

Technical and Financial Appraisal of a Contemporary Repair Technique for Rails and Crossings

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Maintenance welding on British Railways (BR) track is confined to two areas—crossings are repaired to fix the batter and cracking caused by passing traffic (these repairs outperform the original crossing material), and plain line is repaired to fix the damage caused by wheelslip and to remove rolling contact fatigue (“squat”) defects. These two types of repair operate in different stress environments; crossings are mainly subject to impact and plastic deformation, whereas plain line is subject to rolling contact fatigue and wear. Maintenance repair of rails within BR was until recently carried out almost exclusively with manual metal arc (MMA) welding using 3.2- or 4-mm diameter electrodes and small portable site welding alternators capable of producing welding currents up to 250 A. Welder training and repair procedures have been developed and improved over the years; however, these techniques are governed by the weldability of the base material and the limitations of the MMA process. Therefore, further development of the present system for improved productivity and quality is limited. Semiautomatic welding procedures using flux-cored wires have been demonstrated in industry to offer great economic and technical benefits over MMA arc welding, and the application of the concept to the maintenance repair of track components has been the subject of an extensive laboratory and field assessment, the results of which are presented in this paper.

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MMA WELDING

Weld repairs to the permanent way can be broken down into two main categories: (a) maintenance and repair of crossings, and (b) repair of plain line surface defects.

Repair of Crossings

The repair of crossings can be broken down into two distinct types.

Maintenance repair involves the removal of deformed and defective material, which results from the impact loading of passing traffic, and its replacement with sound material (Figure 1). This type of repair is carried out in track, generally before the amount of wear on the crossing exceeds 6 mm in depth. Both the wing rails and the crossing nose (frog) are treated at the same time and in the same manner.

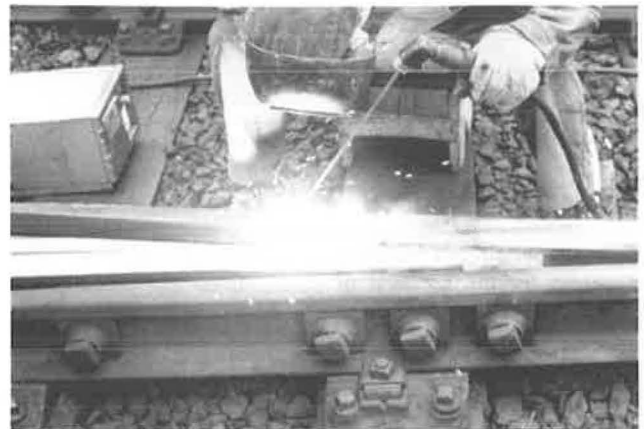


FIGURE 1 Crossing nose undergoing maintenance welding.

Structural repairs to crossings are usually executed out of track and can involve large weld repairs to fatigue cracks or fabrication defects anywhere within the body of the crossing (Figure 2). The objective of both types of crossing repair is to enhance the life of the crossing at minimal cost. Whereas most maintenance welding can be undertaken with the crossing in situ, larger repairs necessitate the removal of the unit before its repair, either at lineside or in a workshop.



FIGURE 2 Crossing nose requiring repair welding.

Repair of Plain Line

The adoption of MMA welding for the rectification of surface damage and defects in plain line is relatively recent and was stimulated by the widespread use of continuous welded rail with its attendant high cost of rail replacement.

Initially repairs were restricted to inherent rail defects (rolling defects) or wheelburns (Figure 3). However, the identification of large numbers of RCF defects (Figure 4) in the mid-1970s (1) enhanced the cost-effectiveness of repairs by welding as an option to rail replacement. Procedures have been developed for the repair of plain-line defects, either with or without possession of the line, to remove cracked or defective material and restore a smooth-running surface with sound, defect-free weld metal.

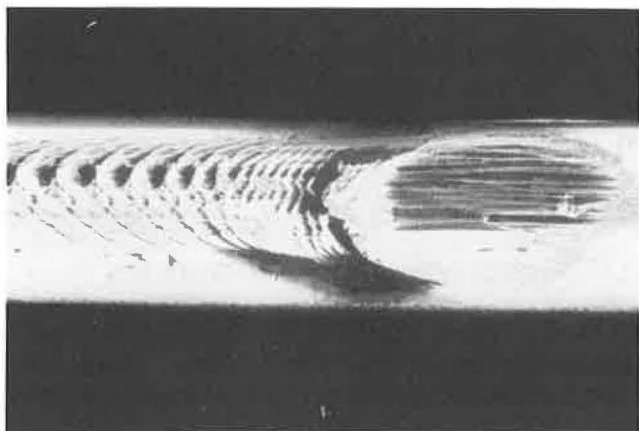


FIGURE 3 Typical wheelburn.

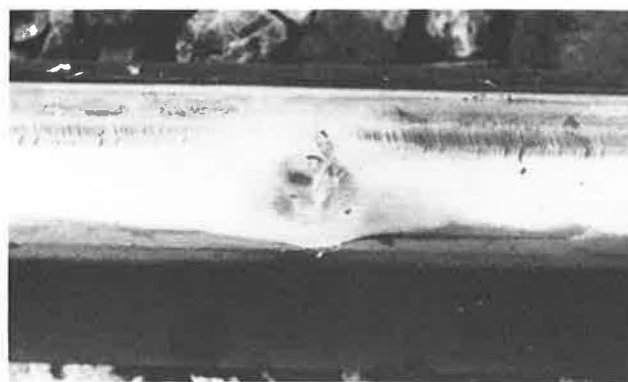


FIGURE 4 Rolling contact fatigue ("squat") defect.

Weld Metal Considerations

The stress environments encountered in these two types of repair are quite different. Crossings are mainly subject to impact loading from the transfer of the axle load from the wing rail to the crossing nose, or vice versa: Plain line is subject to cyclic dynamic loading from the smooth passage of the wheel along the rail. The properties required of any weld metal for these repairs would appear to be quite different, but this is not necessarily the case. For crossings, resistance to impact is of prime importance; other properties required are resistance to fatigue crack initiation and growth and a degree of ductility. A hard, tough weld metal is therefore required. Plain line repairs need to be very resistant to fatigue crack initiation and growth and should wear at approximately the same rate as the rail steel. A hard and tough high-integrity weld metal is required.

In 1967 (2) an assessment of electrodes was completed by BR to determine their suitability for maintenance of crossings. The results of this work, based on weld integrity and hardness, showed that "low alloy," hydrogen-controlled electrodes (2 $\frac{1}{4}$ percent Cr/1 percent Mo) or "stainless" rutile electrodes (18 percent Cr/8 percent Ni/3 percent Mo) produced deposits suitable for surfacing BS 11 normal quality steel (see Table 1). Electrodes of these two broad types were adopted by BR for welding crossings (3), and several electrodes of each type were subsequently approved (Table 2).

Following the adoption of these electrode types, a number of reports were received as to the performance of the repairs. Some reports indicated that the stainless electrode exhibited poor resistance to batter, whereas other reports revealed that although the low-alloy types were more resistant to deformation, problems were encountered with cracking, either as a result of inadequate preheat (4) or as a result of weld defects (5) (see Figures 5 and 6).

In 1970 a project was undertaken by the BR Research Division to investigate further the choice of welding procedure (including preheating requirements) and the most suitable electrode for the repair of worn crossing components. This work culminated in the recommendation that the minimum preheat temperature for normal quality rail steel be 350°C (6) and the finding that the most crack-resistant electrodes were Philips kV3L and Murex Duroid 11. The properties of these two electrodes are given in Table 3. It was also recommended that semiautomatic welding methods be investigated (6).

TABLE 1 RAIL COMPOSITION AND CRITICAL COOLING DATA

	CARBON WT%	MANGANESE WT %	SILICON WT %	CHROMIUM WT %	SULPHUR WT %	PHOSPHORUS WT %	C.E.*	COOLING DATA FOR FULLY PEARLITIC TRANSFORMATION T 800-400 COOLING (SEC) RATE (°C/S)	
BS 11 (1978) NORMAL QUALITY	0.50	0.95	0.05	-	-	-	0.61	40	10.0
	0.60	1.25	0.35	-	0.05	0.05	0.81		
BS 11 (1978) GRADE A	0.65	0.80	0.05	-	-	-	0.73	35	11.4
	0.78	1.30	0.35	-	0.05	0.05	0.97		
BS 11 (1978) GRADE B	0.50	1.30	0.05	-	-	-	0.72	590	0.67
	0.70	1.70	0.50	-	0.05	0.05	0.98		
BSC 110 kg mm ⁻² CHROMIUM	0.68	0.80	-	0.95	-	-	1.06	1200	0.33
	0.78	1.20	0.50	1.25	0.04	0.03	1.27		
NORMAL AUSTENITIC MANGANESE STEEL	1.0	11.0	-	-	-	-	-		
	1.25	-	1.0	-	0.06	0.07	-		
LOW CARBON AUSTENITIC MANGANESE STEEL	0.7	12.0	-	-	-	-	-		
	0.9	16.0	0.4	-	0.05	0.05	-		

$$* CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

TABLE 2 ORIGINAL APPROVED LIST OF MMA ELECTRODES

Electrode	Manufacturer	Type of deposit
kV3	Philips	2-1/4% Cr/1% Mo
Ferron 42	B.O.C.	2-1/4% Cr/1% Mo
Suprex B	Murex	2-1/4% Cr/1% Mo
Duroid 11	B.O.C.	18% Cr/8% Ni/3% Mo
Armex 2	Murex	18% Cr/8% Ni/3% Mo
Manganese Nickel	Murex (Hymet)	0.7% C/11% Mn/4% Ni*

* Used as a work hardening capping layer on cast manganese crossings only.

