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Hot Cracking and its Characteristics of SMAW Weld Metal of T/P92 Steel

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Abstract: To research the performances and characteristics of a kind of short and tiny defect in SMAW weld metal of T/P92 steel, the defect morphology were observed and the alloy elements on defect surfaces were analyzed with EDAX by both an engineering sample obtained from a welding engineering and a laboratory sample made in the laboratory. Results show that dendrites with uniform direction and cells with free solidification crystal surfaces are observed on the defects fracture surfaces. Moreover, it is also observed in the laboratory sample that the defect emerges under high temperature. According to the results, it can be confirmed that the defect is the welding hot cracking, furthermore, the solidification cracking. In the research of weldability of T/P92 steel, the cold cracking susceptibility, embrittlement tendency and IV type cracking tendency in fine grained HAZ are conducted more researches but the hot cracking susceptibility, characteristics and production mechanism have received less attention. The study discoveries that the hot cracking of SMAW weld metal of T/P92 steel is located at the extinguishing position of weld bead and presents star like or linear shapes in different weld depths. Oxidation layer or welding slag may be found in the cracking. Significant segregation of W, Cr, Si and V rather than S, P and B are observed on the cracking surfaces. Welding procedure parameters exert an effect on the formation of cracking. Cracking tendency of welded metal expands as the increasing weld layer thickness and prolonged time of weld metal under high temperature. Due to the characteristics of its shape and size, the defect is difficult to be detected and positioned in ultrasonic inspection which easily leads to an erroneous or an omissive assessment on it. Segregation of W, Cr, Si and V may affect the solidification mode and metallurgical microstructure of the final crystallized zone and then affect the formation of hot cracking, which is clearly distinguishable the hot cracking mechanism of traditionl law alloy CrMo or CrMoV heat resistant steel.

Key words: T/P92 steel, weldability, solidification cracking, hot cracking, weld metal, element segregation

INTRODUCTION

An advanced Martensitic heat-resistant steel T/P92 is widely applied in ultrasuper critical units in thermal power stations predominantly due to its excellent high temperature creep performances and favorable thermo-physical properties. How to ensure the structural integrity and performances of its welded joint in the application has been a matter of great concern. Researches on its weldability show that its welded joint has a certain cold cracking susceptibility (Lomozik *et al*., 2012; Vaillant *et al*., 2008), embrittlement tendency (Vyrostkova *et al*., 2008; Liu *et al*., 2011) as well as IV type cracking tendency in fine grained HAZ (Xue *et al*., 2012; Parker, 2012). Keeping preheating temperature above 150°C, controlling the interpass temperature within 150-250°C and welding heat input within 9-12 kJ cm^{-1} and conducting a post-weld heat treatment during 760-770°C for suitable time can effectively avoid cold cracking, reduce HAZ softening zone and decrease embrittlement degree of the welded joint (Richardot *et al*., 2000; Consonni and Rothwell, 2012; Yang *et al*., 2007).

In the research of weldability of T/P92 steel, its hot cracking susceptibility of weld metal has received less attention so far. According to the traditional formation mechanism of welding hot cracking, the segregation of S, P and B which forms low melting point eutectic with other elements among the crystals solidified in final solid-phase is the metallurgical factor of solidification cracking for heat-resistant steel (Kou, 2002). However, chemical composition of the base material of T/P92 steel are controlled to be S = 0.01, P = 0.02% and B = 0.001-0.006% (ASTM International, 2006). Meanwhile, the relevant welding consumable standards and manufacturers control the content of S, P and B to be much lower. On the other hand, T/P92 steel is developed on the base of chemical composition of T/P91 steel by reducing 0.5% Mo, increasing 1.8% W and increasing

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trace B. Therefore, the susceptibility of hot cracking of weld metal of two steels is comparable. Through Tigamajig welding cracking test, King *et al*. (1986) suggested that hot cracking of weld metal of P91 steel was not a major issue within the composition scope of normal base metal and welding filler materials. A varestraint test was carried out by Li *et al*. (1999) to study the hot cracking susceptibility of T91 steel and the test result shown that T91 steel had a certain solidification cracking tendency but it was not susceptible. Its hot cracking tendency was comparable to 12 Cr1MoVG steel but relatively lower than 0 Cr18Ni9Ti stainless steel and much lower than nickel base alloy. Based on the theoretical analysis, Klueh and Harries (2001) concluded that the hot cracking susceptibility of P91 steel was mainly relevant to the segregation of S, P, B, Nb, Si and V. In addition, it also was aware of the fact that the hot cracking of weld metal of P91 steel was uncommon in welding engineering. It believed that the hot cracking of weld metal of P91 steel can be avoided by controlling the composition of deleterious elements of base metal and the welded consumable and reducing the welding heat input.

