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Study of quality of welded joints of high-strength ferritic steel made with a cover of a mixture of argon and hydrogen

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ABSTRACT

Testing of joints made during welding with a TIG of high-strength, fine-grained ferritic steels confirms that a small addition of hydrogen to the argon-based shielding mixture does not affect the formation of hydrogen cracking. It is very important to strictly adhere to the technological regimes during steel preparation before and after welding. Then, the controlled addition of hydrogen coming from the casing mixture has a positive effect. Due to the presence of 2% hydrogen, the joints are characterized by deeper penetration, lower inclination to edge flooding and smooth face. They are technically correct and impeccable in terms of aesthetics.

Keywords: welding, hydrogen, argon, ferritic steels.

INTRODUCTION

The pursuit of producing reliable products of impeccable quality forces manufacturers to perceive all production processes from different perspectives, and the final assessment of the quality of manufactured products must be treated as the sum of their technical and aesthetic properties as well as the economic and environmental conditions under which they were made. This also applies to welded products, the quality of which has changed dramatically over the last few decades. Just 20 or 30 years ago, it was enough that the welded product met the strength requirements, and if it was made aesthetically, it was a kind of added value. The aesthetics has now become the norm. Naturally, it is not the case that all products must meet the same conditions. It depends on the functions they perform. Therefore, automotive parts and household appliances must meet different requirements regarding technical and aesthetic quality than bridge construction elements. Undoubtedly, meeting all these requirements at the same time causes a lot of trouble. Sometimes, despite correct preparation of the joint, properly selected material and trained personnel, there are problems with making high-quality connections. Some products do not look good enough and even though they are technically correct, they are scrapped.

There may be many reasons for this situation, especially when they occur together. The chemical composition of the steel, internal stresses caused by previous processing and a large amount of heat introduced into the joint have a significant effect. One way to prevent this may be to use a properly composed shielding gas mixture. The appropriate mixture composition improves the stability of the welding arc and may also affect the oxidation of some impurities. Even a small addition of oxygen or nitrogen to the shielding mixture affects the nature of the welding process and improves the mechanical properties of the welded joint [1-3].

Unfortunately, there is a certain difficulty. Although there are many possibilities of composing effective shielding gas mixtures in GMAW welding, when it is necessary to make a joint using a non-consumable electrode – the popular TIG process, there are much fewer mixtures. Although this method is considered very noble, it has significant limitations regarding the gas shield. Under the considered conditions, one can basically choose between a pure argon shield for welding ferritic steels and an Ar mixture with a small addition of H_2 for welding austenitic steels. For many years, the authors have been investigating the possibility of using an argon mixture with the addition of hydrogen as shielding gases for welding steels with a ferritic structure. The research is conducted in three directions. Firstly, whether there is a risk of delayed cracks, so-called "hydrogen" cracks, secondly, what effect does the addition of hydrogen have on the mechanical properties of welded joints, and thirdly, how does the addition of hydrogen to the gas shield affect the content of harmful substances in welding fumes.

This article presents the results of research on cold cracks. For this purpose, tests were carried out on 36 test plates, 12 for each shielding mixture (Ar + 2% H_2, Ar + 5% H_2 and Ar + 10% H_2). As a comparative material, 3 test plates were prepared for each steel grade (S500ML, S700MC and S700MC E) in the shield recommended by welding standards, i.e. in a pure argon shield. The welding parameters for all tests were the same during the entire welding process. The laboratory stand for performing the tests is shown in Figure 1.

THE IMPACT OF HYDROGEN ON STEEL

It is known that the hydrogen found in the structure of steel can change its mechanical and chemical properties, especially when it is absorbed in large amounts. The size of these changes depends mainly on the chemical composition, microstructure, impurities and the type of processing the steel has undergone [4]. The degradation of mechanical properties, characterized by a reduction in strength and plastic parameters, is of great importance when welding ferritic steels, in which hydrogen dissolves only slightly, contributing to delayed cracking. It may also cause cracks due to stress corrosion cracking caused by the formation of galvanic hydrogen cells. Modern research shows that electrochemical hydrogenation significantly reduces the corrosion resistance of metals and alloys due to surface defects and the resulting corrosion pits. Cracks are formed as a result of different amounts of hydrogen absorbed in the tops and walls of the cracks, which causes the crack to extend and, as a result, reduce the durability of the loaded welded structure.

