

Prevent Cracking in Deposition of Carbon Steel on Inconel 625

M. A. Morsy¹, M. R. El Koussy³ and M. M. Farag³

¹Associate professor, Central Metallurgical R&D Institute CMRDI

²Prof, Dept. of Metallurgy, Faculty of Engineering Cairo University

³Welding Engineer, Pertojet Company

Abstract. Welding procedure of clad steel including deposition of carbon steel on nickel base alloy usually gives unaccepted mechanical properties. Cracks were formed along type II boundary in nickel base alloy pass and a martensitic layer was formed in carbon steel pass. In this paper, cracks along type II boundary were prevented by lowering the martensitic start temperature (T_{Ms}) of the martensitic layer. Decreasing of T_{Ms} was obtained by two methods: *Dilution method* and *Grain refining method*. Three levels of T_{Ms} (approximately 350, 200, and 50°C) are obtained. The results showed that: cracks along type II boundary were prevented at T_{Ms} lower than 200°C; however type II boundary itself was prevented at T_{Ms} lower than 50°C. Also post weld heat treatment was necessary to achieve accepted impact properties.

1 Introduction

Welding of carbon steel pipes (X65) clad by nickel base alloy (Inconel 625) are usually being welded by AWS A5.14- ERNiCrMo3 filler metal. A trial was attempted to weld first and second passes by AWS A5.14- ERNiCrMo3 and subsequent passes by AWS A5.1 E7018. Unaccepted mechanical properties were resulted due to creation of cracks along type II boundary and formation of martensitic layer in carbon steel deposit [1]. In the present paper an unconventional idea was developed to prevent cracking along type II boundary. This idea is illustrated schematically in Fig1, where martensite which formed in carbon steel pass (3rd pass) was induced compressive stresses on 2nd inconel pass; hence cracks were prevented. It must be mentioned that the idea of promoting martensitic formation in welds was considered a departure from conventional thinking [2]. But in the present work martensite would be beneficial if lower martensite start temperature was achieved. Lowering martensite start temperature (T_{Ms}) means that more compressive stresses were induced at surrounding passes i.e. transformation induced compressive stresses generation [2-4]. T_{Ms} can be controlled by chemical composition and by grain size [5-7].

Two methods were used to reduce T_{Ms} of the 3rd pass. The first one was described as "*Dilution Method*". In this method, dilution level was increased by increasing the welding current. This means that more alloying elements (mainly Ni and Cr) would transfer from the 2nd pass (Inconel) to the 3rd pass (carbon steel).

These alloying elements will increase the hardenability and decrease T_{Ms} . The second method was described as "*Grain Refining Method*". In this method T_{Ms} decreased by decreasing grain size of the 3rd pass. The composition of the 3rd pass was similar to martensitic stainless steel [1]. Thus, tempering is necessary to provide the required notch toughness [8]. The post weld heat treatment (PWHT) was applied for crack free welds.

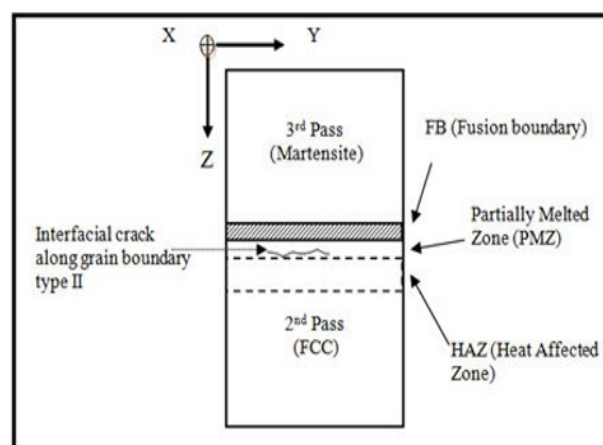


Fig. 1. Schematic diagram illustrated the idea of using martensite which formed in 3rd pass to prevent crack along type II boundary in 2nd pass: "X" longitudinal, "Y" transverse and "Z" through thickness

