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OFFSHORE TECHNOLOGY
REPORT - OTO 94 803

CORROSION RESISTANCE OF DUPLEX FERRITIC-AUSTENITIC STAINLESS STEEL WELDMENTS

PART 1: SUMMARY

Date of Issue: May 1996

Health and Safety Executive

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5550/22/87
NOVEMBER 1987

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SUMMARY OF FINAL REPORT 5550/21/87

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1. INTRODUCTION

Considerable interest in the industrial application of ferritic-austenitic duplex stainless steels arises from their attractive properties of high strength, corrosion resistance and, in particular, immunity to chloride stress corrosion cracking in all but the most adverse environments. This interest has been reflected in extensive research in the last few years into the properties of duplex alloys regarding corrosion, mechanical and welding behaviour. The last property, in particular, is critical since close control of welding conditions is necessary to avoid unfavourable influences on both toughness and corrosion behaviour; thus restrictions on heat input within the range 0.5-1.5kJ/mm with interpass temperatures of 150°C maximum are commonly applied.

In 1984, The Welding Institute considered that there was a need for more precise data on the weldability of these duplex materials especially relating to the influence of welding conditions on corrosion properties. As a result, a group sponsored research programme has been carried out over the last 28 months, which is reported in detail in Final Report 5550/21/87. This present report summarises the various steps in the programme and the main conclusions drawn. Recommendations for a broader, allowable range of welding conditions for duplex stainless steel are made.

2. OBJECTIVES

To define guidelines on filler composition and welding parameters which will give optimum corrosion resistance, especially to pitting attack, of welded girth joints in duplex stainless steel materials.

3. EXPERIMENTAL DETAIL

3.1. Approach

Because of the current wide interest in duplex materials conforming to UNS S31803 specification (21-23%Cr 4.5-6.5%Ni 2.3-3.5%Mo 0.08-0.20%N) studies were made on 12.7mm steel to this alloy grade (Table 1). In Phase 1 of the work an optimum filler composition was determined by assessing a range of duplex MMA electrodes meeting or exceeding the parent material with respect to alloy content. In Phase 2 the optimum filler composition was used in MMA, TIG and MIG joints in plate or pipe to examine the influence of welding conditions on corrosion, mechanical and microstructural properties. In addition, studies were made of hydrogen cracking susceptibility.

3.2. Phase 1: Optimisation of Consumable Composition

3.2.1. Method

Corrosion studies of MMA weld pads produced from 16 experimental and commercial duplex electrodes employing different coating types were carried out by pitting potential measurements in 3%NaCl and 15%NaCl solutions saturated with CO_2 and by immersion testing in $FeCl_3$ solution ($10\%FeCl_3.6H_2O$). The range of consumable composition examined is given in Table 2. The 4mm diameter electrodes were used at a nominal arc energy of about 1kJ/mm (130A).

Selected consumables were employed to produce butt welds, especially for impact testing. Metallographic examination and phase balance determination were carried out.

3.2.2. Findings

Good agreement was found between corrosion test procedures (Fig.1). Some degree of overalloying was necessary to attain parent metal pitting resistance. Statistical analyses were carried out of a number of criteria for pitting resistance: all showed increasing Cr, Mo and nitrogen to be beneficial and Ni to be detrimental. Together with the toughness testing and metallography, a nominal optimum composition filler of 25%Cr 9%Ni 2.7% Mo 0.16%N was determined. Electrode flux type was not observed to affect pitting behaviour significantly, although it did influence toughness characteristics, acid-rutile coatings giving higher transition temperatures than basic-rutile coatings.

3.3. Phase 2: Weldment Properties

3.3.1. Method

The effects of welding conditions on corrosion properties were determined principally by $FeCl_3$ and pitting potential tests on manual MMA and mechanised TIG joints in 12.7mm plate; in addition assessment of mechanised MIG joints in 12.7mm wall x 508mm diameter matching pipe material was made. All joint types were subjected to long term crevice corrosion testing in 90°C, 15%NaCl solution saturated with CO_2.

