Article

The Role of Welding Parameters in Hydrogen Embrittlement Mitigation: A Case Study in Steel

RESEARCH REVIEW International Journal of Multidisciplinary
9(3) 203-212, 2024
©The Author(s) 2024
DOI: 10.31305/rrijm.2024.v09.n03.021
https://rrjournals.com/

Date of Publication: 15 Mar, 2024

[1]Vitalijus Rudzinskas and *[2]Oleksandr Kapustynskyi

[1,2]Vilnius Gediminas Technical University, Plytines g. 25, LT-10105 Vilnius, Lithuania

Abstract: This research investigates the mitigation of hydrogen embrittlement in steel, focusing on the effects of metallurgical hydrogen and the efficacy of various reduction techniques. Key findings demonstrate that vacuum treatment during steel casting combined with thermal treatment significantly lowers hydrogen content, enhancing steel's resistance to embrittlement. Welding processes differ in susceptibility to hydrogen-induced cracking, with submerged arc welding (SAW) showing the least and shielded metal arc welding (SMAW) the most susceptibility. Employing multipass welding, along with preheating and post-weld heat treatments, effectively minimizes hydrogen-related cracking by promoting even hydrogen distribution and desorption. The study highlights the successful application of fluoride-ion-containing welding fluxes, such as CaF2 and KF, to reduce weld hydrogen levels through chemical reactions. Furthermore, the choice of welding parameters, particularly the arc voltage, substantially impacts the hydrogen concentration in the welds. Additionally, the incorporation of hydrogen-binding elements such as yttrium significantly reduces the level of free hydrogen, thereby enhancing resistance to hydrogen corrosion. The research underlines the need for selecting appropriate welding methods and parameters to effectively reduce the adverse effects on welded joints. In conclusion, optimizing vacuum and thermal treatments, along with developing innovative welding materials, is imperative to control hydrogen content, crucial to the longevity and reliability of steel products in hydrogen-sensitive applications such as the oil and gas sector.

Keywords: welding defects, metallurgical hydrogen, metallurgical process technology, hydrogen fragility

1 | INTRODUCTION

A separator is a device designed for the separation of mechanical mixtures of solids or liquids, the removal of impurities from them, and the elimination of solid or liquid particles from gases. The operation principle of various separators is based on the fact that the physical properties of the mixture components are different: particle shape, mass, density, friction coefficient, magnetic and electrical properties, etc. Centrifugal separators are typically used for the splitting and liquid clarification, while gas separators and cyclones are used for the mechanical purification of gases and the removal of solid and liquid particles [1].

An oil-gas separator is specifically designed for separating associated gases from crude oil on their differing densities. Gas separation is facilitated by reducing the pressure, breaking the liquid jet into finer

*Corresponding Author
Oleksandr Kapustynskyi, Vilnius Gediminas Technical University, Plytines g. 25, LT-10105 Vilnius, Lithuania
Email: o.kapustynskyi@vilniustech.lt

streams, reducing the speed, and changing the direction of jet flow. Oil-gas separators are categorized based on their working principle into gravitational, centrifugal, and combined types; by shape into spherical and cylindrical (vertical, angular, horizontal); and by working pressure into vacuum (up to 0.1 MN/m^2), low (0.1-0.6 MN/m^2), medium (0.6-1.6 MN/m^2), and high (1.6-6.4 MN/m^2) pressure. Historically, vertical cylindrical oil-gas separators with tangential jet intake were predominant. The mixture is introduced into the inner part of the oil and gas separator. Oil is collected at the bottom and gas at the very top, to prevent oil from entering the pipeline.

Repairing worn or damaged parts using methods such as welding presents a valuable alternative. Welding operations not only restore the functionality of damaged parts, but also improve them by eliminating flaws in the original product [2]. The application of modern welding technologies and materials can significantly extend the service life of repaired parts and improve their operational characteristics.

Furthermore, welding repair can be much more cost-effective than purchasing new spare parts, especially considering long delivery times and high costs of original components. However, high quality standards are required to ensure the reliability and longevity of the welded joints.

International standards, such as ISO 6520-1 [3], classify and describe various types of welding defects, providing a basis for assessing the quality of welded joints. Among the various defects that can occur during welding, those caused by an excessive hydrogen content are particularly dangerous, as they can lead to metal cracking and reduced joint strength. These defects are difficult to detect and classify, making quality control a critically important aspect of the welding process.

The hydrogen in steel is a key element that significantly affects its physicochemical properties and quality. This element can significantly alter the properties of the material, for example, causing hydrogen embrittlement, making its study particularly important [4].

