RESEARCH ON COLD CRACK SENSITIVITY OF HIGH-STRENGTH WEAR-RESISTANT STEEL NM360 AFTER WELDING

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Abstract:

Due to the high amount of carbon and diffusible hydrogen, high-strength wear-resistant steel NM360, which is widely used on excavating machinery, always tends to develop cold crack after welding. Heat affected zone (HAZ) is the weakest part in a welding joint and is the most probable location for the generation of welding cold crack. In this paper, the effects of preheating temperature and heat input on welding cold crack sensitivity of NM360 steel have been studied by using implant tests. It is found that the preheating temperature and interlayer temperature during CO_2 *arc welding of NM360 steel should be 100 °C or 125 °C to prevent the occurrence of welding cold crack. The critical rupture stress and rupture time under high stress can be improved significantly with a high enough preheating temperature. However, heat input increase has little effect on critical rupture stress. Fracture analysis after performing implant test s indicates that the fracture in HAZ is typical hydrogen-induced cracking under high stress (*$\geq \sigma_{cr}$*). In addition, NM360 steel in HAZ has an intercrystalline quasi-cleavage fracture mode. The area ratio of brittle fracture is increased by increasing test stress.*

1 Introduction

High-strength wear-resistant steel NM360 whose metallurgy mechanism is used to increase the content of carbon and other alloying elements has been widely used in the field of excavating machinery, especially on the part of excavator bucket [1]. However, as a result of high carbon amount of NM360 steel and bearing large force during the work, the cold crack may most likely be generated in heat affected zone (HAZ) in this kind of parts after the welding process. Generally, the generation of welding cold crack has a close relationship with diffusible hydrogen content, constraint stress of the structure as well as the existence of quenched structure. Through the analysis of a simulated HAZ continuous cooling transformation diagram (SH-CCT) of NM360 steel, the structure in HAZ is characterized by

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100% martensite when the cooling time from temperature 800 °C to 500 °C ($t_{8/5}$) is lower than 19.7 s. However, with current standard CO_2 arc welding and manual arc welding procedure, $t_{8/5}$ is around 10-20 s and 5-13 s, respectively. Then it can be predicted that the hardened structure will appear in all probabilities with those two welding methods. Therefore, the welding cold crack is a serious problem for the application of NM360 steel [2, 3].

The cold crack sensitivity in HAZ of NM360 steel should be studied quantificationally due to its significantly potential damage problem. In this paper, to prevent cold cracking after welding, the effects of preheating temperature and heat input on welding and cold crack sensitivity have been studied by using implant tests. After that, the appropriate preheating temperature and heat input for NM360 steel during CO_2 arc welding can be determined. In addition, the cause of welding cold crack will be revealed from the aspects of the microstructure, stress and diffusible hydrogen.

2 Materials and experimental method

The experimental material in this study is high-strength wear-resistant steel NM360 with the chemical compositions and mechanical properties as shown in Table 1 and Table 2, respectively. NM360 steel has quite a high amount of carbon content, which is around 0.54 % and its exponent of cold crack sensitivity is 0.147.

Table 1. Chemical composition of NM360 steel (wt.%).

C	Si	Mn	P	S	Cu	Al
0.139	0.34	1.3	0.026	0.0078	0.039	0.031
Cr	Ni	Mo	Ti	B	N	Fe
0.51	0.26	0.25	0.018	0.0016	0.0053	Bal.

Table 2. Mechanical properties of NM360 steel at room temperature.

σ_b [MPa]	σ_s [MPa]	δ_5 [%]	*HB*	A_{KV} [J]
≥1200	≥1000	10	360	42 (20 °C)

The welding material used in the experiment is GFM-70 with 1.6 mm diameter, which is produced by Harbin Welding Institute. GFM-70 is generally used in CO_2 arc welding and chemical compositions and mechanical properties of weld metal are shown in Table 3 and Table 4, respectively. In addition, the content of diffusible hydrogen in weld metal is 9.4 ml/100 g with welding material GFM-70.

Table 3. Chemical composition of weld metal with GFM-70 (wt.%).

C	Si	Mn	Ni
0.05	0.60	1.75	0.85
Mo	S	P	Fe
0.42	0.011	0.02	Bal.

Table 4. Mechanical properties of weld metal with GFM-70.