Under normal conditions, hydrogen occurs in the molecular form of H_2, which is an energy-neutral form. In this form, hydrogen is chemically less active [5]. The situation is different when hydrogen dissociates into its atomic form. Then, it reacts with almost all elements. It forms ionic, covalent and metallic bonds. Hydrogen atoms are so small that they can move freely in the crystal structure of the metal, and when combined they create molecular

Figure 1. The laboratory stand for performing tests

hydrogen, which is particularly dangerous if found inside the metal. The accumulation of large amounts of hydrogen in the metal causes internal pressure, which then results in stresses in the material, and may consequently lead to the formation of cracks. For welded structures, the process is even more harmful, because a crack in the weld may occur after the joint has cooled down, e.g. 24, 36 or even 72 hours after completion. The dangerous nature of cold cracks results from the fact that they may appear when there is no longer any control over the structure, the joints are painted or even often built into the load-bearing structures.

To sum up, discontinuities in materials, the harmful effects of hydrogen and tensile stresses resulting from the loading of the structure may be the cause of the considered delayed cold cracks, also known as hydrogen cracks [6–10].

THE IMPACT OF HYDROGEN ON THE COURSE OF THE WELDING PROCESS

The hydrogen dissociation process is endothermic and for it to occur it is necessary to provide a proper amount of energy (e.g. heat). The decay of a hydrogen molecule can also occur in the environment of an electric discharge. If the welding process in question is taken into account, both of these conditions are met simultaneously [11]. What does this process look like when welding with a non-consumable electrode? A strictly controlled amount of hydrogen in a mixture with argon flows around the tungsten electrode. Under welding conditions, the process of thermal dissociation of the hydrogen molecule occurs as a result of absorbing a certain amount of thermal energy. As a result, the temperature around the electrode decreases significantly. This is beneficial, as the electrode wear is much slower. Then, when the atoms come into contact with the surface of the welded material, they release the absorbed heat, which causes the metal to melt faster. The molten metal pool is more fluid and therefore less prone to edge flooding. After releasing heat, the atoms combine again to form H_2 molecules. The temperature of the arc also increases due to the combustion of hydrogen in oxygen released from the air. Narrowing the arc results in a tighter weld and a more energetic arc allows for better penetration and higher welding speed. Moreover, the hydrogen contained in the mixture reduces oxides [12].

MATERIAL AND METHODS

The common belief that hydrogen has a harmful effect on steel as well as the fact that it causes very dangerous hydrogen cracks in the area of welded joints raises concerns regarding its use in argon-based shielding gas mixtures. This applies especially to the welding of ferritic steels, where hydrogen diffusion in the crystal lattice is high and the solubility is low.

The harmful effects of hydrogen on metals are indisputable, but how does its small, controlled addition to an argon-based gas shield affect the GTAW process of welding ferritic steels? For this purpose, tests were carried out on welded joints made of high-strength, fine-grained steels with a minimum yield strength of 500 MPa and 700 MPa. The modern hot-rolled microalloyed steel grades used during the experiment are characterized by high quality and excellent engineering properties. They are flexible while maintaining excellent surface quality. The welded joints made of these steel grades have high strength and impact strength in the heat affected zone, which provides them with good resistance to brittle fracture.

When maintaining technological strictness, the discussed steel grades are well weldable, but due to their chemical composition and crystalline structure, their common feature is predisposition to delayed hydrogen cracks.

