EFFECT OF HIGH-STRENGTH LOW-ALLOY (HSLA) STEELS MICROSTRUCTURE ON SUSCEPTIBILITY TO COLD CRACKING

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Microstructure of steel before welding has influence on the steel's susceptibility to cold cracking because it influences hardenability. Two high-strength low-alloy (HSLA) steels both in various heat treatment conditions were subjected to simulated welding thermal cycles. It was revealed that maximum heat affected zone (HAZ) hardness is influenced by microstructure present before thermal cycle was applied. Higher hardness was observed in the case of quenched and tempered microstructure as compared to the microstructure of as rolled and normalised steels.

INTRODUCTION

High-strength low-alloy (HSLA) steels feature high tensile properties, good toughness and weldability. Nowadays, HSLA steels are produced as: normalised, thermo-mechanical controlled processed (TMCP), quenched and tempered, and precipitation hardened with copper addition. High-strength steel plates and pipes are mainly used for advanced welded structures: offshore constructions, oil and gas pipelines, navy ships, and pressure vessels. Severe service conditions for offshore constructions and pipelines require utilising steels with good toughness at extremely low temperatures (- 60 °C), good weldability, and resistance to hydrogen inducted cracking (HIC) and sulphide stress corrosion cracking (SSCC). Cold cracking is a major problem in weldability of HSLA steels. These steels are likely to develop hard martensitic and bainitic structures due to welding thermal cycles, thus heat affected zone (HAZ) toughness is low and cold cracking may occur. Especially, quenched and tempered HSLA steels are susceptible to cold

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cracking due to relatively high contents of carbon and alloying elements (1). Generally, susceptibility to cold cracking depends on: microstructure of HAZ, hydrogen contents in weld, stress imposed to weld, Bailey et al (2), Yurioka and Suzuki (10).

REVIEW OF LITERATURE

Microstructure of HAZ is affected by chemical composition of steel described by a carbon equivalent (CE), and cooling rate described by a cooling time between 800 and 500 °C ($t_{8/5}$). Regarding microstructure developed in HAZ we should additionally take into account:

- microstructure of steel before welding. Steels with the same chemical composition (i.e. the same CE) can be supplied in various mechanical and heat treatment conditions, i. e. as rolled, normalised, controlled rolled, thermo-mechanical controlled processed (TMCP includes controlled rolling with accelerated cooling, or with direct quenching and tempering), and reheat quenched and tempered, Yurioka (11),
- cleanliness of steel which affects its hardenability. Modern high-strength steels seem to be more susceptible to cold cracking due to higher hardenability. Hardenability increases when a level of inclusions decreases in steel, Bourges et al (3), Hart (6), Okumura et al (7).

Microstructure of steel before welding affects hardenability since welding thermal cycle is different from heat treatment one. In the case of welding thermal cycle maximum temperature is as high as 1350 °C and austenitising time is very short. Thus, austenite during welding thermal cycle may not be homogenous. Homogeneity of an austenite during welding depends on microstructure of steel before austenitising, i.e. kinds of phases (ferrite, pearlite, bainite, martensite), and size and distribution of precipitates (carbides, nitrides) and non-metallic inclusions. Maximum hardness of HAZ could be an arbitrary measure of susceptibility to cold cracking of HSLA steels. Thus some authors proposed various methods for evaluating maximum hardness in steel welds, Cottrell (4), Düren (5), Suzuki (8), Yurioka et al (9). Equations in these methods depend on carbon equivalent and cooling time, but do not include microstructural and cleanliness factors.

EXPERIMENTAL PROCEDURE

In order to evaluate an influence of microstructure on susceptibility to cold cracking steels - in various heat treatment conditions - were subjected to simulated welding thermal cycles. Two grades of HSLA steels with various carbon equivalents were used, i.e. C-Mn steel with V microaddition, and Mn-Cr-Ni-Mo-Cu-B steel. Chemical composition of tested steel plates, 12 mm in thickness, is presented in Table 1. Mechanical properties of tested steels in industry quenched and tempered condition are shown in Table 2. Both steel grades were: as rolled, normalised, and quenched and tempered. Thus, various microstructures occurred within the same steel. Heat treatment conditions are presented in Table 3. Simulated welding thermal cycles were applied to samples 10x10x150 mm with the use of special Gleeble-type tester. Seven cooling times ($t_{8/5}$) ranging from 3 to 200 seconds were applied, i.e. $t_{8/5}$ = 3, 6, 12, 24, 60, 120 and 200 seconds.

TABLE 1 - Chemical composition of tested steels.

Steel grade	Chemical composition, wt. % C	Mn	Si	S	P	Cr	Ni	Cu	Mo	V	B
18G2AV	0.19	1.48	0.46	0.019	0.021	-	-	-	-	0.09	-
14HNMBCu	0.17	0.66	0.36	0.017	0.014	0.55	0.70	0.29	0.45	-	0.003

TABLE 2 - Mechanical properties (transverse) of tested steels in quenched and tempered condition.

Steel grade	Tensile strength MPa	Yield strength MPa	Elongation %	Charpy-V notch test Temperature	Energy
18G2AV	718	644	18.0	- 40 °C	28 J
14HNMBCu	773	701	15,7	-20 °C	30 J

TABLE 3 - Heat treatment conditions of samples for simulated welding thermal cycles.