In the process of manufacturing, operating, and repairing steel, including welding, hydrogen can infiltrate the metal from various sources, including atmospheric moisture and added materials.

Thus, studying the impact of hydrogen on steel, including during welding repair operations, as well as developing methods to control and reduce hydrogen, are key tasks of modern metallurgy, aimed at ensuring high quality and reliability of metal products.

Taking into account the facts mentioned above, the repair and reinforcement of parts of oil-gas separators by welding represent an important alternative to replacement of parts. However, to ensure the safety and reliability of oil-gas separators, it is essential to strictly adhere to the quality standards of welded joints and pay careful attention to their inspection and evaluation process.

2 | PROBLEM FORMULATION

Hydrogen in steel is a crucial factor that influences its physicochemical properties and quality [5]. The origins and forms of its presence are diverse, and understanding these aspects is critically important. In steel that has not yet been exposed to hydrogen-aggressive environments, so-called "metallurgical" hydrogen can be contained. Metallurgical hydrogen is one of the primary types of hydrogen found in this material and is introduced during the steelmaking process. Throughout the metallurgical process, particularly when the molten steel contacts the furnace air or reacts with slag additives and components, hydrogen can enter the melt. Water (including steam) in the furnace atmosphere reacts with hot metal, resulting in hydrogen formation which then diffuses into the steel. Hydrogen sources are varied. In addition to the aforementioned processes, hydrogen can originate from pig iron and scrap used in steel production. These materials can contain hydrogen the both in free form and as part of hydrates of iron oxides (rust). Furthermore, hydrogen can be present in steel as moisture, which enters the metal along with added materials or during transportation and storage.

The impact of technological processes is also significant for the concentration of hydrogen in steel. During the vacuum treatment of the metal, where the steel is processed under reduced pressure, its hydrogen content decreases as a result of the removal of gaseous impurities. However, during thermal treatment in reducing atmospheres, often used to prevent metal oxidation, the hydrogen content in steel can increase. The hydrogen content in steel significantly affects its properties [6]. Steel oversaturation with hydrogen can lead to undesirable phenomena such as hydrogen embrittlement, deterioration of mechanical properties, and reduction of fatigue strength. These phenomena are particularly dangerous for critically important structures.

The hydrogen content in acid martensitic steel can reach 30-50 cm^3/kg, while in basic steel it can be 50-90 cm^3/kg. During steel casting through vacuum treatment of liquid metal in a ladle, the hydrogen content decreases (up to 20 cm^3/kg), but during the treatment of liquid steel with steam, it can increase. Figure 1 illustrates the sources of hydrogen emergence and the forms of hydrogen existence in steel. From the hydrogen stream A discharged on the metal, a portion of hydrogen B is mollized on the outer surface and removed from the solution as gas bubbles; another portion of hydrogen C is incorporated into the metal's crystalline lattice. At the same time, a part of the absorbed hydrogen D is released and mollized in internal collectors (voids). A portion of hydrogen E diffuses through the metal thickness and is released on the opposite side, while the remainder of hydrogen F remains in the solid solution in proton form.

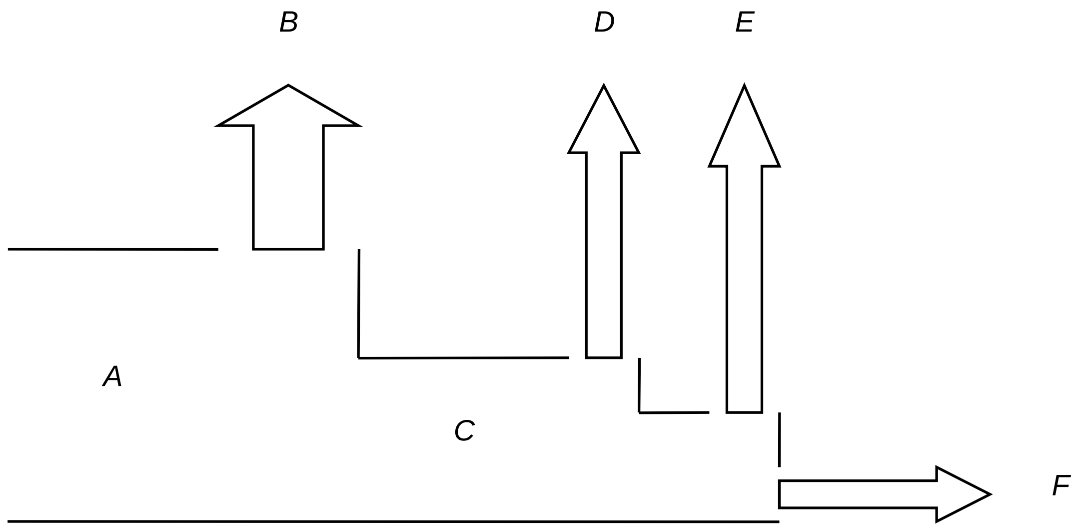


Fig. 1. Sources and forms of Hydrogen Presence in Steel.

