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THE IMPACT OF HYDROGEN ON THE CRACKING RESISTANCE IN WELD JOINTS OF SHIPBUILDING STEELS

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ABSTRACT

The article provides information on the results of the study of hydrogen impact on the nucleation and growth of cold cracks in weld joints of shipbuilding steels. It is shown that as the hydrogen content in the weld seam increases, the crack propagation work decreases. It was found that an increase in the diffusion hydrogen content in weld metal sharply reduces its resistance to brittle fracture. The purpose of this work was an experimental study of the influence of hydrogen on the nucleation and growth of cracks in welded joints of steels used for the construction and operation of ship structures in severe natural climatic and engineering conditions. The object of the study were low-alloyed steel grades 10HSND and 15HSND, cut off from dismantled frames of sea tankers designed to transport oil. It was found that an increase in the diffusion hydrogen content in weld metal sharply reduces its resistance to brittle fracture. It has been shown that as the hydrogen content in the weld seam increases, crack propagation work Acp reduces. A decrease in the air temperature during welding to -30…-40°C and an increase in the dissolved hydrogen concentration in the weld seam to 5-8 cm3/100 g results in the increase of the ductile–brittle transition temperature by approximately 40-50°C.

Keywords: hydrogen, heat-affected zone, tankers, low temperatures, thermal impact zone, cracks, weld joints.

INTRODUCTION

It is known that the welding of low alloy shipbuilding steels at low ambient temperature (-50°C) reduces the resistance of welded joints to delayed fracture and cold cracking, which is caused by the inhibition of the processes of hydrogen diffusion from the weld seam metal into the environment and the heat-affected zone and its content increase in the weld metal [7, 10, 11, 13]. Many researchers believe that the main factor influencing on the process of incubation nucleation and delayed growth and spread of cold cracks at the welding of shipbuilding steels in the circumstances of low ambient temperatures is hydrogen [9, 15]. Therefore, this work is aimed at an experimental study of the hydrogen impact on the crack nucleation and growth in welded joints of steels used in the construction and operation of ship structures in harsh climatic and engineering conditions.

MATERIALS AND METHODS

The object of the study were low-alloyed steel grades 10HSND and 15HSND, cut off from dismantled frames of sea tankers designed to transport oil.

Sampling and experimental testing of samples were conducted in accordance with the procedures provided in [1, 2, 8, 12, 14, 18, 19, 20].

RESULTS

The obtained results of the study showed that as the hydrogen content in the weld metal increases, its plastic distortion capability decreases. For example, Figure-1 shows that as the hydrogen content changes from 1.0 to 7.3 cm^3/100 g, the initial sections of the static bending chart coincide and the fracture occurs at an earlier stage of deformation.

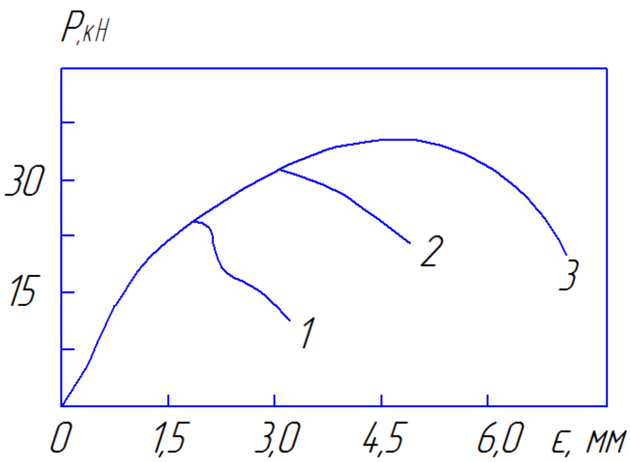

Figure-1. The change in the static bending chart view for the 10HSND type weld metal, depending on the diffusion hydrogen content:
steel 10HSND, electrodes UONI-13/55: 1 - 8.0 cm^3/100 g; 2 - 4.0 cm^3/100 g; 3 - 1.0 cm^3/100 g.