The article presents the results of testing the tendency to cold cracks in the Tekken test of joints welded with a non-consumable electrode in the shield of argon-hydrogen mixtures of selected steel grades with a bainitic-ferritic structure [13, 14]. A Y-groove test was carried out on butt welds on 10 mm thick sheets according to PN-EN ISO 17642-2:2005. This test involves joining two boards with dimensions of 200×75 mm, beveled in a special way (Fig. 2).

The joints were visually examined after 72 hours from execution, so as to definitely exclude cold cracks. Then, the test welds were cut into sections of approximately 10 mm and subjected to metallographic tests. The samples were ground every approx. 1 mm to look for microcracks.

Three grades of fine-grained steel were selected for the study: DOMEX®S500ML, STRENX®S700MC and STRENX®S700E. The test plates were made in a shield of three mixtures of argon and hydrogen from the R1 group (according to ISO 14175): 1) 98% Ar + 2% H_2 recommended for manual welding and 2) 95% Ar

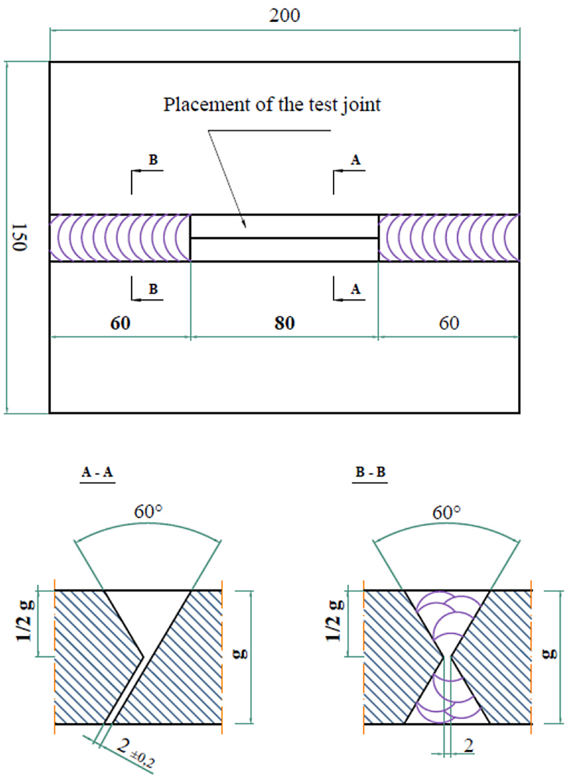


Figure 2. TEKKEN specimen (PN-EN ISO 17642-2:2005)

+ 5% H_2 and 3) 90% Ar + 10% H_2 dedicated to mechanized welding. Comparative joints made of the above-mentioned steel grades were made in a sheath containing 100% Ar (I1, according to ISO 14175), i.e. the one allowed by the welding technology of ferritic steels.

The test stand for the experiment was prepared in a way that allows the steel plates to be effectively immobilized so that the electrode moves perfectly in the sample axis. All welds were made using a welding carriage, which allowed maintaining both a constant welding speed and an arc length. The use of a welding carriage also allowed for the extension of tests by using mixtures recommended for mechanized welding (2 and 3) in order to verify whether cracks would occur in joints made with an increased hydrogen content.

Before welding, the test plates were heated dry to a temperature of 70–80 °C. After welding, the samples were not heated, but placed on a steel tabletop heated with a stream of hot air to a temperature of approx. 50–60 °C. The temperature of the room where the samples were taken was 26 °C and the relative humidity was 52%.

The presented steel grades are characterized by high plasticity and, at the same time, low brittle transition temperature (Table 1). Therefore, their use is justified whenever it is essential to reduce the weight of the structure while maintaining the necessary load-bearing capacity and, indirectly, also to reduce production costs. It should be noted that the steel grades discussed have a fairly high CEV equivalent with a very low carbon content [13, 14]. Alloy micro-additions are responsible for this fact, mainly the high content of manganese (approx. 2.0%).