σ_b [MPa]	σ_s [MPa]	δ_5 [%]	A_{KV} [J]
760	680	22	84 (-20 °C)

Implant testing is employed in this experiment to evaluate the cold crack sensitivity of NM360. Implant testing is a kind of quantitative measurement of welding cold crack sensitivity in HAZ, which is recommended by International Institute of Welding (IIW) [4]. Due to the accuracy and efficient steel consumption during testing, the implant test is widely utilized all over the world. Via implant testing, the critical rupture stress of the steel can be determined and then the ability of materials to withstand the stress without initiating welding cold crack is obtained [5].

The implant specimen was prepared according to the standard procedure of GB9446-88 [6]. At first, NM360 specimen was machined from the middle location of 30 mm thickness plate along with the rolling direction. The schematic illustration of specimen can be found in Fig. 1. At the left side of the specimen, the spiral gap was chosen to produce stress concentration during the test. The back plate is Q345 steel with the dimension 300 × 200 × 20 mm. The equipment HCL-3CM was employed for the implant test.

Before implant testing, the specimens were welded together with a back plate with different weld parameters. During CO_2 arc welding, the depth of fusion needs to be controlled precisely so that the spiral gap can be located in HAZ. During welding and implant testing, the temperature in HAZ was recorded with thermocouple probe on

HCL-3CM equipment. Hence, the important parameters such as $t_{8/5}$ and t_{100} (the cooling time from peak temperature to 100 °C) in HAZ can be obtained. After welding, tensile stress will be performed on the specimen when the temperature in HAZ is equal to the preheat temperature plus 100 °C. The critical rupture stress σ_{cr} during testing is the maximum value, which means that the specimen can remain unbroken at least 21 hours under that value [7].

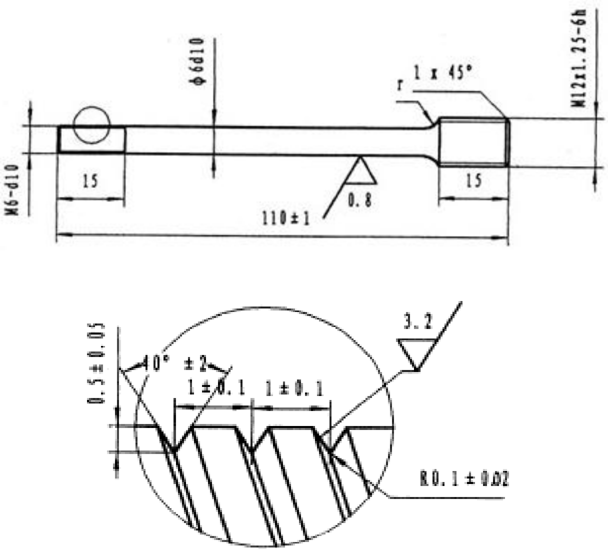

Figure 1. Schematic illustration of the implant specimen.

After implant testing, the specimens were cut into longitudinal sections so as to observe the microstructure in HAZ with OLYMPUS-PMG3 optical microscope. Before being observed, the polished specimens were etched by nital with 2 % nitric acid. Additionally, microhardness in HAZ was measured using a microhardness tester 401MVD in this study.

3 Results and discussion

3.1 The effect of preheating temperature on welding cold crack sensitivity

In order to evaluate the effect of preheating temperature on welding cold crack sensitivity, the specimens and a back plate were preheated to different temperatures: 15 °C, 50 °C, 75 °C, 100 °C and 125 °C before being welded. The welding method used in this experiment was CO_2 arc welding and the parameters in experiment are: current 340-360 A, voltage 30-32 V, weld speed 5.5 mm/s and heat input 19.7 kJ/cm.

Fig. 2 shows implant test results for more than 5 specimens which have gone through different preheating temperatures and the same CO_2 arc welding parameters. Besides, $t_{8/5}$ for more than 5 specimens is 11.8, 13.4, 14.7, 16.2 and 17.9 seconds, respectively. While t_{100} is 194, 453, 775, 1121 and 1594 seconds, respectively. The results illustrate that the preheating temperature has an immense effect on critical rupture stress. Without preheating (15 °C), the critical rupture stress of the specimen is only 480 MPa, which is far below the theoretically determined value of the base material (1000 MPa). By increasing the preheating temperature, the ability of material to withstand critical rupture stress is also significantly increased The critical point of rupture stress is almost equal to that of the base material when the preheating temperature reaches 100 °C. However, when the preheating temperature exceeds 100 °C, it can be observed that this decreases the tendency for critical rupture stress. Besides, the hardness in HAZ decreases with an increase in preheating temperature. All of the measured hardness is higher than that of the base material.

