



Comparison of selected rutile flux-cored wires stored under different environmental conditions

Aleksandra Świerczyńska^{1*}, Michał Landowski¹, Adrian Wolski¹, and Dariusz Fydrych¹

¹ Institute of Manufacturing and Materials Technology, Faculty of Mechanical Engineering and Ship Technology, Gdańsk University of Technology, Gabriela Narutowicza Street 11/12, 80-233, Gdańsk, Poland

Abstract. Among the factors that affect the quality and properties of welded joints, an important role is played by the transportation and storage of consumables. Covered electrodes, flux-cored wires and fluxes are particularly vulnerable to harmful storage conditions. This work presents a comparative study between the effects of marine and land environmental conditions on 5 flux-cored wire grades with different design and produced by different manufacturing techniques. The wires, after storage under different climatic conditions, were subjected to visual, metallographic macro- and microscopic examinations, tensile tests as well as measurements of relative electrical resistance and diffusible hydrogen content in deposited metal. Differential effects of the storage environment on wire quality were found, and a correlation was noted between wire construction resulting from manufacturing technique and resistance to environmental factors. Storage of wires caused changes of mechanical properties and relative resistance, as well as an increase of diffusible hydrogen content from level H5 to a level exceeding H10. It was found that visual surface condition is not a good indicator of wire quality.

1 Introduction

Welding processes are classified as special processes, the implementation of which requires monitoring and documentation of the process at all stages of its progress. The quality of welded joints depends on a number of technological, metallurgical and constructional factors, including the condition of the welding consumables. Flux-cored wires and covered electrodes are particularly susceptible to quality deterioration under storage conditions [1,2]. This is primarily due to the fact that they are made using flux, which is a hygroscopic substance. Manufacturers of consumables publish recommendations on the range of temperature and relative humidity in warehouses, mainly to minimize the risk of corrosion processes and increase the diffusible hydrogen amount in deposited metal [3,4]. Even with appropriate supervision over transport and storage, environmental influence on consumables is difficult to avoid. Some manufacturers recommend scrapping spools based on a negative visual assessment of the wire's surface condition, or unwinding several layers of wire. However, in practice (transportation, energy, mining, offshore, marine, construction industry), especially in harsh climate zones, often these requirements are not met, so it is important to know the effects of storage on the quality of wires and consequently their impact on the properties of welded joints.

An analysis of the literature shows that the storage of flux-cored wires leads to degradation of their surfaces in a degree that depends on relative humidity, temperature, type of environment (urban, marine or land conditions), air pollution and time of exposure to the environment [3,4]. Significant changes were found in the ductility and electrical conductivity of flux-cored

wires [4] as well as in the weld properties [2,5] and an increase of diffusible hydrogen content in deposited metal [4,5]. These changes can be the cause of the unacceptability of welded joints due to the formation of porosity and cold cracks [6–8]. Relationships between factors affecting the diffusible hydrogen amount are very complex and show interactions [9]. The diffusible hydrogen content mainly depends on the amount of total hydrogen (e.g., from shielding gas, moisture, hydrocarbon and organic contamination), but welding parameters also have an important influence [9,10]. An additional consequence of improper storage of flux-cored wires is an increase in production costs due to the need to scrap old and purchase new consumables, as well as the cost of repairing welded joints that do not meet the criteria recommended by standards and regulations. Despite the development of various methods of utilization of leftovers of consumables [11] still the reduction of material losses is one of the most advantageous and easiest solutions beneficial also from the environmental point of view [4].

The purpose of this article is to compare the sensitivity of five grades of flux-cored wires to storage under natural conditions that do not meet the temperature and relative humidity criteria recommended by manufacturers.

2 Materials and Methods

Five grades of unalloyed rutile flux-cored wires with similar properties (YS = 420 MPa and H5 hydrogen level) were selected for the study. Wire grades were coded with the symbols A, B, C, D, E. There were two copper-plated (A, E) and three non-copper-plated (B, C, D) wire grades. All the wires had a diameter of 1.2 mm

* Corresponding author: aleksandra.swierczynska@pg.edu.pl

and were wound on spools weighing 5 kg. The spools were stored in two metropolitan locations with different environmental characteristics: a marine and a land location. Both storage locations were characterized by free access of air to the wires, but without the direct influence of atmospheric precipitation. The exposure period lasted six months (from beginning of March to the end of August). The temperature and relative humidity recorded (Termioplus recorder with the SHT15 sensor) at these locations are shown in Fig. 1 and Fig. 2, respectively.