Hydrogenation can accompany welding as a result of the metal's contact with the crystallization and hygroscopic moisture contained in electrode coatings and fluxes, as well as with rust. In the weld metal and the heat-affected zone, up to 100-1080 cm^3/kg of hydrogen can be contained.

2.1 Impact of Internal and External Factors on Steel Hydrogenation

The penetration into steel increases with an increase in carbon content up to 0.9%. Further increases in carbon content result in a slowdown in hydrogenation. Alloying additives have a relatively minor effect on the solubility and diffusion of hydrogen in steel, unless their introduction is accompanied by structural (phase) transformations. There is a minor impact on hydrogenation by additions of nickel, chromium, molybdenum, silicon, and manganese. Hydrogen-forming elements (Ti, V, Zr, Cr, Nb, etc.) are assumed to retain hydrogen within the crystalline lattice and inhibit its desorption and mollization [7].

The structure of the steel exerts a more noticeable influence on hydrogenation. Significantly greater solubility of hydrogen is observed in steels with a face-centered lattice (austenite) compared to those with a body-centered lattice (ferrite). There is an inverse relationship for diffusion; that is, under equal conditions, hydrogen diffusion in α-iron occurs faster than in γ-iron. Thus, under similar conditions in pure iron (as well as low carbon steel), hydrogen diffusion is a thousand times faster than in austenitic steels and ten times faster than in chromium stainless steel (ferritic).

Hydrogen absorption is primarily determined by defects in the crystalline lattice and the presence of traps in the metal where molecular hydrogen can accumulate. Under constant conditions, the penetration of hydrogen into carbon steel significantly increases when transitioning from martensitic to other types of structures (troostite, sorbite, pearlite).

Hydrogenation intensifies when transitioning from the saturation of steel with an undeformed lattice to steel with a distorted lattice due to cold deformation, and from the latter to steel whose hydrogenation occurs during the deformation process. Shear deformation processes, such as twisting, contribute to the incorporation of hydrogen into the metal. The enhanced adsorption of hydrogen as a result of cold deformation is explained by the initiation of microcracks that merge into micropores.

2.2. Impact of Hydrogen on the Physical-Mechanic Properties of Steel

Significant alterations occur in the plastic properties of steel during hydrogenation. As hydrogen penetrates, there is a noticeable decrease in relative elongation (δ) and a reduction in area (ψ), with ψ decreasing more intensively than δ. A near-linear reduction in ψ with an increase in hydrogen content in steel is observed.

The tensile strength of steel decreases slightly when hydrogen in unloaded samples. The impact toughness of steel at normal testing temperatures drops dramatically as a result of hydrogenation.

Significant deterioration of mechanical properties due to hydrogenation leads to what is known as "hydrogen embrittlement" of steel [8]. Failure occurs under the influence of stresses that can be static or cyclic in nature (in the latter case, hydrogen fatigue occurs). The levels of these destructive stresses are significantly lower than the corresponding characteristics of tensile and fatigue strength of non-hydrogenated steel. Moreover, as mentioned above, hydrogenation, with a corresponding increase in the pressure of gaseous hydrogen in the internal cavities of the metal, can cause delamination (blistering) of steel. This type of destruction can occur even without external load.

The presence of various defects in steel, such as dislocations, vacancies, and grain boundary separations, also plays a significant role. These structural defects can act as traps for hydrogen, increasing its local concentration and contributing to the formation of molecular hydrogen, leading to the creation of internal stresses and, consequently, to the development of brittle material failure.

Cold deformation of steel, for instance, in the processes of twisting or stretching, also significantly affects hydrogenation. Mechanical processing increases the number of defects in the crystalline lattice, thereby creating new paths for hydrogen diffusion and increasing its adsorption. Moreover, deformation processes can contribute to the formation of microcracks, which in turn serve as channels for rapid hydrogen penetration.

In general, understanding the influence of various internal and external factors on steel hydrogenation is critical to prevent hydrogen embrittlement and other hydrogen-related issues. This enables the development of more reliable and durable metal products, as well as effective risk management during the operation of steel structures.