With the wide application of T/P92 steel, however, welding engineering finds that a kind of short and tiny defect in 2-5 mm length and a star like or linear shape often emerges in weld metal of T/P92 steel (Dong *et al*., 2012; Li *et al*., 2010a, b; Masuyama and Yokoyama, 1994; Zhu, 2011; Yan *et al*., 2009). The defect is also found in weld seams including GTAW, SMAW (Dong *et al*., 2012; Li *et al*., 2010a) and SAW (Li *et al*., 2010b; Masuyama and Yokoyama, 1994; Zhu, 2011). Ultrasonic inspection assesses the defect as an exceeding defect. Some literatures (Dong *et al*., 2012; Li *et al*., 2010a; Yan *et al*., 2009) consider the defect as hot cracking, laminar slag or incomplete fusion. Nevertheless, other literatures (Masuyama and Yokoyama, 1994; Zhu, 2011; Li *et al*, 2010b). Judge the defect as welding hot cracking according to its shape, position and size. No matter what this defect is classified into, all of them lack both the deterministic criteria of defect properties and the study on the formation mechanism of the defect and the influencing factors. Analyzing defect properties and adopting corresponding prevention measures have become a technical issue in T/P92 steel application at present.

Based on an engineering sample obtained from a welding engineering and a laboratory sample made in the laboratory, this study researches the properties and preliminary causes of a kind of short and tiny exceeding defects found in the SMAW weld metal of T/P92 steel and analyzes its characteristics such as formation time, morphology, position and reflected wave of ultrasonic inspection by the morphology observation of defect and energy spectrum analysis of the elements on the defect surface.

Engineering sample acquisition and laboratory sample preparation: Engineering Sample Acquisition. P92 steel in the different dimensions of OD531×91 mm and OD775×38 mm were adopted as the main steam piping and the hot reheat piping, respectively in a 1000 MW ultra-super critical unit in a power station. A combined welding process of GTAW as backing weld pass and SMAW as filling and cosmetic weld pass was adopted for all welded joints. After the unit running for 6000 h, ultrasonic inspection found that there were exceeding defects on more than 10 welded joints of main steam piping and hot reheat piping. Take one exceeding defect detected by ultrasonic inspection on the joint of main stream pipe as an example. Cut this defect sample by a way of machine cutting when the defect became visible during removing the weld metal. Keep the sample cool always during cutting. The visible morphology of the defect which appears during removing the weld metal is shown in Fig. 1a. The dye penetrant test shows that this defect is in linear shape in 3.0 mm length. The view of cutting engineering sample is shown in Fig. 1b.

Laboratory sample preparation: A butt welded joint was fabricated from P92 steel pipe in the dimension of

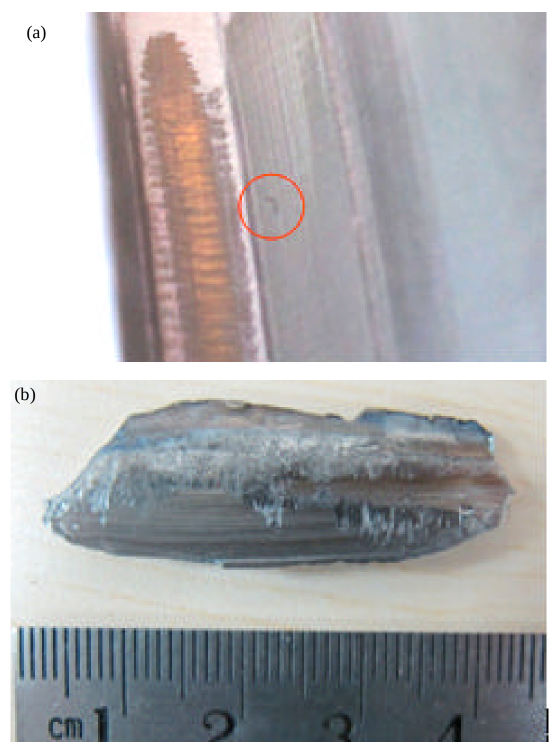

Fig. 1(a-b): Engineering Sample and defect morphology, (a) Defect morphology in weld metal cutting before and (b) View of the cutting engineering sample