When welding fine-grained high-strength steels, it is extremely important to control the welding technique and the amount of heat introduced. For the steel grades discussed, the welding process should be carried out so that the linear energy does not exceed 1 kJ for each mm of weld length. This is related to the so-called brittle transition temperature (TBTT), which depends, among others, on the chemical composition of the steel, heat treatment and the manufacturing process [14–16]. Apposite production technology is essential because the only factor that reduces TBTT and at the same time increases the yield strength is grain refinement. Therefore, welding parameters should be selected so that they do not lead to excessive grain growth [17–19]. The arc intensity and voltage as well as the welding speed in the experiment were set at the same level for all

Table 1. Selected weldability indices of the tested steel grades

Steel	Content C [%]	Equivalent C_{EV}	Equivalent C_{ET}	Equivalent H_{CS}	T. heating [°C]	Factor K_{IC}
S500ML	0.136	0.43	0.30	1.04	157	40J / -60 °C
S700MC	0.060	0.39	0.29	0.13	140	27J / -50 °C
S700E	0.152	0.41	0.25	1.36	149	69J / -40 °C

Table 2. Welding parameters of test plates

Welding current [A]	Arc voltage [V]	Welding speed [mm/min]	Arc energy [J/mm]	Shielding gas flow rate [l/min]
190	13.5	120	770	8

tests (Table 2), but so that the linear energy was significantly below the allowed value. They were selected on the basis of preliminary tests performed during welding in a pure argon shield in such a way that they met two conditions. Firstly, it was assumed that even an approximately 10% "strengthening" of the welding arc with the addition of hydrogen to the liquid pool shield will not exceed the linear energy value allowed by the manufacturer. The second condition, consists in assessing the shape of the weld cross-section and the appearance of the face to obtain a minimum quality class of C according to PN-EN ISO 5817. The linear energy value meeting the test assumptions is 770 J/mm.

RESULTS

The examples of Tekken test welds made in four different gas shields. Figure 3a, made of thermomechanically processed S700E steel, welded in a pure argon shield, clearly shows undercut edges and a very rough face. In the place marked by the arrow, there are visible undercuts on the edges, increasing in the direction of welding, i.e. with increasing temperature of the sheets. Figure 3b shows a weld made of S500ML steel, thermomechanically rolled, welded in an Ar shield with 2% H_2 addition. Visible lack of flooding and a smooth face. The smoothest face and no edge undercuts was obtained in a test made of S700MC steel (Fig. 3c), also thermomechanically rolled, shielded with a mixture of 95% argon and 5% hydrogen. The last 2D photo shows a test weld of S500ML steel welded in a shield of a mixture of Ar and 10% hydrogen. In this case, with the given current parameters, there were significant difficulties in making the connection, mainly due to too high arc energy resulting from the much higher power of the welding arc under the influence of hydrogen contained in the gas mixture.

During the visual examination, a characteristic shape of the heat affected zone (HAZ) was observed for the samples made in particular shielding mixtures.

Thus, the HAZ of a welded joint in a sheath of pure Ar has a "pear" shape, while the HAZ of joints in Ar-H_2 mixtures is uniform from the beginning to the end, similar to a "cigar" shape. This means that the joints welded with the addition of hydrogen allow for achieving the most optimal welding conditions immediately after starting the process, while when welding in Ar alone, reaching the proper energy level takes much longer. Attention should be paid to the characteristic appearance of the 2D weld, revealing high-temperature oxides on the sheet surface (especially in the first 2–3 hours after welding). This indicates much greater energy supplied to the junction. No significant welding defects were found during the visual inspection in test joints or cracks within 72 hours after welding (Table 3).