The influence of internal and external factors on steel hydrogenation represents a significant challenge, especially for oil and gas equipment and other critically important structures. Hydrogenation can intensify depending on carbon content, steel structure, and physicomechanical processing, such as cold deformation. This leads to a reduction in mechanical properties, such as ductility and impact toughness, and increases the risk of hydrogen embritility.

Conducting further research is crucial for developing methods to prevent hydrogen embrittlement and other undesirable effects of hydrogenation. Studies will help better understand the mechanisms of hydrogenation and the impact of different factors on the process. This, in turn, contributes to the creation of more reliable and durable steel products and enhances the safety of oil and gas separators and other critical infrastructures.

3 | MATERIALS AND METHODS

To study the effect of microstructure on hydrogen blistering of steel, samples were prepared from the following steels: HPS 70W, HSLA 100 [9], API 5L X60 and A36, with each of their chemical compositions presented in Table 1.

The resistance to hydrogen-induced cracking (HIC) was evaluated according to the NACE TM 0177-96 standard.

From each sample, three specimens were cut along the rolling direction with dimensions of 100×20×11 mm. Subsequently, the specimens were polished with 320 grit sandpaper and placed in two different solutions saturated with hydrogen sulfide. One solution had a pH of 3.5, while the other had a pH of 5.0. After 72 hours, the specimens were removed from the test solutions and subjected to ultrasonic examination to detect internal discontinuities. This additional test provided information on the distribution of cracks within the sample. Metallographic analysis was performed to determine the sizes of the blisters.

Table 1. Chemical composition of materials

Material	C	Si	Mn	Ni	Cr	Mo
HPS 70W	0.1	0.3	1.2	0.35	0.52	-
HSLA 100	0.063	0.23	0.94	2.92	0.04	0.49
API 5L X60	0.09	0.26	0.82	0.2	0.021	0.3
A36	0.09	0.18	0.71	0.13	0.09	0.05

After processing, the samples were subjected to metallographic and durometric studies, during which the structure and microhardness characteristics of the processed samples were examined. The samples were ground and polished. Equipment for macroscopic and microscopic examination was chosen according to ISO/TR 16060:2003 [10]. The macroscopic and microscopic examination of the laser-treated samples followed the ISO 17639: 2003 standards [11]. Metallographic examinations of the samples were performed using an optical microscope equipped with a video camera, at various magnifications (up to × 1000). The hardness was assessed using the Vickers method with a squared tetrahedral pyramid, under a load of 9.807 N, according to EN ISO 6507-1 [12].

For conducting the experiments, various welding equipment was utilized: submerged arc welding (SAW); gas metal arc welding (GMAW) in an active gas environment, and shielded metal arc welding (SMAW) with coated electrodes. Additionally, various thermal furnaces were employed for the heat treatment of metal samples.

4 | RESULTS AND DISCUSSION

The amount of "metallurgical" hydrogen in steel can be reduced during the steel casting process by applying vacuum treatment to the liquid metal in the ladle. For this, dry vacuum degassers are used, which allow the mass fraction of hydrogen in steel to be reduced to 1.5 ppm.

The amount of hydrogen in the solidified ingots can be reduced by thermal treatment. Dehydrogenation annealing of blooms (600-700°C) helps in reducing the hydrogen content below 20 cm^3/kg and ensures its uniform distribution across the section.

Welding with multiple passes reduces the likelihood of cracks resulting from hydrogen effects, since each new pass thermally treats the previously welded layers. Preheating or post-weld heat treatment also decreases the likelihood of hydrogen-induced cracking, thus reducing hardness and allowing hydrogen sufficient time to desorb from the weld seam.

According to the data obtained during the tempering of steels with different carbon contents (Fig. 2), it can be concluded that the influence of the pre-tempering temperature on hydrogen saturation has an extreme character.

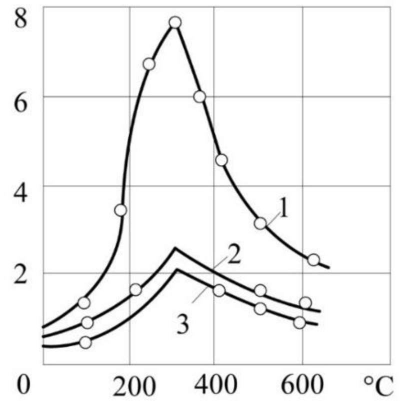


Fig. 2. Dependence of hydrogen saturation concentration on the tempering temperature of steels with carbon content: 1 – 0,99%; 2 – 0,22%; 3 – 0,16%.

