COLD CRACK SUSCEPTIBILITY OF HIGH STRENGTH WELD METAL

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ABSTRACT

This study reviews the factors controlling the weld metal cracking and shows the difference from those of HAZ cracking. It further reviews the recent progresses made in consumable design for improving the crack resistance in the high strength weld metal. Previously the controlling factors for weld metal cracking were regarded as weld metal strength, diffusible hydrogen and weld metal height. However an overall review presented in this article shows that the cold crack resistance can be improve significantly through the microstructural control and that an increase in tensile strength is not necessarily related to a decrease in the resistance to cold cracking.

KEY WORDS

Cold cracking, weld metal, susceptible microstructure, residual stress, diffusible hydrogen

1. Introduction

For many structural applications, lightweight construction has become more and more important. In lightweight construction, two basic approaches are discernible; one is material-based, the other the structure-based approach. Taking the shipbuilding industry as an example, the former has led to an increased use of high strength steels and thus to a reduction in total weight of ship. The second, structure-based approach is based on making better use of material, e.g. by redistributing it over a component volume based on the evaluation of local loading condition. This review aims at facilitating the first aspect.

At present, steels with yield strength in the range of 550 to 690 Mpa are used increasingly for a variety of marine applications[1,2] and 900 Mpa has been proposed for future jack-ups to operate in deep water[3]. Unfortunately, this approach can create weldability problems such as cold cracking. In the past, heat affected zone (HAZ) hydrogen induced cold cracking (HICC) was the most common type of cracking observed in steel weldments. However, recently steel producers have produced a new generation of high strength steels, such as TMCP steel and HSLA steel, with improved weldability. The result is that these steels can be more resistant to HAZ HICC, even at higher strength, hence minimizing or reducing the need for preheat, which is used to prevent weldment from cold cracking.

A consequence of this is the matching weld metal can be more susceptible to cracking, compared to the steel it joins, since consumable manufactures may not have provided comparable changes to the weld metal produced by their consumables. Hence, it is sometimes necessary to use costly preheat to prevent weld metal cold cracking, at temperatures higher than that required to prevent HAZ cracking. This has been appreciated with the introduction of HSLA 80 and 100 steels to replace HY 80 and 100 steels. Weld metal cracking has become a major limiting factor in the use of these new materials[4,5]. Furthermore, Korea and Japan are currently developing C-Mn steels with minimum tensile strength of 650 and 800 Mpa[6,7]. These steels will be designed to have ultra fine-grained microstructures of 1 ㎛ ferrite grain size and at most very low levels of alloying elements. This steel is characterized as high strength steel with mild steel composition. Once this steel develops, the welding consumable may be critical in limiting its use under the current situation.

There is therefore a need to improve the cracking resistance of current high strength steel weld metal so that it is at least equivalent not only to the recently developed steels but also to the new generation of steels, thereby allowing overall reductions in preheat costs to be achieved. This report was prepared to give informations on a proper way to develop new consumables for the steels with improved weldability.

2. Factors Contributing to Hydrogen Induced Cracking

As shown in Fig. 1, it has generally been accepted that hydrogen induced cracking will only occur given the coexistance of a sufficient quantity of diffusible hydrogen, a residual tensile stress and a susceptible microstructure. Sufficiently slow strain rate and low temperature were also essential for hydrogen induced cracking. Removal or prevention of any one of these factors can be employed to control hydrogen cracking. Hence, steel fabricators are now specifying the steels with lower carbon equivalent, strict welding procedures and consumables with lower hydrogen content. Although weld metal hydrogen cracking follows the same basic rules as cracking in HAZ, microstructural aspect in weld metal is rather different. The susceptibility for weld metal was reported not to be related with its chemical composition while that for HAZ has been expressed as carbon equivalent which is a function of chemical composition. Previous investigators[8-10] proposed several equations for the preheat temperature to prevent weld metal cracking in the multipass welds and these equations were expressed by the relationship of the form;

$T(℃) = A\,Rm + B \log [H] + C\,hw + D$

where Rm is the weld metal tensile strength,

[H] is the weld metal diffusible hydrogen content,

hw is the weld metal height, and

A, B, C and D are constants.