Since it is assumed that the time necessary for hydrogen to diffuse from the joint is min. 24 hours and according to some authors even 36 hours, the

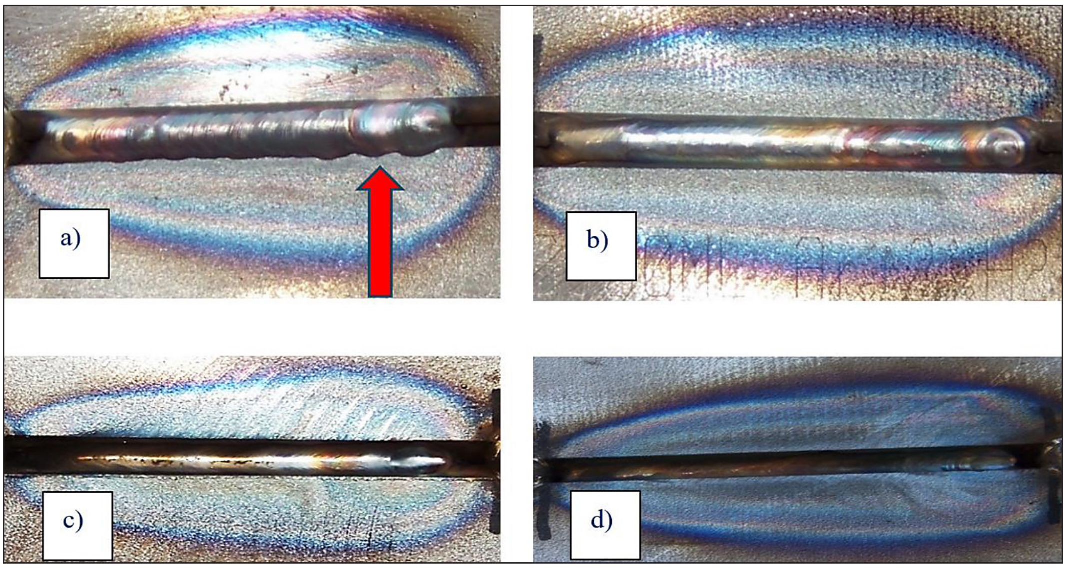


Figure 3. Steel plates for Tekken test, (a) S700E, gas shield 100% Ar, (b) S500ML, gas shield Ar + 2% H_2, (c) S700MC, gas shield Ar + 5% H_2, (d) S500ML, gas shield Ar + 10% H_2

Table 3. Visual inspection report

No.	Steel type	Gas shield	After 2 hours	After 24 hours	After 48 hours	After 72 hours
1	S 500 ML	Ar	No cracks	No cracks	No cracks	No cracks
2		Ar + 2% H_2	No cracks	No cracks	No cracks	No cracks
3		Ar + 5% H_2	No cracks	No cracks	No cracks	No cracks
4		Ar + 10% H_2	No cracks	No cracks	No cracks	No cracks
5	S 700 MC	Ar	No cracks	No cracks	No cracks	No cracks
6		Ar + 2% H_2	No cracks	No cracks	No cracks	No cracks
7		Ar + 5% H_2	No cracks	No cracks	No cracks	No cracks
8		Ar + 10% H_2	No cracks	No cracks	No cracks	No cracks
9	S 700 E	Ar	No cracks	No cracks	No cracks	No cracks
10		Ar + 2% H_2	No cracks	No cracks	No cracks	No cracks
11		Ar + 5% H_2	No cracks	No cracks	No cracks	No cracks
12		Ar + 10% H_2	No cracks	No cracks	No cracks	No cracks

study doubled the observation period to 72 hours. in order to exclude the possibility of missing any cracks. A band saw was used to cut test welds, owing to which any micro-cracks would be visible. Additionally, the conducted penetrant and microscopic tests did not reveal any traces of microcracks in the structure of the welded joints.

Figures 4–6 present photographs of the microstructure of S500ML steel sections made in the discussed gas shields. The photographs confirm a significant increase in the depth of penetration with increasing hydrogen addition to the welding shield. A slight grain growth is visible for all tests, increasing smoothly from the fusion line to the weld axis. Crystals are arranged with the longer axis in the direction of solidification. The S500ML samples presented are characterized by the largest differences in both penetration and weld thickness.