* Corresponding author: morsy_abokhala@yahoo.com

2 Experimental Procedures

2.1. Welding and Material

Base metal was API 5L Grade X-65 pipe steel with 305 mm diameter, 21.4 mm thickness and clad with 2 mm thickness of inconel 625. Filler metals used in this study were AWS A5.14 ERNiCrMo3 and AWS A5.1E7018. The test coupon pipes were fabricated with full penetration single groove butt joint with 60 degrees included angles. Welding was done using flat position "1G". Gas tungsten arc welding (GTAW) process with pure argon shielding gas was used to weld first and second passes using AWS A5.14- ERNiCrMo3 filler metal. The heat inputs of the 1st and 2nd passes were lowered as possible (about 0.9KJ/mm) to minimize dilution.

Two methods were used to weld the 3rd pass. The first one was described as "Dilution Method". In this method; the 3rd pass was welded by shielded metal arc welding (SMAW) process using AWS A5.1 E7018. Three levels of dilution were achieved by using three levels of heat input (about 1.2, 1.4 and 2.0 KJ/mm). The increase in heat input levels was obtained by the increase in welding current from 95 A to 110A and 150 A, respectively. The subsequent passes were welded by AWS A5.1 E7018 using the same heat input of the 3rd pass. The second method was described as "Grain Refining Method". In this method, the 3rd pass was welded by flux cored arc welding (FCAW) process using E70T-4 with amperage of 230 A.. The subsequent passes were welded by SMAW using AWS A5.1 E7018 and applying 1.2 kJ/mm heat input.

2.2. Post Weld Heat Treatment

Tempering was proceeded at 720°C and 3 hours holding time. Tempering was applied only for crack free welds

2.3. Microstructural Characterization

Specimens were cut and prepared for mechanical tests in accordance with ASME-Section IX , where tensile, impact and bend test are required. The specimens for impact test were prepared from cap and root (including the 3rd pass). Microstructural characterization was performed using optical metallography and scanning electron microscope. Because of the wide range of compositions and microstructures, a number of chemical etchants were used. Nital (2 mL HNO₃ and 98 mL ethanol) was used to reveal martensitic structure; Vilella's reagent (5 mL HCl, 1 gram picric acid, and 100 mL ethanol) was used to reveal grains of martensite. Mixed acids (equal parts of HCL, HNO₃, and acetic acids) were used to reveal grain boundaries of nickel base alloy. Microhardness across transition region was measured using diamond pyramid indenter in conjunction with both 10 and 100 gram loads.

2.4 Determination of Martensite Start Temperature (T_{MS}) for the 3rd Pass

In this investigation, T_{MS} was calculated using empirical equations. For dilution method, Gooch equation (Eq.1) [9] was used. This equation is usually used for martensitic stainless. However, for grain refining method; Lee equation (Eq. 2) [10] was used. This equation considers the effects of chemical composition and austenite grain size on martensite start temperature.

$$Ms(^{\circ}C)=540-(497C\%+6.3Mn\%+36.3Ni\%+10.8Cr\%+46.6Mo\%) \quad (1)$$

$$Ms(^{\circ}C)=402-797C+14.4Mn+15.3Si-31.1Ni+345.6Cr+434.6Mo+(59.6C+3.8Ni-41Cr-53.8Mo).G \quad (2)$$

Where *G* is the ASTM austenite grain size and elements in weight fraction

Typical EDX detector was used to measure chemical composition of the 3rd pass. But this detector can detect a limited range of X-ray energies so light elements (*Z*<10) such as carbon, nitrogen cannot be measured accurately. To overcome this problem; in the present work; estimated complete chemical composition was determined using back calculation methodology as follows:

1. Major alloying elements such as Fe, Ni and Cr were determined by EDX analysis. Then dilution levels of major elements were calculated using Eq. 3 [6].

$$D=(C_w - C_f)/(C_b - C_f) \quad (3)$$

Where *D* is the dilution, *C_w*, *C_f* and *C_b* are the concentration of each element in weld metal, filler metal, and base metal respectively.