Unlike the equation for HAZ cracking, preheat temperature is not related with chemical composition directly but related with weld metal tensile strength(Rm). It is also interesting to note the preheat temperature increases linearly with the weld metal height(hw). As described above, the intrinsic factors for cold cracking are the same both in HAZ and weld metal but the extrinsic factors resulted from the quantification are quite different. Such differences are tabulated in Table 1.

Table 1 Quantification of three major factors controlling the cold cracks in HAZ and weld metal(WM).

Intrinsic Factors	Extrinsic Factors	
	HAZ crack	WM crack
Microstructure	CE	Rm
Hydrogen	[H]	[H], hw
Residual stress	Kt	hw

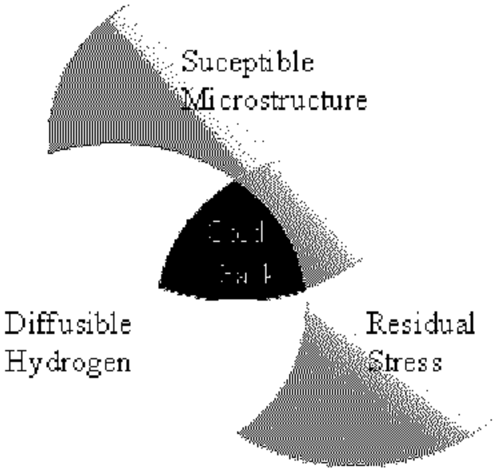

Fig. 1 Factors controlling cold cracks in weld metal.

3. Strategies for controlling residual stress

As all the cracks formed in the welded joint are attributable to tensile component of residual stress the weld metal cracking and thus can be suppressed by minimizing the tensile residual stress. This could be accomplished with the bulk expansion obtained by γ→α transformation. As shown in Fig. 2, the martensitic transformation taking place at sufficiently low temperature can induce a compressive residual stress in the weld. This concept has been applied by Hiraoka *et. al.*[11] in developing welding consumables and found that a weld metal of Ms temperature around 150℃ had a strong resistance to cracking compared with the commercial product. As it contains very high content of alloying elements like 10%Co-10%Ni, however, it would not be interested in the commercila market.

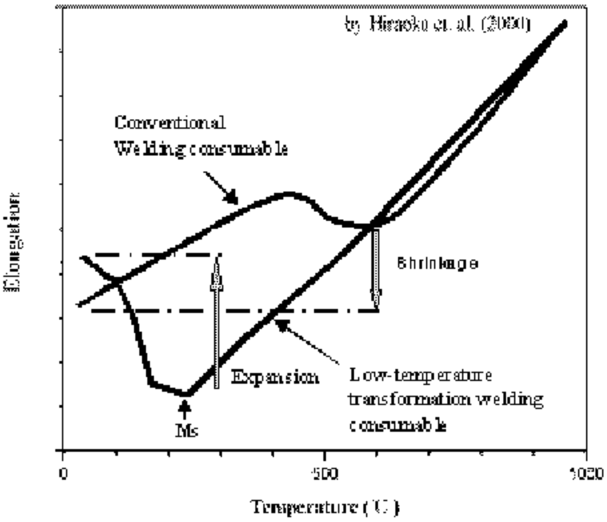

Fig. 2 Schematic illustration for designing welding consumable by controlling residual stress[11].

4. Strategies for controlling the hydrogen content

Probably the most popular method of avoiding hydrogen cracking lies in the control of weld hydrogen levels by limiting hydrogen input to the weld. In shielded metal arc (SMA) and submerged arc (SA) welding, the relationship between weld hydrogen content and moisture content in the flux has been extensively studied and has been found to depend on the baking temperature, the tendency of flux to regain moisture, and the environmental conditions. On the other hand, addition of compounds such as fluorides, carbonate or rare earth metals(REM) has been reported[12,13] to be beneficial in suppressing the hydrogen input to the weld. Table 2 shows one of the examples demonstrating the effect of REM addition on hydrogen control in the weld[12]. The beneficial effect of a small REM addition on weld metal hydrogen appears to be worth exploiting further in detail for the consumable design in commercial basis.

Table. 2 Effect of REM additions on diffusible hydrogen content in welds[12].

