A Study on Delta Ferrite in Thin Walled Stainless Steel Tube Welding for Nuclear Reactor Fuel Elements

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1. INTRODUCTION

Thin walled stainless steel tubes have been accepted as reference cladding for all fast nuclear reactor fuel elemens around the world. The Indian Nuclear Programme has also chosen stainless steel (AISI 316) tubes as cladding material for the Fast Breeder Test Reactor to be commissioned in Kalpakkam, Madras. During fabrication of the fuel elements, these thin walled tubes are arc welded to solid end plugs of stainless steel (AISI 316) inside a glove box by an automatic remote TIG welding technique.

Cracking has been one of the major defects observed in these welds during our initial welding development programme. The problem of cracking becomes more severe as it cannot normally be intercepted by accepted NDT techniques. Cracking on similar stainless steel fuel element welding has also been reported by American[1] and Belgium[2] workers during their development programme. However none of the workers have reported to have studied the role of delta ferrite in the cracking. Role of delta ferrite and factors affecting its content in multipass high current welding is well known[3] and different types of electrodes are recommended to avoid such cracking in different types of stainless steels. However in stainless steel fuel element fabrication, clad tube and end plugs have a fully austenitic structure and welding is done by low current ($\sim$ 25 amp), without any filler material. Delta ferrite generally appears in an otherwise austenitic structure during welding as reaction rate for equilibrium in these steels is very slow and requires long time and slow cooling rate. Presence of delta ferrite in such welds is influenced by the welding prarameters. An investigation has been overdue to study the influence of welding parameters in presence of delta ferrite and its role in the cracking behaviour of the weld, which was undertaken by the authors in Radiometallurgy Div sion of BARC.

Arc has been struck on stainless steel rods of dimension and composition similar to the clad tubes, thus avoiding the stress pattern produced by thin tube and thick plug, and weld pool studied for the presence of delta ferrite by varying welding parameters like welding current, arc gap, gas flow rate, gas composition, annealing time and annealing current. Actual weld samples both with and without cracks have been studied to correlate the presence of delta ferrite in the weld pool with cracking behaviour. In this context different metallographic etching techniques have been assessed for a reproducible development of the weld microstructure revealing the distribution and morphology of the delta ferrite phase. This paper presents the detailed observation from the experiments carried out, analyses the available data and discusses the role of delta ferrite in the quality of the weld.

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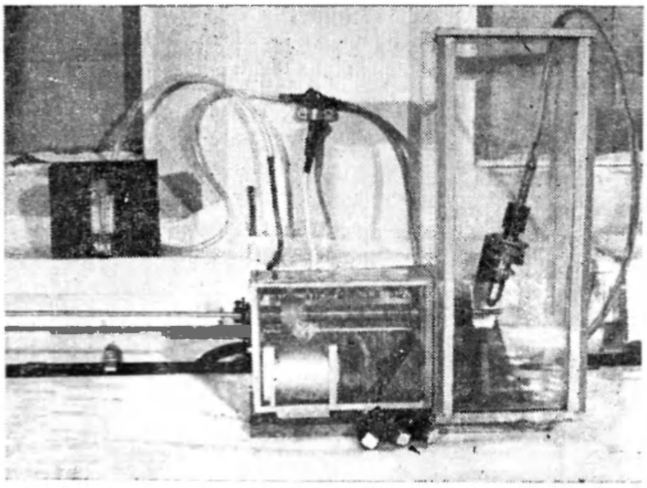
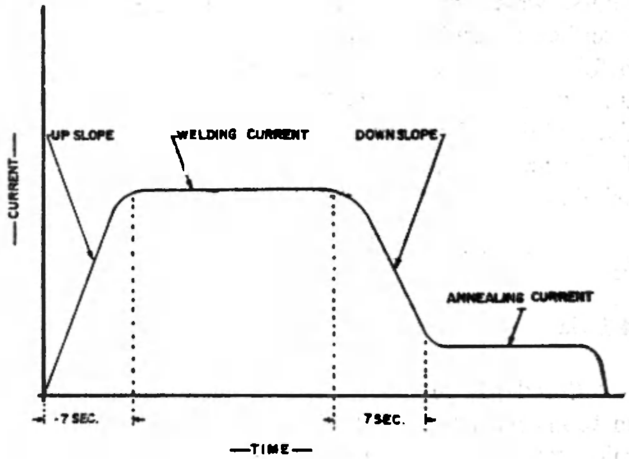