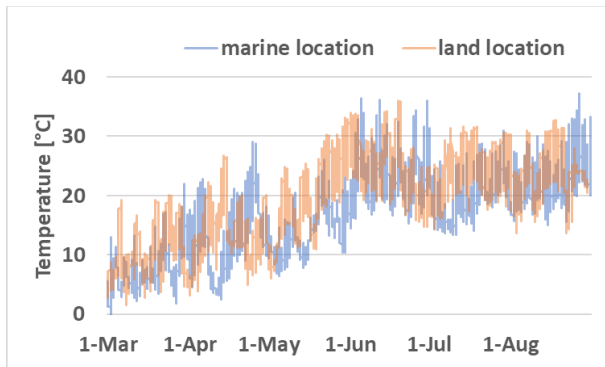


Fig. 1. Changes in air temperature at test stands during storage of wires.

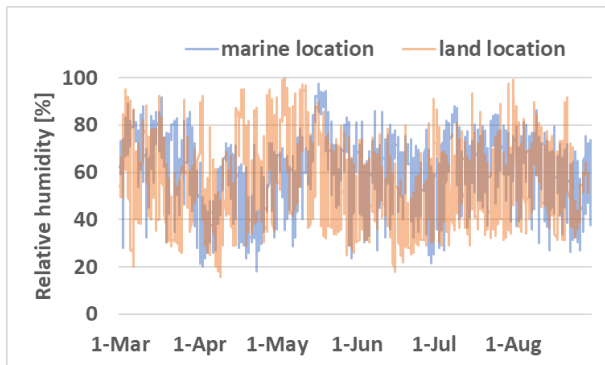


Fig. 2. Changes in relative humidity at test stands during storage of wires.

All wires at successive stages of storage were subjected to visual testing. For the selected wires, metallographic specimens were taken with their longitudinal cross-sections and they were subjected to microscopic observations on an Olympus BX51 light microscope.

Electrical resistance measurements were carried out according to the procedure and on the test stand presented in the article [4]. A wire of the same grade, but in the initial state, was used as a reference wire. Three trials were performed for each condition and at least ten measurements for each trial were recorded. Electrical resistance change was calculated according to the formula (1):

$$R_r = (R_t - R_{ref})/R_{ref} \times 100\% \quad (1)$$

The tensile tests (five trials for each condition) of the wires were carried out on a Hung Ta HT-2401 testing machine with additional tooling for stretching small diameter bars. Only results in which the fracture occurred in the central part of the specimen, outside the

jaws, were selected for the results. The cross-sectional area determined from the perpendicular cross-section of the wires in the initial state was used to calculate the tensile strength.

Specimens were made automatically using a MIG 4004i Pulse welding machine and an ESAB Miggytrac 1001 welding trolley. The shielding gas used was M21 (Ar + 18% CO₂) with a flow rate: 18 l/min, and the other parameters were: welding current 220 A, arc voltage 25 V, welding speed 30 cm/min, CTWD 25 mm.

Diffusible hydrogen measurements were done according to ISO 3690 standard procedure by the mercury method using B type specimens and copper fixture. Hydrogen extraction was carried out at 45°C for 72 h. Three trials were performed for each condition.

3 Results and Discussion

An analysis of the temperature and relative humidity conditions recorded at the two locations shows that they did not differ radically. It can be seen that in land conditions the temperature was usually higher than in marine conditions (Fig. 1), but in both places it varied according to the season. For the storage and transportation of consumables, especially low temperatures can be detrimental. Combined with high humidity, condensation can occur on the surface of the wires. The spring and autumn periods favor such conditions. Changes in relative humidity were significant (Fig. 2), characterized by a higher frequency of change than temperature, with no seasonal trend. Except for the period from mid-April to mid-May, it was the marine conditions that had higher relative humidity. Even so, the measured humidity values exceeded the safe level declared by manufacturers for almost the entire storage period, including during the summer. This means that none of the surveyed locations are suitable for storage, and environmental differences within the temperate climate zone are a less important factor than the type of climate.

All stored flux-cored wires were subjected to visual testing. Fig. 3 shows the surface of each grade of wire tested after 6 months in marine and land conditions. It is noticeable that during storage, land conditions caused greater degradation of the surface of each wire. This is visible for both copper-plated and non-copper-plated wires. The surfaces of the A, C and D wires appeared unchanged after 6 months in marine conditions. Their surfaces were shiny and clean. In contrast, the other wires were characterized by the presence of fine, scattered corrosion products - B wire (Fig. 3c) or larger, locally concentrated and extended corrosion centers - E wire (Fig. 3i). After the same time in land conditions on each wire the impact of the environment can be observed. The A, B and E wires were covered with an even layer of corrosion products of varying thickness. The surface of the C wire was covered with smaller, as well as very elaborate corrosion spots (Fig 3f). The least degradation under these conditions was observed in D wire, whose surface became matt and covered with dispersed, fine corrosion products (Fig. 3h).