2. Average dilution level (*D_{av}*) of the major alloying elements was determined.
3. Eq.4 was used to calculate the concentrations of other alloying elements

$$C_w = [(C_b - C_f) * D_{av}] + C_f \quad (4)$$

3. Results and Discussion

3.1. Effect of T_{MS} value on type II grain boundary conditions

It is accepted that grain boundary type II worked as a weak line which easy cracked [11, 12]. In the present work martensitic transformation which formed in 3rd pass was used to produce compressive stresses on 2nd

pass, hence tensile stresses were reduced and cracks were prevented. Because of elastic modulus increase with decreasing of metal temperature; the amount of compressive stresses generated from martensitic transformation increased with decreasing of TMs [13, 14].

Because of quantitative measurements of stresses at type II grain boundary are hard to conduct, a qualitative method was used to give an indication about stress level. This technique was proceeded by observing any cracks near the fusion boundary i.e. observation of cracks means high tensile stresses. Thus an approach of the relation between TMs values of the 3rd pass and stresses level at fusion boundary was built. Depending on this methodology effective levels of TMs were approximately determined as the following:

- a. Case I of Dilution Method: heat input was about 1.2 KJ/mm which gave 6.5% average dilution. Mechanical properties are shown in Table 1, 2 and 3, where unaccepted results of side bend test and notch impact toughness are noted. Table4 shows that TMs for the fusion zone of the 3rd pass equaled to 354°C. Fig2 reveals the cracks along type II boundary. This means that at 354°C; the created compressive stresses were not sufficient to overcome the tensile stresses, hence crack was occurred.
- b. Case II of Dilution Method: Heat input was about 1.4 KJ/mm which gave 13.5% average dilution.

Mechanical properties are shown in Tables 1, 2 and 3. As shown in Table 4, TMs for the fusion zone of the 3rd pass equaled to 197°C. Fig.3 shows type II grain boundary appeared without any interfacial cracks. This means that at 197°C, the created compressive stresses were sufficient to overcome the most of tensile stresses and cracks were prevented. This observation reflects the resulted accepted side bend test and improved notch toughness (Table2, and 3 respectively).

- c. Case III of Dilution Method: heat input was about 2 KJ/mm; giving 20.22% average dilution. This heat input is considered relatively high heat. Mechanical properties are shown in Table 1, 2 and 3, where unaccepted results of side bend and notch impact toughness tests are noted. Fig.4 reveals microstructure near fusion boundary where planar solidification region and type II grain boundary are not found i.e. cellular structure continued until fusion boundary. Depending on Nelson et al. work [15, 16], the tensile stress which worked as a driving force for type II boundary formation, was nil. Table 4 shows that TMs for fusion zone of the 3rd pass was 480°C. Based on these results, it can be concluded that: at TMS equal or lower than 48°C the generated compressive stresses at fusion boundary were sufficient to overcome all tensile stresses so type II boundary itself disappeared.

Table 1. Tensile test results in as weld conditions

Method		Ultimate Tensile Stress (N/mm ²)	Failure Location	Comment
Dilution	Case I	641	W.M	Acceptable
		669	W.M	Acceptable
	Case II	645.33	W.M	Acceptable
		656.6	W.M	Acceptable
	Case III	649.74	W.M	Acceptable
		669.34	W.M	Acceptable
Grain Refining		668.36	W.M	Acceptable
		664.44	W.M	Acceptable

Table 2. Guided side bend test results in as weld conditions

Specimen No.	Dilution Method			Grain Refining Method
	Case I	Case II	Case III	
1	Rejected	Accepted	Rejected	Accepted
2	Rejected	Accepted	Rejected	Accepted
3	Rejected	Accepted	Rejected	Accepted
4	Rejected	Accepted	Rejected	Accepted