Fig. 1. Tig Welding Machine



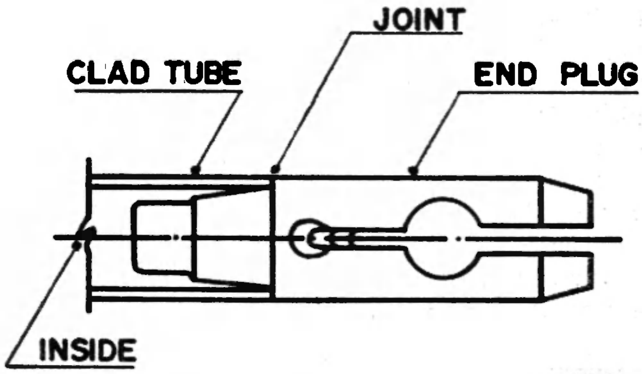
CURRENT PROFILE

Fig. 2.

2. MACHINE AND MATERIALS USED

An automatic, remotely operable TIG welding machine shown in fig. 1 has been used for all experimentation. Special miniature type welding torch having 1.5 mm thoriated tungsten electrode and 2 mm copper nozzle has been used. Welding cycle has been automic and the sequence includes job motor on, H.F. on, up slope, welding, down slope, annealing and arc off : Welding has been done by keeping the torch stationary and rotating the job at constant speed. General current profile used in our experimentation is shown in fig. 2.

Weld joint involving thin walled clad tube and solid end plug, shown in fig. 3, has been face to face butt joint. Two types of solid end plugs (Bottom plug and Top plug) of identical joint characteristics have been used. Stainless steel rod has been used to study the effect of welding prarameters in presence of delta ferrite. Composition of all materials used in our experimentation i.e. clad tube, bottom plug, top plug and S.S. rod has been given in Table 1 and also shown on Schaeffler diagram in fig. 4.



MATERIAL : S.S. 316 X 5

Fig. 3. Typical Weld Joint.

3. EXPERIMENTS PERFORMED

Twentythree arcs have been struck on solid S.S rods by varying welding prarameters like welding current, arc gap, gas flow, gas composition, annealing current and annealing time. The range of variations of different welding parameters has been chosen to get a stable welding arc. Arc gap has been measured by filler gauges. In addition to this, a larger number of tube-end plug welding (50 Bottom plug welding and 43 top end welding) has been done and studied for weld micro-structure. All details about quality of weld

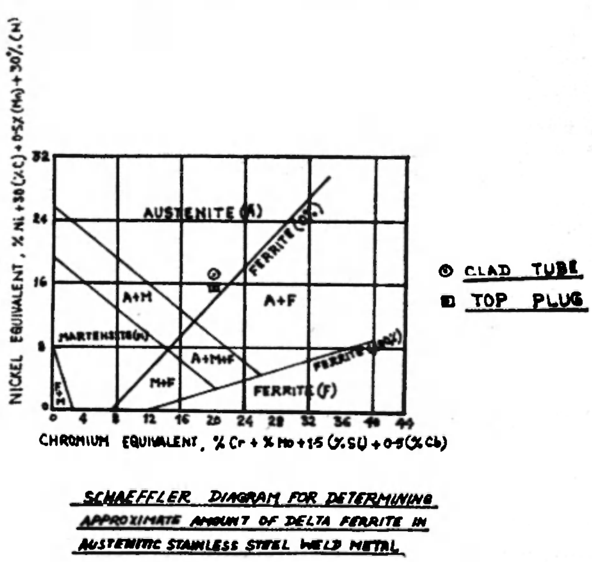


Fig. 4. Schaeffler Diagram.

joints, which could enhance the welding stress like interface fit and circumferential gap were also noted before welding. In all 17 weld samples (8 cracked and 9 uncracked) and all 23 welds on S.S. rod were chosen for detailed delta ferrite measurement. Results on the delta ferrite measurement of all weld samples have been tabulated in Tables 2 and 3.