Another method of reducing the amount of hydrogen in the weld seam is the use of fluxes containing fluoride ions (F-), such as CaF_2, KF, MnF_3, K_3AlF_6. This occurs because fluoride reacts with hydrogen in the arc atmosphere, resulting in the formation of a HF compound, which is then removed from the seam with the slag. Studies have shown (Fig. 3) that fluoride-containing fluxes effectively protect the weld seam from hydrogen. The best results were observed with fluxes containing CaF_2 and KF.

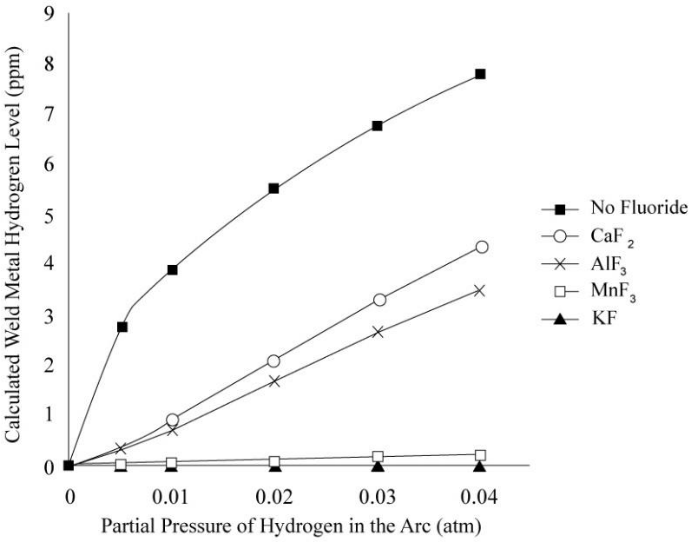


Fig. 3. Impact of fluxes containing fluoride ions on the amount of hydrogen in the weld seam

According to the experimental results, it can be concluded that the amount of hydrogen in the weld seam also depends on the welding process. Studies have shown that the least sensitive to the occurrence of cracks due to hydrogen effects is the submerged arc welding (SAW) process; more sensitive is the gas metal arc welding (GMAW) in an active gas environment; and the most sensitive is the shielded metal arc welding (SMAW) with coated electrodes. HPS 70W steel samples were welded with chemically similar welding materials using different welding processes: SAW, SMAW, and GMAW in a hydrogenating environment (Fig. 4).

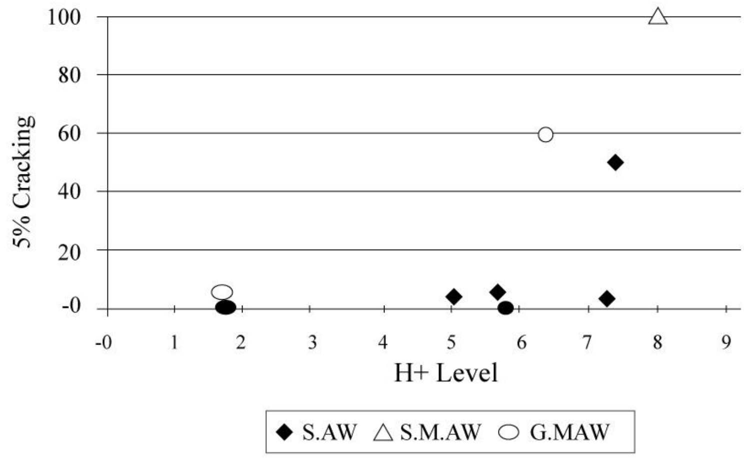


Fig. 4. Effect of Diffusible Hydrogen on: G-BOP Cracking.

In addition, the amount of hydrogen in the weld depends on the welding parameters. The amount of hydrogen in the weld decreases significantly with welding at low arc voltage. This is due to the fact that at higher voltage, the arc can extend to such an extent that the arc atmosphere fails to protect against the moisture from the surrounding environment.

The amount of free hydrogen in steel also depends on the addition of hydrogen-binding elements, e.g., yttrium, which possesses a high energy for hydrogen binding. This allows reducing the amount of free hydrogen in the weld seam by 40%.

HSLA 100 steel samples were welded using electrodes with the following composition: C – 0.06%, Mn – 1.2%, Si - 0.3%, Ni – 2.5%, Mo – 0.5%. One sample was cooled in air (resulting in 4% residual austenite), the other – in liquid nitrogen (0% residual austenite) (Figs. 5-6). After that, the samples were hydrogenated. Thermal desorption studies showed that yttrium effectively binds to free hydrogen in the weld seam, preventing the hydrogen from forming molecules within internal voids.