Table 3. Notch impact toughness results (Joule) at 0°C for as welded conditions

Position	WM			FL			FL+2			FL+5		
	1	2	3	1	2	3	1	2	3	1	2	3
Dilution Method												
Case I												
Cap	69	60	94	110	50	65	140	115	125	118	117	106
Root	<u>10</u>	<u>12</u>	<u>10</u>	95	110	85	140	145	150	165	160	155
Case II												
Cap	64	55	89	105	45	60	135	110	120	113	112	101
Root	<u>19</u>	<u>23</u>	<u>23</u>	91	106	81	136	141	146	161	156	151
Case III												
Cap	52	43	77	93	33	48	123	98	108	101	100	89
Root	<u>9</u>	<u>11</u>	<u>13</u>	78	93	68	123	128	133	148	143	138
Grain Refining Method												
Cap	100	53	86	130	105	109	105	97	96	70	79	103
Root	<u>23</u>	<u>26</u>	<u>22</u>	92	90	76	127	143	141	150	148	144

*WM: weld metal * FL: Fusion Line *FL+2: Fusion Line+2mm *FL+5: Fusion Line +5mm

However, a plan view of 2nd pass is illustrated in Fig.5, where parts from filler metal are observed. Parts from filler metals were forced inside the 2nd Inconel pass and solidified giving martensitic islands. Micro-hardness of these regions was ranged from 497 to 522 HV. These results are supported by SEM and EDX analyses in Fig.6 where iron percentage was about 92%. These islands were obtained as a result of using high welding current [17, 18]. As shown in Fig.7 cracked type II boundary is observed parallel to these filler metal islands. As shown in Table 4, T_{MS} of martensitic islands within 2nd pass is

310°C. This means that: at 310°C compressive stresses were very low compared with tensile stresses so cracking occurred.

Although type II boundary near fusion boundary were prevented, formation of filler metal martensitic islands with cracks within 2nd Inconel pass led to poor impact toughness and unaccepted side bend results. These results are given in Table2 and Table3 respectively.

Table 4. Chemical analyses of base metal, filler metal and estimated chemical analyses and T_{MS} of the weld metal

Element (%)	Base Metal X65	Filler Metals			Dilution Method				Grain Refined Method
		AWS A5.1 E7018	AWS A5.14-ERNiCrMo3	E70T-4	Case I	Case II	Case III		
							WM	Islands	
Ni	0.011	0.03	64.6	0.02	3.02	6.32	9.46	3.94	4.72
Cr	0.011	0.00	21.7	0.00	1.12	2.29	3.42	1.46	1.74
Fe	Bal.	Bal.	0.6	Bal.	93.44	88.28	83.32	91.95	89.94
Mo	0.228	0.15	8.9	0.00	0.47	0.97	1.46	0.6	0.73
Nb	0.008	0.00	3.5	0.00	0.21	0.43	0.65	0.27	0.32
C	0.007	0.07	0.08	0.23	0.07	0.07	0.08	0.07	0.22
Mn	1.4	1.05	0.00	0.5	1.02	1.00	0.97	1.02	0.52
Si	0.22	0.55	0.1	0.28	0.55	0.54	0.54	0.55	0.30
P	0.01	0.016	0.00	0.011	0.02	0.02	0.02	0.02	0.03
S	0.005	0.01	0.00	0.003	0.01	0.01	0.01	0.01	0.01
Al	0.008	0.01	0.00	1.5	0.02	0.04	0.06	0.03	1.38
Ti	0.1	0.001	0.00	0.01	0.02	0.04	0.06	0.03	0.04
Co	0.00	0.00	1.00	0.00	0.05	0.11	0.16	0.07	0.08
T_{MS} °C					354	197	48	310	56

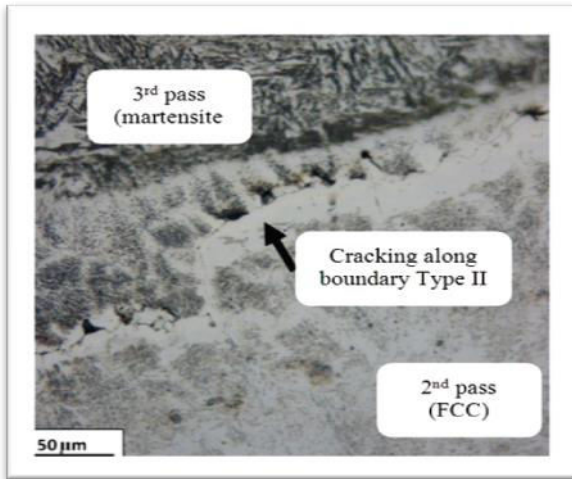


Fig. 2 Case I of dilution method: Interfacial cracks are running along grain boundary type II.