Steel grade	Heat treatment	Heat treatment parameters Temperature [°C]	Time [hours]	Coolant
18G2AV	As rolled	1100	3	Air
	Normalised	920	1	Air
	Quenching &	920	0.5	Water
	Tempering	630	1.5	Air
14HNMBCu	As rolled	1100	3	Air
	Normalised	940	1	Air
	Quenching &	940	0.5	Water
	Tempering	650	1.5	Air

Peak temperature of each thermal cycle was 1250 °C. Obtained simulated microstructures present coarsed grains region of HAZ after welding with various heat inputs.

Simulated HAZs and parent metals were subjected to metallographic examination with the use of optical microscope and transmission electron microscope (TEM). Then Vickers hardness test with 10 kg load was performed on cross sections of the samples.

TABLE 4 - Maximum HAZ hardness after simulated welding thermal cycles.

Steel grade	Heat treatment	Maximum HAZ hardness HV10						
Cooling	**time $t_{8/5}$ [s] →**	**3**	**6**	**12**	**24**	**60**	**120**	**200**
18G2AV	As rolled	423	396	388	386	297	258	257
	Normalised	416	405	394	345	280	268	259
	Q&T	455	420	400	347	277	262	251
14HNMBCu	As rolled	451	448	440	442	353	330	306
	Normalised	449	441	438	457	453	328	303
	Q&T	457	456	453	462	460	442	307

Q&T - quenched and tempered

RESULTS AND DISCUSSION

Obtained results of hardness test show that maximum hardness of simulated HAZ is affected by microstructure of steel existing before thermal cycle (c.f. Table 4). Especially, for a fast cooling rate (short cooling time) the difference in maximum hardness is significant (Fig. 1-2). Hardenability and maximum hardness depend on carbon distribution in the phases of original microstructure. The highest hardness was observed for quenched and tempered original microstructure before welding. Lower hardness was found in steels after hot rolling and normalising (with ferrite and pearlite in the original microstructure).

Metallographic examinations revealed differences in size and distribution of carbides and nitrides in steels matrix before welding. Quenched and tempered microstructure consists of tempered martensite and bainite. In this structure carbides and nitrides are very fine so they may easily dissolve during welding thermal cycle. Thus, hardenability of quenched and tempered steels is higher than of the normalised steels having the same chemical composition. Maximum hardness may be used as an arbitrary measure of susceptibility to cold cracking.

With the increase in HAZ hardness a structure becomes more brittle (martensite contents increases) and susceptibility to cold cracking grows.

CONCLUSIONS

- susceptibility to cold cracking is affected by microstructure of steel before welding. Steels in quenched and tempered condition seem to be more susceptible to cold cracking due to their higher hardenability,
- other metallurgical factors influencing steel weldability, besides carbon equivalent, ought to be taken into consideration. These factors are: kinds of phases, size and distribution of carbides, nitrides, and non-metallic inclusions.

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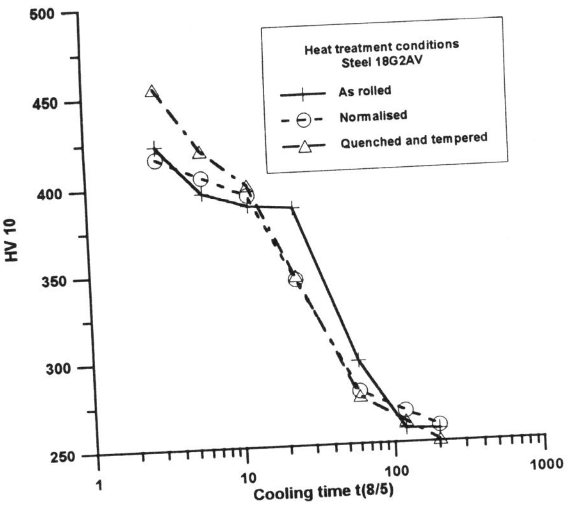

Figure 1. Maximum HAZ hardness versus cooling time $t_{8/5}$ for 18G2AV steel under various heat treatment conditions

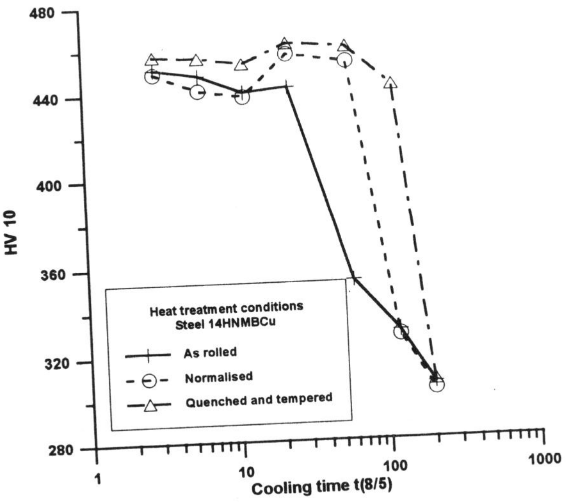

Figure 2. Maximum HAZ hardness versus cooling time $t_{8/5}$ for 14HNMBCu steel under various heat treatment conditions