Although the foregoing investigation was aimed primarily at the repair of crossings, the repair of wheelburns was also being studied (7). MMA, oxyacetylene, and aluminothermic processes were considered. However, the MMA welding was found to be the most practical, and, as in the work on crossings, the Philips kV3L electrode was found to be the most suitable for the repair of wheelburns.

FLUX-CORED SEMIAUTOMATIC WELDING

Background

By the early 1970s it was recognized that the use of a continuous wire "semiautomatic" welding process might be of benefit to the civil engineer, both in terms of productivity and deposit quality.

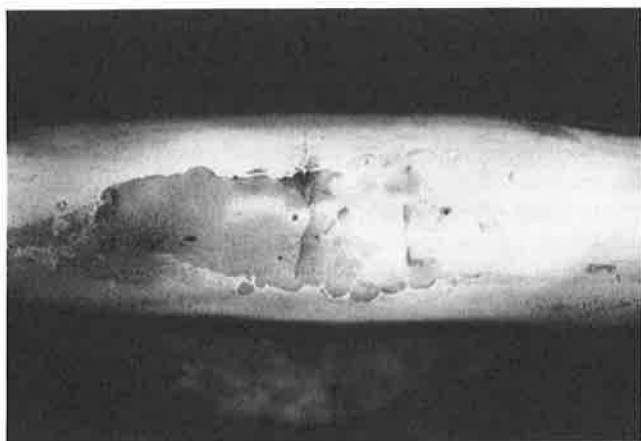


FIGURE 5 MMA repair of cracked plain line.

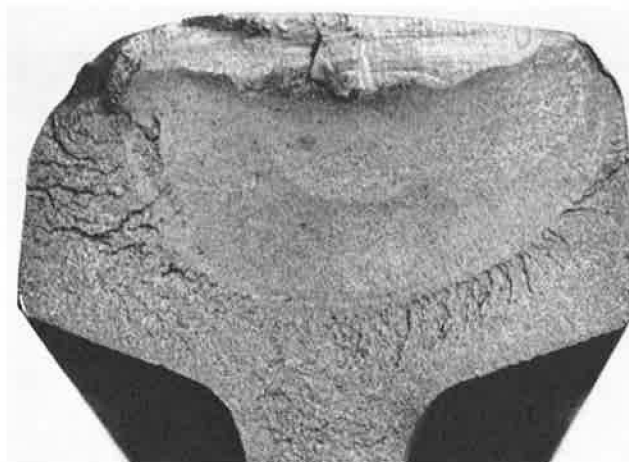


FIGURE 6 MMA repair of fractured rail.

TABLE 3 CHARACTERISTICS OF CURRENT APPROVED MMA ELECTRODES

TYPE	"Low Alloy"	"Stainless"
APPROVED PRODUCT	Philips kV 3L	Murex Armoid 1 *
electrode : dia. (mm) length (mm) coating type AWS Class	3.2, 4.0 350 Basic (low hydrogen) BS2493 - 2 Cr Mo B E 9015 B 3L	300 Rutile BS2926 - 20-9-3 -
Welding - O.C.V. AC/DC tgp. current (a)	80 DC+ or AC 4 mm:- 115-165	80 DCT or AC 3.2 mm:- 110-130
Typical Composition (wt %) C Si Mn S P Cr Ni Mo	.07 0.4 0.9 .014 .018 2.5 - 1.0	.06 .90 2.03 .013 .033 20 8.2 3.2
U.T.S. (N/mm ⁻²) Y.P. (N.mm ⁻²) % Elong Hardness (Hv 30)	810 - 903 602 - 765 21 - 31 310 - 320	670 - 760 450 - 540 31 - 48 235 - 290
Microstructure	Fine Bainite	Austenitic + 25% Ferrite

* Murex Armoid 1 is the current alternative to Murex Duroid 11, which is no longer available.

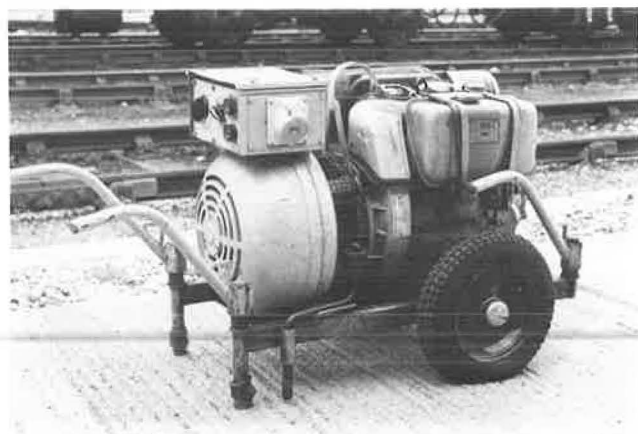


FIGURE 7 Hayter "Mighty Midget" 250a AC welding machine.

An analysis of typical maintenance repairs to crossings demonstrated that only 25 percent of the welder's time on site was actually spent welding (see Appendix A). The remaining time was consumed by ancillary operations, some of which were peculiar to the MMA process (electrode drying and changing, slag removal, etc.). In addition, a large number of repairs subsequently failed as a result of welding defects such as lack of fusion or porosity.

Semiautomatic welding in industry has proved to offer great economic and technical benefits over MMA welding (in addition to the improved weld quality), primarily as a result of higher deposition rates and greater heat input. The concept, therefore, if applied to track repairs, could both increase the speed of repairs, thus releasing staff for more repairs,

and reduce the number of subsequent failures. A further potential benefit was the possibility of repairing rail steels not repairable with MMA as a result of the greater heat input.

A preliminary appraisal of a number of products was carried out between 1968 and 1973. However, the consumables were off-the-shelf products deposited using conventional heavy-duty plant, and the appraisal drew attention to their limitations for use on site. This was primarily because of the need for additional shielding gas (CO_2) and heavy, high-current (350 to 400 A) welding machines because of the large-diameter (3 to 4 mm) wires then available (8).

From this initial review of products, requirements were formulated for a suitable process for site deposition of a wear-resisting surface on rails. The basic criteria were as follows:

1. The process should use self-shielding consumables to avoid the need to supply and transport gas bottles, and
2. The process should operate satisfactorily from existing portable MMA welding power sources.

Both aspects required considerable development, and although they are obviously interrelated, for the purpose of this paper they will be examined separately.

Equipment Development

The most common type of MMA welding machine used by BR is the Hayter 250a AC "Mighty Midget" alternator, of which approximately 400 are currently in service. The majority are diesel powered (Figure 7). The unit operates nominally at 427 Hz, and the output is rated as 250 A maximum at 60 percent duty cycle. Machine tests have shown that the

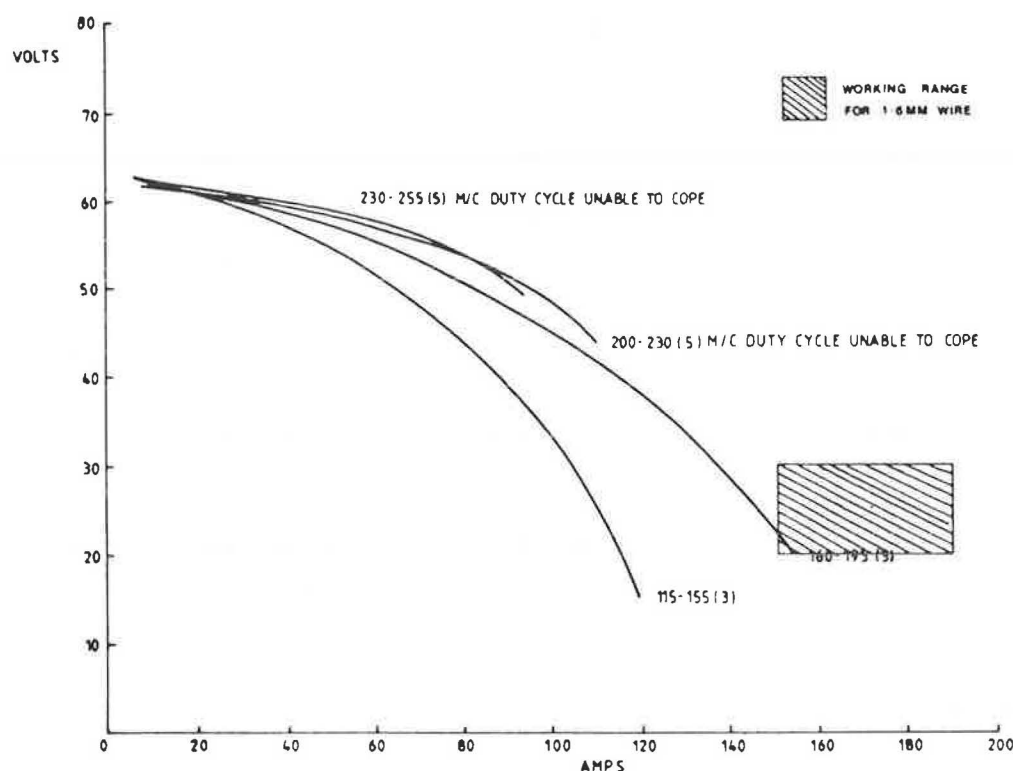


FIGURE 8 Current-voltage relationship for the "Mighty Midget" operating on ac.