The welds were produced using preferred composition fillers on the basis of Phase 1 (Table 3). Welding conditions were varied as summarised in Table 4.

Mechanical testing was carried out on the butt welds. This involved transverse tensile tests, Charpy impact tests, and hardness studies. Metallographic examination was undertaken, with assessment of ferrite:austenite balance by point counting and Magnegage, and EDX analysis to evaluate partitioning of major alloying elements.

Using self-restrained joint tests (CTS and Y-groove) an assessment was made of the hydrogen cracking susceptibility of duplex steel weldments made with the MMA process, using dried and humidified electrodes, or the TIG process, using Ar-5%H_2 shielding gas.

3.3.2. Findings

Corrosion Test Method

Evaluation was made of testing variables for the $FeCl_3$ and potentiodynamic methods. For the former case, most satisfactory results in terms of defining critical pitting temperatures were obtained with weldment samples which were pickled on the test face, all other faces being electropolished. Exposure of individual samples at each test temperature gave lower critical temperatures than did exposure of a single sample at progressively higher temperatures. Pitting potential studies evaluated only root weld metal behaviour. A scan rate of 0.33mV was adopted. Some scatter was found in test data obtained at a current density of $0.05mA/cm^2$, i.e. the pit initiation potential, results apparently being more satisfactory for pit propagation potentials measured at $5mA/cm^2$ (Fig.2).

Results from the three corrosion test procedures were consistent in showing that welding with low heat input conditions (within the range studied) had no significant effect on pitting resistance, whereas high heat input welding reduced pitting resistance. However, differences were observed especially in the location of preferential corrosion between the $FeCl_3$ and long term tests in the 15%NaCl solution at 90°C. This is considered to reflect the different redox potentials involved.

Effect of Welding Conditions on Corrosion Behaviour

Considering primarily the MMA and TIG welds, weldment corrosion properties showed a clear influence of the effects of arc energy and interpass temperature (Fig.3). Low heat input weldments had the best corrosion properties (weld 27), whilst high heat input welding and/or high interpass temperatures were detrimental to corrosion resistance (welds 29, 32). Little variation in corrosion properties was seen between interpass temperatures over the range 150-225°C, whilst an increase to 300°C gave accelerated attack (cf welds 28 and 32).

For both processes, welds were produced closely matching the parent steel pitting resistance. Similar weld metal pitting resistance was obtained also for the MIG welds, although using this process slight propensity was noted at low arc energy (ca 0.2kJ/mm) for preferential pitting in the HAZ with the particular parent steel employed.

Weldment corrosion was manifested in three main ways: general attack of reheated root weld metal areas containing secondary austenite; preferential attack of austenite in the transformed HAZ or highly partitioned root weld metal; and preferential HAZ attack in regions some mm remote from the fusion boundary. Corrosion in the last two cases was especially related to welding with high heat input and high interpass temperatures.

The overall corrosion test results have been examined, together with published data on corrosion of duplex weldments. Recommendations are made below for preferred welding conditions for duplex stainless steels of the type studied.

Mechanical Properties

All welds and parent plate samples showed generally acceptable mechanical properties. Transverse tensile strength for all joints exceeded parent material specification requirements. Weld metal toughness increased in the order MMA, MIG and TIG welding.

Weldment hardness data were determined both as Vickers (HV5) and Rockwell (HRC) measurements. Maximum hardness levels for all processes were considered to be below the 28 HRC value commonly applied as a limit for solution annealed duplex materials in sour (H_2S containing) environments.

Metallurgical Examination

Acceptable ferrite:austenite phase balances were found for all corrosion and mechanical test weldments, as determined by point counting and Magnegage measurements of EFN. From the Phase 1 weld pads, an equation relating % ferrite to EFN values was determined according to:

$$\% \text{ ferrite} = 0.57 \text{ EFN} + 8.82.$$

In all cases, reheated areas showed higher levels of austenite than as-deposited regions, due to the precipitation within the ferrite of fine secondary austenite. The partitioning of alloying elements between austenite and ferrite was found to be more severe in reheated weld metal than in as-deposited regions, especially with higher heat input.