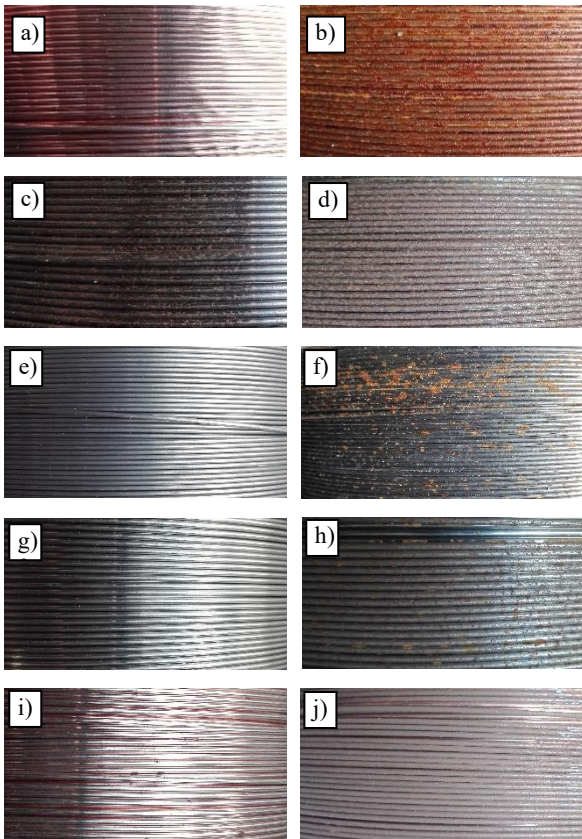


Fig. 3. Surface of the wires after 6 months of storage. a) A wire stored in marine conditions; b) A wire stored in land conditions; c) B wire stored in marine conditions; d) B wire stored in land conditions; e) C wire stored in marine conditions; f) C wire stored in land conditions; g) D wire stored in marine conditions; h) D wire stored in land conditions; i) E wire stored in marine conditions; j) E wire stored in land conditions.

Longitudinal cross-sections of wires were subjected to microscopic observations and the surface view for wire D is shown in Fig. 4. This was the wire that was selected as the least degraded based on visual testing. In the initial state (Fig. 4a), a smooth, flat surface is visible, with small undulations due to the structure of the wire. After storage, the surface changes its texture significantly. A cross-section of the wire stored in marine conditions (Fig. 4b) shows developed pits that were not visible during macroscopic observations. Apart from them, the surface looks uniform and smooth. The surface of wire stored in land conditions is very different (Fig. 4c). It is extensive, clearly showing both degradation inside the wire causing the wire fragment to almost break off, as well as surface degradation products, probably corrosion products.

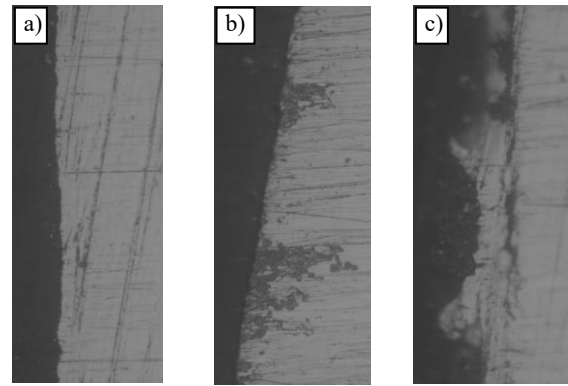


Fig. 4. View of the wire surface. A) D wire in initial state; b) D wire after 6 months in marine conditions; c) D wire after 6 months in land conditions.

The change in electrical resistance measured between the wire in the initial state and the stored wire for two representatives - copper-plated and non-copper-plated wire is shown in Fig. 5. It shows that by measuring this property, changes in the wire itself were also recorded. However, the direction of these changes is not clear. The most noticeable change was in C wire stored in marine conditions. Each successive measurement period shows increasing resistance of the stored wire. Similarly, in land conditions - this wire has an increased resistance relative to the initial state, but measurements showed that a large change was recorded during the initial storage period when conditions were also most unfavorable. Wire stored longer showed a smaller difference in resistance suggesting that the cause of these changes is not constant and under the influence of the given conditions it may change. In contrast, copper-plated wire showed approximately no change in resistance under marine conditions, and the results in land conditions after 6 months even show a visible decrease in resistance.