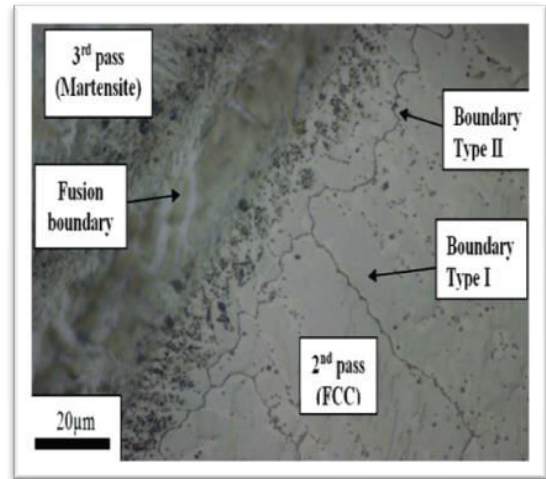


Fig. 3. Case II of dilution method: Grain boundary type II appeared without cracks

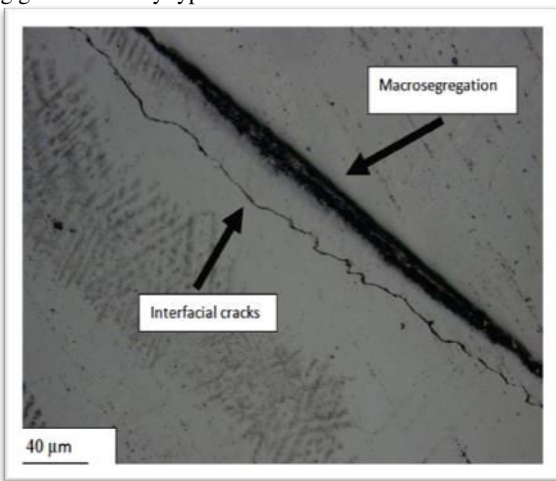


Fig. 4. Case III of dilution method: Parts from filler are forced inside the 2nd pass forming martensitic island inside with cracks

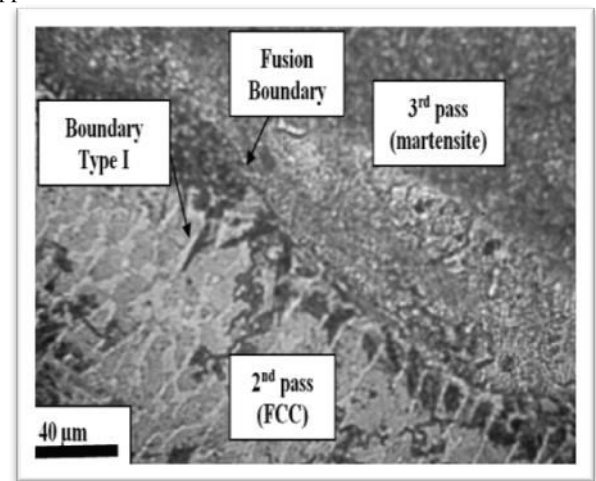


Fig. 5. Case III of dilution method: Type II boundary disappeared and cellular structure continued until fusion boundary