Hydrogen Cracking

Although fairly high weld metal and HAZ ferrite levels were found (up to 80%), no susceptibility to hydrogen cracking was determined, for the test methods and hydrogen levels employed. Deposited weld metal hydrogen levels of up to 16ml/100g were obtained for the MMA process.

4. RECOMMENDATIONS

To ensure good weld metal corrosion properties, the use of duplex filler materials with a higher pitting index than that of the parent material is recommended. In the present case, an increase in conventional pitting index* from 33 to 37, achieved by employing a filler material with 25%Cr, produced acceptable weld metal corrosion properties.

Based on the results of the present work, together with an assessment of recently published corrosion data for duplex stainless steel weldments, it is considered that current restrictions typically applied for welding duplex steels of arc energies in the range 0.5-1.5kJ/mm, with a maximum interpass temperature of 150°C, can be broadened.

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* Pitting index = %Cr + 3.3%Mo + 13%N

Providing good weldment phase balance is obtained, arc energies in the range 0.5-2.0kJ/mm, with a maximum interpass temperature of 225°C, are considered acceptable. The application of these conditions to materials of widely differing thickness or pitting index values from those employed in the present work should be treated with caution.

To minimise the risk of HAZ corrosion under low arc energy conditions, for example in mechanised MIG and TIG procedures, consideration should be given to optimisation of parent material properties by use of controlled, minimum nitrogen levels of 0.14%.

Table 1 **Chemical composition of parent plate and pipe materials (wt %)**

	C	S	P	Si	Mn	Cr	Ni	Mo	N	V	Cu	Nb	Ti	Co	O_2	Al	Reference
IC 509,510,511 Parent plate (NKK) 12.7mm thickness	0.017 0.014	<0.001 0.0003	0.020 0.020	0.51 0.50	0.96 0.94	21.9 22.09	5.9 5.86	3.04 2.93	0.11 0.12	0.05 -	0.02 -	<0.01 -	<0.01 -	0.03 -	 -	- 0.014	TWI S/85/463, ON/85/157 NKK analysis
IC 520 508mm diameter pipe (NKK) 12.7mm thickness	0.018	<0.001	0.021	0.50	0.95	22.0	5.9	3.06	0.12	0.05	0.02	<0.01	<0.01	0.02	0.003	-	TWI S/86/170, ON/86/88
UNS S31803 specification	0.03 max	0.02 max	0.03 max	1.0 max	2.0 max	21.0 23.0	4.5 6.5	2.5 3.5	0.08 0.20	-	-	-	-	-	-	-	

- = not determined or not specified

C and S by Leco CS 125 carbon sulphur analyser

O and N by Leco TC 136 oxygen nitrogen analyser

Remaining elements by X-ray fluorescence analysis

Table 2 **Compositional range studied with MMA electrodes**

Element	Range, Wt %
Cr	21.8-26.7
Ni	7.0-11.0
Mo	2.39-4.50
N	0.06-0.20

Note:

electrodes with acid-rutile and basic-rutile coatings were employed

Table 3 Chemical analysis and pitting indices results of filler materials used in Phase 2 studies (wt %)

Sample	C	S	P	Si	Mn	Cr	Ni	Mo	N	V	Cu	Nb	Ti	Co	O_2	TWI Reference	Pitting Index[a]
Nominal optimum composition						25	9	2.7	0.16								36.0
Electrode 5 (4mm)	0.025	0.006	0.020	0.55	1.39	25.0	9.1	2.66	0.16	0.05	0.03	0.02	<0.01	0.05	0.08	S/85/439, ON/85/145	35.9
Electrode 5/2 (3.2mm)	0.024	0.009	0.018	0.57	1.46	25.5	9.3	2.94	0.17	0.06	0.05	0.02	<0.01	0.02	0.07	S/86/299, ON/86/138	37.6
Wire 5 (0.8mm)	0.020	0.004	0.013	0.30	1.00	24.9	9.1	3.44	0.16	0.05	0.03	<0.01	<0.01	0.02	0.006	S/86/329, ON/86/155	38.3
Wire 5/2 (0.9mm)	0.016	0.004	0.012	0.29	1.00	24.6	9.0	3.43	0.14	0.05	0.03	<0.01	<0.01	0.02	0.007	S/86/328, ON/86/155	37.8