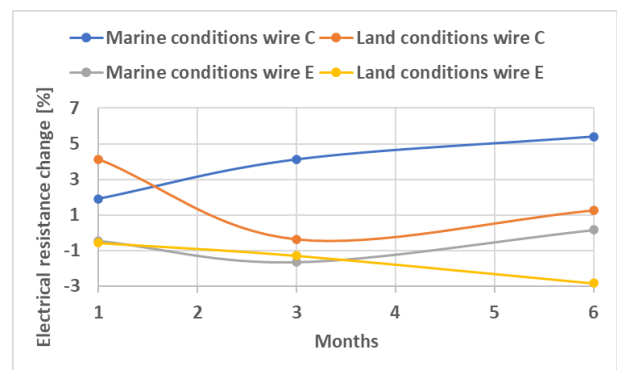


Fig. 5. Changes in electrical resistance for wires C and E stored in marine and land conditions.

The tensile strength test results of five grades of wires stored for 6 months in land conditions are shown in Table 1. No significant change in tensile strength was observed for the three wire grades, labeled B, C and D. Each had similar strength properties, only wire D had a slightly lower tensile strength, but this did not change due to storage. A slight change was observed for the A – copper-plated wire and it was a decrease in strength. It could have been due to the actual decrease in wire cross-sectional area - the equal cross-sectional area of the

wires before and after storage was assumed for the calculations. In contrast, the second copper-plated wire showed an increase in tensile strength of about 60 MPa. Such an increase may be due to the emergence in this wire of a mechanism for strengthening the material under the influence of the environment. From a practical point of view, this is an unfavorable phenomenon - the wire will exhibit increased stiffness as it moves through the rollers in the feeder and through the spiral. This makes it more difficult for it to slide out through the current tip and changes the angle at which it will slide out. This change can be particularly disadvantageous for mechanized workstations, for which changes in weld dimensions will occur, but it will often be difficult to identify the cause of these changes.

Table 1. Tensile strength of wires stored in land conditions.

Wire	UTS of wire at initial state [MPa]	UTS of wire after storage [MPa]
A	695	675
B	599	603
C	599	604
D	565	567
E	613	677

The results of measurements of the diffusible hydrogen content in deposited metal for the padding welds made with wires stored in marine conditions are shown in Fig. 6. The results indicate that although all of the wires were described by the manufacturers as meeting the H5 level, in the state assumed in this research as the initial state - after removal from the package - one of the wires already exceeded this level. The other wires met the requirements for the low-hydrogen process. It can be seen that wire storage affected the diffusible hydrogen content, but the dynamic of these changes was not the same for each wire grade. The A, C and E wires showed an increase in hydrogen content in deposited metal after 1 month, but further storage, which was carried out during the summer months, resulted in changes in the amount of moisture accumulated in the wires and a slight decrease compared to the 1-month results. This suggests the appearance of suitable conditions for local drying of wires. Nevertheless, wire B showed no change after 1 month, and after 3 months a greater increase in diffusible hydrogen content was registered for it. It also underwent partial drying, but only at the last of the recorded times, when the high ambient temperature lasted longer. In contrast, D wire was the only one to show a steady increase in hydrogen content in deposited metal during storage. However, in the initial state it had a very low diffusible hydrogen content, so even after 3 months of storage it made it possible to achieve a low-hydrogen process. Only after 6 months of storage it resulted in an increase above 6 ml/100g.

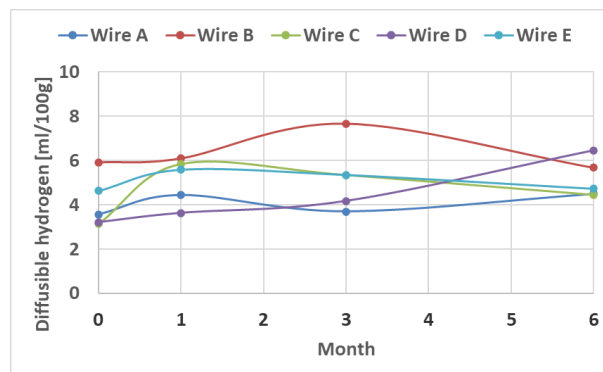


Fig. 6. Diffusible hydrogen content in deposited metal obtained with the use of wires stored in marine conditions.