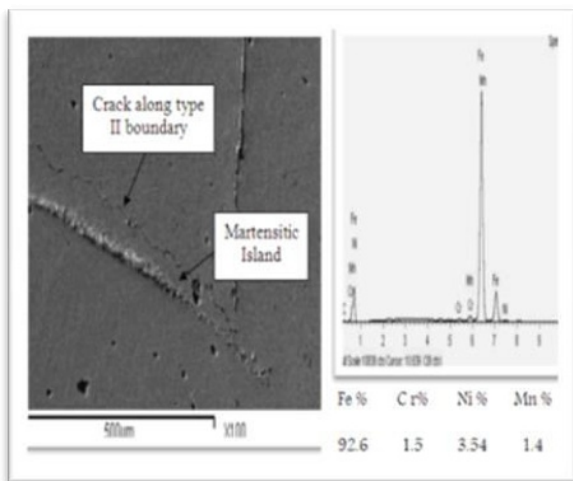


Fig. 6. Case III of dilution method - SEM and EDX for filler metal islands within the 2nd Inconel pass

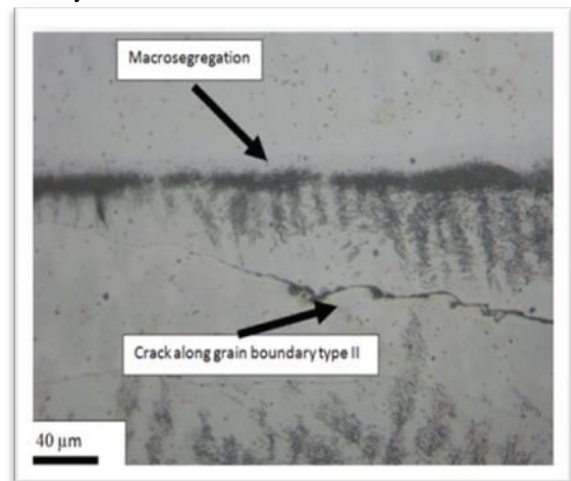


Fig. 7. Case III of dilution method-cracked type II boundary parallel to filler metal islands within the 2nd Inconel pass

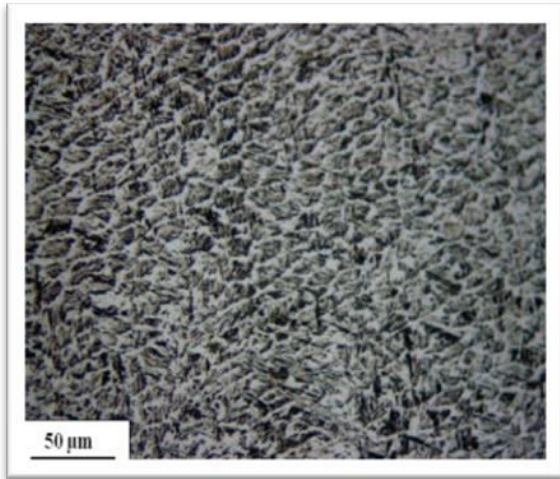


Fig.8. Grain Refinement method - Prior austenite grains of 3rd pass; etched with Vilella's reagent

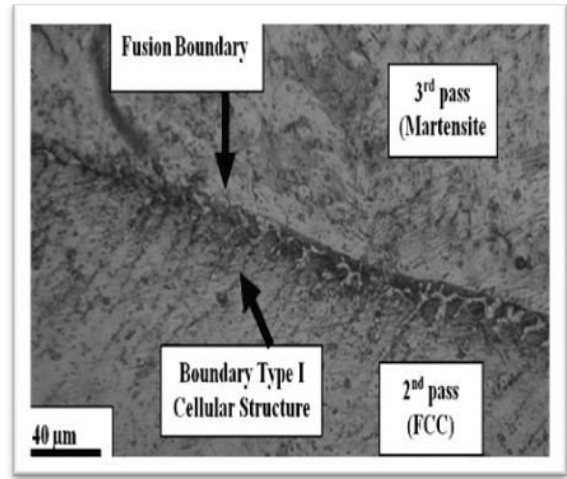


Fig. 9. Grain refining method: Type II boundary disappeared and cellular structure continued until fusion boundary

a) **Grain Refining Method:** The effect of austenitic grain size on T_{Ms} was studied by several researchers [19- 21]. One argument is that a refinement of the austenite grain size leads to the Hall–Petch strengthening of austenite, thereby making it difficult for martensite to form [22]. Grain refinement of the 3rd pass was achieved by using E70T-4 which acted as a source of aluminum oxide and aluminum nitride. Aluminum nitrides and aluminum oxides which may be considered as non-metallic inclusions and impair mechanical properties were used here as nucleation sites causing grain refining. **Fig. 8** shows the prior austenite grains of the 3rd pass which is martensite. Grain size was measured using intercept Method –ASTM E112 giving ASTM grain size number equals to 12.