(a) pitting index = Cr + 3.3Mo + 13N

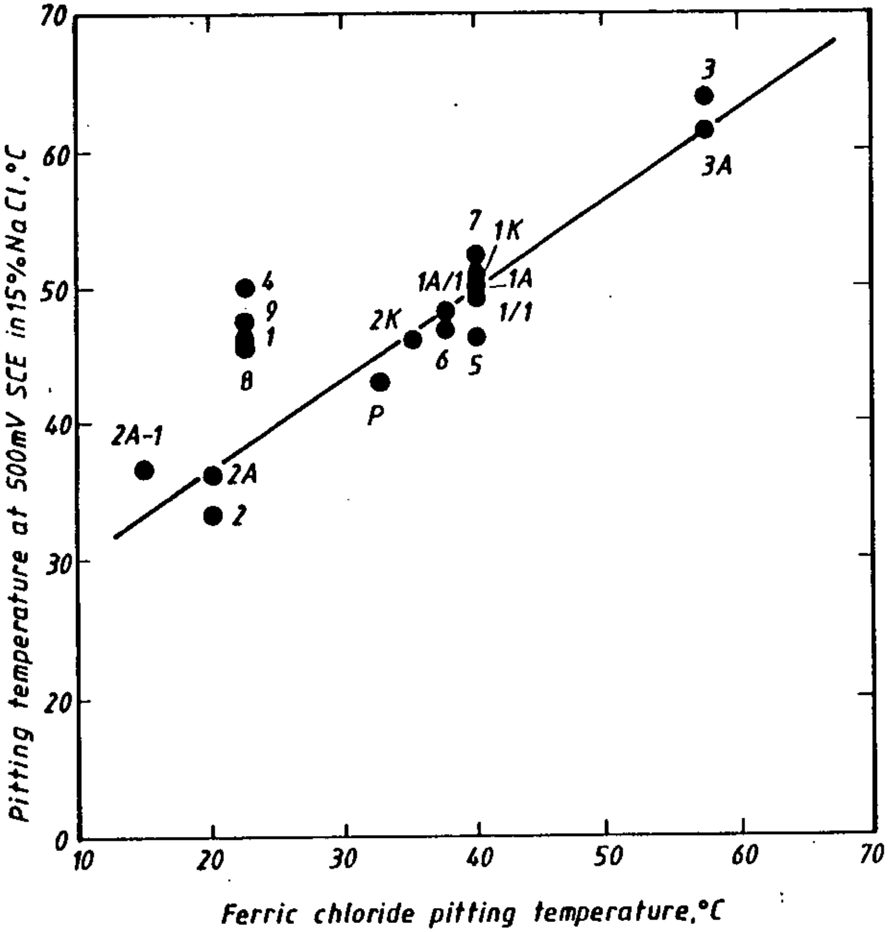
C and S by Leco CS 125 carbon sulphur analyser