P, кН	P, KN
E, мм	E, mm

As the diffusion hydrogen content increases in weld metal, its resistance to brittle fracture sharply reduces. As Figure 2 shows, at the hydrogen content of 8.1 cm^3/100 g for weld metal on steel 10HSND at $W_{cooling}$ = 40°C/sec, crack nucleation work A_{cn} = 1.5 J, and if the hydrogen content is reduced to 1.5 cm^3/100 g, the value of A_{cn} increased to 17.6 J, i.e. by more than 11 times. An increase in the cooling rate to 55°C/sec results in further reduction of A_{cn}, and at the hydrogen content of more than 5.0 cm^3/100 g, it is virtually equal to zero. As the content of hydrogen dissolved in metal increases, the maximum breaking load also decreases, however it slightly grows if the cooling rate accelerates.

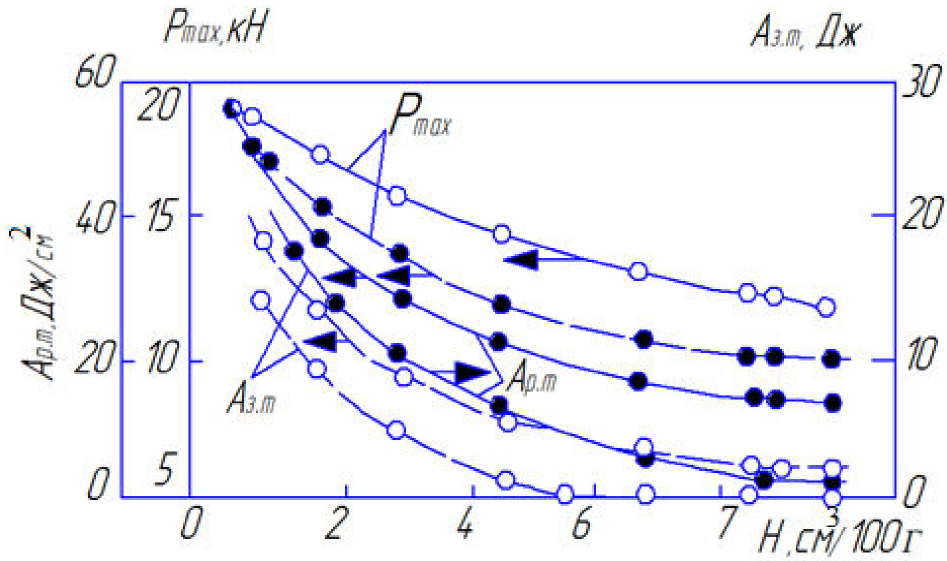

Figure-2. The influence of the diffusion hydrogen on crack propagation and the maximum breaking load for the 15HSND type weld metal: steel 15HSND: ------ - = 50°C/sec, - - - - = 50°C/sec.

Pmax, кН	Pmax, KN
Азт, Дж	Acn, J
А рт, Дж/см^2	А ср, J/cm^2
Pmax	Pmax
Н, см^3/100г	H, cm^3/100 g
Азт	Acn
Арт	Acp

As the hydrogen content in the weld seam increases, the crack propagation work also decreases. For example, when the hydrogen concentration is 1.0 cm^3/100 g for a weld joint of steel 10HSND at $W_{cooling}$ = 40°C/sec, the value of A_{cp} = 48.5 J/cm^2, while as the hydrogen concentration increases to 8.0 cm^3/100 g, it reduces to 18.5 J/cm^2, i.e. by approximately 2.7 times. We should also note the change of the fracture surface of the tested specimens. For example, when [H] < 10 cm^3/100 g, the fibrous surface makes 90–95% of the fracture pattern (at T = 20°C), and at [H] = 8.0 cm^3/100 g, it makes 30–40%, which indicates the higher ductile–brittle transition temperature. As the cooling rate of the welded joint reaches the value of 55°C/sec, work A_{cp} was found impossible to determine, as a complete breakdown was observed on the static bending diagram.