4. METALLOGRAPHY

4.1 Sample Preparation :

Standard metallographic sample preparation methods have been used for development of the weld microstructure. A number of special etchants as given in table 4 have been reported in the literature (4, 5, 6) for revealing the delta ferrite phase in the weld microstructure and these have been tried during the course of this work. Modified Murakami's reagent (K_2 $Fe_3(CN)_6$—1 part, NaOH—1 part., H_2O—2 parts in boiling conditions for 15 minutes) has given the most satisfactory performance in revealing the delta ferrite phase. Due to involvement of cyanide solution, precautions have been taken to protect the operator. We have assembled a special set up shown in fig. 5, to take care of safety of operator and also to ensure repeatability. This has been done by trapping and dissolving the vapours (generated during etching) in suitable liquids and controlling the temperature of the heater.

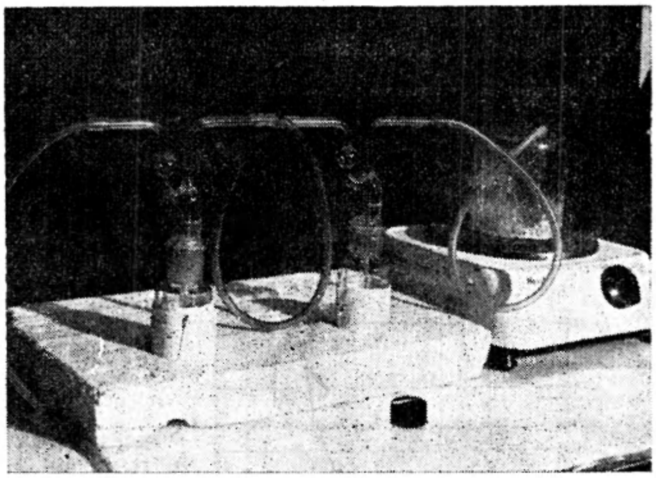


Fig. 5. Set up for Cyanide Etching.

4.2 Delta Ferrite Measurements :

After successful etching, five equidistant areas of each sample, shown in fig. 6, have been photographed. Delta ferrite content measurement has been done by point counting method (7,8) on every photomicrograph

Table 1

Sl. No.	Material's Detail	Clad tube (SS 316M)	Top Plug (SS 316M)
1.	Chemical composition		
	Cr	17.32	17.65
	Ni	13.65	13.25
	Mo	2.41	1.92
	Mn	1.79	1.60
	C	0.04	0.04
	N	0.039	0.02
	Si	0.34	0.37
	Fe	Rest	Rest
2.	Supplied by	M/s Fine Tube U.K.	M/s. CEA FRANCE
3.	Metallurgical condition	20% cold worked	Annealed
4.	Equivalent (Cr)	20.24	20.23
5.	Equivalent (Ni)	16.92	15.85

Table 2

B = Bottom Plug
T = Top Plug

Sl. No.	Sample No.	Welding Current (A)	Arc Voltage (V)	% of Delta Ferrite	Remarks
1.	B-44	23.5	10	2.10	Cracked
2.	B-48	24	10	3.70	Cracked
3.	B-38	24	10	2.20	Cracked
4.	B-52	24	10	2.50	Cracked
5.	B-33	24.5	10	2.10	Cracked
6.	B-28	24.5	10	2.90	Cracked
7.	B-53	24	10	3.0	Cracked
8.	B-60	24	10	2.10	Cracked
9.	B-1	19.75	10	3.20	Uncracked
10.	B-61	24	10	2.80	Uncracked
11.	B-37	24	10	2.80	Uncracked
12.	B-144	24.0	10	3.40	Uncracked
13.	T-16	24.5	10	2.90	Uncracked
14.	T-28	24.5	10	3.40	Uncracked
15.	T-52	24	10	3.70	Uncracked
16.	T-33	15	10	3.20	Uncracked
17.	T-49	15	10	3.00	Uncracked