O and N by Leco TC 136 oxygen nitrogen analyser

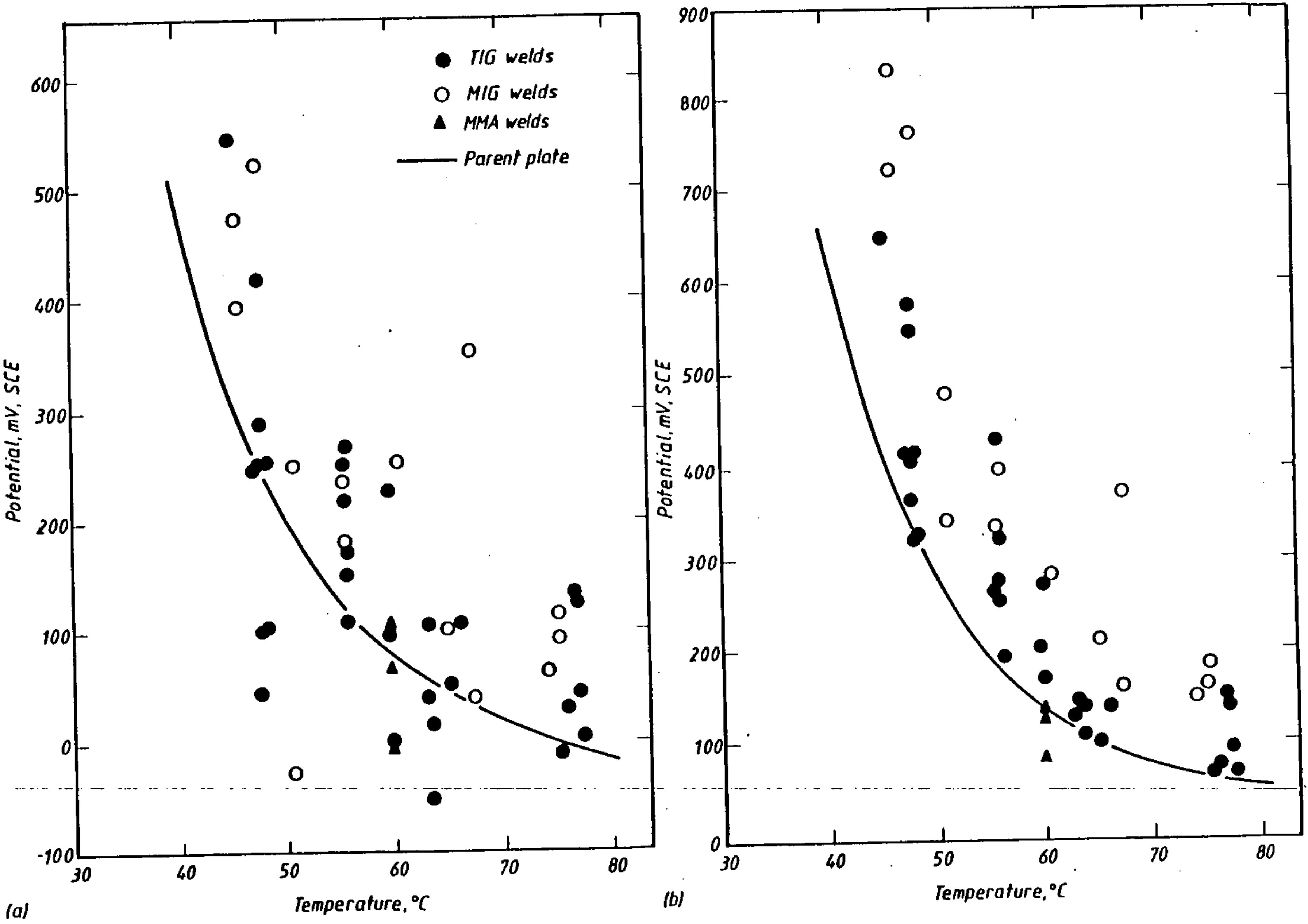
Remaining elements by X-ray fluorescence analysis