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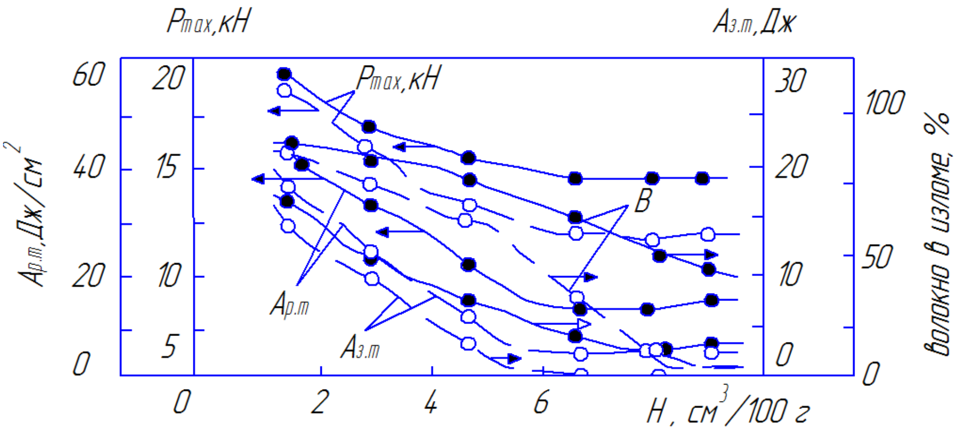

Figure-3. Crack nucleation and propagation work:
P_{max} is the maximum breaking load, steel 10HSND:
------- - T = +30°C ; - - - T = -30°C.

Pmax, кН	Pmax, KN
Азт, Дж	Acn, J
А рт, Дж/см^2	A cp, J/cm^2
Pmax	Pmax
Н, см^3/100г	H, cm^3/100 g
Азт	Acn
Арт	Acp
Волокна в изломе, %	Fibers in fracture,%

As seen in Figure-3, at a constant temperature, an increase in the hydrogen content reduces the fiber component (B) in the fracture. When welding was performed at room temperature and the hydrogen content was 1.5 cm^3/100 g, value B = 90–100% and the fracture surface was in a viscous state. But when the welding was carried out at T = -40°C and the hydrogen content was 8.0 cm^3/100 g, parameter B = 10–20% and the surface was in a brittle state. Lowering the temperature during welding from -30 to -40°C leads to lower fiber content in the fracture to 20–30%, and the weld metal with the hydrogen content of 5–8 cm^3/100 g becomes brittle. It is an indication of the fact that in case of the ambient temperature decrease and the concentration of dissolved hydrogen increase, the ductile-brittle transition temperature (T_{cr})becomes higher by about 40–50°C.

The obtained results demonstrate that the hydrogenous embrittlement for brittle state metal welded at low temperatures manifests itself at a greater extent than the for metal in the viscous state.

DISCUSSIONS

Currently, there are numerous hypotheses of hydrogenous embrittlement of steel [16, 17], but they cannot sufficiently substantiate all available factual data on the issue. Noteworthy is the hypothesis of the mechanism of steel embrittlement under the influence of the diffusion hydrogen. Let us consider these hypotheses in terms of the existence of various forms of hydrogen in weld metal, in order to explain the mechanism of crack nucleation and growth in weld joints.