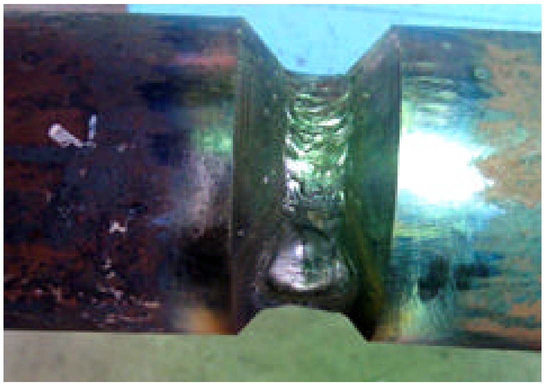

Fig. 2: Cracking in the SMAW weld

Fig. 3: Metallographic microstructure of metal of P92 steel weld metal of the engineering sample

OD57×12 mm. One layer of backing weld with 3 mm thickness was welded on GTAW. SMAW is utilized for filling weld with 200-300°C inter-pass temperature, 3.2 mm diameter electrode, 100-110 A welding current and within 3-6 mm thickness of every weld layer. During the welding process, the cracks could be found at the arc extinguishing position of weld bead. After finishing welding, the cracks could be found at multiple arc extinguishing positions but not at the weld bead. The shape of the crack found at arc extinguishing position is shown in Fig. 2.

Defect morphology observations and defect property analysis: Metallographic Microstructure and Defect Morphology of the Engineering Sample. After inlaying, grinding, polishing and etching by using standard metallographic procedures, the metallographic microstructure and defect morphology of the engineering sample are observed in different methods.

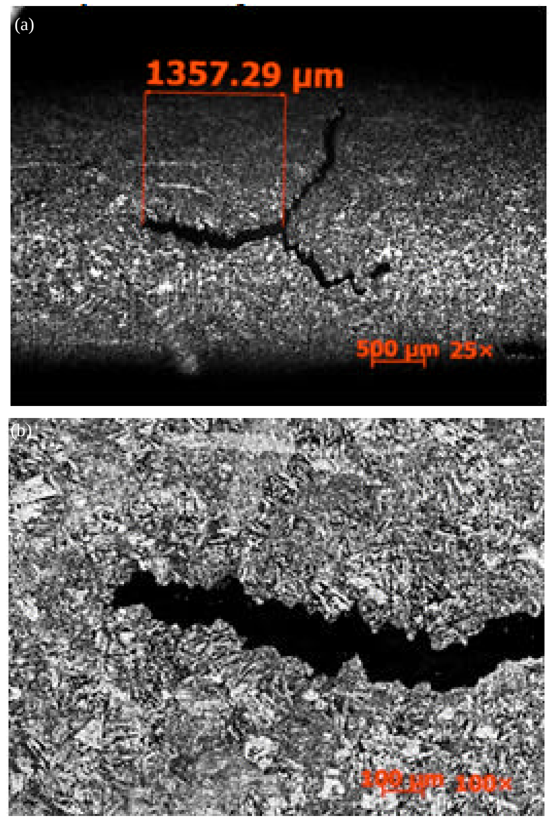

Fig. 4(a-b): Cracking shape of engineering sample, (a) Overall morphology under light microscope and (b) Morphology of cracking tip

The metallographic microstructure of weld metal is tempered Martensite with clear orientation and coarse grain (Fig. 3). Massive ferrite is visible in local region.

As the grinding goes by, it is found that the defect shape changes from linear (Fig. 1a) to star like cracking (Fig. 4a). One end of three cracks converges at one point and the other ends of each crack extends toward different directions. Crack is intergranular fracture with a blunt tip (Fig. 4b). There are inclusions inside cracks. Analysis of the conclusions by EDAX finds that there are not only oxides (Fig. 5a) mainly composed Cr and Fe but also oxides (Fig. 5b) mainly composed Ca, Si, V and Ti. The main elementary compositions (wt) in Fig. 5a are respectively O 7.83, Si 0.097, Cr 8.35 and Fe for the residual. The main elementary compositions (wt) in Fig. 5b are respectively O 27.57, Si 7.12, Ca 24.74, Ti 8.96, V 0.65, Cr 8.47, Mn 5.71 and Fe for the residual. Judged from their compositions, it can be confirmed that the former is the oxide layer of Cr and Fe and the latter is welding slag.