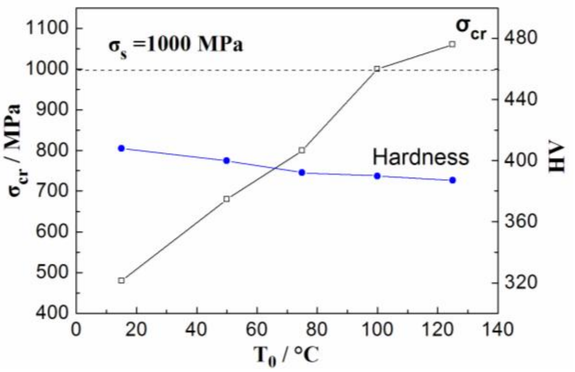

Figure 2. Implant test results for specimens with different preheating temperature.

Apart from preheating temperature increasing, one of the reasons for σ_{cr} increase is self tempering in HAZ with the extension of $t_{8/5}$. Though the structure in coarse grained region of HAZ is still characterized by 100 % martensitic structure, the preheating process can promote self tempering of martensite effectively. As a consequence, when more martensite undergoes

self tempering, cold crack sensitivity in this area will be decreased significantly. On the other hand, by increasing t_{100}, which represents the escape time of diffusible hydrogen in HAZ, the initiation of cold crack can be effectively avoided.
Moreover, the relationship between σ_{cr} and rupture time implies the effect of preheating temperature and stress condition on the cold crack sensitivity of NM360. As shown in Fig. 3, the rupture time reaches the duration of 22 hours only by reducing the test stress of 480 MPa when the specimen is not preheated (15 °C). By increasing the testing stress, the rupture time is reduced rapidly. For example, the rupture period lasts only 1.5 hours as long as/provided the test stress reaches 800 MPa. However, for the specimen that were subjected to the preheating temperature of 125 °C and then being welded with the same welding parameters, the rupture period lasted 21 hours when the test stress reached 1060 MPa. It is thus clear that the critical point of withstanding rupture stress and rupture time under high stress can be improved significantly with a high enough preheattemperature.

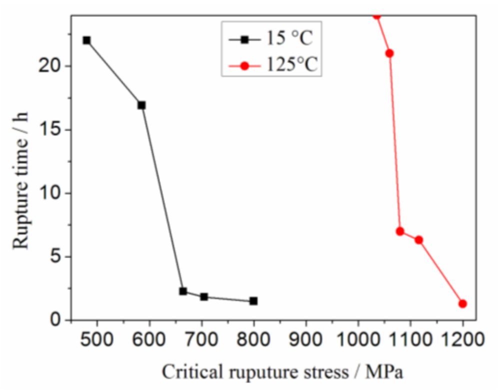

Figure 3. The effects of preheating temperature on critical rupture stress and rupture time.

To avoid welding cold cracking, the criterion $\sigma_{cr}>\sigma_s$ is employed [8]. Based on the experimental research and above analysis, the preheating temperatures of 100 °C and 125 °C are suitable for NM360 steel. Therefore, by CO_2 arc welding of NM360, the preheating temperature and the interlayer temperature during the process should be 100 °C or 125 °C so that the welding cold crack can be prevented effectively.

3.2 The effect of heat input on welding cold crack sensitivity

With the same preheating temperature of 100 °C and different heat inputs through changing the welding speed as shown in Table 5, the implant tests were carried out and the corresponding results were shown in Table 6. The welding method used in this experiment is CO_2 arc welding and the welding stick is GFM-70 with 1.6 mm diameter.
Table 6 shows that the critical rupture stresses of the specimens with heat inputs of 15.6 and 19.7 kJ/cm are both 1000 MPa, which reach the yield strength of NM360. As the heat input is 26.8 kJ/cm, the critical rupture stress reaches the maximum value of 1280 MPa, which exceeds the tensile strength of NM360. However, the critical rupture stress is decreased to 1180 MPa as soon as the heat input is increased to 29.8 kJ/cm. That suggests that the rupture stress will be decreased when the heat input exceeds 26.8 kJ/cm. Moreover, the hardness in overheated zone is decreased by increasing the heat input. When the heat input is 26.8 and 29.8 kJ/cm, the hardness in overheated zone is lower than in that of the base material.