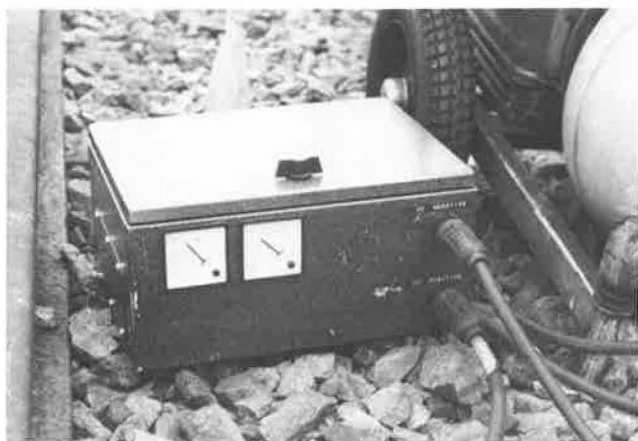


FIGURE 9 Example of an ac-dc rectifier.

maximum current at 100 percent duty cycle, which would be required for a continuous wire process, can be as low as 160 A, particularly if deterioration of the equipment is taken into consideration. In common with other MMA welding plant, the curve of machine output has a "drooping" characteristic, effectively producing constant current over the normal working range (see Figure 8).

Most commercially available wire feed systems operate off "flat" characteristic or constant voltage power supplies, using the welding current to drive the feed rolls. It was necessary, therefore, to develop a wire feed unit that would operate from the MMA supply and be lightweight yet robust in design. Welding Alloys Ltd. was developing a prototype machine, and one unit, designated the WASA 70, was purchased for research.

Initial welding trials were centered around commercially available "low alloy" hard facing flux-cored wires 1.6 mm in diameter (9; W. A. Mosley, private communication, July 1980; 10). Most of these were subsequently found to be unsatisfactory (see the next section). In addition to poor weld quality, it was found that when the portable ac supply was used, only a small amount of weld metal could be deposited before the duty cycle of the source was exceeded, and the power supply was cut. Attempts to reduce the wire to 1.2 mm in diameter to reduce the required welding current resulted in a variable weld quality due to variations in the density of the flux fill. Attention therefore was turned to the power supply. Trials with a dc mains transformer gave no such problems; additional benefits were a more stable arc, enhanced deposition characteristics, and increased arc energy (i.e., heat input). The attachment of an external rectifier or "converter" (Figure 9) to the output of the ac power supply was found to increase the output of the unit such that the duty cycle of the machine was no longer being exceeded (see Figure 10). It also produced the improved welding characteristics noted for the dc mains supply (W. A. Mosley, private communication, Oct. 1980).

The WASA 70, operating from a rectified ac supply, was subsequently used for the first site trials with the process, and certain modifications became desirable for the production model, which have subsequently been incorporated into an improved unit, the WASA 90 (Figures 11 and 12).

Rectified three-phase ac welding machines have also been investigated and are now recommended as the preferred and more economical alternative to the purchase of new ac plant with a separate rectifier. An example of one such unit is shown in Figure 13; its output is shown in Figure 14.

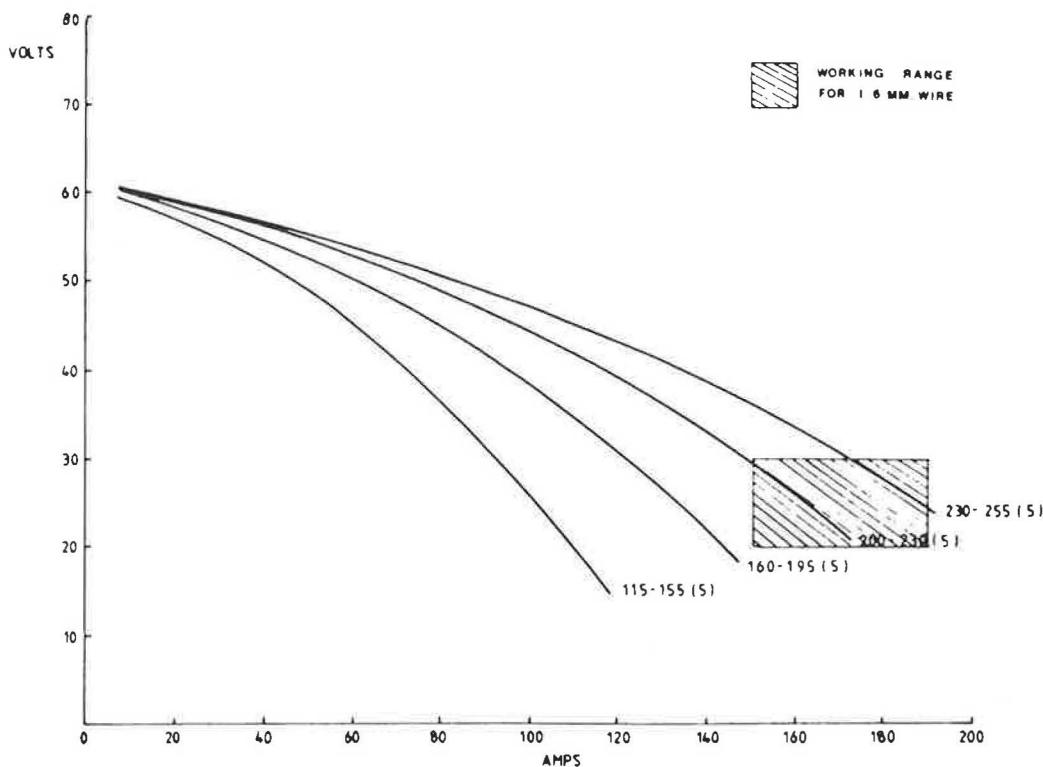


FIGURE 10 Current-voltage relationship for "Mighty Midget" and rectifier.

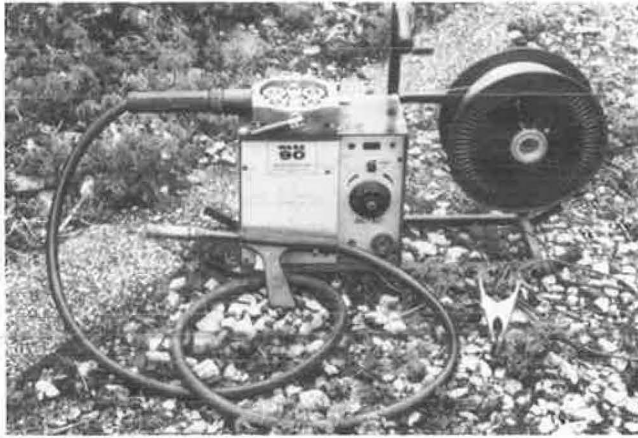


FIGURE 11 Welding Alloys WSHA 90 wire feed unit.

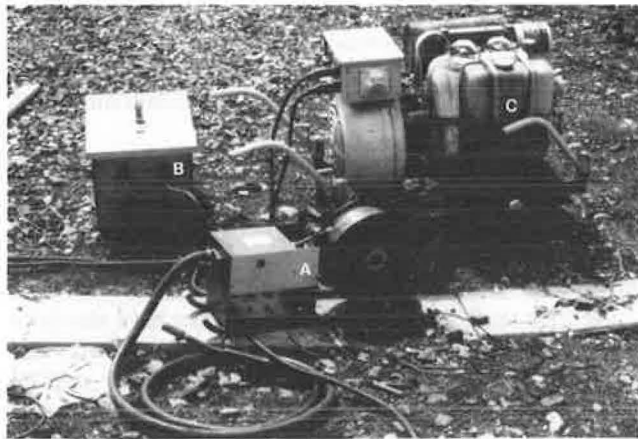


FIGURE 12 Equipment arrangement consisting of (A) welding torch, (B) converter, and (C) ac welding machine.

Development of Wire for Repair Welding

Initial Work

The basic requirements of any deposit on rails are high integrity (freedom from defects), resistance to deformation and wear, and resistance to fatigue cracking, with good welding characteristics.

Initial trials with commercially available consumables proved unsatisfactory. The main problems were as follows:

1. Defects occurred in the weld metal—porosity and slag were trapped because of premature freezing of the deposit as a result of the low current available for depositing large-diameter wires (>1.6 mm) (9).
2. Conventional hard-facing consumables, typically containing high C, Si, and Mn levels, resulted in excessively hard and brittle deposits (W. A. Mosley, private communication, July 1980).
3. Consumables containing titanium (added as a deoxidant) resulted in retention of large titanium carbonitride inclusions in the weld metal (10), which impaired the fatigue properties.
4. Deposits that were sound, defect free, and metallurgically acceptable were usually too soft compared with



FIGURE 13 Petbow Arc Centre 200 dc welding machine.

MMA deposits (W. A. Mosley, private communication, Oct. 1980).

From the experience gained through this work, the requirements of candidate wires became more evident.

Wires had to be limited to 1.6-mm diameter or less and dc current was necessary to obtain adequate welding characteristics from site plant, and to increase the duty-cycle capacity of the equipment. A “stringer” bead welding technique tended to increase defect levels (W. A. Mosley, private communication, Oct. 1980). Therefore a weave technique was proposed. The use of deoxidants such as titanium was to be avoided, as were high carbon and manganese levels. Preheat could be reduced to 250°C for normal-quality rail steel as a result of the higher heat input of the process (W. A. Mosley, private communication, July 1980).

Evaluation Program

To handle the number of products that were expected to be submitted for assessment, the evaluation program used simple, low-cost procedures for initial sorting, following by more sophisticated tests on selected wires.

The program evolved around two deposition arrangements, with the candidate wire being deposited on mild steel plate for “undiluted” weld metal analysis and on prepared lengths of BS 11 normal-quality rail steel for diluted weld metal analysis. The tests used and their order are given in Table 4 (test specimen weldments are shown in Figure 15).

A number of possible consumables have been assessed; one of the most successful is a CR/Mn wire submitted in August 1983. The wire was initially supplied as a single 13-kg reel; however, additional reels were made available following the satisfactory preliminary assessment (11).