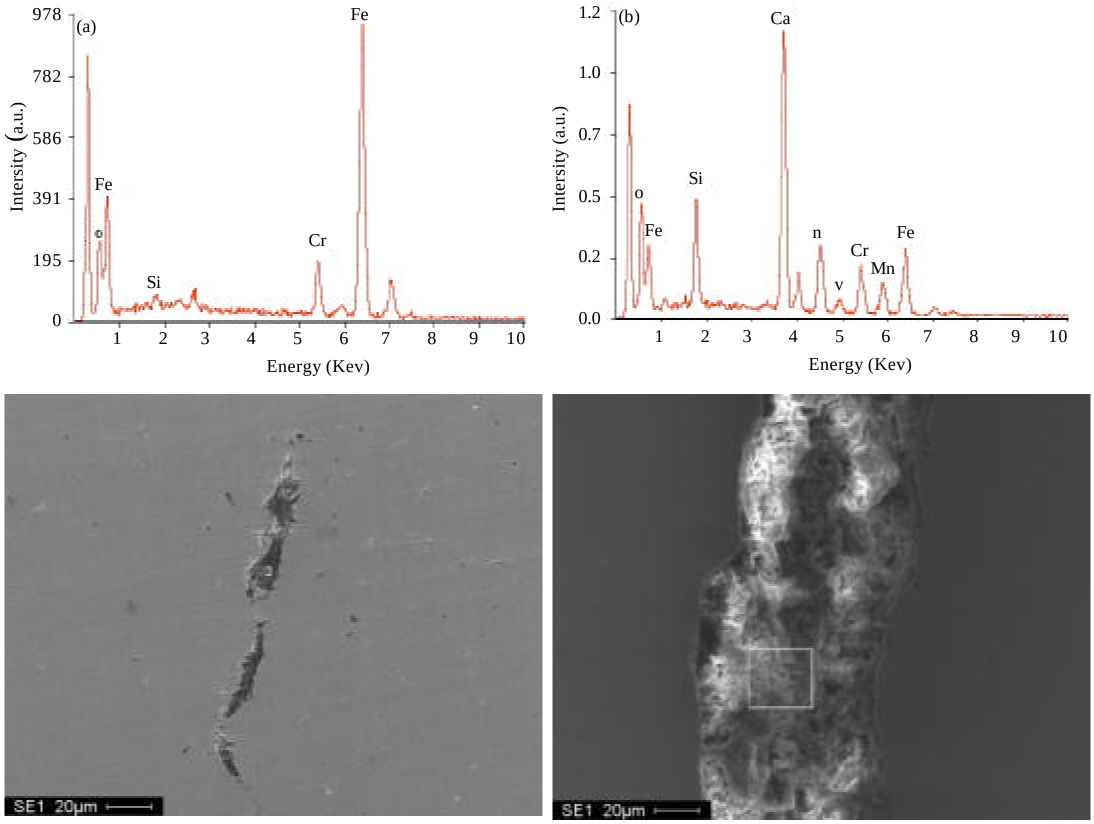

Fig. 5(a-b): Analyzed for composition of conclusions in cracking by EDAX EDS, (a) One region and (b) Another region

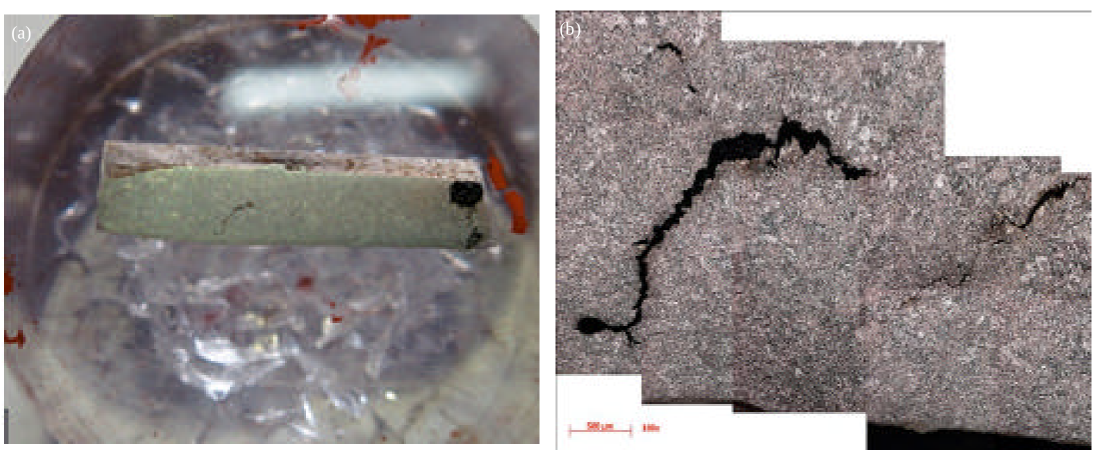

Fig. 6(a-b): Defect shape after grinding 0.8 mm in depth of the sample shown in Fig. 4, (a) Shape under visible observation and (b) Shape under light microscope