Note :- Other welding parameters like welding speed (32 cm/min), argon gas flow (30 SCFH), arc gap (20 thou), annealing current (5 amp) and annealing time (6 secs) were maintained constant.

Table 3

Sl. No.	Welding current -Amp-	Arc voltage -V-	Gas (Ar) flow -CFH-	Arc gap	Annealing current -Amp-	Annealing time seconds	Percentage of delta ferrite
			Current varying				
R-1	11	10	10	20	5	6	2.40
R-2	15.5	10	10	20	5	6	2.60
R-3	21	10	10	20	5	6	2.70
R-4	25	10	10	20	5	6	3.00
			Arc gap varying				
R-5	16	10	10	15	5	6	2.20
R-6	16	10	10	20	5	6	2.30
R-7	16	10	10	25	5	6	2.30
R-8	16	10	10	30	5	6	2.40
			Gas flow varying				
R-9	16	10	5	20	5	6	2.40
R-10	16	10	10	20	5	6	2.70
R-11	16	10	15	20	5	6	2.20
R-12	16	10	20	20	5	6	2.20
			Gas Composition varying				
			He Ar				
R-13	12	14	40 Nil	20	5	6	1.90
R-14	12	14	22 10	20	5	6	1.80
R-15	12	14	22 10	20	5	6	2.10
R-16	12	14	20 20	20	5	6	2.40
R-17	12	14	10 30	20	5	6	1.70
			Annealing current varying				
			Ar				
R-18	12	14	20	20	5	6	2.40
R-19	12	14	20	20	7	6	3.50
R-20	12	14	20	20	9	6	4.00
			Annealing time varying				
R-21	12	12	20	20	5	9.9	2.50
R-22	12	12	20	20	5	13.0	2.80
R-23	12	14	20	20	5	5.0	2.40

Note :- In all the above rods welding speed is 32 cm/min.

Table 4

Sl. No.	Etchant	Composition	Technique
1.	Murakami's Reagent	1 part K_3 Fe $(CN)_6$ 1 part NaOH (KoH) 10 part H_4O	80°C to boiling temperature
2.	Modified Murakami's Reagent	1 part K_3 Fe $(Cn)_6$ 1 part NaOH (KoH) 2 part H_2O	80°C to boiling temperature
3.	Kalling's Reagent	2 gms Cucl$_2$ 40 ml. HCl 40 to 80 ml. of Methanol or Ethanol 95% 40 ml. H_2O	Chemical Etching
4.	Modified Kalling's Reagent	2 gms. of Cucl$_2$ 40 ml. HCl 40 to 80 ml. of Ethanol or Methanol	Chemical Etching
5.	Lactic Acid HCl Alcohol	45 ml. 10 ml. 45 ml.	Electrolytic Etching at 6V for 10 sec. to 30 sec.
6.	HNO_3 Acetic Acid HCl Glycerol	10 ml. 10 ml. 15 ml. 5 ml.	Chemical Etching
7.	Lactic Acid HCl HNO_3	20% 63% 17%	Chemical Etching
8.	HCl HCO_3	1 part 1 part	Chemical Etching

by four different operators and average values have been reported in table 2 and 3. A total of 800 fields from 200 photomicrographs have been counted for the delta ferrite measurements in this work.