It is known [2] that the hydrogen diffusion coefficient for weld metal and heat-affected zone is equal to 10^{-5}–10^{-7} cm^2/sec. For comparison, the coefficients of carbon and nitrogen diffusion in iron at 20°C are 2×10^{-17} and 8.8×10^{-17} cm^2/sec, respectively. The large difference in the mobility of diffusion hydrogen (10-12 orders of magnitude) in steel, compared to other interstitial elements, can be explained by the fact that diffusion hydrogen in weld metal and a heat-affected zone is in the form of protons , as was found by I.K. Pohodnya and V.I. Shvachko [3]. This is indirectly supported by different content of diffusion hydrogen in the weld seam metal, depending on the current type and polarity. The high mobility of diffusion hydrogen also evidences the fact that it is not bound. Assuming that the diffusion hydrogen in the weld metal is in the form of protons, we can explain the processes of its diffusion from the weld seam into the heat-affected zone both during and after welding, the interaction with dislocations, and constancy of metal yield point σ_t at the increase of diffusion hydrogen. For example, dislocations in steel have become too large for hydrogen protons to be able to fix them and change the yield strength. Carbon and nitrogen interact with dislocations in iron [21 - 24]. These elements are capable of fixing, which increases σ_T. The authors of [4.5] explain the thermal aging and blue brittleness of metal by the interaction of dissolved carbon and nitrogen with iron dislocations.

The mechanism of weld metal embrittlement under the diffusion hydrogen influence consists in the proton interaction with outer electrons of the iron atom. As a result of this interaction, the binding forces between atoms in the iron lattice weaken, resulting in the effective surface energy reduction. The above-mentioned research results show that as the diffusion hydrogen content increases in a weld seam to 5-8 cm^3/100 g, the work of crack nucleation sharply reduces (by 10-12 times), and the work of crack propagation reduces by 3-4 times. In this case, the amount of the fibrous component in the fracture also decreases and the ductile–brittle transition temperature increases.

During welding, residual hydrogen can accumulate in various micropores of the weld seam metal and the heat-affected zone. During welding, because of its short duration, and in the first minutes after the welding, the pressure of molecular hydrogen in micropores is apparently high, and during this period, the role of residual (molecular) hydrogen in the embrittlement mechanism is insignificant. However, after the welding is completed, the pressure of molecular hydrogen in the micropores of the weld seam metal and heat-affected zone increases. The pressure value depends on the diffusion hydrogen concentration, temperature, time after the welding, etc. The pressure of mobilized hydrogen in micropores enhances the effect of the force factor and, thereby, contributes to cold cracking. This explains the fact that the hydrogen-influenced cold cracking in the weld metal and heat-affected zone takes place after the welding is completed.

There are other views on the mechanism of hydrogen embrittlement of steel and weld joints. However, the role of hydrogen in reducing brittle strength of weld seams and heat-affected zones is not doubted and is generally recognized.

CONCLUSIONS

Thus, the following conclusions have been made based on the obtained results:

a) It was found that an increase in the diffusion hydrogen content in weld metal sharply reduces its resistance to brittle fracture. When the content of hydrogen is 8.1 cm^3/100 g in the weld metal and the cooling rate $W_{cooling}$ = 4.0°C/sec, crack nucleation work A_{cn} = 1.5 J, and at 1.5 cm^3/100 g, A_{cn} increases to 17.6 J, i.e. by more than 11 times. If the hydrogen content is higher than 5.0 cm^3/100 g, and $W_{cooling}$ = 55°C/sec, the value of A_{cn} is virtually equal to zero.

b) It has been shown that as the hydrogen content in the weld seam increases, crack propagation work A_{cp} reduces. For example, when the hydrogen concentration is equal to 1.0 cm^3/100 g for a welded joint of steels 10HSND and 15HSND at $W_{cooling}$ = 4.0°C/100 g, the value of A_{cp} = 48.5 J/cm^2, while if its content is increased to 8.0 cm^3/100 g, work A_{cp} reduces to 5.18 J/cm^2, i.e. by approximately 2.7 times.

c) A decrease in the air temperature during welding to -30…-40°C and an increase in the dissolved hydrogen concentration in the weld seam to 5–8 cm^3/100 g results in the increase of the ductile–brittle transition temperature by approximately 40–50°C.

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