As shown in **Table 4**, T_{Ms} of the 3rd pass is 56°C, which was calculated using Lee equation. **Fig. 9** shows that planer solidification region and type II grain boundary are disappeared where cellular structure is continued until

fusion boundary. This means that: at 56°C compressive stresses created at fusion boundary were sufficient to overcome all tensile stresses so type II boundary itself disappeared. Preventing formation of type II boundary was reflected on mechanical properties of weld metal, where accepted side bend test results and improved notch toughness (23 Joule 0°C) are noted in **Table2** and **Table3** respectively.

3.2 Effect of Post Weld Heat Treatment

It is well known that the accepted notch toughness of carbon steel at 0°C is 27 Joule [22]. However, in the as welded conditions, unaccepted notch toughness at 0°C was resulted as shown in **Table1**. Thus in order to obtain accepted notch toughness, tempering was necessary. Tempering was proceeded at 720°C for 3hr holding time. Based on the results taken from as welded conditions, tempering was applied only for crack free cases (case II of dilution method and grain refining method). The results of mechanical properties are represented in **Table 5**.

Table 5. Average results of mechanical properties for increased dilution case II and grain refined methods in as weld and tempered conditions

Method	Ultimate Unit Stress (N/mm ²)	Side Bend	Impact Toughness at Root (including interface between 2 nd and 3 rd Pass) (Joule at 0°C)
As welded condition			
Increased Dilution	654	Accepted	22
Grain Refining	680	Accepted	23
As tempered condition			
Increased Dilution	649	Accepted	43
Grain Refining	663	Accepted	30

Fig.10a and Fig.11a give a plan view for fusion boundary between 2nd and 3rd pass for case II dilution and grain refined methods respectively. Tempered martensite was noted in the 3rd pass and dark etched region was found at the interface between 2nd pass inconel and 3rd pass (martensite). Micro hardness was illustrated in Fig.10b and Fig.11b where highly localized hardness peak was noted. As documented in literatures [23-26], this dark layer was enriched carbide layer which formed due to carbon migration from ferrite side to austenite side. This layer was clearly observed in grain

refining method than dilution method due to difference of carbon content (0.22% and 0.07% respectively). The effect of this layer on notch toughness is also noted in Table 5. For case II of dilution method; notch toughness increased from 22 to 43Joule (as welded and tempered condition respectively). However for grain refining method notch toughness increased only from 23 to 30Joule (as welded and tempered condition respectively).