As the sample grinding running on, it is found that the defect shape changes gradually from star like to linear shape again. Figure 6a and b show the defect morphology under visual observation and light microscope

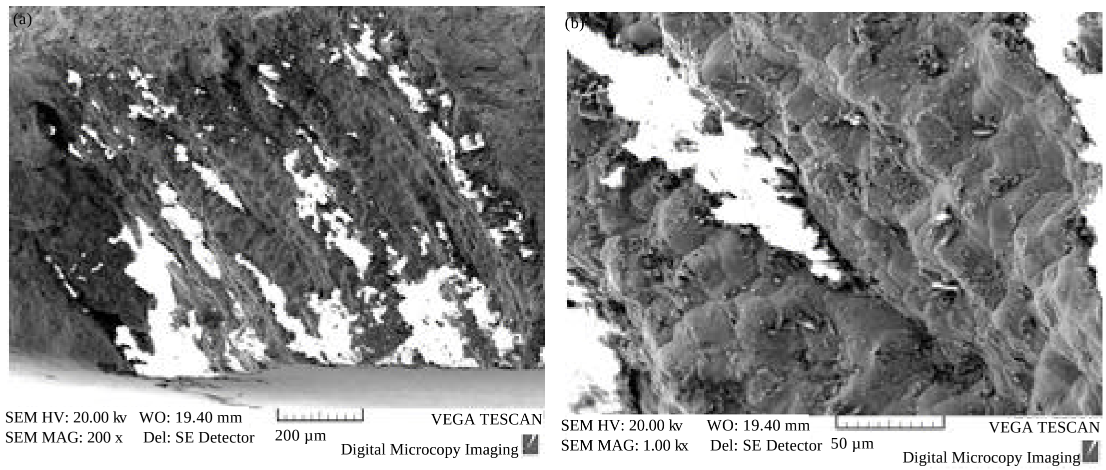

Fig. 7(a-b): Morphology of cracking fracture under SEM, (a) Overall morphology and (b) Local zone morphology

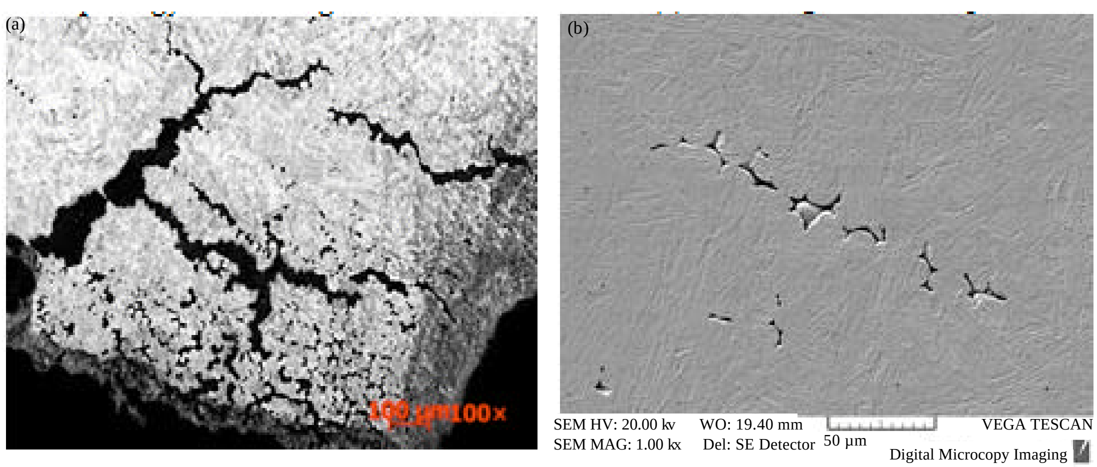

Fig. 8(a-b): Crack morphology of the laboratory sample, (a) Under light microscope and (b) Local zone under SEM

respectively after the morphology sample shown in Fig. 4 is ground in 0.8 mm depth. Seeing from the Fig. 6a, one segment of the star like crack is looked like to disappear and the defect shows in linear shape again in visual observation. Under light microscope, however, the residual segment of the crack is still clearly visible. At the same time, another crack near this crack begins to emerge.