In relation to the comparative joint (100% Ar shield), the difference in the depth of weld

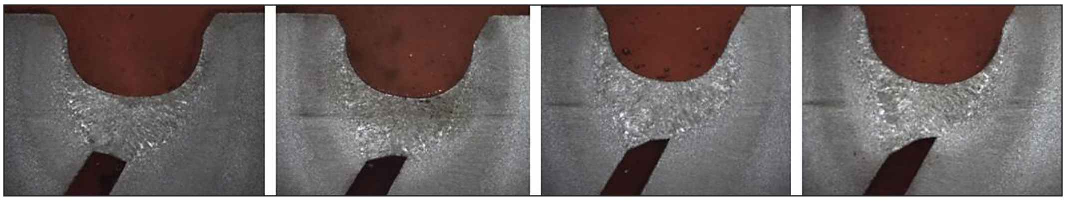


Figure 4. S500ML, Ar shield + 2%H_2

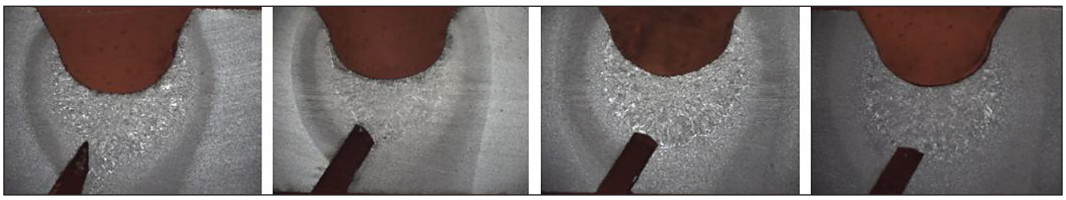


Figure 5. S500ML, Ar shield + 5%H_2

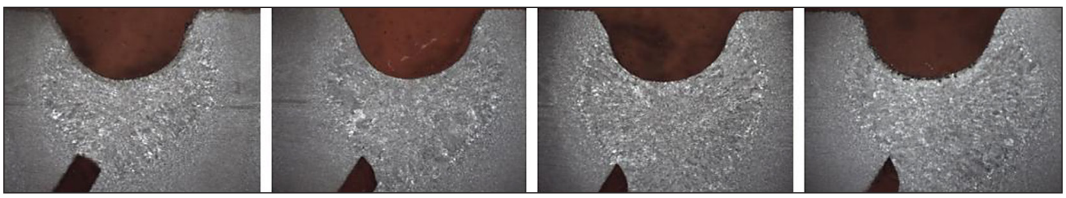
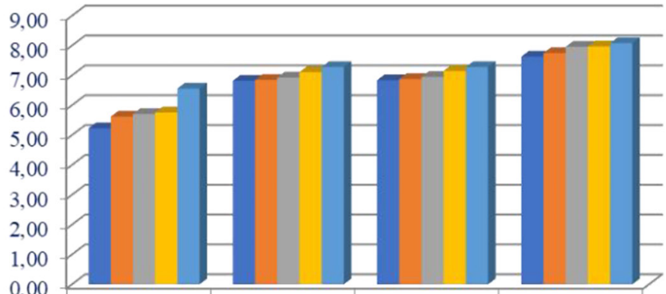
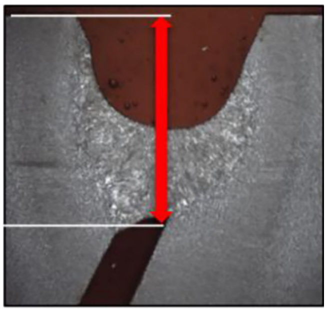