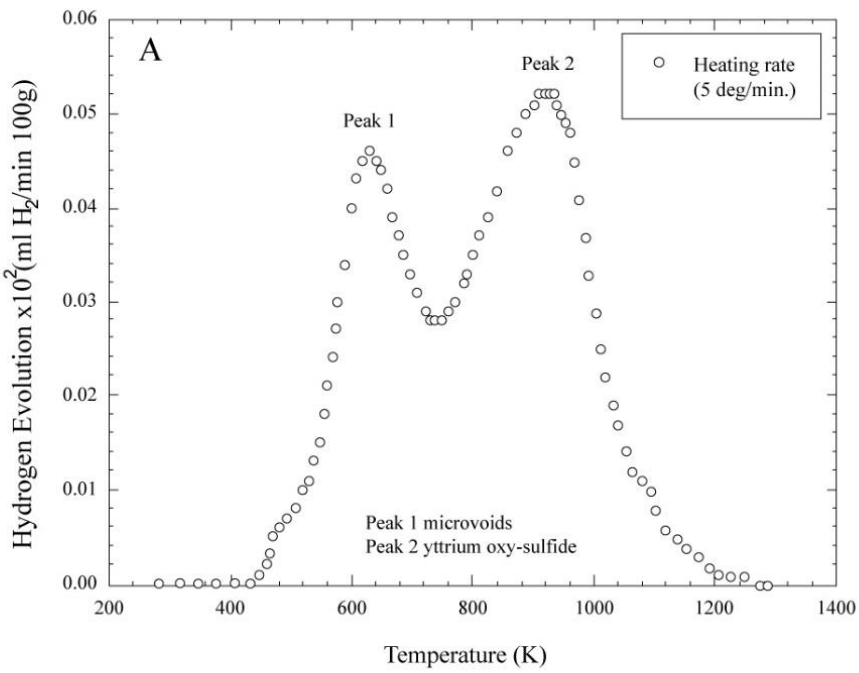


Fig. 5. Thermal Desorption Studies of HSLA 100 Steel

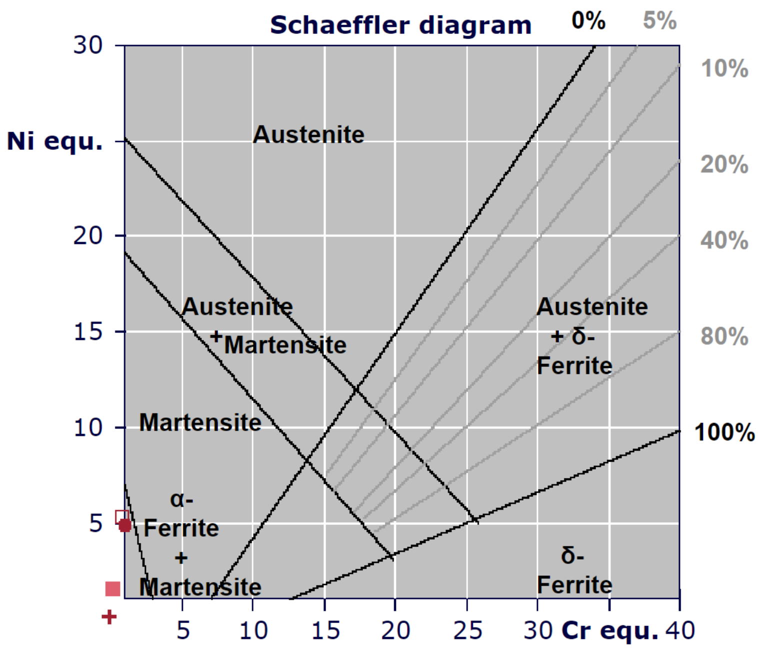
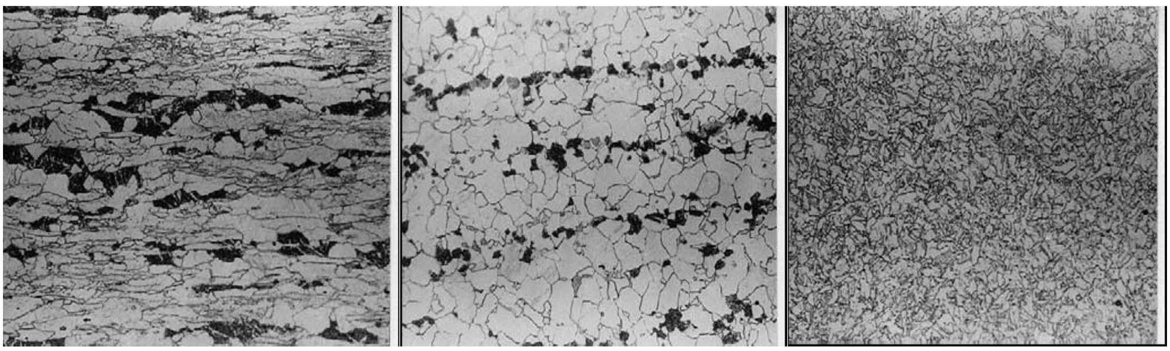