4.3 Metallographic Observation :

The welds have shown high penetration around 250-300% of clad tube thickness and the pools are fairly

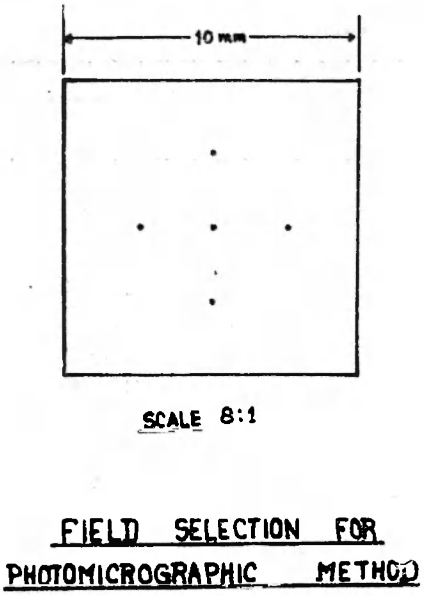


Fig. 6.

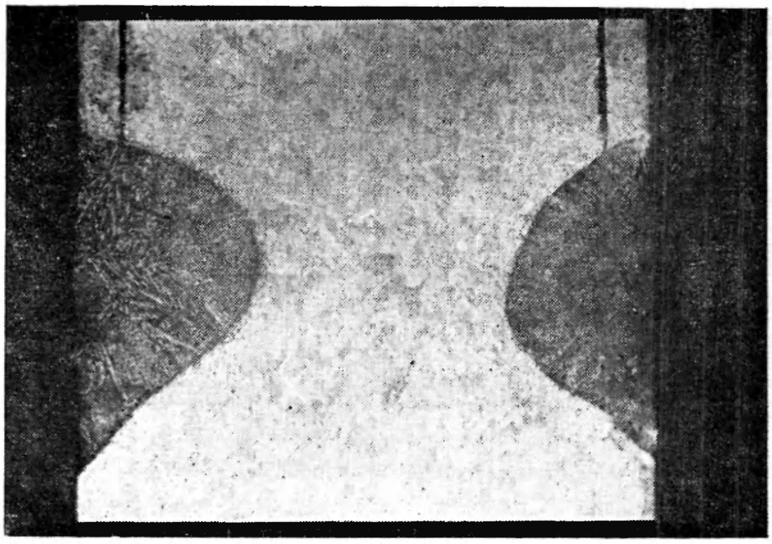


Fig. 7. Symmetrical weld pools MAG. 20X

symmetric on the sections observed. A typical photomicrograph is shown in fig. 7. A large number of bottom end plug welds (32 Nos.) out of 50 have shown the presence of cracking. The crack observed appears systematically almost in the same location and is of similar nature although the extent is varying. All the cracks have been observed in the bottom end plugs only and typical micrographs revealing the cracking have been presented in fig. 8. The occurrence of porosity and lack of penetration is very few and no inclusion is observed in any of the sectioned welds. Details of the appearance of Delta ferrite phases in these sectioned welds have been discussed in later sections.