Laboratory Assessment of Cr/Mn Flux-Cored Wire

Before any test samples were prepared, “exploratory” weld deposits were produced to determine the welding parameters. All welds were made using rectified ac, a 25-mm weave, and a run length of approximately 90 mm. All the welds on normal-quality rail were deposited using 250°C preheat.

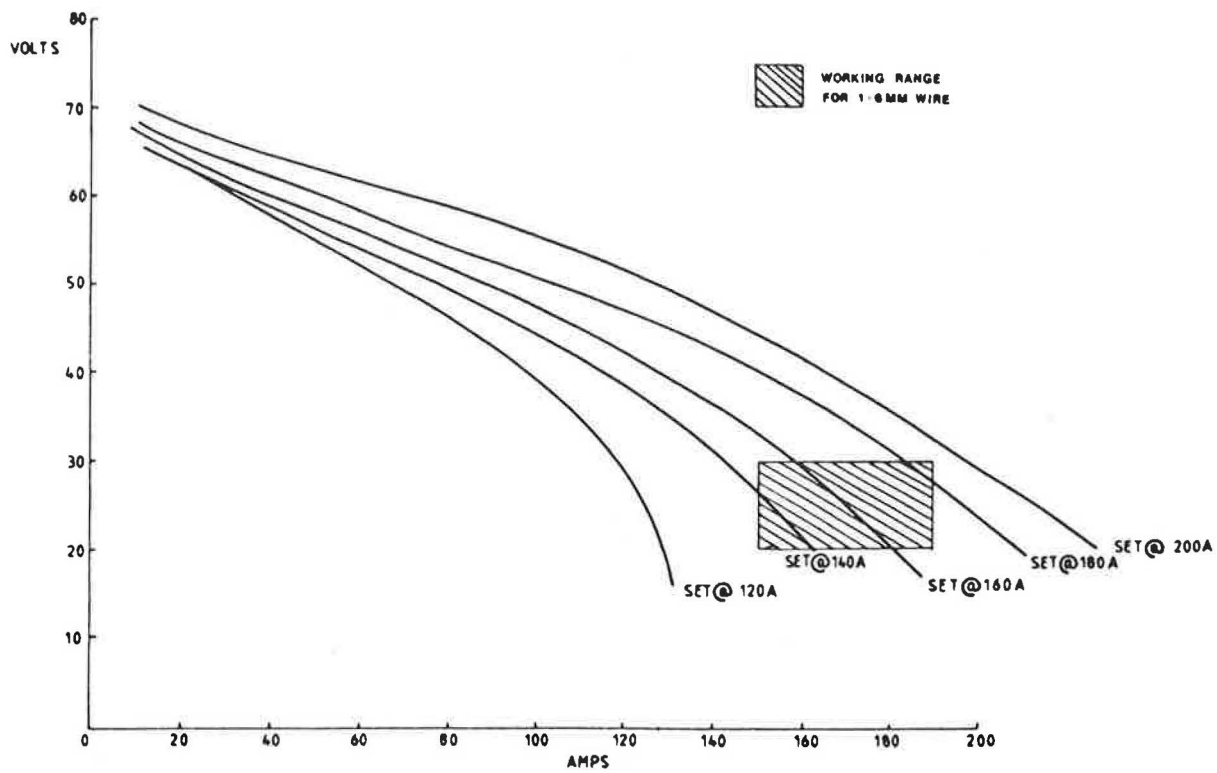


FIGURE 14 Current-voltage relationship for Pethow Arc Centre 200.

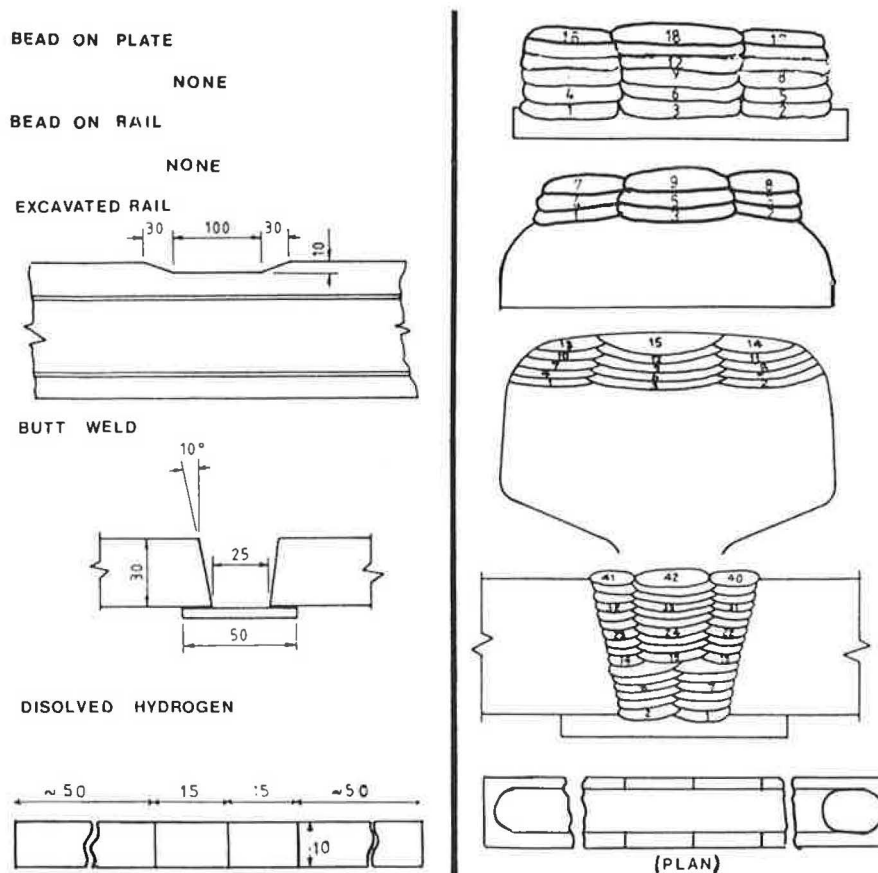


FIGURE 15 Preparation (*left*) and welding sequence (*right*) for test samples.

TABLE 4 TESTS USED TO EVALUATE WIRES

Test Piece	Applicable Test Program
Bead on MS plate (six-layer pad)	Radiography Chemical analysis Metallography Hardness
Bead on rail (three-layer pad)	Metallography Chemical analysis Hardness
Excavated rail	Fatigue test Metallography
Butt-welded M/S plate	Tensile test Toughness (Charpy V notch) Deformation (flow under impact)
Bead on plate	Diffusible hydrogen

The results of these exploratory tests are summarized in Tables 5–8, and the fatigue data are shown in Figure 16 with comparative data for MMA welds.

Metallographic examination of the weld metal in the undiluted form revealed a coarse dendritic structure (Figure 17) with a very low level of nonmetallic inclusions and no visible porosity. The microstructure of the weld metal consisted of coarse bainite and ferrite (Figure 18). The heat-affected zone in normal-quality rail steel (250°C preheat) showed no evidence of any brittle transformation products.

To assess their relative resistance to deformation, specimens of weld metal were tested in a “flow under impact” machine developed by the Research Division. An impact force produced by a compressed air cylinder was applied to 12.5-mm diameter cylindrical specimens of undiluted weld metal. The plastic deformation of the specimen after successive blows

was measured and recorded as a percentage of the original length (the smaller the value, the greater the resistance to deformation). The results for 1,000 impacts for the weld metal and comparative data for rail steels are plotted against impact stress in Figure 19.

Diffusible hydrogen determinations were carried out using the technique specified in BS 639 (12). Test samples were produced from the wire in the “as received” condition and exposed to the atmosphere without the protective container for 72 hr. The measured diffusible hydrogen content of the Cr/Mn wire and comparable data from low-hydrogen electrodes (13) are given in Table 9.

Field Trials with Cr/Mn Wire

Following the laboratory tests, a tentative specification for the wire was agreed on with the manufacturer, and a small batch of wire was purchased for field trials in the London Midland Region. Eighteen wheelburns were repaired, and subsequent nondestructive testing (NDT) examination using magnetic particle and eddy current techniques showed the deposits to be defect free. During 1985 a series of wheelburn repairs was carried out using another batch of Cr/Mn wire, but subsequent NDT examination showed that of the 26 repairs installed, 11 were found to contain transverse cracks (see Figure 20). An additional installation consisting of 36 repairs was found to contain 21 cracked deposits.

An examination of the sites showed that the cracks occurred some time after welding (when the deposit was cold), whether the repair had been exposed to traffic or not. Cracked deposits were found in both continuous welded rail and bolted track and in relatively new as well as in old rail.