Table 5. Welding parameters for the specimens with different heat input.

Heat input [kJ/cm]	Current [A]	Voltage [V]	Welding speed [mm/s]
15.6	340~360	30~32	7.0
19.7	340~360	30~32	5.5
26.8	340~360	30~32	4.0
29.8	340~360	30~32	3.6

Table 6. Implant test results for specimens with different heat input.

Heat input [kJ/cm]	$t_{8/5}$ [s]	t_{100} [s]	HV in overheated zone	σ_{cr} [MPa]
15.6	10.9	892	400	1000
19.7	16.3	1121	385	1000
26.8	27.3	1539	354	1280
29.8	32.7	1569	340	1180

The temperature gradient and cooling rate during welding can provide conditions for the crack initiation and evolution. When the heat inputs are 15.6 kJ/cm and 19.7 kJ/cm, the values of $t_{8/5}$ are quite short, which is 10.9 s and 16.3 s, respectively. The values of t_{100} are also quite short. That means that a short enough escape time for diffusible hydrogen will be responsible for higher cold crack sensitivity of NM360 steel. The coarse grained region in HAZ is characterized by martensite with high tendency of hardenability after welding, as can be seen in Fig. 4 a) and Fig. 4 b). By increasing the heat input to 26.8 kJ/cm, $t_{8/5}$ is increased significantly (27.3 s) and hardenability in HAZ is decreased accordingly. Meanwhile, a longer diffusible hydrogen escape time t_{100} (1539 s) will induce the reduction of cold crack sensitivity. However, if the heat input is too high, the cold crack sensitivity will be changed for worse attributed to the cooling speed decrease and grain growth coarsening in fusion zone, as shown in Fig. 4 d). That is the reason for critical rupture stress decrease under a higher heat input process.

It is thus clear that an increase in critical rupture stress sections mainly depends upon the HAZ phase change since an increase in the heat input is attributed to longer cooling time of $t_{8/5}$. However, an exorbitant heat input will result in grain growth coarsening and then in decreasing the critical rupture stress.

3.3 Fracture appearance analysis of implant specimen

The fracture appearances of implant specimens with preheating temperature of 125 °C and CO_2 arc welding are illustrated in Fig. 5, which indicates that the crack is a typical hydrogen-induced delayed crack [9, 10]. Two different regions are included in Fig. 5 a) and Fig. 5 b). The upper side of the fracture surface has typical brittle fracture appearance, which is characterized by small deformation, plane surface and facets with metallic luster. The lower side of fracture surface has ductile fracture characteristics, which undergoes big deformation and has uneven surface. The area ratio of those two regions has close relationship with test stress. The area of brittle fracture increases with test stress. As shown in Fig. 5, the area ratio of brittle fracture is

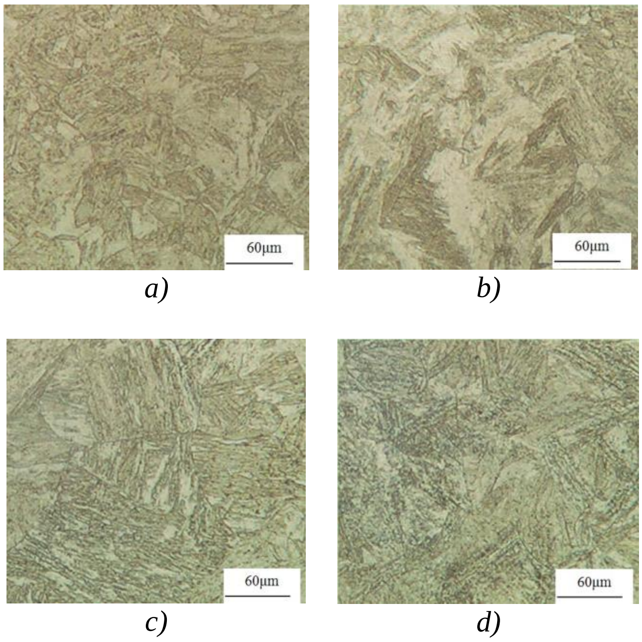

Figure 4. Microstructure in coarse grained region in HAZ of the specimen with different heat input: a) 15.6 kJ/cm, b) 19.7 kJ/cm, c) 26.8 kJ/cm and d) 29.8 kJ/cm.