Te addition(㎎/㎝)	0	0.5	1.0	1.5	2.0	2.5	3.0
Diffusible hydrogen(㎖/100g)	8.05	4.21	3.71	3.75	3.29	3.24	3.24

Y-SiFe addition (㎎/㎝)	0	2.5	5.0	12.5	25.0
Diffusible hydrogen(㎖/100g)	7.26	4.33	4.54	4.17	4.17

However, for flux cored arc (FCA) welding consumables, little detailed information exists about the factors that may decrease weld hydrogen levels. The hydrogen content of rutile-type FCA wires currently available is about 6 ~ 8 ml/100g of deposited metal, which is substantially high compared with that of low-hydrogen SMA electrode. Considering the extensive use of FCA welding in the oriental countries, this process would be remained as the major welding process for the higher strength steels. It should lead to further reduction of hydrogen level, safely down to 4ml/100g of deposited metal, in order to apply this wire without preheat for 650 Mpa strength steels of 50mm thickness[14].

5. Strategies for controlling the microstructure

The approaches made by the hydrogen control have successfully reduced the occurrence of HAZ HICC. However, the major improvement in the resistance to HAZ HICC of the recent generation of high strength steels has been accomplished by the modification of HAZ microstructure and by the decrease in HAZ hardness resulted from the decrease of alloying content. This course of action, at present, has not been pursued in the area of welding consumables, because of a lack of understanding concerning the relationship between weld metal microstructure and susceptibility to HICC. However, the logic and the success of steel development programs to reduce susceptibility to HAZ HICC suggest that it would be possible to achieve similar improvements through the control of weld metal microstructure. Nonetheless the effect of microstructure on weld metal hydrogen cracking has not yet been studied by many investigators.

Hart[15] reported that at the high level of hydrogen, weld metal hardness is an effective measure of susceptibility to cracking whereas at less than 5 ㎖/100g hydrogen, hardness was not as influential and microstructure became the dominant factor. However, he did not mention about the preferable microstructure for the better resistance. Studying the crack path in C-Mn welds many investigators claimed that grain boundary ferrite played an important role in the cracking mechanism and in particular, crack propagation[16,17]. Based on this, the present author have tried to minimize the grain boundary ferrite through the control of chemical composition in the design stage of welding consumables. With a 0.02%C-3.5%Ni-Mn-1.0%Mo system experimentally designed in the laboratory[18], it was found that the increase of Mn eventually changed the microstructure to one that had little grain boundary ferrite as shown in micrograhs shown in Fig. 3. More detailed study in TEM showed that this microstructure consists of acicular ferrite and martensite as shown in Fig 4. Mn also increased the tensile strength and reached around 840Mpa with Mn content of 1.4%. Preliminary study on cold cracking susceptibility on the experimental wires showed no pre-heating is required in the restraint submerged-arc multipass cracking tests, while for the commercial wire numerous transverse cracks were observed in the bead surface even at the preheating temperature of 125℃. The test results are summarized in Table 3.

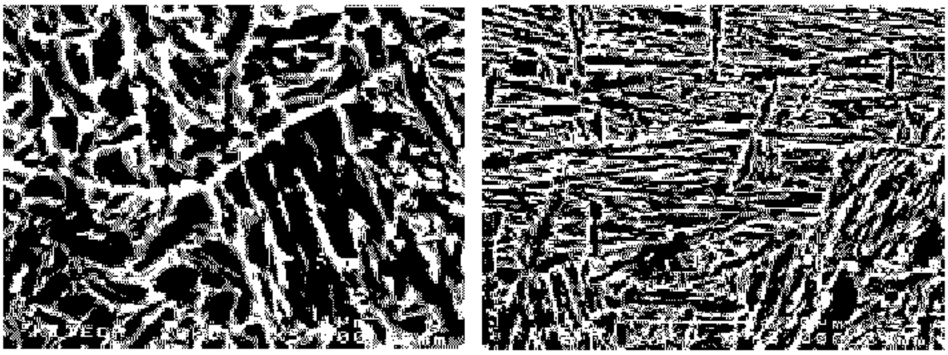

Fig. 3 SEM micrograph of low C-Ni-Mn-Mo weld metal.