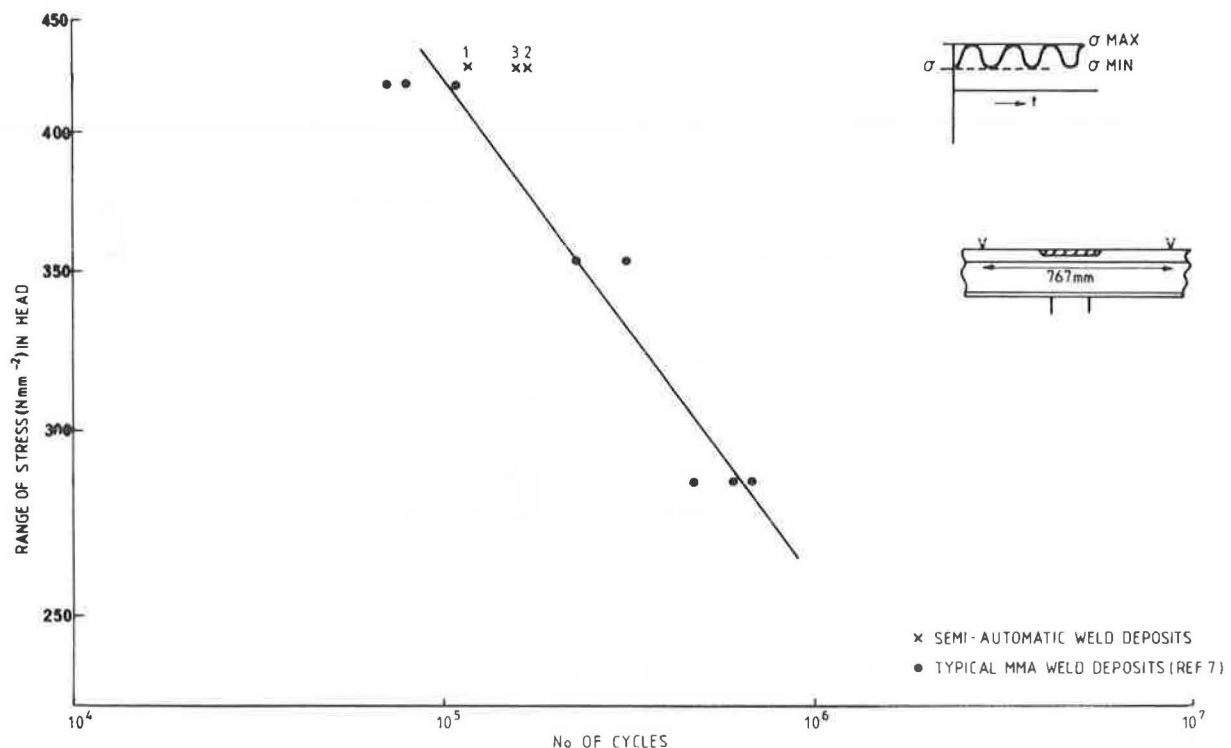


FIGURE 16 Fatigue test results for semiautomatic repairs compared with MMA repairs.

TABLE 5 CHEMICAL COMPOSITION AND HARDNESS OF CR/MN WIRE

	Batch No./Date Received				Provisional Specification ^d	
	BR-EXP/11-83 ^a	41205 ^b /3-85		EXPTL-MOD 2 ^c /10-85	Min ^e	Max ^e
		Undiluted	Diluted			
Composition (wt %)						
C	0.27	0.31	0.30	0.25	0.2	0.25
Si	0.16	0.13	0.13	0.15		0.5
Mn	1.83	2.2	2.11	1.86	1.7	1.9
Ni	0.07	0.09	0.08	0.05		
Cr	1.18	1.48	1.44	1.23	1.00	1.20
Mo	0.14	0.17	0.15	0.01		0.20
Al	2.7	2.9	2.69	1.4	1.3	1.5
Mean hardness (Hv 30)	310-350	365	—	319	300	350

^aUndiluted. Weight, 13 kg; diameter, 1.6 mm; welding current, 160-190 A; welding voltage, 23-27 V.

^bBatch resulting in defective repairs. Weight, 13 kg; diameter, 1.6 mm.

^cExperimental "low alloy" reel for crack-free deposit. Undiluted. Weight, 13 kg; diameter, 1.6 mm.

^dWeight, 13 kg; diameter, 1.6 ± 0.05 mm; welding current, 170-190 A; welding voltage, 22-24 V.

^eUndiluted weld metal.

TABLE 6 FATIGUE TEST RESULTS ON WELDED RAIL

Test Piece	Stress Range (N/mm ²)	Endurance (cycles)	Failure
1	430	112,000	Surface grinding
2	430	103,000	Isolated gas pore
3	430	158,000	Small crater crack

NOTE: Rail tested with rail head in tension.

TABLE 7 HOUNSFIELD TENSILE TEST RESULTS

Material	Yield Stress (N/mm ²)	Ultimate Tensile Stress (N/mm ²)	Elongation (%)
Corewire CS41 (mean)	623	870	14
MMA (kV3)	673	860	25
BS 11 (normal quality) rail	—	830	14

TABLE 8 CHARPY V-NOTCH IMPACT TEST RESULTS

Material	Test Temperature (°C)	Mean Impact (J)
Corewire CS41	-15	12
	0	12
	23	18
MMA (kV3)	-15	35
	0	58
	23	81
BS 11 (normal quality) rail	Ambient	5 (typical)

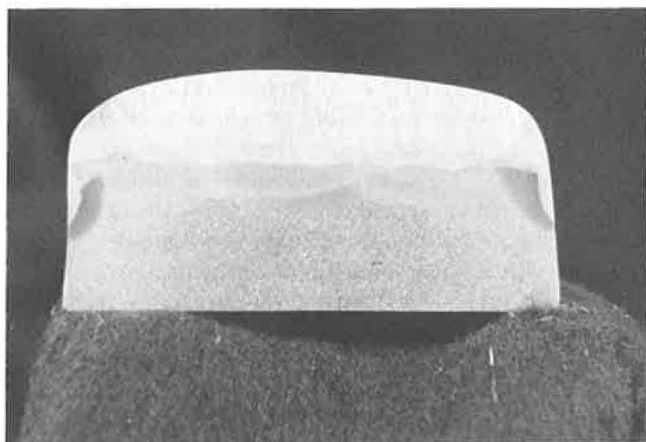


FIGURE 17 Transverse section through fatigue test specimen.

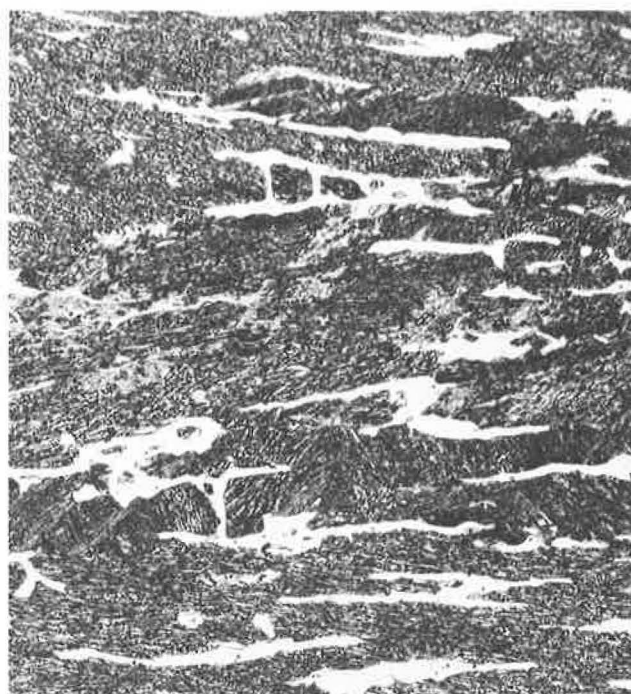


FIGURE 18 Photomicrograph of undiluted Cr/Mn weld metal.

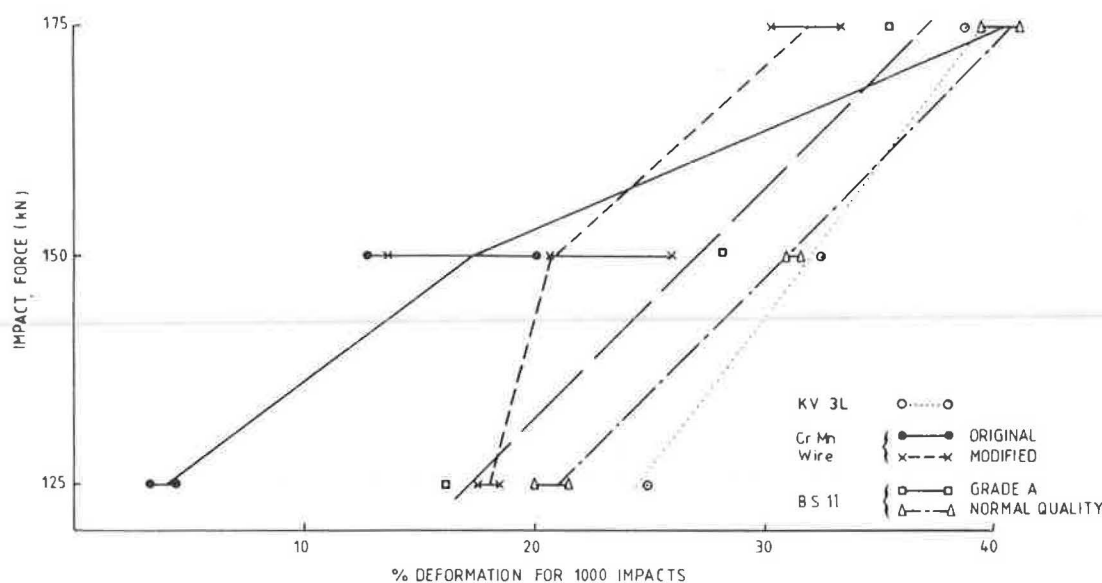


FIGURE 19 Deformation test results for semiautomatic flux-cored weld metals.

Attempts to reproduce the cracking in the laboratory have been unsuccessful, even using a range of stress environments on the test samples before, during, and after welding. As of 1987, laboratory simulation of the cracking mechanism still had not been accomplished, but cracking had been reproduced in a site trial on the Research Division test track

TABLE 9 DIFFUSIBLE HYDROGEN DETERMINATION

Consumable	Diffusible Hydrogen (m/100 g of weld metal)		Dried for 1 Hr at 300°C
	As Received	Exposed ^a	
Cr/Mn wire	5.08	4.07	—
Philips kV3L	5.74	8.40	4.76
Bohler Fox CM2K	3.9	2.64	1.99
KS1 kV 111	4.73	5.09	1.98
Oerlikon Chromaly 21	4.8	8.28	7.66

NOTE: All results are the mean of four samples.