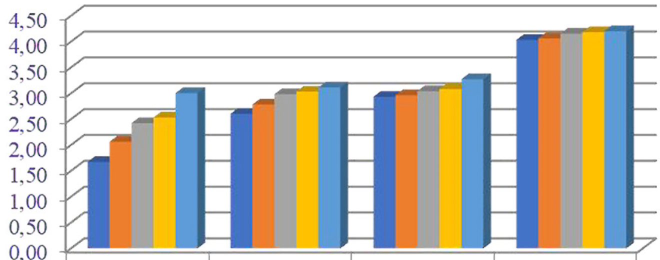
Figure 6. S500ML, Ar cover + 10%H_2

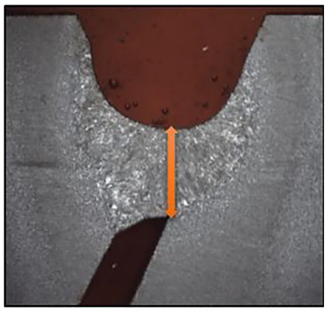




	100% Ar	Ar+2% H2	Ar+5% H2	Ar+10% H2
cross-sect. 1	5,23	6,82	6,84	7,63
cross-sect. 2	5,62	6,85	6,88	7,75
cross-sect. 3	5,71	6,93	6,95	7,96
cross-sect. 4	5,76	7,11	7,15	7,97
cross-sect. 5	6,56	7,28	7,28	8,08

Figure 7. The depth of material melting measured from the sheet surface to the bottom of the weld [mm]





	100% Ar	Ar+2% H2	Ar+5% H2	Ar+10% H2
cross-sect. 1	1,67	2,60	2,93	4,03
cross-sect. 2	2,06	2,78	2,96	4,06
cross-sect. 3	2,42	2,98	3,04	4,15
cross-sect. 4	2,53	3,03	3,08	4,18
cross-sect. 5	3,00	3,11	3,27	4,20

Figure 8. Thickness of the weld calculated from the face surface to the weld root [mm]

penetration, calculated from the surface of the sheets to the weld root, was approximately 20–21% more for the mixtures with 2% and 5% hydrogen and 36% more than when the shield was used with the addition of 10% hydrogen (Fig. 7).

Even greater differences were noticed when measuring the weld thickness for this steel grade. There was an increase of 24%, 31% and 77%, respectively, for individual Ar-based shielding mixtures with the addition of H_2 compared to the argon-shielded joint (Fig. 8). The graphs (Fig. 7 and Fig. 8) clearly show the tendency for the welded material to lay evenly from the beginning to the end of the weld, regardless of the amount of hydrogen added. It is also clearly visible that the time necessary to achieve the appropriate welding energy in an argon shield is much longer.

In the samples from the other two steel grades, i.e. S700MC and S700E, no such large differences were found and they accounted for a 3% to 4% increase in depth in the test of welds made with 2% and 5% of hydrogen and 11% deeper penetration when 10% hydrogen was added, measured based on the surface of the welded material. The result of measuring the weld thickness increased by 2%, 3% and 22%, respectively, for individual mixtures compared to the joints welded in pure Ar.

CONCLUSIONS

Taking into account the beneficial aspects of adding hydrogen to the welding mixture and its harmful effect on metals and alloys, it can be assumed that a small, strictly controlled addition of hydrogen to the argon shield protecting the molten metal pool does not affect the occurrence of hydrogen cracks in welded joints.

The tests carried out during welding of fine-grained ferritic steels with a minimum yield strength of 500 MPa and 700 MPa, in a sheath of 2%, 5% and 10% of hydrogen added to argon, show no effect on delayed hydrogen cracks and confirm the technological possibility of using these mixtures. In other words, welding with a non-consumable electrode in the atmosphere of the above-mentioned mixtures allows for the production of high-quality welds, characterized by deeper penetration, greater smoothness of the face and a lower tendency to undercut the edges compared to the joints covered with pure Ar. The evidence confirming this is the lack of any cracks in all 36 test joints carried out during the study. Neither NDT nor microscopic examinations have shown this. The experiments conducted indicate that when welding products made of structural steel, they may even be recommended, especially when it is necessary to obtain a good quality joint with impeccable appearance. This applies to most welded products made of ferritic and austenitic steels, such as metal furniture, machine housings and household appliances.

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