Break up the sample shown in Fig. 6 after liquid nitrogen cooling. Its fracture morphology under SEM is shown in Fig. 7. It can be observed that there are columnar crystals with uniform direction and crystal cells with round and smooth surfaces and free solidification configuration, which is commonly known as “potato”.

Defect morphology of the laboratory sample: The cracking in weld metal of P92 steel is located at the arc extinguishing position and in star like shape (Fig. 2) by visual observation. Under light microscope, it can be found that there are multiple cracks and dendritic crystallization morphology in above position (Fig. 8a). By SEM, columnar crystal and free growth end of cell, namely “potato”, can be found. The cracks exist among dentritic crystals with round and smooth cell ends and have the typical morphology configuration of free solidification (Fig. 8b).

Crack properties analysis: Cells with free solidification surfaces which are feature criterion of free solidification crystals have been observed in the fracture surface of the defects in both the engineering sample and the laboratory sample. It indicates that no combination of solid metallic bonds takes shape among cracking surfaces and the

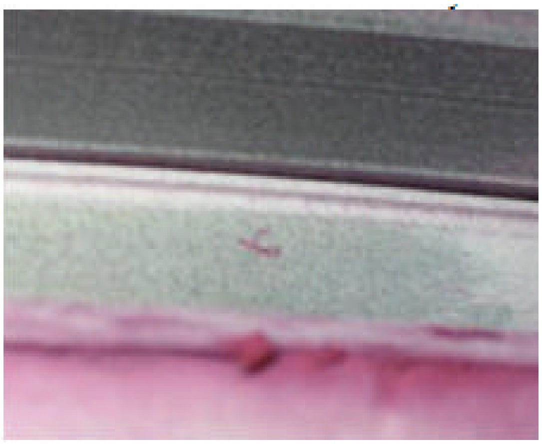

Fig. 9: Defect with star like shape

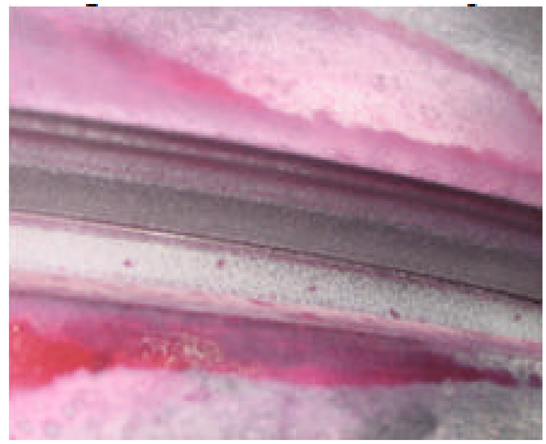

Fig. 10: Multiple defects in the equal weld depth

initiation and growth of the crack derive from the separation of liquid weld metal. That means the cracking is welding hot cracking and moreover, the solidification cracking.

For laboratory sample, crack formation under high temperature is also observed except for the free solidification crystal cell similar with the engineering sample. These indicate that the crack is welding hot cracking, as well as solidification cracking.

HOT CRACKING CHARACTERISTICS OF THE SMAW WELD METAL OF T/P92 STEEL

Characteristics of hot cracking position and shape: Ultrasonic inspection demonstrates that the defects are all in the SMAW weld metal rather than both sides of fusion line or HAZ of welded joint. Based on the observation results of defects in the engineering sample, laboratory sample and weld metal of more than 10 repaired welded joints in which the exceeding defects sometimes became visible during removing the weld metal, the position and shape characteristics of hot cracking in the SMAW weld metal of P92 steel are summarized as follows:

- **Distribution in different depth:** Hot cracking can be found in different depth of filled layer except backing layer and cosmetic layer. However, it is also found at backing layer or cosmetic layer in other welding engineering of P92 steel
- **Different morphology in different weld depth:** During removing the weld metal, two types of defect shapes are observed, star-like cracking (Fig. 9) and linear defect (Fig. 1a) both in lengths of less than 5 mm. It can be determined from aforementioned analysis that star like cracking is welding hot cracking but linear shape, at least in part, is the shape of hot cracking in different weld depth. Although there are slag inclusions among the defect, it is unreliable that judge it as welding slag inclusion or incomplete fusion
- **Location at the arc extinguishing position of weld bead:** According to observations during removing the weld metal, partial defects exist independently (Fig. 1a) in weld metal, while sometimes multiple defects exist at the same depth of welded joints, as shown in Fig. 10. Five defects represented in Fig. 10 are in star-like shape or linear shape with interval 30-50 mm each other. The welded joint is welded by electrode in 3.2 mm diameter. The interval among defects approximately equals to the deposited metal length of one electrode. It further proves that the crack is generated from the arc extinguishing position of weld bead. The result is also consistent with that of laboratory test