^aExposed to atmosphere for 72 hr.

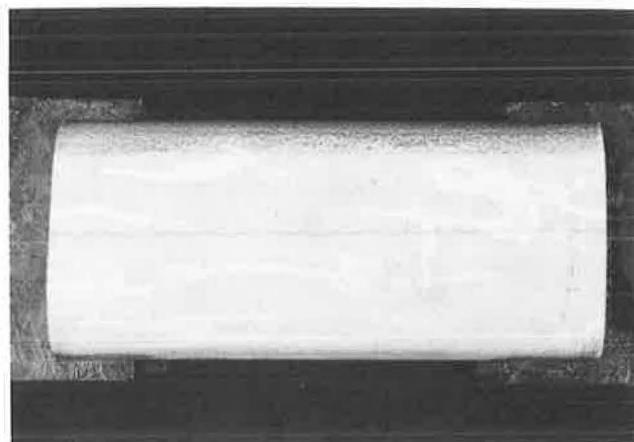


FIGURE 20 Transverse cracks in a repair on the Derby-Birmingham route.

using the batch of wire that had previously been used for the defective repairs (Batch 41205). In all cases the repairs were found to be crack free immediately after deposition, whereas 24 hr later the cracks were found to have formed, which indicated a cold (hydrogen) cracking mechanism.

Following removal of the defective rail from track, a number of the cracked deposits were broken open for scanning electron microscopy, which confirmed that the cracks were of a delayed, "cold" type. Optical microscopy of sections prepared through the cracked deposits showed that the weld metal exhibited a coarse, acicular structure consisting of high carbon bainite and martensite with a band of martensite adjacent to the fusion line (see Figure 21). It was concluded that the cracking was caused by hydrogen in the weld metal aggravated by a microstructure with inherently low levels of ductility and toughness.

The conventional solutions to the hydrogen cracking problem were considered:

1. *Use lower hydrogen levels in consumables:* The diffusible hydrogen levels were already considered to be effectively in the low-hydrogen range, and a further reduction, particularly if the likely site and storage conditions were taken into account, was thought to be impractical.

2. *Use higher preheat levels to reduce weld and heat-affected-zone (HAZ) hardnesses:* The 250°C preheat used for the process was based on metallurgical assessment of the HAZ. An increase in preheat was possible but would affect the cost benefits attributed to the process (see Appendix A).

3. *Use weld metal of lower hardenability and higher toughness:* Examination of the defective repairs showed that the weld metal was considerably harder and more brittle than the laboratory work had revealed. Subsequent chemical analysis showed that the weld metal did not comply with the agreed composition range (see Table 5, Batch 41205). Of particular note were the high aluminum and manganese levels.

Following discussion with the manufacturer, two reels of wire with lower carbon, manganese, chromium, and aluminum



FIGURE 21 Photomicrograph of transverse cracks associated with a brittle martensitic weld metal.

levels were supplied, and a further site trial on the research test track was arranged to evaluate weld metal chemistry and preheat.

The work showed that increasing preheat temperatures from 250° to 350°C (the level currently used for MMA repairs) had

no significant effect on the incidence of cracking. However, using the lower-alloy consumable (see Table 5), crack-free welds were produced, confirming the susceptibility of more highly alloyed weld metals to the problem of cracking.

The "modified" wire was subsequently subjected to the full laboratory assessment, apart from the diffusible hydrogen determination and fatigue tests. The results are summarized in Table 10 with comparative data from the original experimental batch. The results of the deformation tests are included in Figure 19. It can be seen that the modified weld metal was still more resistant to deformation than the parent rail steel and the equivalent MMA repair weld metal.

A formal specification was prepared limiting the composition of the wire (Table 5), and a batch of 21 reels was ordered. Sample reels were used to produce test pads for chemical analysis. The results are shown in Figure 22. The data show that half the batch exceeded the agreed range; consequently all reels above number 11 were rejected.

As of 1987, site trials with the revised-specification Cr/Mn wire have been mainly crack free. Of the 130 repairs being monitored, only 3 have been found to be cracked, one of which was a repair of a previously cracked deposit. The Western Region has had extensive numbers of repairs using both "high specification" and "revised" batches of wire and has reported no problems. A random sample of 100 repairs on the highrail was examined by the Research Division, and only one showed any evidence of cracking.

Manufacturers of wire have been contacted for possible consumables. The most promising to date is a 1.6-mm Cr/Mn/Ni wire that has been used on Swiss National Railways with apparent success (14, 15).

Cr/Mn/Ni Flux-Cored Wire

The wire used on Swiss National Railways is 2.4 mm in diameter and is used with portable dc welding machines of

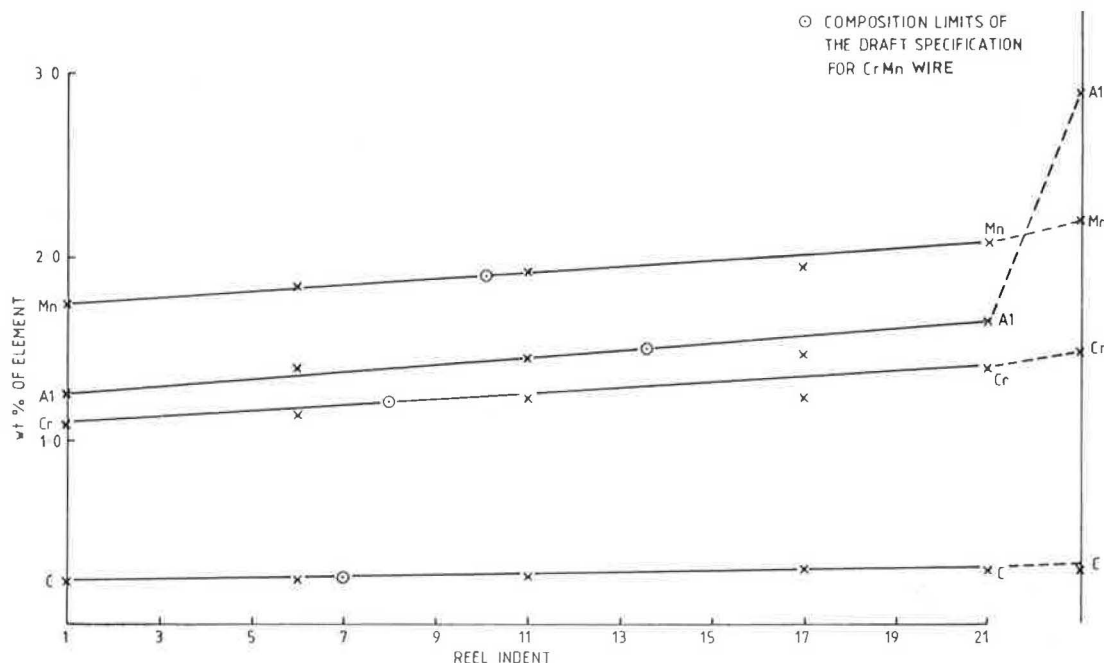


FIGURE 22 Variation in weld metal composition through a batch of Cr/Mn wire (21 reels).

TABLE 10 TEST DATA FOR CR/MN AND CR/MN/NI FLUX-CORED WIRES

	MODIFIED Cr/Mn	Cr/Mn/Ni	ORIGINAL Cr/Mn (BR-EXP)
Undiluted Weld Composition (wt%)			
C	0.25	0.15	0.27
Si	0.15	0.27	0.16
Mn	1.86	1.12	1.83
S	0.003	0.004	-
P	0.13	0.021	-
Ni	0.05	2.31	0.07
Cr	1.23	0.81	1.18
Mo	0.01	0.48	0.14
Al	1.4	1.52	2.7
U.T.S (N/mm)	1000	1001	870
Y.P. (N/mm)	682	737	623
% ELONG	11	14.0	25
Hardness (Hv30) (mean)	<u>311-328</u> 319	<u>298-321</u> 308	<u>310-340</u> 315
Impact (Joules)			
-15°C	8	8.2	12.0
0°C	10	10.5	12.0
+23°C	12.6	14.5	18.0
+50°C	15.6	20.1	-
Deformation (%) for 1000 impacts			
Impact Force (kN)			
125	17.5 - 18.5	1.9	3.5 - 4.2
150	15 - 26	32	12.5 - 20
175	31.5 - 33	35	37.5 - 38.5

300-A capacity (220 A dc at 100 percent duty cycle). Samples of the wire were subsequently drawn down to 1.6 mm-diameter for laboratory assessment using the evaluation program described earlier. The results of the laboratory work are given in Table 10. The microstructure of the undiluted weld metal was found to be similar to the MMA weld metal produced using kV3L electrodes (see Figure 23).

Following the laboratory work, an extensive site trial of the wire was carried out in the London Midland Region, where more than 40 repairs of wheelburns have been installed. To date, none of these repairs has shown any evidence of cracking.

COST BENEFITS

As previously stated, semiautomatic welding using continuous wire has been demonstrated to be a high-productivity process compared with MMA welding. During the early stages of development, the Research Division undertook a cost analysis for possible application.

Repairs to Wheelburns

An initial laboratory assessment of the relative costs of the two options for the repair of wheelburns was achieved by welding prepared excavations in a length of normal-quality rail (see Figure 24). The comparison demonstrated that the track occupation time could be halved using semiautomatic welding, and the direct cost (i.e., materials and labor) was also reduced.