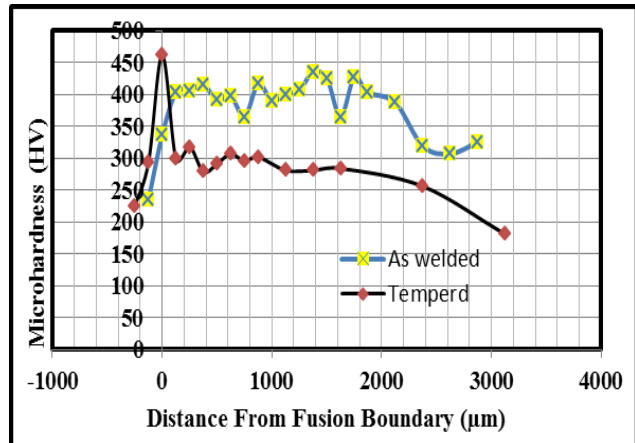
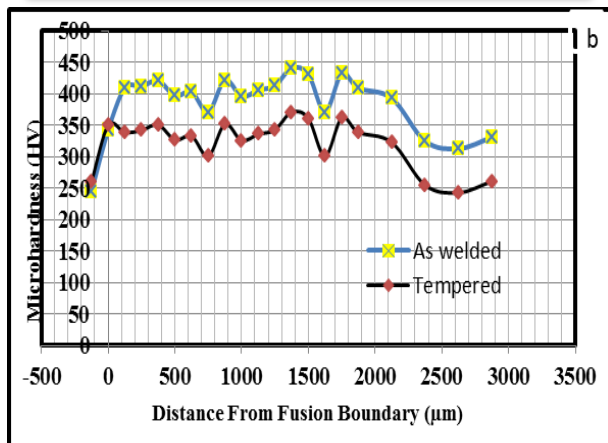
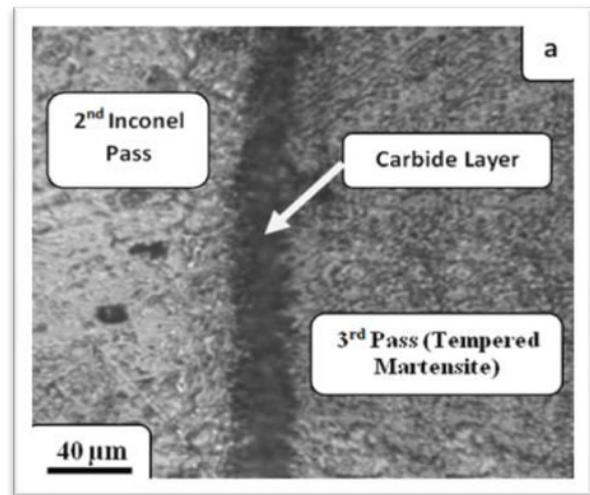
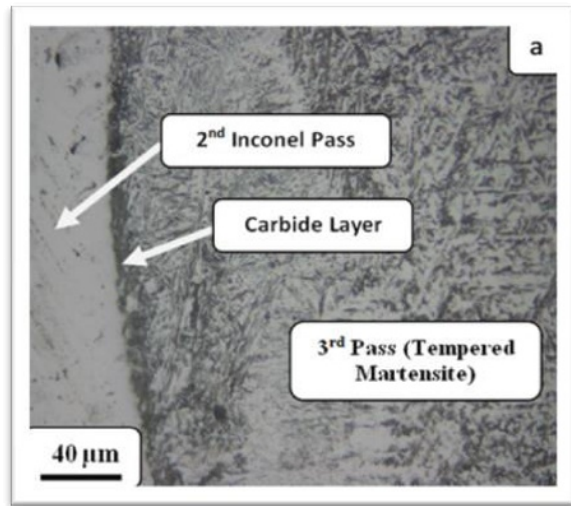


Fig. 10. Case II of Dilution Method
 a)- Microstructure b)- Micro hardness

Fig. 11. Grain refining Method
 a)- Microstructure b)- Micro hardness

4 Conclusions

Based on the results and discussion presented in this investigation, TMs of the 3rd pass was considered the controlling factor that determines the conditions of stresses at type II boundary. Three levels of TMS of the 3rd pass can be obtained:

At TMs $\geq 300^{\circ}\text{C}$, lower compressive stresses are generated from martensitic transformation in the 3rd pass. So, high tensile stresses are residue causing cracking along type II boundary.

At TMs $\approx 200^{\circ}\text{C}$, relatively high compressive stresses are generated from martensitic transformation in the 3rd

pass. The net stresses which resulted at fusion boundary are tensile but with low magnitude value. These low tensile stresses work as a driving force for type II boundary formation and are not sufficient to cause cracking.

At TMs $\approx 50^{\circ}\text{C}$, high compressive stresses are generated from martensitic transformation in the 3rd pass. In this case, all tensile stresses are compensated. Therefore the driving force for formation of type II boundary is nil hence, type II boundary itself is not created.

PWHT is necessary to achieve accepted impact strength (i.e. higher than 27Joule at 0°C). Thus mechanical

properties are accepted only when cracks are inhibited and PWHT is applied.

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