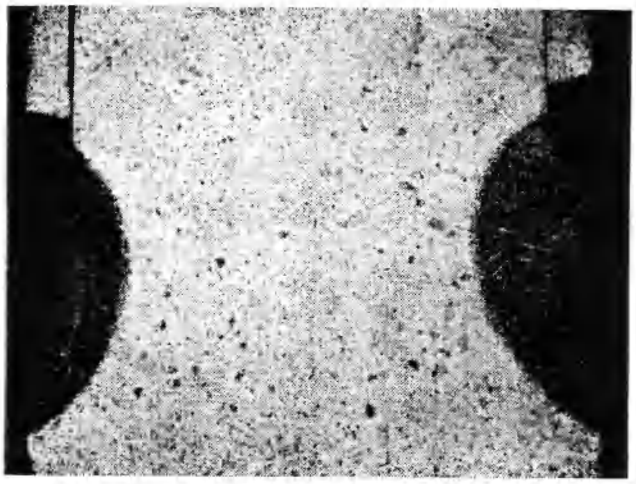
5. DISCUSSIONS

It has been noticed (Table 2) that cracking has occurred in weld samples having generally a low amount of delta ferrite and with poor quality (too tight interface fit and incomplete matching at the weld joint between the clad tube and the end plug) of weld joint. It has also been observed that cracking has appeared only in the bottom end plug welds. Bottom end plugs have not been of good quality and due to lack of matching between the clad tube and end plugs, a small gap has been noticed before welding which could have acted as stress raiser. Later, a large number of welds with low current and better interface fit and matching of components (S. No. 16, 17 of table 2) have been done and these have shown no such cracking, This must have significantly reduced the welding stress and therefore indicate that reduction in welding stress plays a significant role in tube welding for avoiding cracking. However, at the same time delta ferrite content must be kept as high as possible. The delta ferrite in uncracked welds has been above 3 % and generally about 1 % more than that in the cracked welds and it confirms that presence of delta ferirte plays a crucial role in avoiding cracking. Delta ferrite in cracked and uncracked weld microstructure has been shown in fig. 9.

The content of delta ferrite cannot be increased substantially as no filler material is allowed, however, welding on S.S. rods have been carried out to find out the variation in content of delta ferrite with respect to welding parameters. Results shown in table 3 indicate that arc gap, gas flow and composition of gas (Ar & He) have not influenced the delta ferrite content significantly. This could be due to the small anode spot size which might not have been affected by nitrogen pick up from surrounding air. Results shown in table 3 also indicate that welding current and annealing time have affected the content of delta ferrite only marginally while annealing current has significantly affected the delta ferrite. Alternately, composition of end plug could be chosen to get higher amount of delta ferrite. Morphology of delta ferrite in clad tube end plug weld and S.S. rod weld have been different and is shown in fig. 10. This difference may be due to the difference in their cooling rate.

6. CONCLUSIONS

(1) Amount of delta ferrite in non-cracked weld samples is generally above 3 % and on an average about 1 % higher than cracked weld samples. Welding para-



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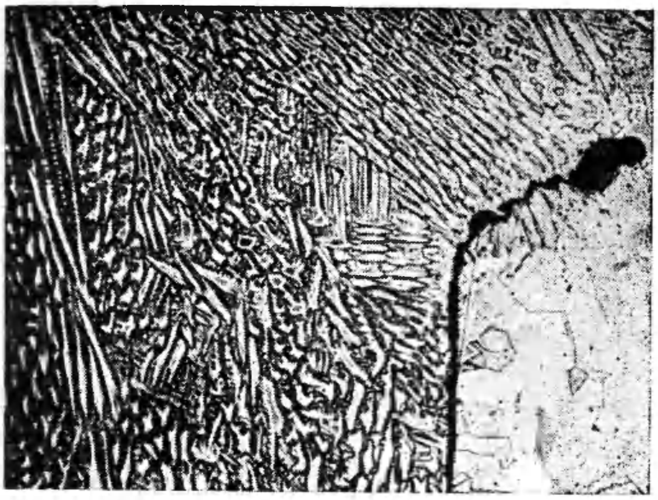