A more extensive cost analysis for plain line repairs was undertaken for the London Midland Region (see Appendix A). It can be seen that the main time saving is achieved by the increased size of the individual weld beads. Overall a time saving of 149 min (59 percent) was achieved by using the semiautomatic welding process, and the unit cost of deposited weld metal was almost halved.

Maintenance Welding of Crossings

The potential cost savings for welding crossings are more difficult to derive. The cost analysis shown in Appendix A

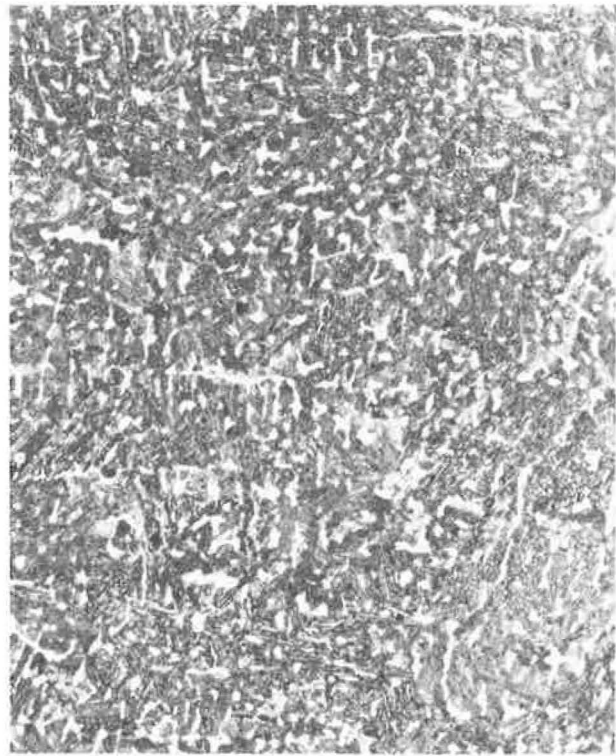
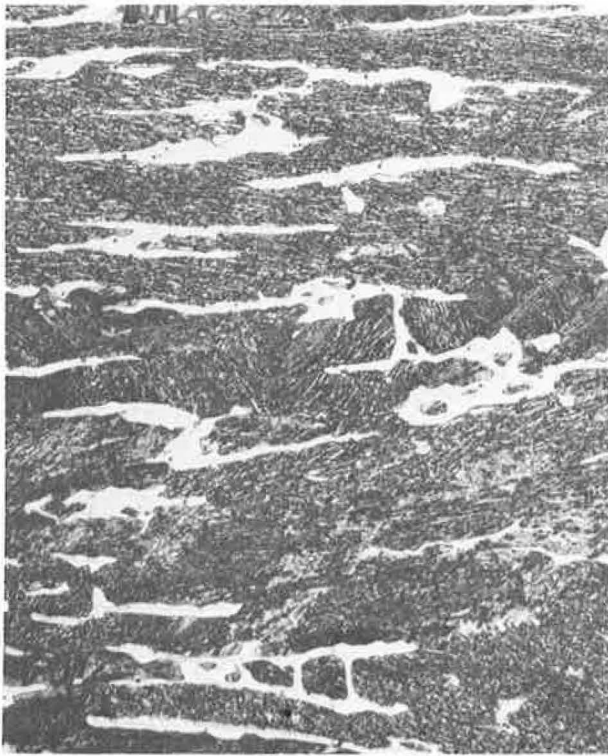
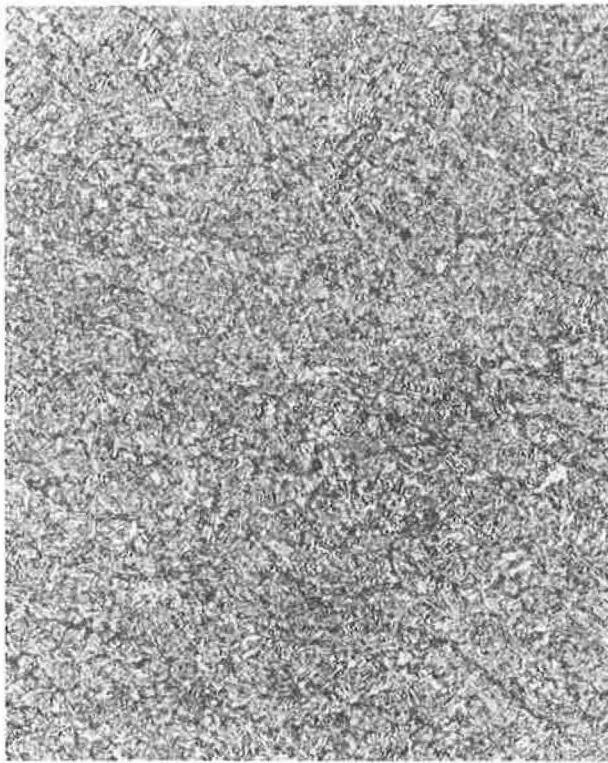


FIGURE 23 Photomicrographs of undiluted MMA and flux-cored wire weld metals ($\times 149$). *Top left:* Phillips kV3L; *top right:* Cr/Mn/Ni wire; *lower left:* original Cr/Mn wire; *lower right:* modified Cr/Mn wire.

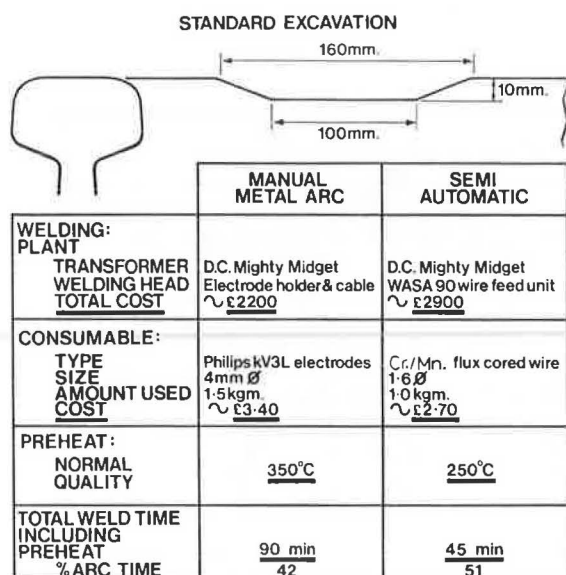


FIGURE 24 Comparison of MMA and semiautomatic repair to simulated wheelburn excavation.

demonstrates that a typical MMA repair would take approximately two shifts if both the nose and wings were to be repaired. A comparable semiautomatic repair should be accommodated within one shift.

The number of crossings in track in September 1984 was as follows:

Track Category	Track Miles	S & C Miles	Crossings	Crossings per Mile
A	2,220	79	2,370	1.07
B	6,339	264	7,920	1.25
C	8,559	330	9,900	1.16
D	4,001	397	11,910	2.98
			32,100	

Assume that the frequency of weld repair of these crossings is as follows:

Line Category	Months Between Repairs
A	9
B	12
C	18
D	None

The total number of repairs required per annum is calculated as follows:

Category A: $2,370 \times 12/9 = 3,160$;
 Category B: $7,920 \times 12/12 = 7,920$;
 Category C: $9,900 \times 12/18 = 6,600$;
 Total = 17,680 repairs/annum.

Thus the use of semiautomatic welding in place of MMA welding for the build-up repair of crossings could result in the following saving:

$17,680 \times (\text{MMA cost} - \text{semiautomatic cost}) = 17,680 \times (£305 - £162.50)$ (see Appendix A) = £2.5 million per annum.

As explained in Appendix A, the repair of a crossing using MMA welding can take two working shifts as opposed to one when the semiautomatic process is used. Therefore, assuming that the commitment to crossing repair is not increased, approximately 17,500 working periods will be released for plain line repairs without a change in the current maintenance budget.

Investment

The saving could only be achieved if investment were made in the purchase of the new equipment. It is proposed that approximately 240 welders be trained for semiautomatic welding, and on the basis of the current commitment to the welding of crossings (both maintenance welding and repair welding) approximately 24,000 welds may be required per annum, equivalent to approximately 120/day. Therefore the final investment in welding sets could be between £130 and £250 (including spare units). The British Railways Board has undertaken to purchase 120 sets, with either ac/dc converters or dc welding machines. The remaining sets are to be funded out of the regional investment budget.

Assuming an initial purchase of 130 units, two options are available (based on 1983 prices):

- 130 wire feed units at £750/unit = £97,500 + 130 ac/dc converters at £250/unit = £32,500 + spares (£1,000) = £131,000.
- 130 dc power supplies at £1,250/unit = £162,500 + 130 wire feed units at £750/unit = £97,500 + spares (£3,000) = £263,000.

Based on a 5-year writeoff period and the current crossing repair commitment, the nondiscounted cost/repair per option is as follows:

Option 1:

$$\frac{131,000}{24,000 \times 5} = £1.1/\text{repair}$$

Option 2:

$$\frac{263,000}{24,000 \times 5} = £2.2/\text{repair}.$$

In practice the cost/repair amount should be much less, because a greater number of repairs per annum should be expected.

CONCLUDING COMMENTS

It can be seen that equipment development is now almost complete, equipment specifications having been formulated. Current work is centered around the development of wires and procedures to further reduce the possibility of delayed cracking.

The most significant element in the wire is thought to be aluminum, which is introduced as the primary deoxidant. It is

known to have a deleterious effect on toughness because of the formation of aluminum-based inclusions, but it appears that a reduction in aluminum does not, in itself, result in an improvement in toughness (see Table 10). Indeed, ductility and toughness are reduced, whereas the strength is increased. This is probably due to the reduction in the volume fraction of delta ferrite in the weld metal. Most wire manufacturers recommend a minimum aluminum level of approximately 1.5 percent, below which the weldability deteriorates and weld metal contamination with oxygen and nitrogen starts to occur. Any change in the aluminum content affects the recovery of other reactive elements (Cr, Mn, C). Hence this interactive effect of aluminum has to be taken into account when modifications to the wire are considered. The current BR specification limits the aluminum level to between 1.3 and 1.5 percent.

