 1% Cr low alloy steels. The 1% Cr-Mo-V cast steel is after Haigh [4] and the band for AISI 4140 is after Thielen and Fine [5]. Test data points are from four welded specimens (open symbols) and one parent specimen (closed symbol).

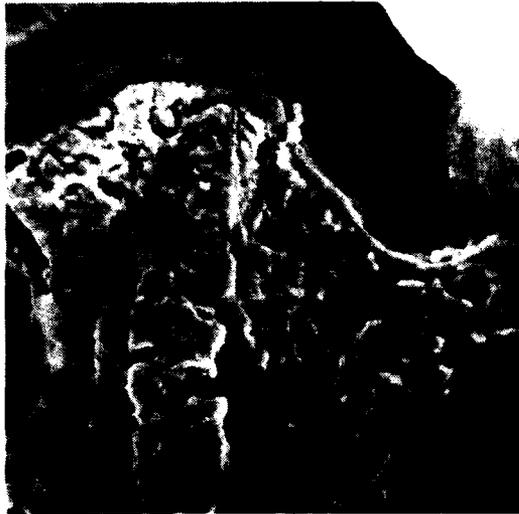


FIGURE 10

Crack growth across shrinkage porosity in cast frame. The crack, growing upwards, has re-initiated after jumping across the void, and resumed growth by the striation mode. Martensitic transformation has caused rumpling on the free surface of the void.

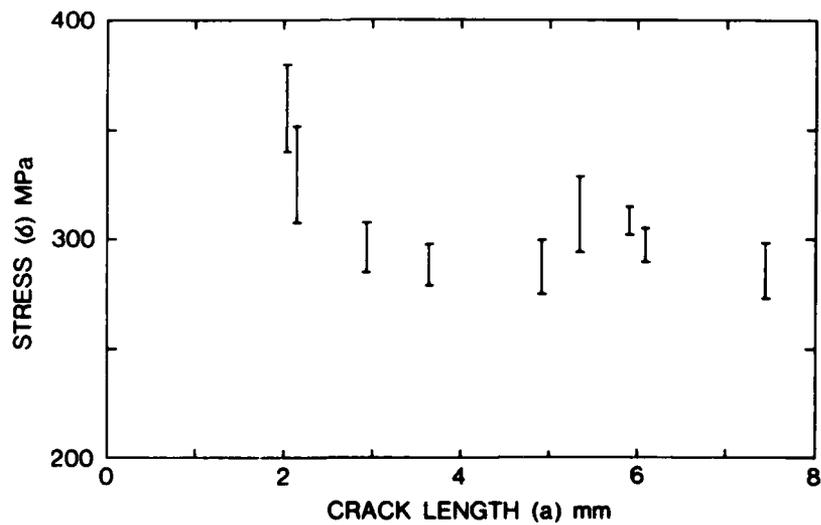


FIGURE 11

Estimates of the fatigue crack driving stress in the cast frame based on measurements of the crack shown in Figs. 7 and 8.

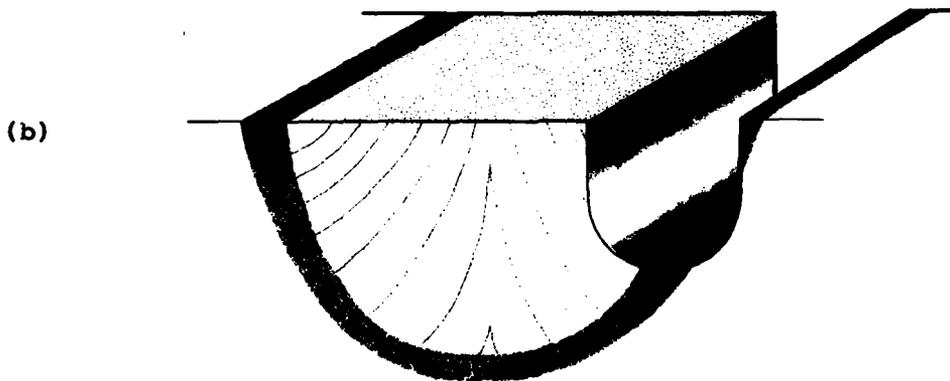
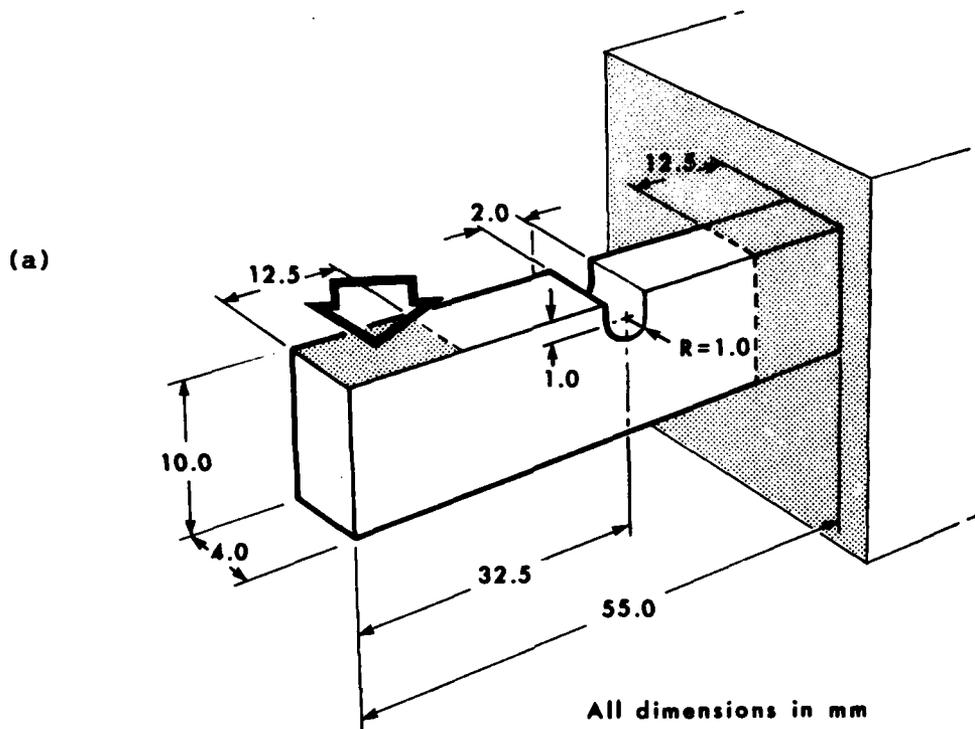