Table 4 Variation in welding conditions

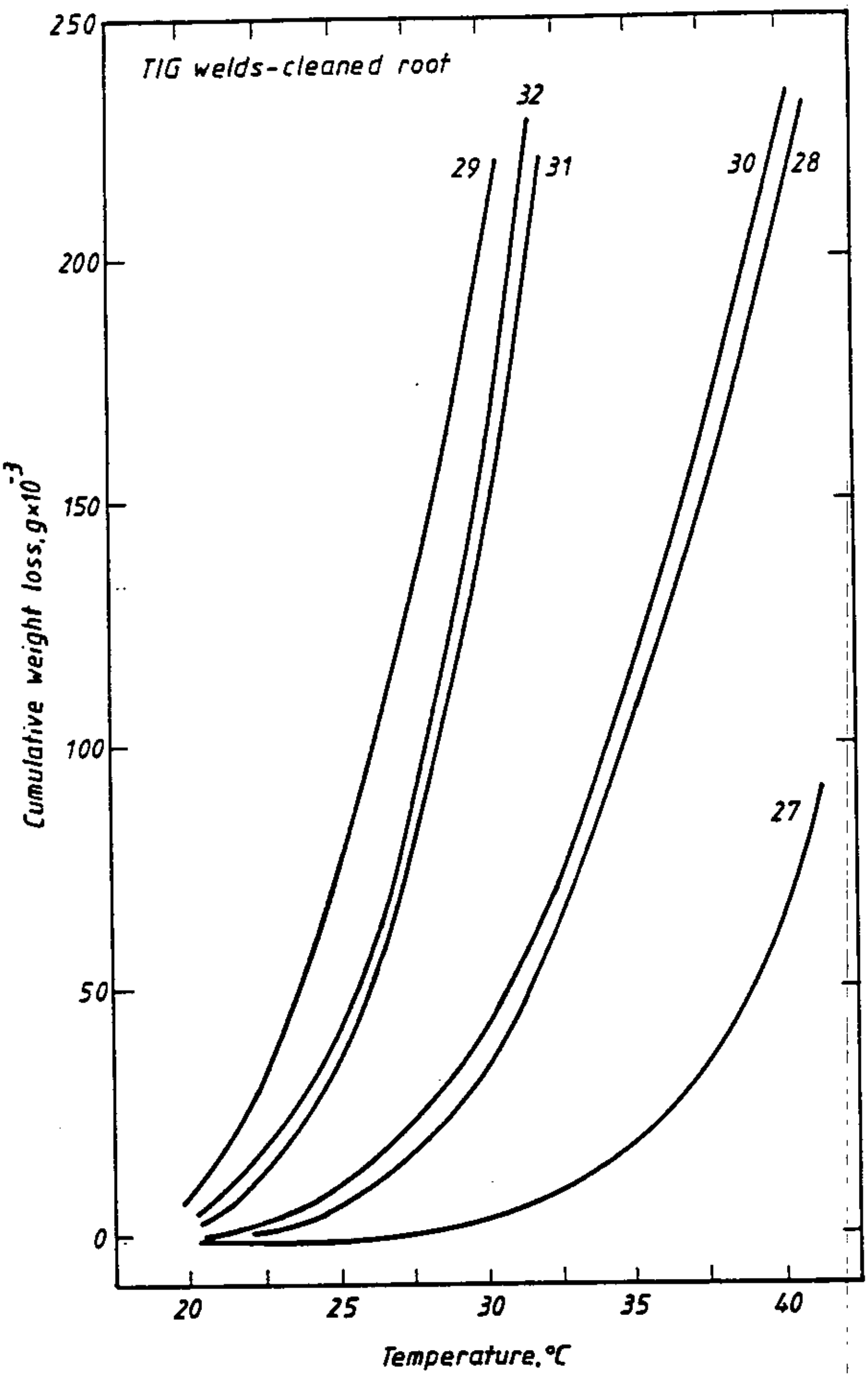
Process	Arc Energy, kJ/mm		Preheat/Interpass Temperature, °C
	Root	Fill	
MMA	0.5-0.6	0.7-3.2	20-300
TIG	0.5-2.5	0.5-2.5	25-300
MIG	0.2-0.45	0.75-1.2	29-120



1 *Ferric chloride and 15%NaCl + CO_2 pitting temperatures for all-weld metal pad samples, illustrating the general correspondence between the two test methods and the critical temperatures achieved for different pad compositions. Note, P = parent steel.*



2 *Pitting potential data for all optimum composition root weld metals determined at:*
a) *0.05mA/cm² current density;* b) *5.0 mA/cm² current density.*



3 *Cumulative $FeCl_3$ weight loss data for TIG welds.*