The results of measurements of the diffusible hydrogen content in deposited metal for the padding welds made with wires stored in land conditions are shown in Fig. 7. The different nature of the changes compared to marine conditions is evident. Under these conditions, after just 1 month, storage of A, B, C, D wires resulted in an increase in the diffusible hydrogen content in deposited metal. For B wire, it was the largest increase and the hydrogen content reached about 9 ml/100g. Further storage - during the summer months - resulted in a decrease in hydrogen content for wires A, B and C. There was still more of it than in the initial state, and the B and C wires still exceeded the H5 level. After 6 months, a strong increase in the diffusible hydrogen content of the padding welds made with the B wire is visible. It exceeded the H10 level and reached an average value of 14 ml/100g. At the same time, for the padding welds made using E wire, the hydrogen content did not change despite exposure to the same conditions as the other wires. Meanwhile, D wire increased the amount of hydrogen gradually, as in the marine conditions, but even after 6 months it only slightly exceeded 5 ml/100g.

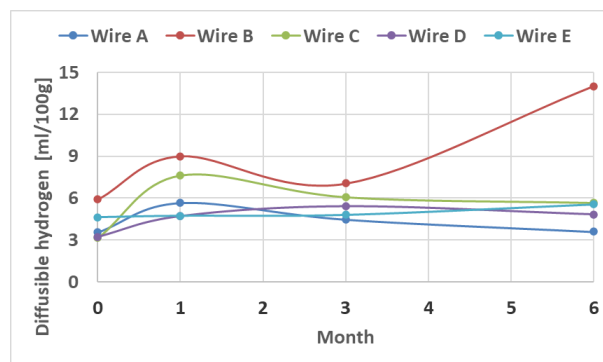


Fig. 7. Diffusible hydrogen content in deposited metal obtained with the use of wires stored in land conditions.

All the rutile flux-cored wires tested, according to their manufacturers, had similar performance properties and are intended for use in the same industry sectors. However, although they appear to be substitutes for each other, their resistance to different environments is not the same. Long-term storage in unfavorable conditions should never occur for welding consumables [12]. But when it does take place, many manufacturers nevertheless choose to use the stored materials, even if they are visually degraded. The conditions presented in

the article are considered to be unfavorable and caused a visual change in surface condition on most of the wires tested. Metallographic examinations revealed that wires not showing damage during visual testing also underwent various forms of degradation. Further tests were conducted on wire parts where surface degradation was not evident. The functional properties of welding wires depend, among other things, on their undisturbed feeding into the welding pool and the possibility of stable arc performance. By determining electrical resistance change, it was found that storage conditions had an effect on the electrical properties of the wires. The most important factor was the grade of wire, followed by the environmental factor and storage time. Measurements of tensile strength of wires allowed to confirm for non-copper-plated wires no noticeable effect of storage on this property. At the same time, for both copper-plated wires, the recorded results indicate that land conditions combined with long storage affect the tensile strength of the wires. An important determinant of the quality of welded joints is the diffusible hydrogen content in deposited metal. For responsible structures, it is recommended not to exceed the H5 level. Among the tested wires, worrying results were already found in the initial state. The padding weld made with the new wire, just after taking it out of the undamaged package, contained about 6 ml/100g of diffusible hydrogen, exceeding the declared H5 level. This wire also showed the largest increase in the diffusible hydrogen amount after storage in land conditions, up to 14 ml/100g. Interestingly, this wire was not the most visually degraded wire among the land conditions. On the other hand, after 6 months of storing D wire in marine conditions, it had the highest diffusible hydrogen content. Significantly, the surface of the same wire on visual inspection appeared completely clean and acceptable for use in welding processes. Meanwhile, heavily surface-degraded in land conditions A and E wires showed only slight fluctuations or gentle increases in hydrogen content measurements. This allows to conclude that the influence of the environment on welding wires can be difficult to predict as well as manifest itself in the change of various features and properties. Inspection of storage conditions for welding consumables, as well as raising awareness among welding personnel, can significantly improve the quality and repeatability of welding works.

4 Conclusions

1. Five different grades of flux-cored wires were exposed to the natural environment in a marine and land locations for a period of six months from spring to autumn.
2. Visual testing of wires showed surface degradation of varying form and intensity, while microscopic examination identified traces of pitting corrosion also on visually undegraded wires.
3. Storage of wires in unfavorable conditions can affect their tensile strength and electrical resistance thus changing the conditions for stable welding arc performance.

4. The diffusible hydrogen content of the padding welds made with two of the wires stored in marine and land locations exceeded the H5 level after just one month, while longer storage also caused the H10 level to be exceeded.
5. There was no clear correlation found between visible surface degradation and changes in the properties of wire or padding weld.

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