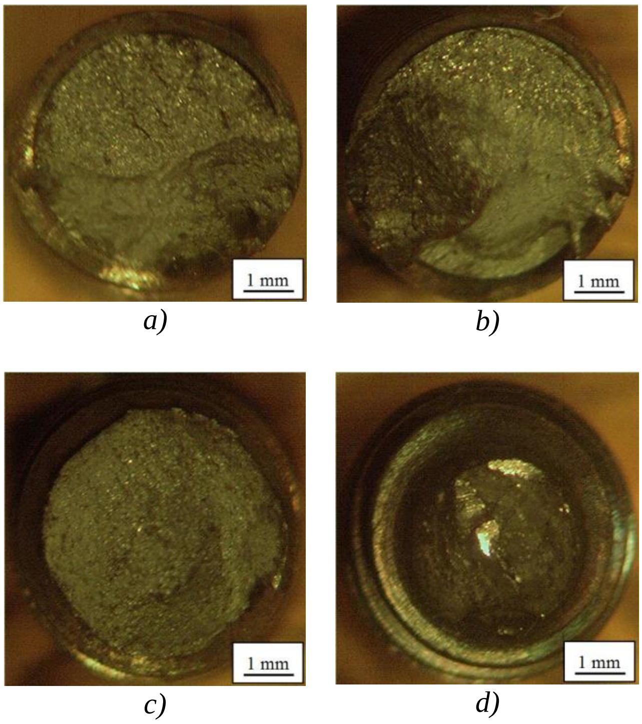

Figure 5. Macrofracture of the implant specimen with test stress: a) 1120MPa, b) 1080 MPa, c) 1060 MPa, d) 1040 MPa.

around 50 % when the test stress is 1120 MPa. With the test stress of 1080 MPa, the area ratio of brittle fracture is about 30 %. When the test stress is reduced to 1060 MPa, there is no brittle fracture area any more, which can be seen in Fig. 5 c). With the test stress of 1040 MPa, the implant specimen can withstand that stress for 24 hours.

After 24 hours, by increasing test stress until the sample has been broken, 100 % ductile fracture can be observed on the fracture surface, as shown in Fig. 5 d).

Through the comparison of area ratio between brittle fracture and ductile fracture in Fig. 5, it can be found that this ratio is decreased by decreasing the test stress. During the crack initiation, the hydrogen content in HAZ is quite large enough, which means that the stress intensity at crack tip is increased. Meanwhile, the diffusion hydrogen will be enriched at grain boundary and then material will be made brittle in this area. During the crack growth, the average hydrogen content decreases and then the stress intensity at crack tip will be also decreased. As a result, the area of ductile fracture is increased.

Research indicates that hydrogen-induced brittle crack is easy to occur in HAZ when the structure in that area is mainly martensite characterized by high hardenability tendency with the addition of grain coarsening in an overheated zone. Hydrogen-induced brittleness weakens the bonding force of grain boundaries. As a consequence, the intercrystalline fracture will take place. The fracture analysis suggests that fracture of NM360 steel in HAZ has hydrogen-induced brittle crack characteristics under high tensile stress (more than σ_{cr}). NM360 steel has intercrystalline quasi-cleavage fracture mode.

4 Conclusion

In this paper, the effects of preheating temperature and heat input on welding cold crack sensitivity of NM360 steel have been studied by using implant testing. The main achieved results can be summarized as follows:

1) The high enough preheating temperature can prolong the escape time for diffusible hydrogen and then decrease the hydrogen content in weldment. With lower hydrogen content, the welding cold crack can be avoided effectively. The preheating temperature and interlayer temperature during CO_2 arc welding of NM360 steel should be 100 °C or 125 °C to prevent initiation of welding cold crack. The critical area subjected to rupture stress and rupture time under high stress can be improved significantly with higher preheating temperature.
2) The increase of heat input can prolong cooling time during elevated temperature ($t_{8/5}$), while it has little effect on the cooling time from peak temperatures to 100 °C (t_{100}). As a consequence, the change of heat input cannot improve areas under the critical rupture stress.
3) Fracture analysis indicates that the fracture in HAZ of NM360 is a typical hydrogen-induced cracking fracture under high test stress (more than σ_{cr}). NM360 steel in HAZ has intercrystalline quasi-cleavage fracture mode. In addition, the area ratio of brittle fracture is increased by increasing the test stress.

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