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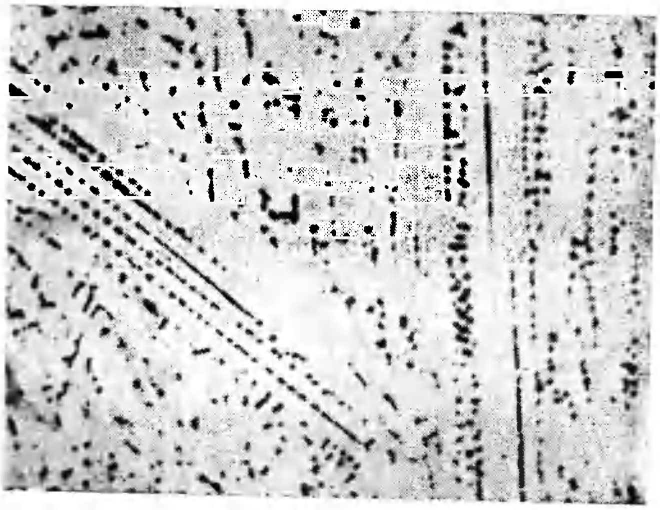
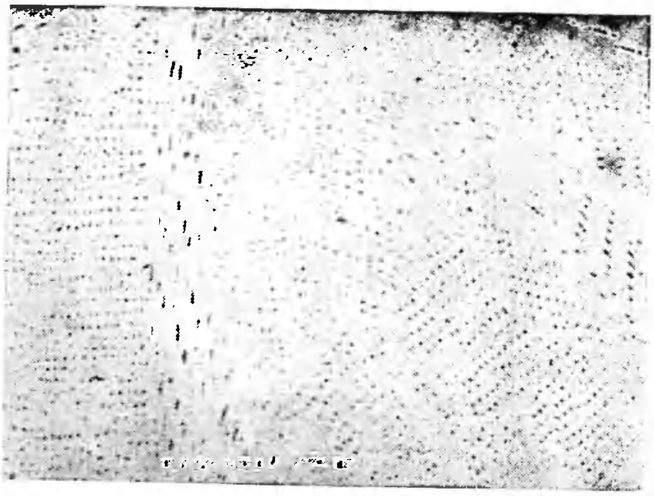
Fig. 8. Cracked Weld Samples



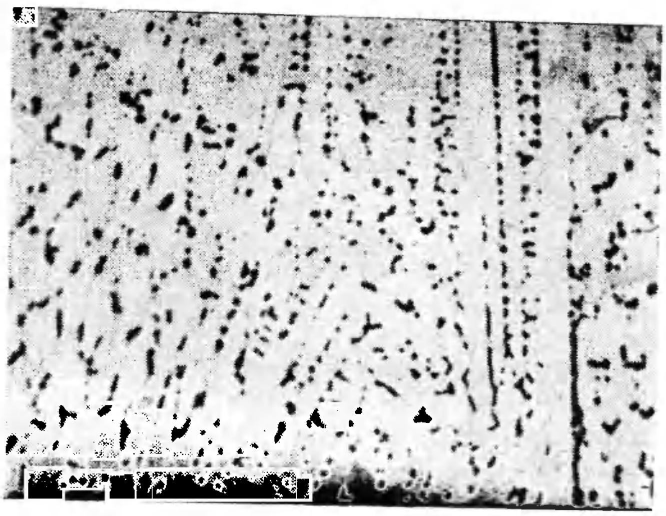
MAG. 350X Delta Ferrite in Cracked Sample

MAG. 350X

Fig. 9. Delta Ferrite in Uncracked Sample



MAG. 350X General Delta Ferrite Appearance in Rod



MAG. 350X

Fig. 10

meters should be tailored to have high amount of delta ferrite i.e. high annealing (finishing) current and high annealing time. High welding current should be avoided as this may increase the welding stresses.

(2) The interface fit and matching of (joint) surface also plays an important role in welding stress pattern thus influencing the cracking behaviour of the weld.

(3) Effect of annealing current on amount of delta ferrite has been most significant and plays a dominant role in avoiding cracking. Higher the annealing current, higher is the amount of delta ferrite in the weld pool.

(4) Welding current and annealing time have only a marginal effect on the content of delta ferrite. The amount of delta ferrite increases, only marginally with increase in welding current and annealing time.

(5) Arc gap, gas flow, gas composition (He & Argon) also appear to influence the ferrite content but the effect is very marginal and the trend is not very clear from the available experimental evidence.

(6) Amount of delta ferrite observed in rodwelds has been generally smaller compared to tube-plug welds. Morphology of delta ferrite in these two type of welds is also different.

(7) Modified Murakami's reagent with NaOH solution under boiling condition has been found to be most satisfactory in revealing the delta ferrite structure.

7. ACKNOWLDGEMENT

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