Fig. 6. Scheffler diagram

Heat treatment of the metal enhances its resistance to hydrogen corrosion. Studies of API 5L X60 steel samples by the NACE TM 0177-96 method for resistance to hydrogen corrosion in a hydrogen sulfide environment showed that the least susceptible to hydrogen corrosion is improved quenched and tempered steel with a bainite-martensite structure (Fig. 7). The tests demonstrated that hydrogen cracking did not occur only in the improved quenched and tempered steel with a uniform bainite/martensite structure.



rolled *normalized* *enhanced quenched and tempered*

Fig. 7. Testing of API-5L-X60 Steel Samples for Susceptibility to Hydrogen Cracking in H_2S Environment According to NACE TM 0177-96 Method.

Studies of samples welded from dissimilar steels (austenitic and ferritic) demonstrated that martensite forms at the weld fusion boundary, whose hardness exceeds 400 HV. A sample of A36 steel was welded with ER308 welding material (Cr – 20.51%, Ni – 9.69%) in a hydrogenating environment. Upon deformation of the sample across the weld seam, a crack formed along the weld fusion boundary. Cracks resulting from hydrogen effects appear in the weld metal zone with a martensitic phase, which has a high hardness (400-550 HV). In areas where the hardness was less than 350 HV, no hydrogen-induced cracks were detected (Fig. 8).

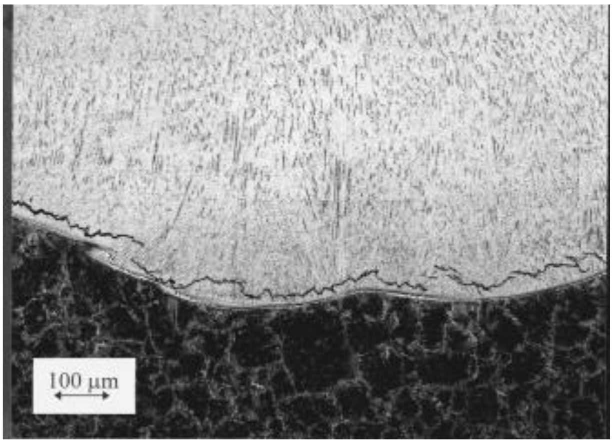


Fig. 8. Studies of Samples Welded from Dissimilar Steels

5 | CONCLUSIONS

Within the scope of modern research, it has been established that the application of vacuum treatment during steel casting, combined with the thermal treatment of crystallized ingots, significantly reduces the content of metallurgical hydrogen in steel. This not only improves its fundamental properties but also enhances its resistance to hydrogen embrittlement. Concurrently, the use of multi-pass welding methods, as well as preheating or subsequent thermal treatment of weld seams, helps to minimize the risk of crack formation due to hydrogen influence, ensuring uniform distribution and efficient desorption of this element.

Furthermore, the use of welding fluxes containing fluoride ions has proven to be effective in reducing the amount of hydrogen in welds due to chemical reactions that hinder its presence. It is also important to emphasize that the choice of welding method and the parameters of the welding process have a significant impact on the level of hydrogen in the welded joints, necessitating careful selection of technological conditions.

Among other measures aimed at reducing the risk of hydrogen cracking, the addition of elements such as yttrium to steel stands out, which facilitates the binding of hydrogen and thereby improves the resistance to hydrogen corrosion.

Therefore, the conclusions highlight the importance of further research in this area. Specifically, studies aimed at optimizing vacuum and thermal treatment processes, as well as developing and testing new welding materials and fluxes to achieve more effective control over hydrogen content, are necessary. Particular attention should be paid to determining optimal welding parameters for various types of steels and welding processes to maximize the impact of hydrogen on welded joints. Additionally, research on the influence of microstructure and phase composition of steels on their resistance to hydrogen cracking remains relevant, which will aid in developing new methods to improve the strength characteristics of metal products.