Characteristics of element contents on the cracking fracture surface: Based upon the difference in the morphology and position, the cracking fracture shown in Fig. 7 is classified into three zones: Cell Surface Zone (CSZ), columnar-crystal tearing surface zone (CTZ) which is also crack tip zone and Fracture Surface Zone (FSZ) which is a newly formed zone when the defect is broken. The element contents of different zones analyzed by EDAX are shown in Table 1, in which the chemical composition of P92 steel required by ASME standard, typical deposited metal composition of the electrode used to the welded joint and weld metal composition which is obtained by PerkinElmer Optima2100DV emission

Table 1: Chemical composition of base metal, deposited metal and cracking faces (wt%)

Element	C	Mn	P	S	Si	Cr	W	Mo	V
Base metal	0.07~0.13	0.20~0.60	<0.02	<0.01	<0.50	8.5~9.5	1.5~2.0	0.30~0.60	0.15~0.25
Deposited metal	0.11	0.65	/	/	0.27	8.95	1.72	0.53	0.19
Weld metal	0.12	0.72	0.013	0.007	0.25	0.74	1.62	0.51	0.22
CSZ1	4.17	2.64	0.09	0	1.10	11.69	0	0.08	0.60
CSZ2	5.16	2.06	0.05	0	1.78	9.33	0	1.44	0.48
CSZ3	4.78	1.88	0.03	0	1.27	9.47	0	1.07	0.59
CSZ4	5.50	1.29	0.03	0	1.30	9.1	0	1.02	0.41
CSZ5	5.87	1.54	0.09	0	1.46	9.2	0	1.28	0.52
CTZ1	4.80	7.44	0.17	0	4.68	12.26	0	0.59	1.11
CTZ2	3.89	3.44	0.10	0	1.30	12.12	0	0	1.07
CTZ3	4.79	7.94	0.08	0	4.11	12.4	0	0.8	0.85
CTZ4	4.54	11.9	0.06	0	3.40	19.33	0	0.64	1.22
FSZ1	7.80	1.17	0.06	0	0	8.83	3.82	0.6	
FSZ2	7.41	1.63	0	0	0	8.79	3.3	0.96	
FSZ3	2.76	1.55	0.19	0	0	9.39	4.08	1.11	
FSZ4	3.16	1.74	0.14	0	0	9.23	4.32	1.28	
Element	Nb	N	B	Ni	Ca	Ti	O	Na	Others
Base metal	0.04~0.09	0.03~0.07	0.001~0.006	<0.40					Al<0.040
Deposited metal	0.044	0.045		0.70					
Weld metal	0.045	0.06	0.005	0.10		0.002			
CSZ1					2.47	0.92			
CSZ2					0.87	0.89			
CSZ3					0.93	0.88			
CSZ4					0.78	0.37			
CSZ5					0.77	0.56			
CTZ1					19.79	4.77	10.72	1.21	
CTZ2					2.33	1.68	4.63		
CTZ3					12.5	5.27	19.14	1.4	
CTZ4					3.19	5.11	24.88	0.86	K 1.03 Al 1.18 Mg 0.24
FSZ1									
FSZ2									
FSZ3									
FSZ4									

spectrometer and CS-902G HF infrared C-S analyzer are also listed. It can be deduced from the data in Table 1 that element contents of cracking fracture surface have the following characteristics:

- No apparent segregation of S, P and B. Examination on the composition of weld metal by chemical method shows S 0.007, P 0.013 and B 0.005%. Such low content of three elements indicates that the absolute value of composition obtained by EDAX has only a certain reference but the data in CSZ, CTZ and FSZ have relative comparability. Table 1 shows that no presence of S and B can be found in the three different zones. Meanwhile, P content also has no apparent difference. It suggests that there isn't significant segregation of S, P and B in the cracking zone in the weld metal. Similar phenomenon has ever been reported by other literatures. Huang *et al*. (2005) didn't find segregation of S in hot cracking in root welding of P91 steel during the research of the distribution of S in cracking fracture surface by EDAX. Studies on mechanism of solidification cracking on weld metal of stainless steel find that the cracking is relevant with primary phase and solidification mode of weld metal rather than with segregation of S and P under certain welding conditions (Kou, 2002; Hochanadel *et al*., 2011). Masuyama and Yokoyama (1994) reported a hot cracking on SAW weld metal of P92 steel caused by element B. The crack vanishes when B content in the welding material is lowered from 0.0044 to 0.0028%. In our project, segregation of element B has not been found for its low content
- Segregation of element Si and V in the cracking zone. The contents of Si and V in CSZ and CTZ are far higher than the average valve of weld metal, while they can't be detected in CFZ. It indicates that they have apparent segregation at cracking surface and cracking tip. Si is the element promoting the formation of hot cracking. The hot cracking susceptibility increases significantly with the increasing Si content in welded joint (Gu *et al*., 1984; Maroef *et al*., 2005). Element V itself has smaller impact on the formation of hot cracking but it can form low melting point eutectic with Nb Klueh and Harries (2001). No Nb segregation is observed in theweld metal because of its low content
- Rich in Cr and poor in W in cracking zone. In CSZ and CTZ, namely cracking zone, Cr content is obviously higher than that in FSZ, while W content