FIGURE 12 (a) Detail of fatigue test specimen.

(b) Location of notch in welded test specimen, with the root radius of the notch in the weld heat-affected zone.

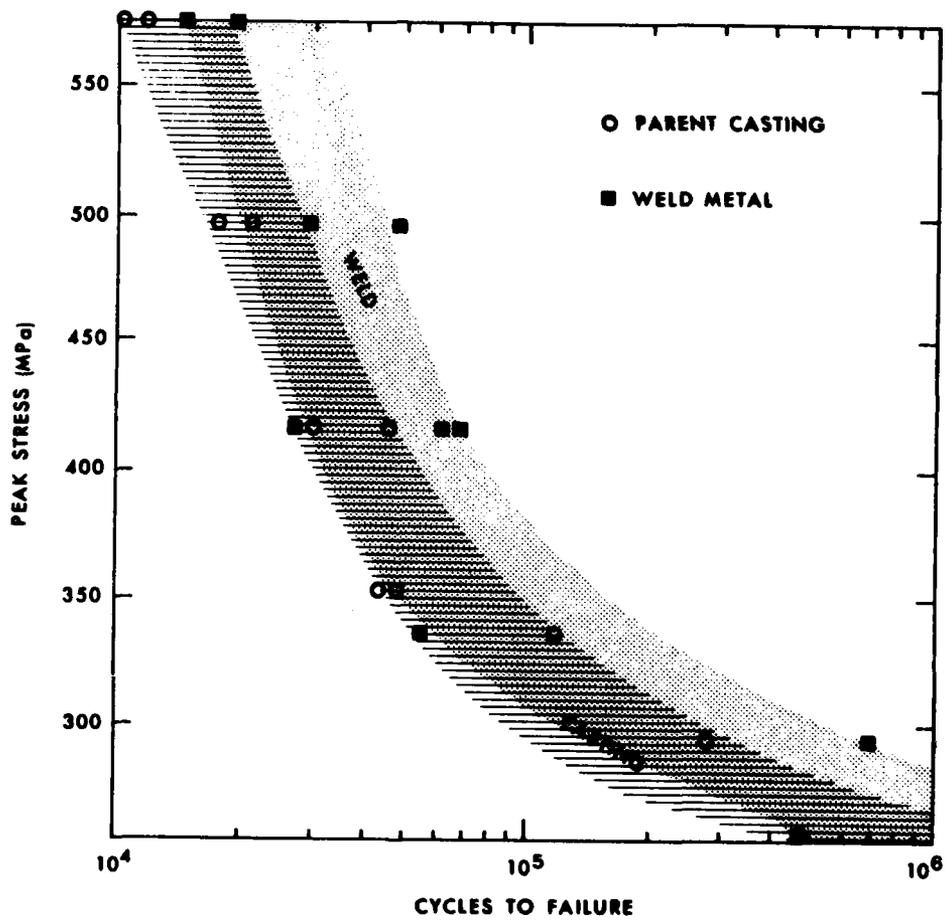


FIGURE 13

Fatigue S-N data generated for sound casting material and from as-deposited Ni-Cr-Mo weld metal.

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