Fig. 4 TEM micrograph of low C-Ni-Mn-Mo weld metal.

As a result of this study, it has been demonstrated that the preheating temperature required for the 800Mpa strength level could be lowered with the modification of microstructure through the change in chemical composition and thus the increase in tensile strength would not be necessarily related to a decrease in the resistance to cold cracking. It needs further study to understand the microstructural aspect in controlling the cold cracks in weld metal.

Table. 3 Result of restraint submerged-arc(SA) multipass cracking test[18].

I.D. of SA wire	Preheating Temperature				
	25℃	50℃	75℃	100℃	125℃
1.0 Mn			X	X	X
1.2 Mn			X	X	X
1.4 Mn	X	X	X	X	X
Commercial			O	O	O

X : No Crack, O : Crack

6. Evaluation of HICC Susceptibility of Multi-pass Weld Metal

The majority of cracking tests have been designed for a single pass weld and results applied to multipass welds on the grounds that in multipass welding it is the root pass that is critical. It is argued that if the root pass can be deposited without cracking then subsequent tempering of the HAZ coupled with slower cooling rates effectively prevents further cracking. There are, however, occasions in practice when cracking occurs in the upper part of the completed multipass SA welds. The most commonly observed case is transverse cracks in the weld metal, particularly in heavy section welds. Studies shows that a contributing factor in weld metal cracking is hydrogen build-up in multipass welding[19].

G-BOP test has been adopted for single pass weld[15] but there has been no widely adopted test for multipass welds. Graville showed several test methods used in the laboratory simulation tests[20]. Fig. 5 shows the geometry of test specimens the present author have used[18]. Since the weld metal cracking test needs thick plate welding it costs too much time and materials. Therefore, there is the need to make weld metal cracking test more simple, and it will assist in the development of improved consumables and the prediction of suitable welding procedures.

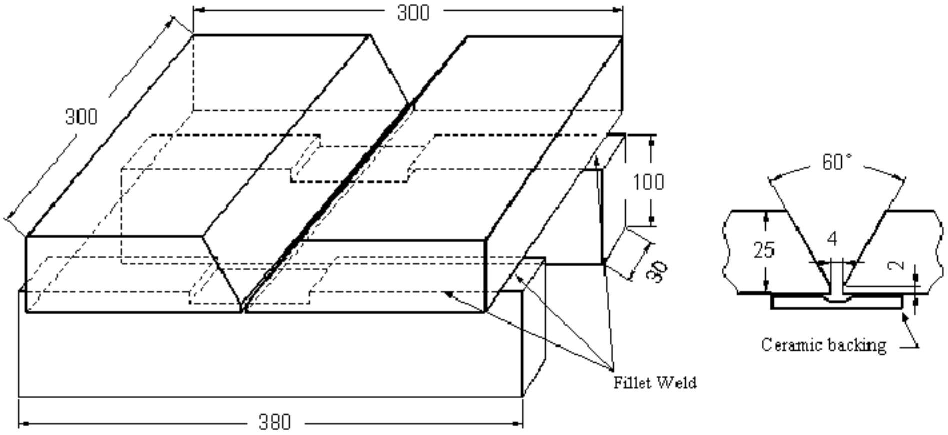

Fig. 5 Specimen geometry for evaluating the cold crack susceptibility of multipass weld metal.

7. Summary

It is of increased interest to improve current matching welding consumables for providing weld metal with equivalent HICC resistance to that of newly developed structural steels with strength level of 650 and over. This aim could be accomplished either by lowering hydrogen content or by improving a microstructure more resistant to hydrogen induced cracking. Traditionally, hydrogen control has been pursued mainly for suppressing the HICC in HAZ but it also has contributed to HICC in weld metal. Facing the limitations in reducing the hydrogen content, it is now important to consider the microstructural control approach in order to improve the HICC resistance of weld metal. It has been shown that changes in alloy design, and hence composition and microstructure, was quite effective in producing high strength weld metal with improved resistance to cold cracking as the weld metal of tensile strength over 800Mpa could be deposited with multipass welding even at room temperature. Besides the economic test methods for evaluating susceptibility of multipass weld metal is essential to promote the development of welding consumables.

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