is too low to be detected. In FSZ, however, W content is higher than the average content of weld metal. It indicates that liquid metal in final crystallized zone is poor in W but rich in Cr. Considering both Cr and W as ferrite formation element (Richardot *et al*., 2000), changes in weld metal composition of final crystallized zone are expected to have a significant effect on solidification mode, microstructure and hot cracking susceptibility. Klueh and Harries (2001) who studied weldability of steel MANET II discovers that the steel's hot cracking of weld metal also roots in Cr concentration

- No apparent segregation of element Mo. Mo increases hot cracking susceptibility but it is slightly less than other elements (Gu *et al*., 1984). In this experiment, no obvious discrepancy of Mo is discovered in the three zones
- Contents of element O and deoxidant elements like Mn, Si, V, Ca and Ti are significantly higher in crack tip zone. It demonstrates that crack tip is attached with slag inclusions

In summary, apparent segregation of element S, P and B which all have a drastically affect on hot cracking susceptibility isn't observed for their low contents but obvious segregation of two type elements are discovered on the surface of free crystal cell. One is Cr and W element which have great influence on crystallization microstructure and the others are Si and V element which can form low melting point eutectic with other elements. The segregation of these elements may exert impact on primary solidification mode and microstructure of final crystal zone and then affect the formation of hot cracking. Characteristics of Welding Procedure of Generating Hot Cracking. According to the observation of defects in the laboratory sample, cracking isn't always emerging when the weld layer is thin but cracking tendency increases with increasing weld layer thickness and the prolonged time of weld metal at arc extinguishing position under high temperature. It indicates that the formation of hot cracking on weld metal of P92 steel is related to the welding procedure. But more quantitative studies are needed to assess the impact of weld procedure on hot cracking.

Characteristics of reflected wave by ultrasonic inspection: Ultrasonic inspection finds out that the reflected wave of defect is the highest when the ultrasonic probe and weld joint are at a certain angle. When probe moves slightly at that time, the reflected wave amplitude swiftly descend which poses difficulty for locating precisely the zenith of reflected wave. Reflected wave is characterized with sharp wave form, clean root free from clutter and wide amplitude. Reflected wave takes on multiple crests in moving probe right and left; nomadic range of reflected wave is smaller in moving probe front and back. The dB value on the same defect differ greatly using different probes with different K value. For the above characteristics, the defect is difficult to be detected and positioned in ultrasonic inspection which easily leads to an erroneous or an omissive assessment on them.

CONCLUSION

The short and tiny defect in the SMAW weld metal of T/P92 steel is solidification cracking. Dendrites with uniform direction and round and smooth cells with free solidification crystal surface which indicates the result of liquid metal separating are observed on the defects fracture surface on both engineering sample and laboratory sample. It is the feature morphology of welding solidification cracking and deterministic criteria of welding hot cracking.

Hot cracking in the SMAW weld joint of T/P92 steel emerges at arc extinguishing position under high temperature. It presents star like or linear shape in different weld depths. Oxide layer or welding slag may exist in cracking. Welding procedure parameters have influences on the cracking formation. Cracking is more likely to emerge with increasing weld layer thickness and the prolonged time of weld metal at arc extinguishing position under high temperature. The cracking is difficult to be detected and positioned in ultrasonic inspection and an erroneous or an omissive assessment on them is occurred sometimes for the characteristics of its shape and size.

No significant segregation of S, P and B are discovered on the cracking fracture surface but segregation of Cr, W, Si and V elements are discovered. The segregation of these elements may exert impact on the solidification mode and microstructure of final crystal zone and then affect the formation of the hot cracking.

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