An added complication is that the cracking problem is only prevalent in single- or double-layer deposits, when the weld metal is highly diluted with the parent material. This condition is commonly generated when shallow defects such as wheelburns are repaired. The Cr/Mn-based wires now have a specification that is thought to be the minimum alloy level for acceptable hardness. However, the cracking problem still occurs, albeit at a much reduced level. Current development is based on the use of Cr/Mo/Ni wires, which, although having similar strength and hardness to the Cr/Mn types, show a slight improvement in toughness.

As explained earlier, resistance to deformation is a major requirement of weld metals for repairing crossings. Consequently a simple flow-under-impact machine has been developed to enable the comparison of different materials. The test has one deficiency: with large deformations there is a tendency for bulk collapse or "bulging" of the specimen, for example, against surface flow. Therefore an experiment is being undertaken to investigate lower-impact forces (resulting in less deformation). In addition, crossings repaired with either Cr/Mn or Cr/Mo/Ni deposits (with MMA repairs as a control) are being monitored in service to assess the deformation of the repair.

Should the trials show that the "crack-resistant" weld metals are too soft, consideration will be given to reverting to the original formulations and amending the preheat procedure to reduce the hardenability of the deposit.

A large number of semiautomatic wheelburn repairs are now being monitored in track by the Research Division to assess their susceptibility to cracking and their wear resistance. Several brands of wire are being studied. The weld metals containing nickel appear to be the most crack resistant and also display a finer-grained acicular bainitic microstructure with less delta ferrite than the plain Cr/Mn types. Laboratory trials are about to start with a Cr/Mo/Ni wire that has an undiluted hardness of 330 to 350 Hv and an aluminum content less than 1.2 percent. If the trials are successful, this wire will be considered for use on wear-resisting rails (including 110 kg/mm² Cr grade).

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APPENDIX A

Analysis of Costs Comparing Conventional MMA with Semiautomatic Repair Techniques

REPAIR OF PLAIN LINE DEFECTS

A limited site trial has been performed with the semiautomatic process to enable a comparison to be drawn with the MMA process. The trial took place at Didcot West Curve (Western Region), where a large number of isolated wheelburns were present. Two similarly sized defects were excavated by grinding to give similarly shaped and sized preparations 550 mm long, 45 mm wide, and 5 mm deep. The whole operation was

TABLE 11 COMPARATIVE TIMES FOR WHEELBURN REPAIRS

Characteristic	Welding Process	
	Manual Metal Arc	Semiautomatic
Type of electrode/wire	Dymal-2 coated electrode	Corewire CS41BR flux-cored wire
Diameter of electrode/wire (mm)	4.0	1.6
No. of weld layers	2	1
No. of weld runs		
First layer	15	5
Second layer	6	
Preheat temperature (°C)	350	250
Repair time (min)		
First layer		
Electrode drying	60	
Preparation	23	17
Preheating	15	6
Preheating	24	6
Welding	35	25
Grinding	5	18
Dye penetrant testing	30	30
Second layer		
Preparation	0	
Preheating	14	
Preheating	4	
Welding	14	
Grinding	20	
Dye penetrant testing	30	
Total (hr/min)	4/11	1/42

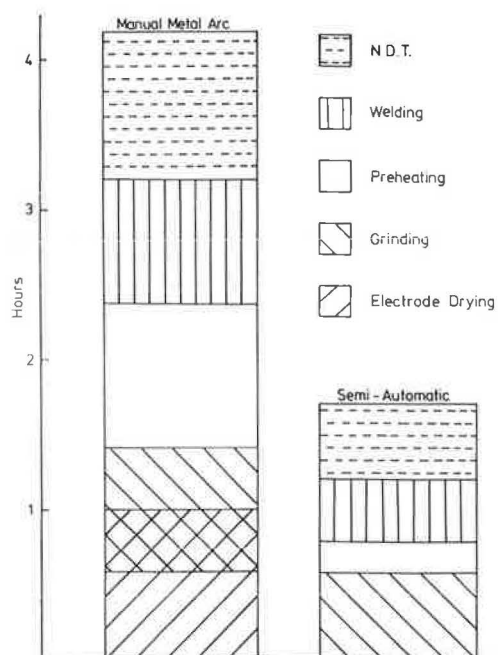


FIGURE 25 Comparison of times for wheelburn repairs.

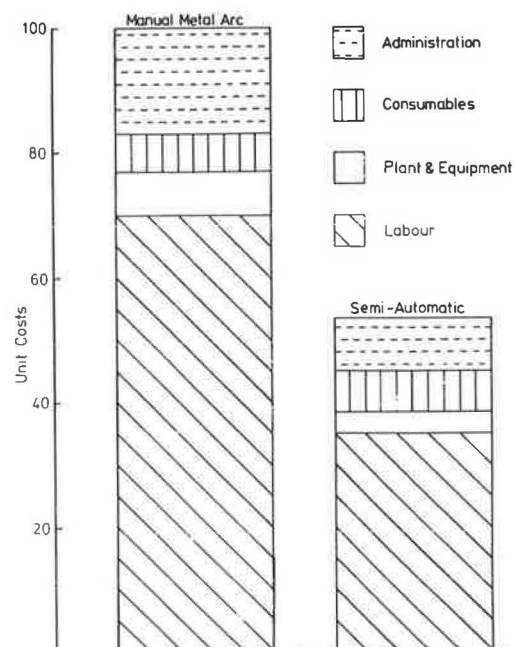


FIGURE 26 Comparison of costs for track repairs per unit volume of deposited weld metal.

timed, and a breakdown is given in Table 11. The times are also presented as a bar chart (Figure 25) and converted to costs per unit volume of weld metal (Figure 26). This conversion is based on the information presented in the next section of this appendix.

REPAIR OF CROSSINGS

The maintenance welding of crossings takes place during weekdays; welders work four 7.5-hr shifts. The 10-hr weekend shift is normally reserved for new installations.

The following times for the MMA maintenance welding of crossings have been estimated to fit in with a 7.5-hr shift. The times are based on discussions with a number of CCE welding teams and observations of MMA repairs being carried out on site and in the laboratory.

1. Traveling to site and unloading equipment, 1.5 hr;
2. Drying electrodes, 1 hr;
3. Grind crossing, 0.25 hr;
4. NDT crossing, 0.25 hr;
5. Preheating and interrun heating, 0.5 hr;
6. Welding, 2.25 hr;
7. NDT crossing, 0.25 hr;
8. Final grinding, 0.5 hr; and
9. Loading equipment and traveling to base, 1.5 hr.

Total time is 8 hr. In practice, operations 3 and 4 are carried out during operation 2, thus saving 0.5 hr and making the total time 7.5 hr.

Semiautomatic welding can save 0.5 hr by eliminating operation 2 and 0.25 hr by reducing the temperature to be attained and maintained in operation 5. Thus, the time saved can be used in operation 6, extending it to 3 hr.

The total amount of weld metal that can be deposited in one shift can be calculated as shown in Table 12.

TABLE 12 CALCULATION OF AMOUNT OF WELD METAL DEPOSITED IN ONE SHIFT

Item	Welding Process	
	Manual Metal Arc	Semiautomatic
Welding time in 7.5-hr shift (hr)	2.25	3
Arcing time		
Percent of welding time		
(measured in laboratory trials)	40	50
Hours	1	1.5
Deposition rate ^a (kg/hr)	1	2.35
Total amount of weld metal deposited in one shift ^b (kg)	1	3.5

^aWelding Institute Standard Data.

^bArcing time in hours times deposition rate.

Assuming that a typical repair of a 1 in 9.1/4 crossing requires 1 kg of weld metal depositing on the crossing nose and 1 kg on the wing rails,

1. With MMA welding only the crossing nose can be repaired in one shift. Two shifts are required to repair the whole crossing.

2. With semiautomatic welding both the crossing nose and the wing rails can be repaired in one shift.

ESTIMATED COSTS

Using a 1981 cost breakdown by the BR Department of Civil Engineering Welding Assistant, the costs shown in Table 13 were estimated for the repair of one crossing unit. A saving of £142.50 per repair is therefore evident.

TABLE 13 COSTS FOR REPAIR OF ONE CROSSING UNIT

Item	Welding Process	
	Manual Metal Arc	Semiautomatic
Labor		
Welders (2) at £37.50 per day	150	75
Look-out at £27.50 per day	50	27.50
	205	102.50
Plant and equipment at £10 per day	20	10
Consumables (electrodes, diesel, fuel-gas, etc.)	30	25
Incidentals (supervision, assistance, administration, etc.) at £25 per day	50	25
	305	162.50

NOTE: Costs are given in 1981 pounds.

APPENDIX B

General Specification for Semiautomatic Wire Feed Units

1. To feed 1.2-, 1.6-, and 2.0-mm diameter flux-cored wires for welding at a current range of 150 to 250 A.

2. To operate from open circuit and welding voltages of drooping characteristic welding sets on both fully rectified alternating and direct current. Typical voltages are open circuit, 70 to 120 V; welding, 20 to 30 V.

3. To carry a 300-mm o.d. wire spool.

4. To weigh less than 20 kg without wire spool.

5. To be supplied complete with a minimum 3-m-long hose and air-cooled welding torch.

6. To be supplied with wire inch controls at both the wire feed unit and welding torch.

7. To have wire feed speed control independent of the welding current.

8. To be supplied complete with protective covers to prevent entry of moisture.