REFERENCES

Ershov, M., & Lomakin, V. (2019). Investigation of the performance of the oil gas separator, depending on the gas content of the pumped liquid. development of methods for optimizing the geometry of flow-through parts of centrifugal gas separators. IOP Conference Series: Materials Science and Engineering, 589(1), 012033. https://doi.org/10.1088/1757-899x/589/1/012033

Nesterenkov, V. M., Orsa, Y. V., & Khripko, K. S. (2019). Renewal of elements and construction units of gas turbine engines by means EBW. IOP Conference Series: Materials Science and Engineering, 582(1), 012049. https://doi.org/10.1088/1757-899x/582/1/012049

International Organization for Standardization. Welding and allied processes — Classification of geometric imperfections in metallic materials — Part 1: Fusion welding. [ISO Standard No. 6520-1:2007]; 2007.

Popov, B. N., Lee, J.-W., & Djukic, M. B. (2018). Hydrogen permeation and hydrogen-induced cracking. Handbook of Environmental Degradation of Materials, 133–162. https://doi.org/10.1016/b978-0-323-52472-8.00007-1

Massone, A., Manhard, A., Drexler, A., Posch, C., Ecker, W., Maier-Kiener, V., & Kiener, D. (2020). Addressing H-material interaction in fast diffusion materials—a feasibility study on a complex phase steel. Materials, 13(20), 4677. https://doi.org/10.3390/ma13204677

Xinxin, G., Baocheng, L., Xiaoming, L., & Lihua, Y. (2018). Hydrogen embrittlement of dissimilar steel welding joints. IOP Conference Series: Materials Science and Engineering, 423, 012038. https://doi.org/10.1088/1757-899x/423/1/012038

Dwivedi, S. K., & Vishwakarma, M. (2018). Hydrogen embrittlement in different materials: A Review. International Journal of Hydrogen Energy, 43(46), 21603–21616. https://doi.org/10.1016/j.ijhydene.2018.09.201

Barrera, O., Bombac, D., Chen, Y., Daff, T. D., Galindo-Nava, E., Gong, P., Haley, D., Horton, R., Katzarov, I., Kermode, J. R., Liverani, C., Stopher, M., & Sweeney, F. (2018). Understanding and mitigating hydrogen embrittlement of Steels: A review of experimental, modelling and design progress from Atomistic to continuum. Journal of Materials Science, 53(9), 6251–6290. https://doi.org/10.1007/s10853-017-1978-5

Dhua, S. K., Mukerjee, D., & Sarma, D. S. (2003). Effect of cooling rate on the as-quenched microstructure and mechanical properties of HSLA-100 Steel plates. Metallurgical and Materials Transactions A, 34(11), 2493–2504. https://doi.org/10.1007/s11661-003-0009-0

International Organization for Standardization. Destructive tests on welds in metallic materials — Etchants for macroscopic and microscopic examination (ISO 16060:2003). ISO. [ISO Standard No. 16060:2003]; 2003.

International Organization for Standardization. Destructive tests on welds in metallic materials — Macroscopic and microscopic examination of welds (ISO 17639:2003). ISO. [ISO Standard No. 17639:2003]; 2003.

European Committee for Standardization. Metallic materials — Vickers hardness test — Part 1: Test method (EN ISO 6507-1:2018). CEN. [EN ISO Standard No. 6507-1:2018]; 2018.

Author's Biography:

***Vitalijus Rudzinskas** is an Associate Professor at the Vilnius Gediminas Technical University, Faculty of Mechanics (Lithuania). His research focuses on the material engineering, and welding's.*

***Oleksandr Kapustynskyi**, is an accomplished mechanical engineer and researcher with a diverse educational background. Currently is Research Fellow and Lecturer at Vilnius Gediminas Technical University, Faculty of Mechanics (Lithuania). In 2011 he obtained a Junior Specialists degree in Chemical and Petroleum Engineering from Berdychiv College of Industrial, Economics and Law, Ukraine. After continued his studies at the National Technical University of Ukraine "Kyiv Polytechnic Institute," where earned his Bachelor's degree (2014) and his Master's degree (2016) in Mechanical. In 2023 he obtained a Doctoral degree at the VilniusTECH Faculty of Mechanics (Lithuania). His research focuses on the mechanical and material engineering, laser technologies, and welding's.*

How Cite this article?

Rudzinskas, V., & Kapustynskyi, O. (2024). The Role of Welding Parameters in Hydrogen Embrittlement Mitigation: A Case Study in Steel. *RESEARCH REVIEW International Journal of Multidisciplinary*, *9*(3), 203–212. https://doi.org/10.31305/rrijm.2024.v09.n03.021